Title: 13th Topical Conference on High Temperature Plasma Diagnostics
Scientific Program

Author(s): Cris Barnes, P-24

Submitted to: 13th Topical Conference on High Temperature Plasma Diagnostics
June 18-22, 2000
Tucson, Arizona

Los Alamos
NATIONAL LABORATORY

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13th Topical Conference on High Temperature Plasma Diagnostics

June 18-22, 2000
Tucson, Arizona

Sponsored by Physics Division and the ICF and Radiation Physics Program at Los Alamos National Laboratory and by General Atomics. Endorsed by the American Physical Society and its Division of Plasma Physics and the Offices of Fusion Energy Sciences and Inertial Fusion and the NIF Project of the U. S. Department of Energy.
June 5, 2000


As of my writing this we have 220 registered participants from 15 countries presenting 23 invited talks and 273 contributed posters in 7 sessions. The staff of Reviews of Scientific Instruments, led by new Editor Albert Macrander, are on hand to once again turn out the wonderful conference proceedings issue whose quality makes this a great conference. This should be another excellent meeting in the series of Princeton, Monterey, Rochester, Santa Fe, Hyannis, Lake Tahoe, Hilton Head, Napa, and back to my first in Boston. And I hope you will enjoy Tucson and its many activities despite being the summer solstice in the Sonoran Desert.

I appreciate the endorsements of this conference by the American Physical Society and its Division of Plasma Physics and by the Offices of Fusion Energy Sciences and Inertial Fusion and NIF Project of the Department of Energy. And I am grateful for the sponsorship of the conference by the Physics Division and the Inertial Confinement and Radiation Physics Program at Los Alamos National Laboratory. I acknowledge the help and advice from the conference Organizing Committee and my Local Conference Co-Chair, Robin Snider. Much appreciation goes to the Conference Secretary, Martha Austin; during the week, she and the Los Alamos staff who planned the meeting (LeeRoy Herrera and Angelica Cisneros) will be present and happy to provide whatever help you need to make this a great conference.

Cris W. Barnes
Los Alamos National Laboratory
Local Conference Chairs

Cris W. Barnes
Los Alamos National Laboratory

Robin Snider
General Atomics

Conference Organizers

Alan Costley
ITER Design Diagnostics Group

James P. Knauer
University of Rochester
Laboratory for Laser Energetics

Raymond J. Fonck
University of Wisconsin

Ramon J. Leeper
Sandia National Laboratory

David W. Johnson
Princeton Plasma Physics Laboratory

Neville C. Luhmann
University of California at Davis

Robert Kaita
Princeton Plasma Physics Laboratory

Darlene Markevich
Office of Fusion Energy Sciences, DOE

Robert L. Kauffman
Lawrence Livermore National Laboratory

Thomas J. Murphy
Los Alamos National Laboratory

Christopher J. Keane
Office of Inertial Fusion and NIF Project

Richard D. Petrasso
Massachusetts Institute of Technology

Joseph D. Kilkenny
Lawrence Livermore National Laboratory

Paul Woskov
Massachusetts Institute of Technology
**Monday Morning, June 19**  
**Reflectometry, ECE, RF, Magnetics, Probes, and Runaway Electrons** – Bob Kaita, Chair

### 8:30 a.m. - 10:30 a.m. Presidio Ballroom 5

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
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<td>AI1</td>
<td>Taylor</td>
<td>PPPL</td>
<td>USA</td>
<td>Electron Bernstein Wave Electron Temperature Profile Diagnostic</td>
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<td>AI2</td>
<td>Gilmore</td>
<td>UCLA</td>
<td>USA</td>
<td>Correlation Reflectometry For Magnetic Field And Turbulence Measurements</td>
</tr>
<tr>
<td>AI3</td>
<td>Deng</td>
<td>UC Davis</td>
<td>USA</td>
<td>ECE Imaging Of Electron Temperature And Electron Temperature Fluctuations</td>
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### 10:45 a.m. - 12:30 p.m. Presidio Ballroom 1-4

<table>
<thead>
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<th>Code</th>
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<td>AP1</td>
<td>Silva</td>
<td>EURATOM/ISI</td>
<td>Portugal</td>
<td>Performance Of The Microwave Reflectometry Diagnostic For Density Profile Measurements On ASDEX Upgrade</td>
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<tr>
<td>AP2</td>
<td>Silva</td>
<td>EURATOM/ISI</td>
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<td>Simulation Of Reflectometry Density Profile Changes Using A 2D Full-Wave Code</td>
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<tr>
<td>AP3</td>
<td>Varela</td>
<td>EURATOM/ISI</td>
<td>Portugal</td>
<td>Assessment Of Density Profile Automatic Evaluation From Broadband Microwave Reflectometry Data</td>
</tr>
<tr>
<td>AP4</td>
<td>Bizarro</td>
<td>EURATOM/ISI</td>
<td>Portugal</td>
<td>On A Variational Approach To The Extraction Of Quadrature Signals From Broadband Reflectometry Data</td>
</tr>
<tr>
<td>AP5</td>
<td>Manso</td>
<td>EURATOM/ISI</td>
<td>Portugal</td>
<td>Radar Concepts Applicable To Experimental Results From Microwave Reflectometry</td>
</tr>
<tr>
<td>AP6</td>
<td>Ribeiro</td>
<td>EURATOM/ISI</td>
<td>Portugal</td>
<td>Microwave Reflectometry For Turbulence Studies On ASDEX Upgrade</td>
</tr>
<tr>
<td>AP7</td>
<td>Zeng</td>
<td>UCLA</td>
<td>USA</td>
<td>Implementation Of Reflectometry As A Standard Density Profile Diagnostic On DIII-D</td>
</tr>
<tr>
<td>AP8</td>
<td>Hirsch</td>
<td>IPP Garching</td>
<td>Germany</td>
<td>Doppler Reflectometry For The Investigation Of Propagating Density Perturbations</td>
</tr>
<tr>
<td>AP9</td>
<td>Tokuzawa</td>
<td>NIFS</td>
<td>Japan</td>
<td>Pulsed Radar Reflectometry On LHD</td>
</tr>
<tr>
<td>AP10</td>
<td>Roh</td>
<td>UC Davis</td>
<td>USA</td>
<td>Density Profile Measurements On SSPX Via USPR</td>
</tr>
<tr>
<td>AP11</td>
<td>van Gorkom</td>
<td>FOM</td>
<td>Netherlands</td>
<td>The Ten-Channel Pulsed Radar Reflectometer At The TEXTOR-94 Tokamak</td>
</tr>
<tr>
<td>AP12</td>
<td>Sabot</td>
<td>CEA</td>
<td>France</td>
<td>X Mode Heterodyne Reflectometer For Edge Density Profile Measurements On Tore Supra</td>
</tr>
<tr>
<td>AP13</td>
<td>Lin</td>
<td>MIT PSFC</td>
<td>USA</td>
<td>Experimental And Two-Dimensional Full-Wave Study Of Reflectometry Fluctuation Measurements In The Alcator C-Mod Tokamak</td>
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<tr>
<td>AP14</td>
<td>Kubota</td>
<td>UCLA</td>
<td>USA</td>
<td>Millimeter-Wave Reflectometry For Profile And Fluctuation Measurements On NSTX</td>
</tr>
<tr>
<td>AP15</td>
<td>Solomon</td>
<td>ANU</td>
<td>Australia</td>
<td>Collective Microwave Scattering Diagnostic On The H-1 Heliac</td>
</tr>
<tr>
<td>AP16</td>
<td>Kogi</td>
<td>U. Tsukuba</td>
<td>Japan</td>
<td>Measurement Of Cross-Polarization Scattering Using Ultrashort Pulse Microwaves</td>
</tr>
<tr>
<td>AP17</td>
<td>Garstka</td>
<td>U. Maryland</td>
<td>USA</td>
<td>Fast Broadband Measurements Of Electron Cyclotron Emission In High-Performance Tokamak Plasmas</td>
</tr>
<tr>
<td>AP19</td>
<td>Udintsev</td>
<td>FOM</td>
<td>Netherlands</td>
<td>The New ECE Diagnostics On The TEXTOR-94 Tokamak</td>
</tr>
<tr>
<td>AP20</td>
<td>Domier</td>
<td>UC Davis</td>
<td>USA</td>
<td>3-D Fluctuation Imaging Diagnostic For TEXTOR</td>
</tr>
<tr>
<td>AP21</td>
<td>Hsu</td>
<td>UC Davis</td>
<td>USA</td>
<td>Millimeter-Wave Imaging Array Development For ECE And Reflectometric Imaging</td>
</tr>
<tr>
<td>AP22</td>
<td>Deng</td>
<td>UC Davis</td>
<td>USA</td>
<td>ECE Imaging Diagnostic For TEXTOR</td>
</tr>
<tr>
<td>AP23</td>
<td>Rosenau</td>
<td>UC Davis</td>
<td>USA</td>
<td>Advances In Quasi-Optical Grid Array Technology For Millimeter-Wave Plasma Imaging Diagnostics</td>
</tr>
<tr>
<td>------</td>
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</tr>
<tr>
<td>AP24</td>
<td>Zerbini</td>
<td>Culham</td>
<td>UK</td>
<td>ECE Temperature Measurements In JET Optimized Shear Experiments</td>
</tr>
<tr>
<td>AP25</td>
<td>Mase</td>
<td>Kyushu U.</td>
<td>Japan</td>
<td>Application Of Millimeter-Wave Imaging System To Large Helical Device (LHD)</td>
</tr>
<tr>
<td>AP26</td>
<td>de la Luna</td>
<td>CIEMAT</td>
<td>Spain</td>
<td>Multichannel Electron Cyclotron Emission Radiometry In TJ-II Stellarator</td>
</tr>
<tr>
<td>AP27</td>
<td>Hartfuss</td>
<td>IPP Greifswald</td>
<td>Germany</td>
<td>Extreme Broadband Multichannel ECE Radiometer With “Zoom” Device</td>
</tr>
<tr>
<td>AP28</td>
<td>Kawahata</td>
<td>NIFS</td>
<td>Japan</td>
<td>The 14-Channel Grating Polychromator For ECE Measurements At LHD</td>
</tr>
<tr>
<td>AP29</td>
<td>Zolfaghari</td>
<td>MIT</td>
<td>USA</td>
<td>Measurements Of Internal MHD Fluctuations In PBX-M By An ECE Heterodyne Radiometer</td>
</tr>
<tr>
<td>AP30</td>
<td>Preinhaelter</td>
<td>Czech Acad.</td>
<td>CZ</td>
<td>Propagation Of Electron Bernstein Waves In Spherical Tori</td>
</tr>
<tr>
<td>AP31</td>
<td>Nakamura</td>
<td>U. Tsukuba</td>
<td>Japan</td>
<td>Axial Profile Measurement Of Alfven Ion Cyclotron Eigenmodes</td>
</tr>
<tr>
<td>AP32</td>
<td>Ichimura</td>
<td>U. Tsukuba</td>
<td>Japan</td>
<td>Probe Wave System For Studying Excitation Of Alfven Eigenmodes In The Ion Cyclotron Range Of Frequency</td>
</tr>
<tr>
<td>AP33</td>
<td>Matsunaga</td>
<td>Nagoya U.</td>
<td>Japan</td>
<td>A System For Alfven-Eigenmode-Spectroscopy Using Electrode In CHS Heliotron/Torsatron</td>
</tr>
<tr>
<td>AP34</td>
<td>Matsunaga</td>
<td>Nagoya U.</td>
<td>Japan</td>
<td>Excitation Experiments Of Alfven Eigenmodes By Loop Antennas In The CHS Heliotron/Torsatron</td>
</tr>
<tr>
<td>AP35</td>
<td>Watson</td>
<td>UC Irvine</td>
<td>USA</td>
<td>Fast Wave Density And Species Mix Diagnostic</td>
</tr>
<tr>
<td>AP36</td>
<td>Eom</td>
<td>KAIST</td>
<td>Korea</td>
<td>Heterodyne Wavenumber Measurement Using A Double B-Dot Probe</td>
</tr>
<tr>
<td>AP37</td>
<td>Tsuji-Iio</td>
<td>Tokyo Inst.</td>
<td>Japan</td>
<td>Fiber-Optic Heterodyne Magnetic Field Sensor For Long-Pulsed Fusion Devices</td>
</tr>
<tr>
<td>AP38</td>
<td>Slough</td>
<td>U Washington</td>
<td>USA</td>
<td>Small, High Frequency Probe For Internal Magnetic Field Measurements In High Temperature Plasmas</td>
</tr>
<tr>
<td>AP39</td>
<td>Edlington</td>
<td>Culham</td>
<td>UK</td>
<td>Initial Results From MAST Magnetic Diagnostics</td>
</tr>
<tr>
<td>AP40</td>
<td>Bagatin</td>
<td>RFX</td>
<td>Italy</td>
<td>Integration Of Magnetic And Non-Magnetic Measurements For Current Profile Reconstruction In RFX</td>
</tr>
<tr>
<td>AP41</td>
<td>Sontag</td>
<td>U Wisconsin</td>
<td>USA</td>
<td>Diagnostic Suite Used For MHD Equilibrium Reconstruction On The Pegasus Toroidal Experiment</td>
</tr>
<tr>
<td>AP42</td>
<td>Bak</td>
<td>KBSI</td>
<td>Korea</td>
<td>Diamagnetism Measurements In The Hanbit Magnetic Mirror Device</td>
</tr>
<tr>
<td>AP43</td>
<td>Bak</td>
<td>KBSI</td>
<td>Korea</td>
<td>Performance Test Of Sample Coils In The KSTAR Magnetic Diagnostics Test Chamber</td>
</tr>
<tr>
<td>AP44</td>
<td>Na</td>
<td>Seoul Nat. U</td>
<td>Korea</td>
<td>Real-Time Extraction Of Plasma Equilibrium Parameters In KSTAR Tokamak Using Statistical Methods</td>
</tr>
<tr>
<td>AP45</td>
<td>Lee</td>
<td>KBSI</td>
<td>Korea</td>
<td>Magnetic Diagnostics For Korea Superconducting Tokamak Advanced Research</td>
</tr>
<tr>
<td>AP46</td>
<td>Lee</td>
<td>KBSI</td>
<td>Korea</td>
<td>Triple Langmuir Probe Measurements In The Hanbit Magnetic Mirror Device</td>
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<td>AP47</td>
<td>Ohkuni</td>
<td>NIFS</td>
<td>Japan</td>
<td>Study Of Structural Effects Of Langmuir Probe Array On Edge Fluctuation Measurement In The CHS Heliotron/Torsatron</td>
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<td>AP48</td>
<td>Solomon</td>
<td>ANU</td>
<td>Australia</td>
<td>Composite Mach And Triple Probe For Fluctuation Measurements</td>
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<td>AP49</td>
<td>Rudakov</td>
<td>UCSD</td>
<td>USA</td>
<td>Fast Electron Temperature Diagnostic Based On Langmuir Probe Current Harmonic Detection On DIII-D</td>
</tr>
<tr>
<td>AP50</td>
<td>Fredriksen</td>
<td>U. Tromsø</td>
<td>Norway</td>
<td>Diagnostics Of Electron Temperature Fluctuations In A Turbulent Plasma</td>
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<tr>
<td>AP51</td>
<td>Riccardi</td>
<td>U. Milan</td>
<td>Italy</td>
<td>Comparison Between Fast-Sweep Langmuir Probe And Triple Probe For Fluctuation Measurements</td>
</tr>
</tbody>
</table>
### Monday Evening, June 19

**Engineering, Data Acquisition and Analysis, Diagnostic Suites, Ion Beams, Fast Neutrals - Dave Johnson, Chair**

#### 7:00 p.m. - 8:30 p.m. Presidio Ballroom 5

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Affiliation</th>
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<td>BI1</td>
<td>Voitsenya</td>
<td>IPP Kharkov</td>
<td>Ukraine</td>
<td>Diagnostic First Mirrors For Burning Plasma Experiments</td>
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<td>Sudo</td>
<td>NIFS</td>
<td>Japan</td>
<td>Overview Of LHD Diagnostics</td>
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<tr>
<td>BI3</td>
<td>Bell</td>
<td>LLNL</td>
<td>USA</td>
<td>Target Area And Diagnostic Interface Issues On The National' Ignition Facility</td>
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#### 8:45 p.m. - 10:30 p.m. Presidio Ballroom 1-4

<table>
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<td>BP1</td>
<td>Bilato</td>
<td>RFX</td>
<td>Italy</td>
<td>Singular Spectrum Analysis As A Powerful Tool For Plasma Fluctuations Analysis</td>
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<tr>
<td>BP2</td>
<td>Shi</td>
<td>Central Queensland</td>
<td>Australia</td>
<td>Application Of The Continuous Wavelet Transform To The Fluctuations And Electric Field Analysis In The H-1 Heliac</td>
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<td>BP4</td>
<td>Kukushkin</td>
<td>Kurchatov IAE</td>
<td>Russia</td>
<td>Observations Of Radial Wild Cables In Tokamak Plasmas</td>
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<tr>
<td>BP5</td>
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<td>Kurchatov IAE</td>
<td>Russia</td>
<td>Observations Of Radial Wild Cables In Z-Pinch Plasmas</td>
</tr>
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<td>BP6</td>
<td>Kolbasov</td>
<td>Kurchatov IAE</td>
<td>Russia</td>
<td>Similarity Of Microtubules In Tokamak Dust And Macrotubules In Tokamak Plasma</td>
</tr>
<tr>
<td>BP7</td>
<td>Shurygin</td>
<td>Kurchatov IAE</td>
<td>Russia</td>
<td>Impurity Transport Analysis: Analytical Model For Determination Of Empirical Transport Coefficients From Observations Of Line Emission Profiles In Tokamak Plasmas</td>
</tr>
<tr>
<td>BP8</td>
<td>Beiersdorfer</td>
<td>LLNL</td>
<td>USA</td>
<td>Newly Developed Double Neural Network Concept For Reliable Fast Plasma Position Control</td>
</tr>
<tr>
<td>BP9</td>
<td>Jeon</td>
<td>Seoul Nat. U</td>
<td>Korea</td>
<td>Mass Data Acquisition Systems In JT-60 Data Processing System</td>
</tr>
<tr>
<td>BP10</td>
<td>Matsuda</td>
<td>JAERI Naka</td>
<td>Japan</td>
<td>4K CCD: A Universal Approach To Diagnostic Readout For The National Ignition Facility</td>
</tr>
<tr>
<td>BP11</td>
<td>Sewall</td>
<td>LLNL</td>
<td>USA</td>
<td>Effect Of Film Development On Uniformity And MTF Of GXI And FXI Data</td>
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<tr>
<td>BP12</td>
<td>Kyrala</td>
<td>LANL</td>
<td>USA</td>
<td>Accessing TJ-II Data With RPC</td>
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<tr>
<td>BP13</td>
<td>Sanchez</td>
<td>CIEMAT</td>
<td>Spain</td>
<td>Design Of The National Ignition Facility Diagnostic Instrument Manipulator</td>
</tr>
<tr>
<td>BP14</td>
<td>Hibbard</td>
<td>LLNL</td>
<td>USA</td>
<td>Precision Metrology Of NSTX Surfaces During Installation, Vessel Bakeout, And Plasma Operations Using Coherent Laser Radar Ranging</td>
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<td>BP15</td>
<td>Kugel</td>
<td>PPPL</td>
<td>USA</td>
<td>Millimeter Wave Notch-Filters For Protection Of Microwave Plasma Diagnostics</td>
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<td>BP16</td>
<td>Ermak</td>
<td>IRE</td>
<td>Ukraine</td>
<td>Debris Characterization Diagnostic For The National Ignition Facility</td>
</tr>
<tr>
<td>BP17</td>
<td>Miller</td>
<td>LLNL</td>
<td>USA</td>
<td>Diagnostic First Mirrors For Burning Plasma Experiments</td>
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<td>BP18</td>
<td>Voitsenya</td>
<td>IPP Kharkov</td>
<td>Ukraine</td>
<td>Optical Characterization Of Plasma Facing Mirrors For A Thomson Scattering System Of A Burning Plasma Experiment</td>
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<td>BP19</td>
<td>Orsitto</td>
<td>Culham</td>
<td>UK</td>
<td>Physics Of Tokamak Machines Working In Advanced Regimes And Related Control Diagnostics</td>
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<td>BP20</td>
<td>Orsitto</td>
<td>Culham</td>
<td>UK</td>
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</table>
BP21 Ebisawa ITER JCT Japan Plasma Diagnostics For ITER-FEAT
BP22 Roquemore PPPL USA Diagnostic Requirements For High Power Auxiliary Heating On NSTX
BP23 Wurden LANL USA Diagnostics For A Magnetized Target Fusion Experiment
BP24 McLean LLNL USA Plasma Diagnostics For The Sustained Spheromak Physics Experiment
BP25 Perry LLNL USA Calibration Facilities At Bechtel Nevada - Livermore Operations
BP26 Howard RPI USA Detection Of RF Perturbations Using An Ion Beam Diagnostic
BP27 Lei RPI USA Calibration And Initial Operation Of The HIBP On MST
BP28 Demers RPI USA Suppression Of Plasma Electrons In The Diagnostic Ports Of MST
BP29 Nedzelskiy Euratom/IST Portugal Measurements Of The Plasma Potential By Heavy Ion Beam Probing Using A Time-Of-Flight Method
BP30 Nedzelskiy Euratom/IST Portugal The Modified Biased Split Detector For The HIBP Electrostatic Energy Analyser
BP31 Melnikov Kurchatov Russia Redesign Of The HIBP For ITER-FEAT
BP32 Kamiya JAERI Japan Development Of Mesh-Probe for the Calibration of HIBP Diagnostic System in the JFT-2M Tokamak
BP33 Bondarenko IPP Kharkov Ukraine Installation Of An Advanced Heavy Ion Beam Diagnostic On The TJ-II Stellatator
BP34 Osakabe NIFS Japan Development Of Fast Response Calorie Meter For Neutral Beam Shine-Through Measurement On CHS
BP35 Osakabe NIFS Japan In Situ Calibration Of Neutral Beam Port-Through Power And Estimation Of NB-Deposition Power On LHD
BP36 Fiksel U Wisconsin USA A Diagnostic Neutral Beam System For The MST Reversed-Field Pinch
BP37 Reardon U Wisconsin USA Rutherford Scattering Diagnostics For The MST Reversed-Field Pinch
BP38 Branas Ciemat Spain Atomic Beam Diagnostics For Characterization Of Edge Plasma In TJ-II Stellator
BP39 Medley PPPL USA Design Of The Neutral Particle Analyzer Diagnostic For NSTX
BP40 Costa RFX Italy First Results Of RFX Vertical Time Of Flight
BP41 Isobe NIFS Japan Charge Exchange Neutral Particle Analysis With A Natural Diamond Detector On LHD
BP42 Yamamoto Nagoya U Japan An Application Of Electrically Cooled Si-Detector To Fast Neutral Measurement On CHS
BP43 Hirata U Tsukuba Japan Development Of Novel Ion-Energy Spectrometer Using A Semiconductor Collector Under A Circumstance Of Simultaneously Incident Ions And Electrons With X Rays
BP44 Cho U Tsukuba Japan Simultaneous Observations Of Spatially Resolved Ion And Electron Temperatures Using A Semiconductor Detector Array
BP45 Yoshida U Tsukuba Japan Simultaneous Observations Of Temporally And Spatially Resolved Profiles Of Ion-Confining Potentials And End-Loss Ions
BP46 Hollmann UCSD USA Ion Mass Distribution And Temperature Measurements Using An Omegatron Mass Spectrometer
BP47 Bangke Nanyang Tech U Singapore Elective Laser Induced Plasma Deposition Of Diamond Like Film
Abstract for the 13th Topical Conference
On High Temperature Plasma Diagnostics
Tucson, Arizona
June 18-22, 2000

Electron Bernstein Wave Electron Temperature Profile Diagnostic*
G. TAYLOR,** Princeton Plasma Physics Laboratory, Princeton University

Electron cyclotron emission (ECE) has been employed as a standard electron temperature profile diagnostic on many tokamaks and stellarators, but most magnetically confined plasma devices cannot take advantage of standard ECE diagnostics to measure temperature. They are either “overdense”, operating at high density relative to the magnetic field (e.g. $\omega_{pe} >> \Omega_{ce}$ in a spherical torus) or they have insufficient density and temperature to reach the blackbody condition ($\tau > 2$). Electron Bernstein waves (EBWs) are electrostatic waves which can propagate in overdense plasmas and have a high optical thickness at the electron cyclotron resonance layers, as a result of their large $k_r$. This talk reports on measurements of EBW emission on the CDX-U spherical torus, where $B_o ~ 2$ kG, $\langle n_e \rangle \sim 10^{13}$ cm$^{-3}$ and $T_e = 10 - 200$ eV. Results will be presented for both direct detection of EBWs and for mode-converted EBW emission. The EBW emission was absolutely calibrated and compared to the electron temperature profile measured by a multi-point Thomson scattering diagnostic. Depending on the plasma conditions, the mode-converted EBW radiation temperature was found to be $\leq T_e$ and the emission source was determined to be radially localized at the electron cyclotron resonance layer. A Langmuir triple probe was employed to measure changes in edge density profile in the vicinity of the upper hybrid resonance where the mode conversion of the EBWs is expected to occur. Changes in the mode conversion efficiency may explain the observation of mode-converted EBW radiation temperatures below $T_e$. Initial results suggest EBW emission and EBW heating are viable concepts for plasmas where $\omega_{pe} >> \Omega_{ce}$.

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** In collaboration with P. Efthimion, B. Jones, T. Munsat, J. Spaleta, J. Hosea, R. Kaita, R. Majeski, J. Menard, Princeton University, J. Wilgen, T. Bigelow, Oak Ridge National Laboratory, A. Bers, A. Ram, Massachusetts Institute of Technology
Abstract

Investigation of dual mode (O-X) correlation reflectometry for determination of magnetic field strength

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A new method to measure the internal magnetic field in a plasma, based on cross-correlation of ordinary (O) mode and extraordinary (X) mode reflectometer signals originating from naturally occurring turbulence, is investigated. This method relies on identifying the O- and X-mode frequency pair (f₀, fₓ) where cross-correlation is maximum. Proof-of-principle experiments have been conducted in the LAarge Plasma Device (LAPD), a linear machine with a simple magnetic geometry and well-known magnetic field. Maximum cross-correlation is found to occur at an X-mode frequency slightly lower than the righthand cutoff frequency. It is shown that the magnetic field strength can be determined from reflectometer data interpreted via a one-dimensional numerical model, given estimates of the k-spectral width of the electrostatic plasma turbulence, and the electron density gradient scale length. In addition, preliminary data from the Electric Tokamak at UCLA will be presented, and insights gained from these studies into the fundamental physics of reflectometry will be discussed.

† With W.A. Peebles, and X.V. Nguyen
A novel plasma diagnostic technique, the Electron Cyclotron Emission Imaging (ECEI), has been developed and applied to TEXT-U and RTP tokamaks for the study of electron temperature profiles and fluctuations. Instead of a single receiver located in the tokamak midplane as in conventional ECE radiometers, the ECEI systems utilized the newly developed millimeter wave imaging arrays as the receiver/mixers. Combined with specially designed imaging optics, these compact, low cost arrays have resulted in the excellent spatial resolution of the ECEI systems, and their unique capability of two-dimensional measurements. Using the correlation techniques, ECEI systems have proven to be an extremely useful tool for the measurement of plasma electron temperature fluctuations. Technical details of the diagnostic will be described. Illustrative experimental results will be presented, emphasizing on the plasma fluctuation studies.

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Performance of the Microwave Reflectometry Diagnostic For Density Profile Measurements on ASDEX Upgrade

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ABSTRACT
The broadband reflectometry system on ASDEX Upgrade is now providing density profiles routinely. The plasma is probed from zero density to $n_e = 6.64 \times 10^{19} \text{m}^{-3}$, at the Low Field Side (LFS) with O and X modes, and from $n_e = 0.318 \times 10^{19} \text{m}^{-3}$ to $n_e = 6.64 \times 10^{19} \text{m}^{-3}$ at the High Field Side (HFS) with O mode. Here we assess the experimental results taking into account the expected system performance based on the system design. We address important questions for profile reflectometry: the sensitivity to radial plasma movements; the capability to measure profiles with high and low density gradients; the range of distance that can be measured with each antenna; the access to the plasma core. We analyze the quality of the highest frequency band (75-110 GHz) that is being commissioned and will permit to extend the probing densities to $n_e = 1.5 \times 10^{20} \text{m}^{-3}$ at the LFS. Taking advantage of the unique feature of the diagnostic to probe simultaneous HFS/LFS we illustrate the profile evolution during a MARFE and infer about the deformation of the magnetic field surfaces. We present also the profile asymmetries caused by the injection of pellets from the HFS into ELMy H-mode plasmas. Finally we discuss the importance of the plasma characteristics in determining the final performance of the reflectometry diagnostic.

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Simulation of reflectometry density profile changes using a 2D full-wave code

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ABSTRACT

Broadband reflectometry is used to obtain density profiles in fusion plasmas. The measured quantity is the distance to the cut-off layer whose density is determined by the incident wave frequency. Superimposed on the distance information are perturbations caused by plasma fluctuations and/or local density changes. Due to the combination of those effects the reflected signals can be severely perturbed. In order to understand the signal perturbations observed with broadband reflectometry in ASDEX Upgrade, we are developing a Finite Difference Time Domain (FDTD) two-dimensional full-wave code. This is adequate to describe broadband swept reflectometry experiments and is based on existing fixed-frequency codes. It is modular in order to easily simulate different experimental devices and reflectometry lay-outs, namely different methods of detection and data analysis. Presently it simulates a homodyne detection scheme. The code runs in Linux and Solaris and does not require excessively demanding resources.

Two applications are presented. The first one simulates density profiles featuring edge density changes observed in the reflectometry data of ASDEX Upgrade. A low frequency interference signal is obtained and analysed with the same tools used for the experimental data. The obtained results reproduce important features of the experimental signals and show that local profile changes overcome turbulence effects. In the second case the input profiles feature a time evolving density plateau with decreasing frequency, simulating the effect of a rotating magnetic island coming to lock. The numerical results reproduce the signal perturbations observed in experimental data and are used to show how the relation between the sweep frequency and the island rotation frequency affects the reflected signals. The potentialities of the two-dimensional code to enlighten profile measurements from broadband reflectometry are discussed.

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Assessment of density profile automatic evaluation from broadband microwave reflectometry data

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ABSTRACT

On ASDEX-Upgrade, the automatic evaluation of electron density profiles from broadband microwave reflectometry has been achieved, in all plasma regimes, due to the combination of a high performance system and advanced data analysis tools. The data from the different microwave channels is processed simultaneously to extract the group delay. This permits to take advantage of the phase memory, which is a characteristic of waves propagating in plasmas. Here we assess the performance of the data evaluation process with results obtained in a wide range of plasma scenarios: Ohmic phase, L-phase, ELMy H-mode and plasmas with improved core confinement. Single sweep versus burst-mode analysis (from consecutive sweeps) and the use of data rejection algorithms is illustrated. The detailed density profile evolution is presented, resolving the abrupt gradient changes occurring at the edge and core regions, at the L-H transition and during the occurrence of ELMs. Particularly interesting are the profile asymmetries observed at the high-field side (HFS) and low-field side (LFS). Systematic comparison with density data from other diagnostics is also presented. It is shown that in similar shots, density profiles can be differently disturbed and very often local perturbations appear and disappear suddenly. This reinforces the need to obtain redundant data in very short time intervals (in ASDEX Upgrade, profiles can be measured in 20μs with a repetition rate of 30μs) to apply rejection/averaging procedures that improve the accuracy of the density profiles while still maintaining good temporal resolution.

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On a variational approach to the extraction of quadrature signals from broadband reflectometry data

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A basic problem in broadband reflectometry diagnostics used to measure the electron density profile in fusion devices remains the retrieval of a phase out of the measured data or, equivalently, the construction of a complex signal from the real, acquired one. Recently, arguments have been advanced in favour of the analytic signal, which, in practice, coincides with the more conventional quadrature (or exponential) signal whenever the latter has a clear physical meaning [1]. According to standard models, reflectometry signals are high frequency carriers with slow modulation of amplitude and frequency, whose amplitude and phase are assigned precise and distinct physical interpretations, which thus leads to the quadrature signal as the natural complex form to choose. However, problems arise when the interpretation of the quadrature signal in terms of non-overlapping spectra of amplitude and phase becomes questionable, in which case distinction between these two quantities is, to say the least, a troublesome and ambiguous task.

In this work, a variational method is used that yields the carrier frequency and the so-called in-phase and quadrature components of a real-valued signal (hence, the amplitude and phase of the exponential signal), in such a manner that these components have the smallest possible amount of functional variation [2]. More precisely, for each possible positive value of the carrier frequency, a functional measure for the joint variation of the in-phase and quadrature components is minimized via a standard Euler-Lagrange variational technique, and the outcome is subsequently swept in frequency to look for its minimum value. The idea behind the method is the reasonable assumption that, for given data, those components are expected to be as slow as possible (as they contain the slow modulations of amplitude and phase), while rapid variations are accounted for by the carrier frequency. This new approach is applied to a set of broadband reflectometry signals, its advantages and shortcomings are discussed, and a comparison with the analytic signal is also carried out.


Topic: Reflectometry

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AP4
Radar Concepts Applicable to Experimental Results
From Microwave Reflectometry

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ABSTRACT
Reflectometry uses the radar principle to measure the distance to the cut-off layers, where waves with different frequencies are reflected (density profile measurement). Several techniques have been developed to measure the density profile but it was only recently that a comprehensive analysis of the different methods was presented, based on vacuum radar concepts. Here we quantify the modification of the vacuum values, namely precision and bandwidth of analysis, due to the plasma propagation. We present criteria derived from telecommunications to optimise those parameters and estimate the improvement in profile accuracy, using a numerical analysis. The study is applied to experimental results obtained in ASDEX Upgrade. A set of practical tools is presented that permits to optimise the data analysis for each measurement, without any a-priori assumptions about the shape of the density profile. The results obtained with the optimized analysis (adaptive data processing) are compared with fixed parameter analysis, normally used in the experimental ASDEX Upgrade data. It is shown that fixed parameters give small errors except when the profile exhibits significant changes of the density gradient. We also review the criteria for spatial sampling based on the gradient scale length. It is shown that a higher spatial sampling rate than that foreseen by the vacuum analysis must be employed to reduce the probability of extracting incorrect data points originated by the plasma turbulence.
Microwave reflectometry for turbulence studies on ASDEX Upgrade

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ABSTRACT

The reflectometry system installed in the tokamak ASDEX Upgrade has eleven channels primarily aiming at profile measurements and two dedicated channels operating at fixed frequency to study density fluctuations. The channels used for profile measurements can also be operated at fixed frequency.

In this paper we describe the potential of the system to study important characteristics of the plasma turbulence, from combined fixed frequency and profile measurements (to localize the reflecting layers). The numerical tools used to treat fixed frequency data are briefly described. Using a set of similar discharges and the ability of the microwave reflectometry system to probe simultaneously different layers with several channels, we obtain the time evolution of the integrated power spectra of the different signals versus the minor radius of the plasma. In plasmas with H-mode edge and internal transport barrier (ITB), we could identify a zone at the plasma core and another at the edge with reduced fluctuation levels, coinciding with the increase of central electron temperature and the L-H transition, respectively. Before each barrier is established, the turbulence is observed to decrease at the lower frequency range and is enhanced at the higher frequencies. In modulation ECRH (electron cyclotron resonance heating) experiments similar modifications in turbulence spectra are observed and maybe correlated with the modulation period.
Implementation of Reflectometry as a Standard Density Profile Diagnostic on DIII-D, L. Zeng, E.J. Doyle, W.A. Peebles and T.L. Rhodes, UCLA, T.C. Luce, General Atomics — The profile reflectometer system on DIII-D has been significantly upgraded in order to improve time coverage, data quality and profile availability. Utilizing continuous frequency modulated (FMCW) radar techniques, the system performance has been improved as follows: (1) A PC based data acquisition system has been installed, providing higher data sampling rates and larger memory depth. The higher sampling rate, up to 40 MHz, enables use of faster frequency sweeps of the FMCW microwave source, improving time resolution and increasing profile accuracy by decreasing the effect of turbulence. The larger memory depth enables longer data records, such that profiles can now be obtained throughout 5 s discharges at 100 Hz profile measurement rates. Data can be obtained at variable measurement rates. Continuous sampling is available for high time resolution physics studies (2) Availability of the profiles to end users has been significantly improved. Analyzed profile data are stored in the DIII-D MDSplus database, and can be viewed in the standard DIII-D data viewing and profile fitting packages (ReviewPlus and GA profiles). (3) The flexibility of the hardware system has been enhanced; the Q- (33–50 GHz) and V-band (50–75 GHz) reflectometer systems can be configured to use either O- or X-mode polarization on a day-to-day basis, so as to optimize density coverage. (4) The robustness of the profile analysis code has been improved. The code has been rewritten in IDL and routinely extracts the signal phase (time delay) and inverts edge density profiles.

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AP7
Doppler Reflectometry
for the Investigation of propagating Density Perturbations

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In a Doppler reflectometry experiment the line of sight is chosen to be non-perpendicular with respect to the reflecting layer. In contrast to conventional reflectometry such a diagnostic is sensitive to the wavenumber $K_\perp$ of the density perturbation perpendicular to the magnetic field in the reflecting layer. In analogy to a reflection grating or a scattering experiment $K_\perp$ can be chosen by the tilt angle of the optical axis with respect to the reflecting layer. With a sufficiently high wavenumber resolution (i.e. a large spot size) the antenna selects the +1st respectively the -1st order of diffraction whereas the 0th order which contains the reflectometry information about the radial distance to the layer is suppressed. From the Doppler-shift of the ±1st diffraction orders the propagation velocity $v_\perp$ of the density perturbations perpendicular to the magnetic field can be determined. In addition the intensity of the ±1st diffraction orders contains the information about the equivalent corrugation of the reflecting layer, i.e. the amplitude of the density perturbations.

We investigate the diagnostic capability of Doppler reflectometry both theoretically by the use of 2D full-wave code calculations and experimentally by an antenna system installed at the W7-AS stellarator where the tilt angle with respect to the reflecting layer can be varied.

For the values of $K_\perp$ accessible with the antenna used ($K_\perp \leq 9 \text{ cm}^{-1}$) the Doppler-shift varies almost linearly with the tilt angle. This indicates that the perturbations selected by the antenna belong to a broadband spectrum propagating with a common constant velocity $v_\perp$. This velocity and its radial dependence is in good agreement with the ExB velocity of the plasma measured by passive spectroscopy, indicating that the intrinsic velocity of the electron density perturbations on the background plasma is dominated by the ExB drift. The Doppler reflectometer is able to follow transient states of the plasma with a temporal resolution down to 50 μs. As examples we report about measurements of the spin-up of $v_\perp$ at the transition to the quiescent H-mode or between ELMs as well as about measurements of the sudden reversal of $v_\perp$ if the plasma undergoes a bifurcation to a state with positive radial electric field in the plasma centre ("electron root").
Pulsed radar reflectometry on LHD.
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Pulsed radar reflectometry is the suitable reflectometric technique, in order to study the effect of the strong magnetic shear on polarization of microwave in the Large Helical Device (LHD). Because pulsed radar reflectometry is measured the delay time of the reflected wave, it can be distinguished between X-mode and O-mode polarized wave. At X-mode operation it is found the position of the ergodic edge layer is steady in spite of the increased density in the core region during neutral beam is injected. If the electron density is not reached to the critical cutoff one, the pulsed radar system could be used as a delayometer. The measured delayometer signal is almost in agreement with the numerical calculation using the assumption which the polarization of the propagated wave into the plasma is decided at the edge region, nevertheless the angle of the magnetic field line to the magnetic axis is changed in the propagated direction of the launched wave.
Density Profile Measurements on SSPX via USPR**

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Ultrashort pulse reflectometer (USPR) is under investigation by UC Davis as an advanced diagnostic technique applicable for next generation tokamaks as well as existing physics oriented devices including stellarators, spheromaks and tokamaks [1]. A 48 channel USPR system has been installed on the Sustained Spheromak-Physics Experiment (SSPX) device located at the Lawrence Livermore National Laboratory. USPR involves time-of-flight measurements of extremely broadband, high speed chirped signals. This density profile diagnostic installed on SSPX has extremely wideband coverage extending from 33 to 158 GHz.

The SSPX system utilizes an upconverting mixer approach to USPR, in which an impulse signal is converted into a chirp (or series of chirps) covering a frequency bandwidth of 6-18 GHz. The chirped waveform(s) are amplified, upconverted to millimeter-wave frequencies, propagate into and reflect from the plasma, and are downconverted back to a 6-18 GHz frequency range where further amplification, filtering and detection occurs.

On SSPX, an impulse generator with a 5V, 65 ps (10%-10%) impulse output serves as the signal source. This signal, after propagating through a length of dispersive waveguide, forms a short duration (2-3 ns) chirped waveform with frequency components spanning a frequency range of 6-18 GHz. A set of six waveguide balanced mixers are now utilized to up-convert the low frequency chirp to millimeter-wave frequencies, spanning a total frequency range of 33-158 GHz. A microwave switch matrix directs the low frequency chirp to one of the six mixers, each equipped with highpass waveguide filters to ensure single sideband operation. A sufficiently long (1.1 m) section of overmoded (WR-28) waveguide is placed between the vacuum window and horn to ensure that spurious mixer reflections have sufficient time to damp away before the reflected signals arrives back at the mixer. The down-converted reflectometer signal then passes back through the six-way switch where the waveform is then amplified, divided and filtered into 8 channels. Ultrafast Schottky diode detectors (< 400 ps risetime) convert each filtered wavepacket into ~1 ns FWHM pulses whose time-of-flight is then measured.

Installation of the 48 channel USPR system on SSPX took place in December, 1999. Density profile data are acquired at a rate of one complete profile every 19 s, using constant fraction discriminators and time-to-amplitude converters to make double-pass time-of-flight measurements with ~25 ps (~4 mm) resolution. System details and SSPX density profile data will be presented.

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The advent of advanced tokamak scenarios, one of them being the Radiative Improved (RI-) Mode on TEXTOR-94, as well as a general interest in fast and small-scale phenomena, create a need for density profile and fluctuation measurements at high spatial and temporal resolution in the gradient region of tokamak plasmas. To satisfy this need, a new fast pulsed radar reflectometer has been taken into operation at TEXTOR-94. It measures the electron density in the range of $0.4-4 \times 10^{19}$ m$^{-3}$, by launching 1-ns-long microwave pulses of ten different frequencies in the range 18–57 GHz into the plasma at a 20 MHz pulse repetition rate. The time-of-flight of each reflected pulse, typically between 2–10 ns, contains the information on the position of the reflecting density layer.

The pulsed radar technique is suitable both as a density fluctuation diagnostic and as a density profile diagnostic. For fluctuation studies, the very high measuring rate of up to 10 MHz per channel allows the spatial accuracy to be increased by averaging multiple pulses, even when looking at the highest-frequency fluctuations. In addition, the unique feature of two variable frequency sources will in future allow radial correlation measurements. For density profile measurements, the present reflectometer is unique in both its number of channels and its speed: ten channels, which are all launched sequentially within every 500 ns (i.e., fast enough for the fluctuations to be effectively frozen). This will enable for the first time a detailed reconstruction of the density profile by pulsed radar reflectometry.

First results of both profile and fluctuation measurements will be presented and discussed. The robustness of the profile reconstruction to the influence of density fluctuations is investigated.

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X mode heterodyne reflectometer
for edge density profile measurements on Tore Supra

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This work presents the new V band (50-75 GHz) heterodyne X mode reflectometer installed during the last experimental campaign of the Tore Supra tokamak. This diagnostic is dedicated to the measurements of the edge density profiles.

This reflectometer is based on the scheme developed for a O mode 26-36 GHz reflectometer [1]. The microwave source is a VCO (Voltage Control Oscillator) generating frequencies between 13 and 19 GHz. The output power is then split in two: one to probe the plasma, the second as a reference. The probing wave modulated for heterodyne detection, quadrupled by an active frequency multiplier and launched to the plasma through oversize waveguides. A delay line in a coaxial line is used on the reference arm to compensate the phase delay in the launching guides. The reference signal is then quadrupled and mixed with the signal coming back from the plasma. After band pass filtering, detection is completed by a second demodulation with an I/Q mixer to allow phase and amplitude detection.

The diagnostic demonstrates fast frequency sweep capabilities, up to 20μs, that allows the probing wave to be less sensitive to the plasma turbulence. The signal exhibits then low phase fluctuations and ensures very good profile reconstruction. It can achieve a repetition rate of 5μs between sweeps, so the dynamic behaviour of fast plasma events like MHD mode activity can be followed. High cut-off X mode polarisation reflectometry has been designated for being particularly well suited to edge measurements because the start of the plasma can be precisely identified by the reflectometry data itself, so no assumptions on the shape of the edge profile is required. The diagnostic has been routinely operated and the density profiles were fully automatically calculated to be part of the database of Tore Supra. Measurements over various plasma conditions demonstrate the reliability of the technique.

Experimental and two-dimensional full-wave study of reflectometry fluctuation measurements in the Alcator C-Mod tokamak

YIJUN LIN, J.H. IRBY, R. NAZIKIAN, E.S. MARMAR, MIT PSFC, †PPPL — The amplitude modulated ordinary \((O)\) mode reflectometer in Alcator C-Mod tokamak measures density fluctuations near the plasma edge. Signal amplitudes and phases from both side-bands are recorded by quadrature phase detectors. In Enhanced D\(_a\) (EDA) \(H\)-mode we find experimentally that for the quasi-coherent mode the phase measurements, but not amplitudes are well correlated with fluctuation measurements made with other diagnostics. A new 2-D full-wave code has been developed to simulate \(O\)-mode reflectometry signals from these fluctuations. The code uses the finite-difference time-domain method with a perfectly-matched-layer as the absorption boundary. The Huygens technique is used to generate an incident Gaussian beam and also separate reflected waves from total fields. A simulation based on real geometry and a typical EDA \(H\)-mode plasma profile shows that in C-Mod reflectometer signal amplitude is very sensitive to alignment. In contrast, the phase response is nearly constant as a function of alignment. This result indicates that for our geometry the amplitude does not quantitatively represent the fluctuations. The quasi-coherent density fluctuations level has also been estimated based on reflectometer phase data and the simulation, and will be discussed.

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Millimeter-Wave Reflectometry for Profile and Fluctuation Measurements on NSTX

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A millimeter-wave reflectometry system for electron density profile and fluctuation measurements is being developed and installed on the NSTX spherical torus. The initial frequency coverage will be in the bands 12—18, 20—32 and 33—50 GHz, provided by frequency-tunable solid-state sources. These correspond to O-mode cutoff densities ranging from 1.2x10^{12} to 3.0x10^{13} cm^{-3}, which will span both the plasma edge and core. Rotatable waveguide joints will allow for either O- or X-mode launching and receiving. PC-based fast (100 MHz) acquisition and synchronized sweep control hardware allows the system to be operated in either fixed-frequency mode for density fluctuation measurements, or swept-frequency mode for density profile measurements. A detailed description of the hardware design and data from benchtop testing, as well as preliminary results from a 33—50 GHz test system on NSTX will be presented.

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Prefer Poster Session

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Collective Microwave Scattering Diagnostic On The H-1 Heliac

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A multi-channel microwave scattering diagnostic has been developed and installed on the H-1 heliac. The purpose of the new diagnostic is to study small-scale plasma fluctuations in H-1, which are believed to be responsible for the loss of particles and energy from the plasma. The diagnostic is a 2 mm, 4-channel super-heterodyne receiver system. The transmitter and receiver antennas (consisting of their horns and focusing bi-spherical mirrors) are located inside the vacuum vessel of H-1. A radial resolution of $\Delta r/a \sim 0.2$ is achieved. The scattering volume is positioned at $r/a \sim 0.6$ which is the region of the highest density gradient. At present, the system is aligned to probe fluctuations from approximately $10\text{cm}^{-1}$ to $30\text{cm}^{-1}$. The use of the heterodyne detection system allows the fluctuation propagation direction to be determined. The microwave system uses IMPATT semiconductor technology. The microwave power comes from a CW IMPATT diode, finally producing the 50 mW input power. A central synchroniser unit manages the phasing of the system. The low frequency bandwidth of the system is 1 MHz.
Measurement of Cross-Polarization Scattering Using Ultrashort Pulse Microwaves

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Cross-Polarization Scattering (CPS) method has been proposed for measurement of internal magnetic fluctuations. We have performed the CPS measurement using continuous microwaves as a source, and clarified that the scattering process satisfies wave number matching condition similar to the conventional Thomson scattering. In order to confirm the CPS process, it is also important to eliminate the effect of multi-reflection inside vacuum vessel, since it induces the polarization mixture.

We have applied the CPS measurement using ultrashort pulse microwaves (8 V, 65 ps FWHM). The time-resolved measurement in ps range can distinguish between direct CPS signal and reflected signal at the chamber wall. The ultrashort pulse microwave is amplified and injected into the plasma by an O-mode horn located at the bottom port. The CPS signal and the multi-reflected signal are picked up by an X-mode horn at the top port. The amplified signal is divided into 2 channels. Each channel has a band-pass filter (7 GHz and 10 GHz) and a Schottky barrier diode detector. The square-law detected signals are fed to a digital oscilloscope with 10 GSamples/s.

The signal can be observed only at the 10 GHz channel. The incident O-mode with frequency component of 10 GHz approaches a cutoff layer at the local plasma frequency and is reflected, however, a mode converted X-mode wave propagates through this cutoff layer. On the other hand 7 GHz wave cannot propagate in either mode. The values of time-of-flight are nearly consistent with those calculated considering O-X mode conversion.
Abstract Submitted for the
13th Conference on High-Temperature Plasma Diagnostics
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—Begin Abstract—

**Fast Broadband Measurements of Electron Cyclotron Emission in High-Performance Tokamak Plasmas**

G.D. GARSTKA and R.F. ELLIS, University of Maryland-College Park — The Flexible ECE (FLECE) diagnostic on the DIII-D tokamak allows the measurement of electron cyclotron emission over a broad spectral range. This instrument examines plasma radiation that is split off from the input beamline of the Michelson interferometer and directed by Gaussian optics to an InSb detector. A variety of filters, such as dichroic plates and Fabry-Perot etalons, may be introduced into the optical path to tune the measurement to a desired frequency range. The diagnostic has an ECE bandwidth from 80-300 GHz and a time response up to 1 MHz. The primary application of the FLECE diagnostic is the sub-millisecond determination of electron temperature in plasmas with densities above the second harmonic cutoff by measurement of third harmonic emission with a Fabry-Perot interference filter. Other applications include spectral measurement of runaway electrons, identification of MHD mode numbers in conjunction with the 32-channel heterodyne radiometer, and detection of fast electrons generated by resistive reconnections. Measurements from the FLECE diagnostic are shown to agree quantitatively with those from the Michelson interferometer. Results from measurements made with the diagnostic are presented.

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—End Abstract—

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DEVELOPMENT OF A NOVEL MULTICHANNEL FAST-SCANNING MILLIMETER WAVE HETERODYNE RADIOMETER FOR ELECTRON CYCLOTRON EMISSION MEASUREMENTS AND ITS APPLICATION ON HT-7 SUPERCONDUCTING TOKAMAK

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A novel Fast-scanning Electron Cyclotron Emission (FSECE) system was developed and installed on HT-7 Superconducting Tokamak (R=122cm, a=30cm, Bt-1 S-2.5T). The Measuring frequency of the FSECE system covers overall 2mm wavelength, the system is designed for measuring electron temperature profiles and for measuring superthermal electron cyclotron emission (ECE) from a vertically viewing chord.

The millimetre heterodyne radiometer of FSECE was constructed following an innovatory design principle. It is consisted of three channels of radiometer, which are two channels of single sideband frequency (SSB) radiometer that respond to Upper sideband (USB) and Lower sideband (LSB) individually, and one channel of DSB radiometer, two dual-beam interferometers using metal wire grids are integrated to serve as sideband filters. All three radiometer channels are organically combined to employ the same backward-wave oscillator (BWO) as local oscillator (LO) in 118-178 GHz frequency range, and share input ECE signal from one signal path. FSECE measures 3 resonance frequency points of ECE at each local oscillator frequency point of the total 16 LO frequency points in 118-178GHz, therefore the system measures 48 resonance frequency points of ECE in total. The system temporal resolution is as high as 0.65ms, which is much improved from routine design. The intended measuring frequency positions of FSECE can be changed by program to meet specific physics interests during experiments.

Both horizontal midplane view of plasma in low field side and vertically viewing antenna paths with polarization selection of O mode and X mode are installed to study thermal and nonthermal ECE. Radiometers are roughly calibrated on table by internal mounted noise generator, while relative calibration of radiometers at each frequency point was fulfilled by using of stable and repetitious ohmic plasmas with small variations of toroidal magnetic field to construct Te profiles; absolute calibration of temperature was made comparison against temperatures measured by Soft X ray Pulse Height Analyser (SXPHA) and Thomson Scattering System in the same discharges.

The good performance of FSECE system was testified under different experiments such as LHCD, LH heating, and ICRF heating and pellet injected plasma experiments on HT-7.

The new ECE diagnostics on the TEXTOR-94 tokamak.

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To aid the scientific research programme on the TEXTOR-94 tokamak, the existing Electron Cyclotron Emission (ECE) diagnostics for electron temperature studies are being extended with new systems that feature a good temporal and radial resolution. Perturbations in the temperature profile due to MHD modes as well as the non-thermal electron populations in TEXTOR-94 can now be studied with the new ECE systems.

The present ECE diagnostics on TEXTOR-94 (R₀ = 1.75 m, a = 0.46 m, B < 2.9 T) cover the frequency range of 96 – 180 GHz. A new 16-channel frequency tunable heterodyne radiometer has been installed in the same toroidal position as three already existing 6-channel high-resolution spectrometers (104 – 114 GHz, 125 – 130 GHz and 133 – 148 GHz, sampling rate 25 kHz / 2 MHz). The bandwidth of the 16-channel radiometer is 48 GHz, covering a range from 98 to 146 GHz. Each channel has a bandwidth of 3 GHz. The YIG-tuned oscillators allow tuning of the central frequency over 3 GHz. The sampling rate of the system is up to 2 MHz. The ultra-high resolution of the combination of the new tunable radiometer and three 6-channel spectrometers provides the possibility to obtain temperature profiles within the magnetic islands and to measure microscopic temperature fluctuations throughout the plasma. By changing the distance between the channels, temperature correlation lengths can be measured.

The main ECE diagnostic tool for non-thermal electron observations on TEXTOR-94 is a new combined 2nd (111, 113, 117 and 120 GHz) and 3rd (166, 170, 175 and 180 GHz) harmonic system. This allows simultaneous second and third harmonic radiation measurements at four radial positions in the plasma. The comparison of the second and third harmonic profiles gives the quantitative information about the velocity distribution of non-thermal electrons.

The position of the q = 1 and q = 2 magnetic surfaces can be observed by the ECE systems. A local temperature maximum in the center of the m = 2 magnetic island can clearly be seen. The stabilization of the magnetic islands with NB, ICRH and ECRH is studied.

The density dependence of non-thermal electron loss is investigated. A significant non-thermal electron population with energies up to 150 keV is detected during low-density discharges \( n_e = 0.7 - 0.9 \cdot 10^{19} \text{ m}^{-3} \). The high sensitivity of these non-thermal electrons to small density changes is observed. For \( n_e = 0.8 \cdot 10^{19} \text{ m}^{-3} \) a large generation is detected, whereas for \( n_e = 0.85 \cdot 10^{19} \text{ m}^{-3} \) a strong loss is observed.

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\[ \text{AP19} \]
3-D Fluctuation Imaging Diagnostic for TEXTOR**

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After more than four decades of fusion research, plasma transport in tokamaks remains an outstanding issue. The standard hypothesis, that the observed anomalous transport is caused by small scale turbulence, is consistent with experimental observations but it is neither based on a self-consistent theory of plasma turbulence nor on an exhaustive set of turbulence measurements. One of the major obstacles to the development of a satisfactory anomalous transport theory is the inability of standard fluctuation diagnostics to provide the full spectrum of turbulent fluctuations. The result is a nearly complete reliance on numerical simulations. Unfortunately, in spite of the enormous capabilities of today's computers, this is extremely unsatisfactory since any theory or simulation of plasma turbulence can only be driven by direct experimental observations.

The first step in achieving such data was the highly successful UC Davis Electron Cyclotron Emission (ECE) Imaging system, which was first developed for use on the TEXT-U tokamak and later modified for use on the RTP tokamak [1]. Here, correlation techniques are applied to spatially resolved second harmonic ECE signals to provide detailed information about the microturbulence associated with $T_e$ fluctuations. The present work extends this work by developing a similar technique for spatially resolved $n_e$ fluctuations via microwave imaging reflectometry (MIR). The result is a diagnostic capable of the simultaneous measurement of both $T_e$ and $n_e$ fluctuations (both turbulent and coherent) and profiles on toroidal devices such as tokamaks and stellarators.

A 16 channel ECE Imaging system has recently been installed on the TEXTOR tokamak. A prototype MIR system will be installed on TEXTOR in July, 2000, which will operate in V-band (50-75 GHz) and reflect from the X-mode cutoff. Data collected with this system will be utilized in the design of the full 3-D imaging system, which is scheduled for installation on TEXTOR in April, 2001. System details and laboratory characterization results of the prototype reflectometric imaging system will be presented, along with a preliminary design for the full 3-D system.

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Millimeter-Wave Imaging Array Development for ECE and Reflectometric Imaging**

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Millimeter wave imaging arrays have been successfully developed and utilized in the ECE imaging systems [1], which have proven to be an important new plasma diagnostic technique for measuring plasma electron temperature profiles and fluctuations. Recently, there are much interest in developing imaging reflectometry for the study of plasma density fluctuations, which are expected to resolve the long standing issue of ambiguity in the interpretation of reflectometric data.

These low cost imaging arrays are integrated with slot bow tie antenna and Schottky barrier mixer diodes. Although they are broadband, the behavior of the center lobe has shown limited bandwidth (~15%). To meet the various requirements of different diagnostic systems, it is essential to understand the characteristics of the imaging arrays so that one can have a design guide line. One approach is to use computer simulations to predict the performance of the arrays, and the other is to test various design to build a data base, from which we can choose for different needs, and to assist the computer simulation. Both computer simulation results and test results will be presented.

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ECE Imaging Diagnostic for TEXTOR**

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A 16 channel ECE Imaging system, developed by UC Davis in collaboration with the FOM-Instituut voor Plasmafysica Rijnhuizen, has been installed on the TEXTOR tokamak. The system is designed to collect multichannel electron temperature fluctuation data along a vertical chord of constant magnetic field, by collecting second harmonic X-mode emission. By controlling the frequency of a wideband BWO (tunable from 90-136 GHz) that supplies LO power to the imaging array, the emission layer may be positioned anywhere in the low field side of the plasma.

The TEXTOR ECE Imaging system is based largely on the design of an ECE Imaging system previously installed and operated on the RTP tokamak [1]. As was the case on RTP, the TEXTOR ECEI system shares a port with the FOM Thomson scattering system. Unlike the RTP design, in which the two diagnostics had a common beam path and were separated via a wire grid polarizer, the two systems on TEXTOR must sit side-by-side and therefore each only occupy about half of the available window area. Here, the ECEI system is tilted toroidally by 4.4° with respect to the vacuum window while the Thomson scattering system has a -6.2° tilt. When focused at the plasma center, the ECEI emission locations coincide with that of the Thomson scattering system. This allows for easy calibration and comparison with the Thomson system, similar to what was achieved on RTP.

Installation on TEXTOR took place in March, 2000, with operation to begin in late March. Laboratory testing shows a 3 dB spot size of 12-14 mm has been achieved, with an interchannel spacing of 13-16 mm. System details and TEXTOR fluctuation data collected by ECE imaging will be presented.

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Advances in Quasi-Optical Grid Array Technology for Millimeter-Wave Plasma Imaging Diagnostics**


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The application of reflectometric imaging to fusion plasmas drives a need for low cost, wide bandwidth sources capable of supplying the required 100-500 mW power levels required of the transmit beam. Ideally, it would also be advantageous to have antennas which may be steered in real-time to compensate for changes in plasma shape and/or position. Quasi-optical grid array technology offers a potential solution to both these requirements. A quasi-optical grid array consists of thousands of varactor devices and antennas on a single wafer. Spatial power combining allows an increase in power handling of several orders of magnitude over that provided by single devices. This approach is extremely attractive because of its low fabrication cost, small-size realization and graceful degradation qualities. By utilizing varactor grid arrays to provide frequency multiplication, compact high power microwave sources such as the microwave power module, which produces > 100 W in the microwave (2-18 GHz) region, can be extended throughout the millimeter wave region. This hybrid technology source will provide Watt level cw output power up to G-Band. The output of such a source can then be applied to a quasi-optical phased antenna array.

The concept of monolithic Watt-level diode-grid frequency multiplier arrays was implemented by our group in earlier experiments with grid arrays fabricated on GaAs substrates. A Schottky quantum barrier varactor (SQBV) frequency tripler grid array achieved a maximum output power of 5 W at 99 GHz [1]. Broadband quasi-optical overmoded waveguide frequency multiplier grid array systems have been designed, simulated and are under fabrication with a goal of providing Watt level output powers from 50-200 GHz. Fabrication is nearing completion and test results will be presented at the conference. Proof-of-principle systems using a conventional 10 W Ka-band TWT as the driver have resulted in 410 mW at 63 GHz and 77 mW at 96 GHz.

True time delay (TTD) phased antenna arrays (PAA) have been developed by this group, for eventual use in real-time beam steering of reflectometer imaging systems. A 1x8, 1-D array utilizing Schottky varactor loaded transmission lines has been designed, simulated, fabricated and tested. A prototype broadband 4x4 two dimensional array is presently being designed. Results will be presented at the conference.

Grid arrays of micro-electromechanical systems (MEMS) varactors have the potential to provide low cost, high performance, ultra-wideband, low loss phase shifting elements quasi-optical beam steering arrays. Fabricated on Silicon wafers with traditional IC processing techniques, the physical dimensions of MEMS devices are on the order of a few tens of microns. MEMS devices have been successfully fabricated and tested by our group. Results will be presented at the conference.

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ECE Temperature Measurements in JET Optimized Shear Experiments

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The high performance optimized shear regimes obtained in pulses in which an internal transport barrier (ITB) has been established are presently one of the major topics in magnetic confinement experiments. In these conditions the improved confinement produces high plasma temperatures (Te) and very steep temperature profile gradients.

The Electron Cyclotron Emission (ECE) Te is currently measured at JET with a Far Infrared Fourier Transform Spectrometer (FTS), which provides the Te calibrated value, and with a Heterodyne radiometer, providing Te data with high spatial and temporal resolution.

The capability of these ECE diagnostics to provide reliable measurements during the ITB experiments has been thoroughly checked in preparation for the next JET experimental campaign. The measured Te absolute value has been validated by a cross check of the available measurements, while the measured profile slope has been compared with the intrinsic limits of the diagnostics, validating the ITB location obtained from the radiometer. The possible ECE spectral effects on the final data accuracy and on the cross-calibration between the FTS and the radiometer have been investigated. Special attention has been paid to the possibility of radial energy flow between 3rd and 2nd ECE harmonics, which in some conditions could be relevant from both the diagnostic and the energy balance point of view.

Using these results, possible improvements in the ECE diagnostic system to cope with the future requirements have been studied.
Application of Millimeter-Wave Imaging System to Large Helical Device (LHD), A. Mase, Advanced Science and Technology Center for Cooperative Research, Kyushu University, H. Negishi, Plasma Research Center, University of Tsukuba, Y. Nagayama, K. Kawahata, National Institute for Fusion Science, H. Matsuura, K. Uchida, A. Miura, Teratec Co.

In this paper, we describe the application of millimeter-wave imaging array to Large Helical Device (LHD) at National Institute for Fusion Science (NIFS). In order to cover the frequency range of ECE on LHD, the novel detector using monolithic microwave integrated circuit (MMIC) technology has been designed and fabricated. The detector consists of the integration of a bow-tie antenna, a down-converting mixer using a Schottky barrier diode, and hetero-junction bipolar transistor (HBT) amplifiers on a GaAs substrate. The heterodyne response up to 10 GHz was confirmed at 70-140 GHz. The optics for ECE imaging on LHD are designed by using ray-tracing code. An ellipsoidal mirror and a plane mirror located inside the vacuum vessel converges the ECE signals to pass a fused-quartz vacuum window with 192 mm in diameter. An object plane located at the plasma center is 3.0 m in front of the ellipsoidal mirror. The Airy pattern of a point source is measured in order to confirm the performance of the optical system. The magnification of the optical system is also investigated experimentally, which agrees well with the designed value of 0.68.

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AP25
Multichannel electron cyclotron emission radiometry in TJ-II stellarator.
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Measurements of the electron cyclotron emission (ECE) are routinely used in TJ-II stellarator to obtain the electron temperature profile with good spatial and temporal resolution. TJ-II\(^1\) is a four period helical-axis stellarator with a magnetic field \(B_0 < 1\) T and a bean shaped cross-section with an average minor radius between 0.1 and 0.22 m. Plasmas are produced and heated by two gyrotrons (53.2 GHz, \(P \leq 600\) kW, pulse length < 0.3 s, 2nd harmonic X-mode).

ECE measurements are performed using a 16 channel heterodyne radiometer of the single side-band type. The system is absolutely calibrated. The bandwidth of the system, 49 - 62 GHz, covers the range of second harmonic electron cyclotron emission in X-mode polarization for the different magnetic configurations in TJ-II.

One of the problems for radiometry in TJ-II is that the system must be operated close (in frequency) to the strong ECR heating source (\(\text{ECRH} = 53.2\) GHz). This being especially true for ECRH modulation experiments oriented to power deposition profile and heat pulse propagation measurements. To eliminate the stray signal from the gyrotron, two bandpass filters are used and the second harmonic emission is measured above and below 53.2 GHz separately. In this way, after two discharges, the full temperature profile will be obtained.

The temporal resolution for the ECE measurements corresponds to 20 kHz video bandwidth but can be increased to 100 kHz to study fast plasma phenomenal, like MHD modes, which can appear in TJ-II plasmas where high ECHR heating power is applied\(^2\).

ECE measurements have been performed on a wide range of electron temperatures and profile peaking. In particular, very high temperatures (up to 1.5 keV) with respect to the normal TJ-II operational regimes have been obtained in low-density ECRH discharges\(^3\). The deduced electron temperature profiles are in good agreement with those derived from Thomson Scattering system.

\(^{2}\) I. García-Cortés et al., Nuclear Fusion (to be published)
\(^{3}\) F. Castejón et al., Proc. of the 27th EPS Conf. on Controlled Fusion and Plasma Physics. Budapest, 2000 (to be published)
A new radiometer has been built up for the W7-AS stellarator which consists of a frontend with an extreme broadband mixer, two intermediate (IF) parts with 16 channels each and a novel additional 16 filter section with variable IF. The system was designed with the future W7-X in mind. All settings can therefore be remotely changed.

The frontend consists of the sideband filter, a balanced broadband mixer, a PLL-controlled local oscillator (LO), and low noise preamplifiers. The radio frequency band covers 126 to 162 GHz. The LO frequency is 122.06 GHz, so the IF ranges from about 4 to 40 GHz. The total IF band is split by a diplexer, which is integrated in the mixer block into two IF subbands, 4-18 and 18 to 40 GHz.

The two IF parts generate in the conventional way 16 channels in each of the two subbands using amplifiers, power splitters, and individual band filters, followed by Schottky-diode detectors and video preamplifiers.

The novel additional filter and IF section is fed by either the 4-18 or the 18-40 GHz parts. Any frequency band of 4 GHz width within these bands can be converted in a dual conversion scheme to an IF band of 20-24 GHz with one variable LO signal of 13-19 GHz. Within this band 16 additional filters of 120 MHz bandwidth separated by 250 MHz are positioned.

Considering the complete mixing scheme, these 16 narrow spaced filters can therefore continuously be shifted to any band in the ECE spectrum between 126 and 162 GHz.

With this system a temperature profile is simultaneously measured with 32 fixed channels. The high resolution so-called "zoom" device enables with the narrow spaced additional 16 filters a closer look to any interesting part of the temperature profile.

The system is integrated into the ECE systems at W7-AS. EC radiation is collected using elliptical mirrors in Gaussian optics. W7-AS results will be shown.

The "zoom" device is being installed at DIII-D at the moment. First result will also be shown.

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The 14-channel Grating Polychromator for ECE measurements at LHD
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A 14-channel Grating Polychromator for the purpose of measuring the Electron Cyclotron Emission (ECE) spectrum has been installed on LHD ($R_o=3.75$ m, $a=0.95$ m, $B_o=1.5 - 2.75$ T). The Grating Polychromator in a Czerny-Turner set-up. The main advantage of the Grating polychromator is that it has a broad spectral range. Hence, it can be utilized at different magnetic field strengths. This can be done by changing the grating angle or replacing the grating. Gratings with a grid constant of $d=2.3, 3$ and $5$ mm and a blazed angle of $20^\circ$ can be applied and the scattered spectrum is directed to 14 liquid He cooled InSb diode detectors. Standard operation is performed with $d=3$ mm, $f_{range}=148 - 105$ GHz. This is second harmonic ECE emission for $B=2.75$ T.

Each channel has a spectral resolution of $\Delta f(\text{FWHM}) = 2.6$ GHz or $f/\Delta f = 60$ at $f=150$ GHz. The overlap between each channels is approximately $-27$ dB. In order to prevent a preamplifier dominated noise figure, low-noise ($2.4$ nV/$\sqrt{\text{Hz}}$) broadband pre-amplifiers are directly mounted onto the cryostat. The bandwidth of the pre-amplifiers is $300$ kHz. The properties of the diagnostic will be described in this paper. First measurements of LHD ECE spectra will be presented.

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AP28
Measurements of internal MHD fluctuations in PBX-M by an ECE heterodyne radiometer

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Localized measurements of internal MHD activity in PBX-M have been made using a heterodyne radiometer. The radiometer measures third harmonic optically gray ECE from the center to the outer edge of the plasma on 8 radially localized frequency channels from 112-127 GHz. The radiometer uses a focusing gaussian optics system which provides a vertical resolution of approximately 6 cm throughout the plasma. The radial resolution of the diagnostics is limited by the relativistic broadening to approximately 2-3 cm. Long wavelength ($k<0.5$ cm$^{-1}$) temperature and density fluctuations can therefore be detected using this diagnostic. Correlation techniques have been used on the data to provide fluctuation sensitivity as low as 0.4%. An analytical theory has been developed which relates the measured amplitude of the coherent ECE fluctuations caused by a MHD mode to its mode characteristics. Using this analysis, the MHD mode displacement amplitude $\Delta(r)$ has for the first time been calculated for observed MHD activity in a tokamak plasma. $\Delta(r)$ and $\Delta P/P$ have been calculated for high $n$-number MHD modes in high $-\beta$, PBX-M plasmas. The results of these measurements will be presented.

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\textsuperscript{b}In Collaboration with P. P. Woskov, S. Luckhardt, UCSD, R. Kaita, PPPL.
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Electron cyclotron resonance heating (ECRH) is a highly efficiently heating scheme that is widely used in man experiments. Low aspect ratio spherical tori have many theoretical advantages over the traditional large aspect ratio tokamaks. In particular, there are different plasma regimes to be explored, with low aspect ratio, high $\beta$ with absolute magnetic well and high bootstrap fraction. Moreover, with high-$q_\rho$, one should have reduced disruptive behavior. Concerning transport in spherical tori, microinstabilities should be reduced because of geometric and flow shear properties. It has been shown that a linearly polarized X-mode, launched radially in at the mid-plane from the low-field side, will penetrate into the core of the MAST plasma provided the density is less than $2.5 \times 10^{13} \text{ cm}^{-3}$. The power is then resonantly absorbed in the 2nd and 3rd electron cyclotron. However, for over-dense plasma, this straightforward approach fails since the RF power will be reflected at the cutoffs before it could reach the 2nd and 3rd electron cyclotron regions and be absorbed there in the plasma core. However, for the electron Bernstein wave (EBW) there are no density cutoff limits, and so this wave is well suited to heat an over-dense plasma by resonant absorption. One means of exciting the EBW is by mode conversion from O and X modes. We examine O-X-EBW conversion for frequencies under consideration for operation in MAST: $f = 60 \text{ GHz}$ and $f = 28 \text{ GHz}$, and in particular, we estimate the absorbed power at both these frequencies as well as any constraints on required beam alignment and polarization. For O-X-EBW mode conversion, the transition of the O-mode though the plasma resonance region at oblique incidence is crucial. Two different density profiles are envisaged: (a) a simple parabolic profile with exponential decay in the SOL, and (b) a flat-topped profile with sharp density gradients at the plasma resonance region and SOL. On ignoring toroidal effects, a full-wave investigation of wave propagation in warm inhomogeneous magnetized plasma is performed using finite-elements. The effects of magnetic shear will be investigated. We find that at $f = 60 \text{ GHz}$, the incident wave will pass through the plasma resonance only if the beam is extremely well collimated — if there is an angular beam divergence of even several degrees there will be a very detrimental in power absorption efficient or EBW excitation efficiency. This also holds for the density profiles with very steep gradients. On the other hand, the wave with $f = 28 \text{ GHz}$ readily penetrates the plasma resonance region for arbitrary density profiles and for moderately divergent beams (10-20...). Since the UHR is located near the plasma boundary, the toroidal effects and magnetic shear should have little negligible effect. For circularly polarization and optimal oblique incidence will result in incident mode conversion to EBW of more than 90%. 

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Axial Profile Measurement of Alfvén Ion Cyclotron Eigenmodes

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In the GAMMA10 tandem mirror, ion cyclotron range of frequency (ICRF) waves have been used for the central cell ion heating. In a typical discharge, a temperature anisotropy $T_{\parallel}/T_{\perp}$ (defined as the temperature ratio of perpendicular to parallel to the magnetic field line) exceeds 10. Alfvén ion cyclotron (AIC) modes are spontaneously excited in such a plasma with strong temperature anisotropy. By using the magnetic probe arrays arranged in the axial and the azimuthal directions, the detailed structure of the AIC modes is analyzed. The AIC modes are excited as eigenmodes in the axial direction. It has been expected the AIC modes have standing wave structure near the mid-plane of the central cell. Recently, the node of the standing wave is clearly observed in the axial probe array. The width of the standing wave region depends on the plasma parameters and the nodes move in the axial direction. It is experimentally confirmed the boundary condition for the formation of the standing wave is determined from the plasma pressure. The excitation mechanism of the AIC modes in the GAMMA10 tandem mirror is still unknown. The reflection and/or the mode conversion of the Alfvén waves are suggested.
Subject Classification Category: Fluctuation and Transport Measurement

**Probe Wave System for Studying Excitation of Alfvén Eigenmodes in the Ion Cyclotron Range of Frequency**

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The propagation, absorption, reflection and mode conversion of waves in the ion cyclotron range of frequency (ICRF) in plasmas are of great interest for the plasma heating. The formation of the eigenmodes is important for the excitation of the Alfvén waves in the laboratory plasma. In this paper, the excitation of the Alfvén eigenmodes by injecting low power ICRF waves into the plasma for studying the boundary conditions depended on the spatial profile of plasma parameters is reported.

In the central cell of the GAMMA 10 tandem mirror, the Alfvén ion cyclotron (AIC) modes are spontaneously excited due to the strong temperature anisotropy. The AIC modes are observed as eigenmodes in the axial direction. It is indicated the waves are reflected at the boundary which depends on the plasma beta value. The plasma in the anchor cells which are located on both sides of the central cell has also the strong temperature anisotropy. However, the AIC modes in the anchor cells have not been observed up to the present. To measure the plasma responses in the frequency range of the AIC modes, a probe wave system is constructed in the anchor cell. By using a wide band amplifier (up to 500W) and an antenna matching circuit adjusted in a wide range, the waves with the frequency band of several MHz are injected. It becomes clear the antenna loading decreases in the frequency range around 0.9 times ion cyclotron frequency where the AIC modes have positive growth rate. From the magnetic probe measurement, the resonant peak in the frequency spectrum is observed in the AIC modes range. It is suggested the AIC modes are excited externally in the anchor cell.

Prefer Poster Session

Submitted by

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AP32
A System for Alfvén-Eigenmode-Spectroscopy using Electrodes in CHS Heliotron/Torsatron

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Recently, much attention is paid to Alfvén eigenmodes (AEs) destabilized by fast ions in tokamak and helical plasma. For deeper understanding of AEs, it is important to excite AEs without fast ions and to clarify the structure of shear Alfvén spectra experimentally. From this motivation, we have constructed a system for Alfvén-eigenmodes-spectroscopy in the CHS Heliotron/Torsatron. In this system, four electrodes that are installed near the last closed flux surface (LCFS) are employed as the exciter of AEs and a set of magnetic probes and Langmuir probes as the detector. An Alternating current in the range of 50-250 kHz is driven by an external oscillator between two neighboring electrodes along the specified magnetic filed line of CHS. This current parallel to the confinement field line can effectively induce magnetic perturbations perpendicular to the magnetic field line. This method using the alternating current in a plasma edge is very effective for the excitation of shear Alfvén waves. As the first step, AE-excitation experiment was started in low temperature plasma produced by 2.45 GHz electron cyclotron waves at toroidal field $B_T=0.0875$ T. Typical plasma parameters are as follows: electron density is $\sim 10^{16}$ m$^{-3}$, and electron temperature several eV. For the plasma, one of important AEs, i.e., toroidal Alfvén eigenmodes exist in $\sim 100$ kHz range. Due to low temperature and low density plasma, we are investigating detailed internal structure of excited AEs, inserting magnetic probes and Langmuir probes up to the plasma center. This experiment will be extended straightforward to high temperature plasmas at $B_T=0.9-1.8$ T.
Excitation Experiments of Alfvén Eigenmodes by Loop Antennas in the CHS Heliotron/Torsatron

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In tokamak and helical plasmas, Alfvén eigenmodes (AEs) would be destabilized by fast ions and eventually enhance the loss of the fast ions. For reliable prediction of the excitation of AEs and their effects on plasma performance in a reactor relevant plasma, it is very important to measure the excitation and damping rates. A powerful method to obtain the damping rate experimentally is to measure the response of plasma for externally applied magnetic perturbations.

In the Heliotron/Torsatron device CHS, movable four loop Antennas are installed inside the vacuum vessel to evaluate the damping rate of AEs experimentally. These antennas are arranged in the toroidal direction every 90 degrees to specify the toroidal number (n) of the excited magnetic field perturbations. The toroidal mode number is changed by adjusting the polarity of each antenna current. In CHS, these antennas are used in two ways: one is as four external loop antennas with alternating current (AC) and the other is as two pairs of electrodes between which AC is driven. The latter method can excite larger field perturbation than the former one. In the latter method, all antennas as an electrode are inserted into the plasma edge r/a ∼ 0.9, to induce AC flowing along the magnetic field line of CHS. The plasma response is measured by magnetic probe arrays. Excitation experiment of AEs was carried out in an after-glow of NBI heated plasma. In the after-glow phase, the electron density is monotonously decreased. When the current within the frequency range of 100 to 200 kHz is driven between these “electrodes” of which current polarity is adjusted for n=1 mode excitation, magnetic fluctuations are enhanced resonantly at certain electron density in the density decay phase. The frequency of the fluctuations is proportional to the Alfvén velocity. Thus, excited magnetic fluctuations are thought to be related to AEs. What kinds of AEs are excited is being carried out.
Fast Wave Density and Species Mix Diagnostic,* G.W. Watson, W.W. Heidbrink, University of California, Irvine, H. Ikezi, R.I. Pinsker, General Atomics — Since fast Alfvén waves propagate across a plasma at the Alfvén speed, the plasma mass density can be determined through interferometry. In previous measurements on the DIII-D tokamak, fast waves (~100 MHz, ~5 W) were launched from an antenna at the outer midplane, but detection of the signal was hampered by poor sensitivity of the receiving antenna, which was mounted behind protective graphite tiles on the inner wall. We modified several graphite tiles to act as more sensitive receiving antennas. At lower frequencies (~25 MHz), fast waves can reflect from the ion-ion hybrid cutoff layer. The position of this layer is sensitive to the ratio of hydrogen to deuterium in the plasma. Receiving antennas on the outer wall will measure the hydrogen concentration through reflectometry. Launching other frequencies may yield impurity density ratios as well. These techniques may be useful for measuring relative densities of D, T, and alpha particles in burning plasmas.


Heterodyne wavenumber measurement using a double B-dot probe

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An in-situ method of wavenumber measurement inside a helicon plasma has been developed using a double B-dot probe with a heterodyne detection scheme. Each probe in the double B-dot probe measures wave magnetic field and the signals from the two separately located probes inside the plasma are mixed with a local oscillator signal transforming the signals into TTL signals with intermediate frequency. The phase difference is obtained by a phase comparator yielding wavenumber information of a plasma wave.

1This work supported by Korea Basic Science Institute.
Fiber-Optic Heterodyne Magnetic Field Sensor
for Long-Pulsed Fusion Devices

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Accurate measurements of magnetic fields around the plasma are indispensable for real-time control and data analysis in magnetic fusion devices. Commonly used inductive pickup loops suffer from zero-point drifts of long-term integration. A fiber-optic polarimeter has been developed as a magnetic field sensor for long-pulsed fusion devices. The frequency-shift heterodyne technique with the use of acousto-optic modulators (AOM) was adopted to measure the Faraday effect with high resolution and stability. The method is insensitive to beam ellipticity and laser power fluctuations and robust against common-mode refractive effects.

The wavelength of laser beam was chosen to be 850 nm since the radiation-induced loss in optical fibers is significant below 800 nm while the shorter wavelength, the larger Faraday rotation angle we get. Various optical components for 850 nm are commercially available. The laser beam is split to pass through two AOMs and then recombined such that two slightly frequency offset components are polarized perpendicularly to each other. After propagation in polarization-maintaining fiber, the recombined beam is passed through a 1/4 wave plate to generate counter-rotating circularly polarized beam components and launched to a sensor rod. The beam emerging from the rod is passed through a polarizer and detected to give an oscillating signal at the beat frequency that suffers a phase retardation proportional to the Faraday effect.

By the use of a distributed Bragg reflector laser diode and a Faraday isolator, excellent stability of phase measurement was attained. The phase resolution was raised to up to 0.01 deg. by the digital complex demodulation and digital band-pass filtering of the beat signals.

Although the Verdet constant of heavily Tb³⁺-doped paramagnetic glass is larger than that of ZnSe by about a factor of 1.4, ZnSe is superior to the former in terms of negligible temperature dependence. With a 40-mm long ZnSe sensor rod, a resolution of the magnetic field strength of about 1 gauss was found to be possible in several-hour measurements. The evaluation of the ellipticity of polarization and its effect on the Faraday rotation is under study.

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AP37
Small, high frequency probe for internal magnetic field measurements in high temperature plasmas.

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Abstract

In previous experiments on high temperature (>50 eV), high density (>10^{20} m^{-3}) plasmas such as the field-reversed configuration (FRC), it has not been possible to obtain direct information of the internal field structure in a non-destructive way. The reason for this was two-fold: the probe surface would vaporize due to high electron thermal transport as well as ablate due to high energy ion bombardment, and the thermal absorption of the probe itself would limit energy confinement. Typically, after a few to several μsec of exposure, the plasma impurity radiation, or the probe thermal loading would dramatically alter the plasma confinement and structure. In order to minimize these processes, the smallest possible probes made from materials with the longest thermal time to boiling, \( \tau_b \), were constructed and tested. It was found that in order to measure fast magnetic field changes (~ several MHz), as well as not influence the FRC internal electric fields, the wall material had to be constructed from a non-conducting material. Of the insulating materials tested, Berylia was the only material that was found to be suitable. The final probe’s small bore (1 mm ID, 2mm OD) minimized the thermal transport from the plasma to the probe to a level negligible compared to the thermal losses observed without the probe present. In order to measure magnetic fields as small as a few gauss with cm resolution, several loop turns were employed for each B-dot probe. Since there was little room for a winding structure inside the small bore, a chain probe was constructed out of 50 μm diameter magnet wire. A 2 axis, 24 element probe was constructed to measure the principle axial and azimuthal FRC magnetic field components. A 3 axis probe was also constructed, but the third axis was found to be unnecessary. The probe array was used to measure the internal fields of FRCs to as small as a few gauss with a frequency response of ~ 5 MHz. With the probe inserted, no changes in FRC confinement or behavior were observed over the entire lifetime of the discharge (up to 1 msec).
Initial results from MAST Magnetic diagnostics  
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The MAST (MAmpere Spherical Tokamak) experiment is a new, large, low aspect ratio device ($R \sim 0.7m$, $a \sim 0.6m$, $B_T \sim 0.5T$) operating its first experimental physics campaign. Designed to study a wide variety of plasma shapes with up to 2 MA of plasma current with an aspect ratio down to 1.2, the PF coils used for plasma formation, equilibrium and shaping are all inside the main vacuum vessel. To control the experiment and to investigate a wide range of plasma phenomena, an extensive set of magnetic diagnostics have been installed inside the vacuum vessel. More than 600 vacuum compatible, bakeable diagnostic coils are configured in a number of discrete arrays close to the plasma edge with about half the coils installed behind the graphite armour tile covering the centre rod. The coil arrays measure the toroidal and poloidal variation in the equilibrium field and its high frequency fluctuating components. Internal coils also measure currents in the PF coils, plasma current, stored energy and induced currents in the mechanical support structure of the coils and graphite armour tiles. The latter measurements are particularly important when halo currents are induced following a plasma termination, for example when the plasma becomes vertically unstable.

The paper will describe the MAST magnetic coil set and the methodology used to build, commission and calibrate the various coil sub-systems. The way in which the coil data is used to control the plasma equilibrium will be described and data from the first MAST experimental campaign will be presented. This will include examples of plasma equilibria, reconstructed from magnetic data and current measurements after the shot using EFIT\(^1\), measurements of halo currents in the vessel structure during plasma terminations and measurements of the structure of magnetic field fluctuations near the plasma edge. Initial experiments have explored the ST ohmic operating regime. High power ECRH and Neutral beam heating are used to extend the parameter range of the device and magnetic measurements will be presented showing MHD and halo current behaviour for these regimes.

\(^1\) L.Lao et al., Nuclear Fusion 25,1611 (1985)

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Integration of magnetic and non-magnetic measurements for current profile reconstruction in RFX.

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A crucial issue in magnetically confined plasmas characterized by relevant internal current redistribution, such as Reversed Field Pinches (RFP) or Compact Torii, is the determination of their internal magnetic structure. Non-magnetic internal measurements, like multichord far infrared polarimetry (FIR), can give additional constraints to the set of direct magnetic measurements provided by the pick-up coils located outside the vacuum vessel. These new constraints have to be carefully included in the codes used to reconstruct the global field topology.

The presented model considers a plasma described by stationary MHD ideal equations, in which the unknown toroidal and poloidal plasma currents are represented by properly distributed discrete filaments and current sheets respectively. A similar scheme is applied also to the vessel, the shell and the winding systems. At first, a determination of the discrete current sets is provided by the model which uses as input data the total currents in the plasma, in the windings, in the vessel and in the shell, as deduced by the relevant loop voltages. Then, the obtained filamentary currents sets are progressively adjusted by imposing further constraints, which modify the internal current profiles. A constraint is derived from the FIR polarimeter measurements, which impose an integral condition for each implemented measurement chord. A further correction to the current profile is then realized by using the local magnetic field measurements given by external pick-up coils.

The model is validated on a wide experimental database obtained in the RFP experiment RFX. The results are then compared with those obtained with different reconstruction methods. Future developments involving the use of additional measurements about to be implemented in RFX are finally discussed.

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Diagnostic Suite Used for MHD Equilibrium Reconstruction on the PEGASUS Toroidal Experiment*

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Magnetic equilibrium reconstruction on the PEGASUS Toroidal Experiment is a crucial tool to determine macroscopic plasma parameters, such as geometry, $\ell$, $\beta$, and $q$. These parameters are tightly coupled to the plasma shape due to the very high toroidicity in PEGASUS where $A = 1.1 - 1.3$. A systematic scan of model plasma parameters in a magnetic equilibrium code has been employed to determine an acceptable array of diagnostics for accurately characterizing the plasma equilibrium. The magnetic diagnostics used include a poloidal array of magnetic pickup coils and flux loops along with a Rogowski loop for the toroidal plasma current. A 270 GHz $\mu$wave interferometer for line averaged density in conjunction with spectroscopic temperature estimates provide a central pressure constraint. Visible images of the plasma provide constraints on the plasma size and location. A 1-D SXR camera is being developed to provide a measurement of the magnetic axis location. A time evolving current filament model and wall flux loops are used to determine the induced currents flowing in the continuous, resistive vacuum vessel wall. The ability of the equilibrium reconstruction code to reproduce model equilibria using this diagnostic set provides a quantitative measure of the accuracy of these equilibrium reconstructions. A Monte Carlo analysis with Gaussian noise added to the model data tests the robustness of this technique. A comparison of the model equilibria with the reconstructions obtained using noisy data is shown.

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End of Abstract

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AP41
Diamagnetism Measurements in the Hanbit Magnetic Mirror Device.* J. G. Bak, S. G. Lee, J. I. Chung and M. Kwon National Fusion R & D Center, Korea Basic Science Institute. For the estimation of plasma pressure in the Hanbit magnetic mirror device, diamagnetism was measured by a diamagnetic loop in the central cell of the device. The measurements were carried out during RF discharge with frequency of 3.75 MHz and heating power of up to 200kW. Magnetic field is 1.26 kGauss in the central cell. In order to obtain the further reliable data from the loop signal, a compensation loop was additionally installed at the same position that the main loop is located. The recent results from the measurements will be discussed.

* Work supported by the Ministry of Science and Technology of the Republic of Korea.

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Performance Test of Sample Coils in the KSTAR Magnetic Diagnostics Test Chamber.* J. G. Bak and S. G. Lee National Fusion R & D Center, Korea Basic Science Institute. Most of the KSTAR magnetic diagnostics are proposed to be installed inside of the vacuum vessel which is baked out up to 250 °C, and base pressure will be \( \sim 5 \times 10^{-9} \) Torr. Therefore, magnetic diagnostics must be compatible with the KSTAR vacuum vessel conditions. A magnetic diagnostics test chamber (MDTC) is fabricated to test sample coils under similar conditions with the KSTAR vacuum vessel. Experiments such as the performance test of the samples in the MDTC, calibration and frequency characteristics of the samples are carried out, and the results from these works will be presented.

* Work supported by the Ministry of Science and Technology of the Republic of Korea.

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Fast extraction of plasma equilibrium parameters is required for real-time tokamak plasma control. Recently, the statistical methods such as neural network and functional parameterization have been successfully applied. In this study, for the extraction of the plasma equilibrium parameters, various statistical methods are employed and compared. Two typical statistical methods, neural network and functional parameterization, are applied and tested. Also, new concepts of statistical methods such as double network are attempted and compared with conventional techniques. For the determination of the eight output plasma equilibrium parameters, $R_{0}$ (major radius), $a$ (minor radius), $R_{X}$ (X-point radial position), $Z_{X}$ (X-point vertical position), $\kappa$ (elongation), $\delta$ (triangularity), $\beta_{p}$ (poloidal beta), $l_{i}$ (internal inductance), measurements of the normal and the tangential magnetic probes and the magnetic flux loops are utilized for those statistical methods. The equilibrium database of KSTAR equilibria is prepared for tests by using Tokamak Simulation Code (TSC).

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Magnetic diagnostics are essential tools for operation and control of the Korea Superconducting Tokamak Advanced Research (KSTAR) device and for understanding the plasma behavior. The basic approach for the development of magnetic diagnostics for KSTAR is to use standard inductive sensors, which have been proven in operation of existing many tokamaks and employ advanced integrator technology for long-pulse operations. A conceptual design and preliminary engineering design (PED) milestones were already achieved, and an engineering design is under development. Finished PED and current engineering design status of the KSTAR magnetic diagnostics will be presented.

* Work supported by the Ministry of Science and Technology of the Republic of Korea under the KSTAR project contract.
Tripole Langmuir probe measurements in the Hanbit magnetic mirror device,* S. G. Lee and J. G. Bak National Fusion R & D Center, Korea Basic Science Institute. Triple Langmuir probe data were measured in the edge of the central cell of the Hanbit magnetic mirror device. The measured data were obtained during RF discharges which has a frequency of 3.75 MHz with heating power up to 200 kW. Measurements of the electron temperature, density and floating potential were made in a radial scan of the plasma. Measured data and the techniques employed to get these data will be discussed.

* Work supported by the Ministry of Science and Technology of the Republic of Korea.
Study of Structural Effects of Langmuir Probe Array on Edge Fluctuation Measurement in the CHS Heliotron/Torsatron

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Edge plasma turbulent study is regarded as one of the most important issues of the plasma confinement, because plasma turbulence in the edge region often affects the global plasma confinement such as H-mode. Langmuir probe is a very convenient tool to measure the plasma parameters and their fluctuations in edge plasma region with high temporal and spatial resolutions. Moreover, this is a powerful diagnostic method to evaluate the electrostatic fluctuation induced particle and heat fluxes. But it must be used carefully to measure correctly. A Langmuir probe array is installed on the CHS heliotron/torsatron for the study of edge plasma turbulence. The probe array consists of four sets of probes. Each probe set is displaced slightly both in toroidal and poloidal direction to minimize the shadow effect each other. The radial separation of four probe sets makes it possible to measure the radial profiles of plasma parameters in one discharge. Each probe set has four electrodes that are made of molybdenum rod with 0.5 mm diameter and 2.0 mm length. They have an alumina and molybdenum sleeve which isolate them electrically each other and protect them against the plasma bombardment. Each set works as a triple probe. Floating potentials are measured at two positions that are separated by 4.5 mm in the poloidal direction. Fluctuation of poloidal electric field that is needed to calculate the radial particle and heat flux, is estimated from the difference of these floating potentials. Using this probe array, edge plasma parameters from r/a = 0.9 to 1.1 are measured which is moved radially shot by shot in NBI-heated plasmas. Inward particle fluxes are observed in the region of r/a = 0.93 - 0.96. Reduction of the fluxes is brought about by suppression of turbulence, decorrelation of electron density and plasma potential fluctuations or the change of relative phase between them, but the observed inward fluxes are only caused by the change of the relative phase. In order to investigate the structure effect of a probe array on fluctuation measurement, these results are being compared with those previously obtained by four sets of probes which are separated radially and poloidally without the above-mentioned toroidal separation.
Composite Mach and Triple Probe for Fluctuation Measurements W. M. Solomon, M. G. Shats, Plasma Research Laboratory, Research School of Physical Sciences and Engineering, Australian National University A new probe consisting of two poloidally separated triple probes and a Mach probe (TMT probe) has been designed and installed on the H-1 heliac to study fluctuations. Mach probes have been shown to be sensitive to the fluctuations in the plasma parameters of density, electron and ion temperatures, and ion drift velocity \((n, T_e, T_i, V_d)\). If the ion Larmor radius is much larger than the characteristic probe dimension, then the Mach probe is insensitive to the magnetic field. In this regime, the Mach probe can be rotated such that the two tips are separated radially and it becomes sensitive to the radial velocity of the ions. By determining the fluctuating quantities of the radial velocity, electron and ion temperatures, and density, the fluctuation-driven particle and thermal fluxes can be estimated. As the Mach probe provides two ion saturation currents, this is not sufficient to solve the time-resolved signals of the aforementioned plasma parameters. However, by incorporating two triple probes that are located on the same flux surface as the Mach probe, these quantities can be unravelled. A model has been devised to allow
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Category Number and Subject:
[ ] Theory [x] Experiment

Fast Electron Temperature Diagnostic Based on Langmuir Probe Current Harmonic Detection on DIII-D,* D.L. Rudakov, J.A. Boedo, R.A. Moyer, R.D. Lehmer,† G. Gunner, University of California, San Diego, J.G. Watkins, Sandia National Laboratories — A method for the measurement of electron temperature with high spatial and temporal resolution was recently implemented on a fast reciprocating probe on the DIII-D tokamak. The technique, previously used on TEXTOR,1 is based on detection of harmonics generated in the current spectrum of a single Langmuir probe driven by high-frequency sinusoidal voltage. On DIII-D the method was implemented with improvements such as fully digital processing and active voltage feedback. The probe was driven at 400 kHz thus allowing temperature measurements with a bandwidth of up to 200 kHz. Probe voltage and current were recorded at high sampling rate (5 MHz) to perform digital analysis. The first (400 kHz) and the second (800 kHz) current harmonics were then extracted by digital filtering and their amplitudes detected. Those were also detected in parallel by analog circuits for comparison and feedback. Digital processing proved to be superior to analog detection since it did not introduce any phase delays, making the technique suitable for correlation measurements. Initial results from DIII-D show good agreement with swept double probe and Thomson scattering data. The technique was shown to be capable of measuring all the factors contributing to the turbulent (conductive) heat flux.

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Diagnostics of electron temperature fluctuations in a turbulent plasma

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Measurements of fluctuations have been performed in the steady-state magnetoplasma BLAAMANN[1] characterized by a turbulent regime. In such a plasma electron temperature fluctuations can be of the same order of the floating potential ones when the plasma is produced at a quite high neutral pressure. In this work an extensive analysis of the fluctuation levels and of the spectral properties of the electron temperature fluctuations has been carried out and compared with those of the floating potential. A triple probe has been used as a diagnostics and the Beall's technique has been applied in order to study the spectra and the phase between the floating potential and the electron temperature fluctuations. The main goal of this work is related to the possibility to identify the nature of the instabilities occurring in such a plasma with reasonable accuracy, by measuring the phase shift between the density and plasma potential fluctuations.

Comparison between fast-sweep Langmuir probe and triple probe for fluctuations measurements.

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Fluctuations have been investigated both in the plasma core and in the edge region of “Thorrello”, a small toroidal device (minor radius $a=8$ cm and major radius $R=40$ cm) which produces a magnetised plasma in steady-state condition without rotational transform (typical plasma parameters are: $n \approx 10^{11}$ cm$^{-3}$; $T_e \approx 2$ eV; $B = 1500$ Gauss).

In our experiment fluctuations have been measured by means of two methods: triple Langmuir probe and fast-sweep Langmuir probe. [1] [2] A novel, fast-sweep Langmuir probe, has been recently constructed to operate on “Thorrello”. It is a new apparatus based on a new dual channel circuit that compensates for stray capacitance and permits sweep speeds up to 400 kHz, so we can investigate the electrostatic turbulence with good temporal resolution. An automatic fitting procedure, which minimizes the chi-square function, has been developed to analyze the time dependent data. In this way, with these two techniques, we can know simultaneously electron temperature, density and floating potential, as well as their fluctuations.

In this work we want show the reliability of our new apparatus comparing the results with those obtained with the conventional triple probe method. The new apparatus reveals clear advantages, such as: more details of fluctuations in time, the use of just one probe tip avoiding to consider phase delay and shadow problems between different tips and the calculation of error bars to the $\bar{T}_e$ measurements by means of a transparent statistical data analysis. This method is usefull when electron temperature fluctuations are not negligible: in this case the measurement of $\bar{T}_e$ is essential for obtaining a correct interpretation of density and potential fluctuations.

A study on the modification of density and plasma potential in presence of electron temperature fluctuations.

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Electron temperature fluctuations have been investigated in the plasma of "Thorelo" , a small toroidal device (minor radius a=8 cm and major radius R=40 cm) which produces a magnetised plasma in steady-state condition without rotational transform (n \approx 10^{11} \text{ cm}^{-3}; T_e \approx 2 \text{ eV}; B = 1000 \text{ Gauss}).[1] In our experiment two techniques are applied to estimate \( \bar{T}_e \): triple Langmuir probe technique and fast-sweep Langmuir probe method, in both cases, varying the density of the neutral source term (in our plasma, H\textsubscript{2}). The so called triple probe is the conventional method used to investigate \( \bar{T}_e \), while fast-sweep Langmuir probe is a new diagnostic technique recently developed on "Thorelo"[2]. Our measurements have been performed in the frequency range between 0 and 500 KHz. The turbulent plasma exhibits a spectrum quite broad in frequency: power spectra of floating potential and density show the characteristic frequencies are in the range 0-100 KHz, while power spectra of electron temperature can extend up to 150/200 KHz. In the plasma core relative levels of electron temperature fluctuations are about 20\%, but in the edge region these relative levels raise up to 50\%. In situations where electron temperature fluctuations are not negligible, the measurement of \( \bar{T}_e \) is essential for obtaining a correct interpretation of density and potential fluctuations. In our case the level of electron temperature fluctuations is not negligible in the edge region and it was possible to separate \( \bar{T}_e \) and \( \bar{n} \) according to the hypothesis
\[
\frac{\bar{T}_e}{\bar{n}} = \frac{1}{2} \frac{T_e}{n}
\]
and to the theory of thermal drift wave turbulence. Then we can particularly compare the mean values of \( T_e \), the level of temperature fluctuations measured in the same plasma, the power spectrum and the correlation between temperature, density and potential fluctuations applying the digital correlation technique.[3]

A synchrotron radiation diagnostic to observe relativistic runaway electrons in a tokamak plasma.

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For electrons with suprathermal energies, the collisional drag decreases strongly with velocity. These electrons might experience a net acceleration in the presence of a static electric field, such as present in a tokamak to drive the plasma current. In present day devices these runaway electrons are confined long enough to gain energies of the order of several tens of MeVs. At these energies they emit synchrotron radiation in the (near) infrared wavelength range which can easily be detected by thermographic cameras.

Runaway electrons are investigated for several reasons. For future fusion reactors, it is of major importance to know the processes of runaway generation and runaway loss after disruptions, because of the severe damage the local loss of large amounts of these highly energetic electrons may cause on first wall components. Secondly, since the runaway electrons are effectively collisionless, their confinement is determined by the magnetic field turbulence. In this way the runaway transport provides a unique opportunity to probe turbulence in the core of a thermonuclear plasma.

For these studies the synchrotron radiation is the most powerful tool to diagnose the relativistic runaway electron distribution. This diagnostic provides a direct image of the runaway beam inside the plasma. From the spectral features the runaway energy can in principle be obtained, the intensity of the radiation is a measure of the number of runaway electrons, and the shape of the synchrotron spot exhibits information about their perpendicular momentum.

At the medium sized circular limiter tokamak TEXTOR-94 (major radius R₀=1.75 m, minor radius a=0.46 m) runaway electrons are studied with a thermographic camera detecting this synchrotron radiation. This camera operates in the wavelength range of 3-8 μm and has a full poloidal view. Runaway electrons with energies of 25-30 MeV have been observed in low-density steady state discharges as well as during disruptions. Information about runaway generation mechanisms, runaway snakes, runaway losses in stochastic fields and scale size of magnetic turbulence could be deduced using this synchrotron radiation diagnostic.

Based on the experience at TEXTOR-94 the feasibility of a similar synchrotron diagnostic on ITER is discussed. The maximum emission is expected in the wavelength range from 1-5 μm. A runaway current of about 10 kA will already be detectable. The steep short wavelength slope of the synchrotron emission makes it possible to determine the maximum runaway energy by a measurement at only two different wavelengths. The compatibility with an already planned IR wide angle viewing system is investigated.

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AP53

In tokamaks, high energy runaway electrons have been used as a tool to probe the magnetic topology. Average values of magnetic turbulence parameters, such as the radial extent of the ergodic region were deduced from the transport characteristics of runaway electrons in the TJ-I tokamak [1 and references therein]. In currentless stellarator devices, runaway electrons can also be generated during the field coils ramp-up and they may stay confined all along the steady state pulse [2]. The TJ-II flexible heliac has a high magnetic configuration flexibility and the diagnostic capability to study high energy electrons is quite powerful [3]. As well, in this device, the location of resonant surfaces near the plasma periphery can be experimentally determined, with an excellent spatial resolution, using a fast moving Langmuir probe array [4]. Recently, we have obtained experimental evidence that electrons with energies above 70 keV are confined in a narrow radial region close to the m/n=8/5 rational surface, located near the plasma edge [5].

In this work we present the experimental set-up, combining edge and x-ray diagnostics, used to characterize the currents generated by fast electrons confined near the plasma periphery in TJ-II plasmas. Whether or not these electrons may have a relevant influence on the neighbour region, namely on the sheared poloidal flows involved in the formation of internal transport barriers in magnetically confined fusion plasmas, is under investigation. A major issue in this context is to determine the effects of their associated current on the local transport plasma parameters.

ABSTRACT

Fluctuations of magnetic field in tokamak and measurement of electrons distribution function.

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X-Ray spectrums of suprathermal electron distribution function suggestion be used for measurement anomalous diffusion. Anomalous diffusion of electron in stochastic magnetic field is considered. The effects of conditional correlations are taken into account in this work. In the high energies zone the distribution function is a power-low one. That shows nonlocal characteristics of electron transfer. The expressions for the limits of characteristic zones of distribution function behavior are got.

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All diagnostics which use UV, Visible and IR radiation to probe reactor grade plasmas will view the plasma via a mirror. These first mirrors (FM) will have to survive in an extremely hostile environment and maintain a good optical performance. For example, for ITER-FeAT they will receive intense UV radiation (typically 500 kW/m²), neutron heating (typically 8 W/cm²), particle fluxes arising from charge exchange atoms (CXA) (typically 2x10¹⁹ particles/m²/s with energies up to several keV) potentially leading to severe erosion, and will be subjected to the deposition of material eroded from the divertor and first wall. Mirrors used in present magnetic confinement experiments would not survive more than a few seconds under these conditions. For approximately the last three years, there has been an extensive, coordinated, R&D programme underway in Russia, Japan and Europe to develop diagnostic FMs. The key results of this work are summarised in the present paper. Attention is focused on the processes of erosion and deposition which are analysed separately using data obtained in simulation experiments.

Mirrors of several metals (Be, Cu, SS, Mo, Ta, W) with different microstructure (polycrystal, film, single crystal) have been bombarded for long periods (≥15hrs) by deuterium ions of energy 0.1-1.5keV. Due to different sputtering rates of grains with different crystallographic plane orientations, the polycrystal mirrors develop a step structure soon after bombardment starts. They can also develop small scale microrelief inside separate grains. Both effects lead to a degradation of the mirror properties. On the other hand, the long-term bombardment of metal film mirrors (Be, Cu, Rh of ~1.5-10 μm thick), does not demonstrate the step structure or the small scale microrelief [1]. The behaviour of single crystal mirrors (Mo, W) is on the whole similar to that of thin film mirrors, i.e., their surfaces have a high mirror quality after erosion by sputtering of a layer several μm thick. From the data obtained, we estimate that Rh film mirrors of thickness ~10 μm can be used as FMs in locations where the CXA flux onto the mirror surface will not exceed 2x10¹⁸ atom/m²/s (~1/10 of the CXA flux to the first wall [2]). We also find that the single crystal tungsten mirrors can maintain good mirror quality even when subject to CXA flux similar to that at the first wall.

The optical characterization of thin film (≤1 μm) rhodium mirrors on Cu and V substrates was carried for a specific ITER diagnostic - LIDAR Thomson Scattering System (TSS). Rhodium was chosen because it has approximately constant reflectivity, R, (0.7-0.8) in the spectral range of interest (400-800nm), and because it has very low erosion. Optical performance close to that needed was obtained for Rh/Cu mirrors, while for Rh/V the achieved R was lower than expected. The optical planarity of the mirrors was close to λ/10 in the visible, while the roughness was close to 10nm RMS average. The measured hemispherical reflectivity (i.e. specular+diffuse) of Rh/Cu mirrors at 45° angle of incidence was measured as 0.7-0.8, fulfilling the requirements for the LIDAR TSS.

Measurements and calculations of the consequences of a thin contaminating film on the reflectance of a metal mirror were conducted for the films most likely to occur in fusion devices under operation (carbon or boron-carbon) and those that are likely in ITER (beryllium). SS, Mo and Cu were used as substrates. The reflectivity was measured in the UV, Visible and near IR regions at normal incidence and the data obtained were compared with calculations based on formulas given in [3] using optical constants k(λ) and n(λ) of the substrate and film measured by ellipsometry. It follows from the data obtained that even a thin film (of thickness ≥10nm) strongly affects the reflectance (Rₚ₉) of film-substrate combinations. The Rₚ₉(h) degradation depends strongly on λ and h. Methods for protecting and cleaning the mirror surface will be required and possible methods will be discussed in the paper.


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Overview of LHD Diagnostics
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The Large Helical Device (LHD) is the largest helical machine having superconducting helical and poloidal coils. The LHD experiment started in March of 1998. Since then, three experimental campaigns have been carried out. A magnetic field strength on the plasma axis of up to 2.91T has been achieved. The major radius is 3.6–3.75 m, and the minor radius is 0.6 m.

Three heating methods: Electron Cyclotron Heating (ECH), Neutral Beam Injection (NBI), and Ion Cyclotron Heating (ICH) were utilized with the maximum power of 4.5 MW. The energy confinement time of LHD is better by a factor of more than 50 % than the international stellarator scaling law. One of important missions of the LHD experiments is to demonstrate steady state operation. So far, a pulse duration of 80 sec was achieved with NBI, and 68 sec with ICH alone. The limitation of the pulse length is only due to the present constraint of utilities which will be improved.

For detailed analysis of the plasma transport, the profile data have been obtained with the major diagnostics. T_e profile with a Thomson scattering system (130 ch, 50 Hz) and ECE (24 ch, 500 kHz), and n_e profile with an FIR interferometer (13 ch, 1 MHz), and T_i profile with a CXRS method (20 ch, 5 Hz). The other profile information, such as poloidal and toroidal rotation, radiation loss, Hva, and Zeff values, also have been obtained. In particular it has been possible to observe the fine structure of T_e profile owing to the high spatial resolution of the Thomson scattering system. With this diagnostic, it becomes clear that the electron temperature profile has a pedestal feature near the plasma boundary. We are now developing transport analysis based on the profiles, and also we have a plan to put the new 6MeV heavy ion beam for electric potential measurements starting from the next experimental campaign. The amount of diagnostics data is about 400 MB per shot for the present pulsed operation. Major diagnostics were available also for long pulse operation. For some diagnostics, real time data acquisition with 1 kHz sampling was realized. Also important for the data acquisition of steady state plasma is the utilization of an event trigger system. For the huge amount of the data, the data storage consists of 1.2 TB RAID, magneto-optical disks (1.2 TB x 3), and a tape buck up system (10 TB).

The results obtained so far have been encouraging, and we are planning the fourth campaign starting at the end of September, 2000.
Target Area and Diagnostic Interface Issues on the National Ignition Facility

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Abstract

The National Ignition Facility is being built at LLNL for the DOE Stockpile Stewardship Program. It will perform experiments for Inertial Confinement Fusion (ICF) ignition, High Energy Density (HED) science, and basic science. There are many interface issues that experimentalists will encounter in the design, fabrication, and installation of target diagnostics for the NIF. The Target Experimental Systems group at LLNL has had to address a significant number of these interface issues in the development of design requirements. A short description of each interface issue will be presented, and a reference to the appropriate documents will be provided. These documents will be available through the NIF Diagnostics web page. The NIF Target Area interface issues are grouped into three categories as follows. First, the layout and utility interface issues which include: Target Area Facilities Layout; Target Chamber Port Locations; Diagnostic Interferences and Envelopes; Utilities and Cable Tray Distribution; and Timing and Fiducial Systems. Second, the working environment interface issues which include: Unconverted Light and Debris; Radiation/EMI/EMP Effects and Mitigation; Electrical Grounding, Shielding and Isolation; and Cleanliness & Vacuum Guidelines. Third, the operational interface issues which include: Manipulator Based Target Diagnostics, Diagnostic Alignment, Shot Life-Cycle and Setup; Diagnostic Controllers; Integrated Computer Control System; Shot Data Archival; Classified Operations; and Remote Operations.

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Singular Spectrum Analysis as a powerful tool for plasma fluctuations analysis

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We report about the use of an advanced statistical technique applied to the measurements of electron temperature fluctuations with high time resolution in the core of Reversed Field Pinch (RFP) plasmas. They have been performed in the RFX experiment with a two color Soft x-ray spectrometer and applying for the first time in plasma physics the Singula Spectrum Analysis (SSA)technique. SSA is an advanced adaptive technique, which we have improved by adding statistical tests to optimize the de-noising and de-trending of the signals. SSA has been used in other areas of science as digital signal processing, oceanography, paleoclimatology, nonlinear dynamics.
The SSA algorithm is described and other possible applications as a powerful diagnostic tool are discussed.
Temperature fluctuations are typically not larger than few percents and are well correlated both qualitatively and quantitatively with magnetic fluctuations, suggesting that the former are originated by resistive MHD processes.

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TOPIC:
Fluctuation and transport measurements

BP1
Application of the Continuous Wavelet Transform to the Fluctuations and Electric Field Analysis in the H-1 Heliac X. Shi, J. Boman, Faculty of Engineering, Central Queensland University, M.G. Shats, Plasma Research Laboratory, Australian National University Confinement transitions observed in H-1 heliac exhibit variety of dynamic behavior in fluctuation property. These fluctuations affect the turbulent particle transport, and it is important to measure the time-resolved fluctuation-driven particle flux. Recent application of the wavelet transform to the plasma turbulence data demonstrated that this relatively new technique has been a valuable tool for the analysis of transits. In this paper, we extend the Fourier spectral techniques introduced by Powers in studying fluctuations and the particle transport to the use of the continuous wavelet transform (cwt). A highly time-frequency resolved fluctuation-driven particle flux has been obtained from the cross-power spectrum of the two sets of cwt coefficients of the fluctuating electron density and the poloidal electric field. The outward radial flux reverses its direction across the transition to the fluctuating H-mode, or has a significant reduction and a reversal of its direction before the transition to the quiescent H-mode. It has been shown that in H-1 heliac transitions to high confinement mode were triggered by the radial electric field approaching a critical value. A time-frequency analysis of the fluctuations using the cwt indicates that the frequency of the strongest frequency harmonic of fluctuations is well correlated with the average radial electric field in H-1 heliac. This suggests that the frequency observed in the laboratory frame be solely due to the $E \times B$ Doppler shift, similarly to the case in DIII-D tokamak.

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On an alias-free discrete-time Wigner distribution for time-frequency analysis of fusion plasma signals

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The Wigner distribution has been recently introduced as a tool for time-frequency analysis of fusion plasma signals, a tool particularly suited to study non-stationary phenomena that have, necessarily, a time-varying frequency spectrum [1]. As in many fields, most of the signal processing in fusion diagnostics deals with digitized data, hence with discrete-time signals. The straightforward generalization of the continuous-time Wigner distribution to the discrete-time case has the shortcoming of producing aliasing, unless the signal dealt with is analytic or oversampled [2]. Indeed, the aliasing is caused by the fact that the Wigner distribution formed in that manner has period $\pi$ in the periodic reduced frequency variable, whereas the period of the Fourier spectra of discrete-time signals is $2\pi$. An alias-free discrete-time Wigner distribution has already been introduced [2], but it possesses some formal disadvantages. Namely, it has a somewhat awkward dependence on the reduced frequency, which increases the computational complexity, and it must also be computed on half-integer values of the discrete-time variable, while the signal is acquired only at integer values of the latter.

In this work, a new alias-free form is proposed for the discrete-time Wigner distribution that is the translation for signal processing of the rotational Wigner function introduced in quantum mechanics [3]. Besides being free from aliasing, and exhibiting also a set of natural, welcome properties, this new form introduced here is more suitable and less complex. More precisely, the dependence on the frequency variable is similar to that in the continuous-time case, and it is defined on the same points in the time variable where the signal itself is defined. For the sake of illustration, the three discrete-time Wigner distributions that have been mentioned are computed, and compared, for a set of actual broadband reflectometry data.


Topic: Data Acquisition and Engineering
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BP3
OBSERVATIONS OF RADIAL WILD CABLES IN TOKAMAK PLASMAS

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The results of processing the plasma images with the help of the method of multilevel dynamical contrasting (MDC) [1] are presented. The images are taken in visible light, with space resolution ~100 μm and time resolution ~10 μs, in various tokamaks (TM-2, T-4, T-6, T-10). The presence of rigid-body filamentary structures is found. They are similar to those structures formerly found in a Z-pinch, whose long-livingness was proven [2] in tracing their dynamics. The reliability of results is supported by the rich statistics and considerable similarity of the structures in various facilities and regimes, as well as by the insensitivity of observed structuring to specific way of imaging (strict camera, fast photography etc.). Sometimes the structuring may be seen without MDC processing (in such cases, the MDC allows fine resolution of structuring).

The most typical structure is a straight cylindrical block varying in length from few centimeters up to diameter of plasma column. Diameter of such a block varies, respectively, from few millimeters to several centimeters. The most attention is paid to radially directed filaments which, together with toroidal and poloidal filaments, form a network. Detailed analysis of individual cylindrical blocks of several centimeter diameter revealed them to be a coaxial tubular structure with an inner rod (which may be of tubular form as well) of few millimeter diameter.

The similarity of the above structures to coaxial cables may appear to be not occasional: according to hypothesis [3] the elementary coaxial block of diameter not exceeding few millimeters, is a 'wild cable' in which the propagating high-frequency (HF) electromagnetic wave produces a vacuum channel around hypothetical microsolid skeleton [2] and thus protects the skeleton from the ambient high-temperature plasma. An analysis of measurements of HF electric fields, both inside and outside plasma column in tokamak T-10, reveals their reasonable agreement with predictions based on the hypothesis [3].

REFERENCES

OBSERVATIONS OF RADIAL WILD CABLES IN Z-PINCH PLASMA

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The results of processing the Z-pinch plasma images with the help of the method of multilevel dynamical contrasting (MDC) \([l(a,b)]\) are presented. This method was earlier used for (i) analyzing the filaments (and their networks) in a gaseous Z-pinch \([l(a,c)]\) and (ii) characterization of long-living filaments \([2]\) of the lifetime comparable with the entire duration of discharge. The original images were taken in visible light, with space resolution \(\sim 100\ \mu m\) and time resolution \(\sim 2+60\ \text{ns}\).

The long-living structures are found which are assembled from straight cylindrical blocks varying in length from few millimeters to few centimeters. Such blocks are of various orientation in space, and often they form a common frame. The most important phenomenon is the presence of radial (with respect to Z-pinch axis) filaments directed from the periphery to the core, up to the Z-pinch axis. An analysis of the fine structure of the above cylindrical blocks of few millimeter diameter reveals them to be a coaxial structure with the diameter of an inner rod (which may be of tubular form) smaller approximately by the order of magnitude. The comparison is made with similar structures recently observed in tokamak plasmas \([3(a)]\).

The reliability of the above results is supported by the rich statistics and considerable similarity of the structuring in various regimes, and insensitivity to specific way of imaging. Sometimes the structuring may be seen without MDC processing (in such cases, the MDC allows fine resolution of structuring).

The experimental results are analyzed from the viewpoint of the hypothesis \([3]\) about "wild cables" in plasmas of high-current electric discharges. The correlation between the measured values of the high-frequency electric fields in Z-pinch plasma and the values of the Miller force needed to sustain vacuum channels in the plasma which are the essential elements of the wild cable.

REFERENCES

SIMILARITY OF MICROTUBULES IN TOKAMAK DUST AND MACROTUBULES IN TOKAMAK PLASMA

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In order to verify hypothesis [1] about the presence of a microsolid skeleton in the observable long-living filaments, which is assembled from (carbon) nanotubes during electrical breakdown, and survivability [2] of such a skeleton in hot plasmas, an analysis of various types of the dust and films in tokamak T-10 is carried out. This includes (a) dust in the crimps of the tokamak vacuum chamber; (b) dust extracted from the oil used in the vacuum pumping system; (c) films deposited at the internal surface of tokamak vacuum chamber.

Processing of the transmission electronic microscope images of dust particles and the scanning electronic microscope images of dust films reveals the presence of (i) tubules of the size typical for individual carbon multiwall nanotubes (i.e. from few nanometers to few tenth of nanometers); (ii) tubular structures of diameter 50-100 nm, which are assembled from smaller tubules; (iii) the signs of tubular structures on the film’s surfaces, which are of micrometer diameter scale and assembled from smaller tubules.

The above data appear to be compatible with the hypothesis [1] in the following sense: (1) a trend of assembling the larger tubular structures from smaller ones is seen in the dust deposits of nanometer and micrometer length scales; and (2) such a trend is especially distinct when comparing obviously microsolid (dusty) tubular structures, which possess distinguishable topology of links between constituent blocks, with similar structures formerly found out [2] in the plasma of a number of tokamaks (diameter of the latter tubules is of centimeter length scale).

The present results suggest the necessity of correlation analysis in diagnosing the topology of structuring of the plasma and dust deposits in the facilities for producing and confining high-temperature plasmas.

REFERENCES


BP6
Impurity transport analysis: analytical model for determination of empirical transport coefficients from observations of line emission profiles in tokamak plasmas

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Usually anomalous impurity transport in tokamak plasmas is interpreted as a transport of impurity particles across magnetic field. Recently, more general approach has been developed [1] where the problem is analysed in terms of charge-state transport which distinguish between the transport of impurity particles and that of impurity charge-state distributions due to atomic processes in plasma. For the latter case the direct estimations show that the charge state diffusion coefficient \( D \) of middle-Z impurities appears to be about 10-100 m\(^2\)/s that far exceeds well known empirical values of anomalous diffusion coefficient \( D_A \) obtained in the experiments. This difference imposes a serious restriction on the accuracy of impurity transport modeling which uses conventional codes with the data of spectroscopic observations to obtain transport coefficients \( D_A \) and \( V_A \).

In the present paper we analyse two main competitive transport phenomena: the radial charge-state transport (including particle transport) and charge-state transport due to atomic processes. We use steady state case of derived kinetic equation [1] (which is of Fokker-Plank type) for the impurity charge-state distribution function. Integration of this equation taken in terms of radial and charge-state flux densities gives the reduction of the order of initial equation and increase in the accuracy of transport analysis. The derived equation is also of two independent variables: radius and ionic charge considered as continuous variable. However, these variables appears to be connected along the special continuous line which is determined by the relationship between radial position of emission maxima and ionic charges which correspond to these maxima as it follows from spectroscopic observations. We consider the derived equation along this continuous line of maxima where the diffusive term of radial flux density disappears and profile of \( V_A(r) \) can be directly calculated from the measured impurity line emissions using experimental profiles of plasma density and temperature with assumed radial dependences for atomic rates. Then, for each line emission profile we calculate the corresponding profile of \( D_A(r) \) and, therefore, the resulting profile \( D_A(r) \) can be obtained over the entire plasma cross-section.

The developed analytical transport model has been tested on the well documented experimental data taken from PLT [2] where line emission profiles of scandium and molybdenum impurities have been presented for the experiments with neutral-beam heating.

Multi-Parameter Data Acquisition for Spectroscopy

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A very powerful and versatile, yet simple to use multi-parameter data acquisition system has been developed and implemented for use in spectroscopy. In its standard configuration, the system employs a Phillips sixteen-channel time-to-digital converter, a Phillips sixteen-channel analog-to-digital converter, and a LeCroy ten-channel scaler. The modules are operated in a Camac crate controlled by a Sparrow crate controller with a SCSI interface. A Macintosh computer running KMAX software is employed for data recording and real-time display. The system has been implemented on the electron beam ion trap (EBIT) experiment to record the output from four position-sensitive proportional counters in two soft x-ray spectrometers together with the signal from an IGLET-type X-ray pulse height analyzer. Also recorded are the electron beam energy and the pulse height distribution of the proportional counters. All data are recorded as a function of time. Because the relevant parameters are recorded simultaneously, no hardware gates need to be set. Instead, software gates are used to select the data of interest. This has led to a substantial cost saving over earlier data acquisition systems, where hardware gates in the form of NIM-based modules were employed to discriminate, for example, first and second order reflections in a crystal spectrometer. The implementation costs of the present system are, therefore, only about a third of a four-channel-ADC system used earlier. Data are stored in binary or in ascii format for system-independent processing. The operation of the system will be demonstrated in a measurement of the M-shell spectrum of gold. In particular, we used the system to record the 3-4 and 3-5 transitions of gold excited with a simulated Maxwellian with electron temperature of 2.5 keV, which produces emission from Au$^{44+}$ – Au$^{51+}$.

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Abstract Submitted for the 13th Topical Conference on High-Temperature Plasma Diagnostics

Newly Developed Double Neural Network Concept for Reliable Fast Plasma Position Control

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For future long-pulse or steady-state tokamaks such as KSTAR and ITER, plasma control is getting more important. To avoid any disruption event, which is much more dangerous to tokamak based on the superconducting magnet system, the fast and accurate plasma position control is crucial. One promising technique using neural network was successfully proven as a fast and accurate tool, however it was not really convinced as a reliable one yet. In this study, a fast and reliable plasma position identification technique is developed by applying double neural network(double network) concept to the conventional neural network method for real-time plasma position control.

The double network is composed of a primary network and a secondary network with the outputs of the primary network. In this case, the primary network is a collection of neural networks using several subsystems of the database. With this new configuration, more improved properties such as reliability and accuracy can be achieved. Surprisingly, both root-mean-square error and maximum error can be reduced simultaneously. Also, by eliminating any primary network output exceeding a certain level of error range, the unexpected faulty result from various errors due to either minor diagnostic failures or neural network itself can be avoided from this double network. Moreover, the optimization time of neural network is expected to be reduced significantly just by taking less optimized neural network outputs as inputs for the secondary network of the double network. With this improved concept, the double network as a fast and reliable plasma position identifier is developed. Training and test of the newly developed double network are performed with sufficient and broad-range database generated by a simple plasma current model.

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Mass Data Acquisition Systems in JT-60 Data Processing System

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In JT-60 data processing system, a unique mass data acquisition system with fast sampling, the transient mass data storage system (TMDS) has been used since 1988. It is composed of a mini-computer and 61 channels of 4/6 MB memories with 5 microsecond sampling and total amount of data of about 300 MB is transferred to a main computer by using a Fujitsu original LAN. TMDS can handle a large amount of data, but can not enlarge the system, such as CPU power or the number of channels. To solve the problems of TMDS, a new fast VME data acquisition system, FDS, has been developed. It can acquire the data of 6 MB per a channel with 1 or 5 microsecond sampling and consists of a workstation with VMEbus memory modules. Now there are 3 FDS’s with 24 channels. TMDS itself will also be replaced with a new system based on the technology of FDS. To cope with mass data transfer to a data server, they will be connected with the a gigabit ethernet switch.
This paper describes an approach for data acquisition and retrieval to be used on several key diagnostics for experimental support on the National Ignition Facility. The major feature is a direct replacement for film with a large format, scientific grade CCD imager requiring minimum space in the diagnostic environment. Additionally, the system provides rapid data acquisition without film developing or digitizing time, equivalent or better resolution than film (nine micron pixel spacing), and compatibility with our existing diagnostic front ends. The CCD camera has been shown to provide very good linearity and signal to noise.

Features of this camera include a modular design approach from the clocking state machine through the digitizer/data buffer including diagnostic controller software. Changing the imaging device will require only a change in the clock state machine and the pointers in the internal data buffer storage. Also the camera will provide digital output for transmission on a fiber optic line to provide better noise immunity and resistance to EMP.

Results of the 4Kx4K imaging front end used on laser experiments at the LLE Omega facility will be presented.

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Effect of Film Development on Uniformity and MTF of GXI and FXI Data

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We have been investigating the different phenomena that affect the response of the gated x-ray detectors [GXI and FXI] that we use to record sub-nanosecond x-ray images at different laser facilities. As part of that investigation, we noticed that there is definite non-uniformity to the recorded images, even when the incident radiation was uniform. After a significant effort to track down that effect we found that the HOPE automatic developing processors that Los Alamos [LANL] and Livermore [LLNL] uses, which processes the film along the length of the roll, causes the effect. Manual development, which depends primarily on transverse agitation in the developer, and the JOBO processor at Omega, do not introduce such artifacts. We recommend that for absolutely critical missions, such as target symmetry measurements, certain automatic machines should not be used.

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1 This work was performed under the auspices of the U.S. Department of Energy under contract # W-7405-ENG-36.
Accessing TJ-II data with RPC. E. Sánchez, J. Vega, C. Crémy and A. Portas.
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The Data Acquisition System (DAS) of the TJ-II stellarator [1] provides the users with tools for data acquisition, storage, visualization and analysis. The TJ-II database is stored in a central host (ALPHA AXB/UNIX) and the several acquisition systems can integrate experimental data into the central database via local area network using TCP/IP protocols [2].

A library, based on the “de facto” standard ONC RPC (Open Network Computing Remote Procedure Call) has been developed for TJ-II data access and data integration into the database. This library replaces a previous development [3] in which the client implementation had the drawback that it was platform dependent. The RPC programming allows to distribute data access routines over the network [4]. From the user point of view, the client routines can be used for accessing to data (or integrate them into the database) from codes running in the central server or from any other computer in the network in exactly the same way. From the development point of view, the ONC RPC tools allow to generate source code for the clients in an easy and flexible manner, thus reducing the work needed to maintain/upgrade the library for different platforms.

A server program, which implements each access routine as a service on the network, has been developed. It is a concurrent server, that runs in the TJ-II central host. A client library has been developed to provide connection with the data server. This library implements a client routine per service, that interchanges parameters between client and server programs using XDR (eXternal Data Representation). The server program executes the appropriate host-side routine.

The client library has been installed in different UNIX-like platforms, including ALPHA AXB/UNIX, Sparc/SOLARIS, INTEL/LINUX and CRAY/UNICOS. In addition to UNIX-like clients, a version of the library for Windows (NT/95/98) is being developed using an implementation of ONC RPC for Windows environments. Furthermore the support for Windows platforms allows autonomous PC-based acquisition systems to integrate experimental data into the database.

A basic in-house developed identification system is used to control client connections, allowing both UNIX-like and Windows client connections to the data server. The client identification data are passed as a hidden extra argument in the distributed routines, and contain information about the IP address of the client and the user and group identifications, or username, group and domain (depending on the client system). An access policy has been defined in order to assign different permissions according to clients. The implementation of this library is important not only because it increases the portability of the source code for TJ-II data access libraries, but also because it can be used in the future to distribute some modules of the TJ-II data acquisition system, what will allow to improve the performance of the system with an increasing number of users.

References:

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BP13
Design of the National Ignition Facility Diagnostic Instrument Manipulator*

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Abstract

The Diagnostic Instrument Manipulator (DIM) provides a diagnostic platform to insert and retract a variety of instruments in-to and out-of the National Ignition Facility (NIF) target chamber. The DIM is a two-stage telescoping system, designed to fit on any of the DIM designated diagnostic ports on the target chamber, and will provide precision radial positioning, pointing, and alignment-to-target capability. The DIM provides a standard set of utilities, and cables to support the operation of instruments that require insertion into the target chamber. The DIM provides for positioning of diagnostic packages, and enables exchange of manipulator diagnostics between LLNL, CEA, LLE, AWE, LANL and SNL. Principal design requirements for the DIM are presented. A half-length prototype of the DIM was designed and fabricated by AWE in the UK and is being tested at LLNL. The results of this testing are presented.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.
Precision Metrology of NSTX Surfaces During Installations, Vessel Bakeout, and Plasma Operations Using Coherent Laser Radar Ranging.*  H.W. KUGEL, D. LOESSER, A. L. ROQUEMORE (PPPL, Princeton University), M. M. MENON and R. E. BARRY (Oak Ridge National Laboratory) — A frequency modulated (FM) coherent laser radar (CLR) ranging diagnostic is being used on the National Spherical Torus Experiment (NSTX). The distance (range) between the 1.5 m laser source and the target is measured by the shift in frequency of the linearly modulated beam reflected off the target. The range can be measured to a precision of < 100 m at distances of up to 22 meters. The present range accuracy is decided primarily by the vibration level of the floor and support platform on which the CLR system is mounted. Scanning capability is provided by a mechanical beam steering system. An improved design concept incorporating an acoustic-optic device for fine scanning has been completed. Analysis software allows range coordinates measured relative to precision markers to be transferred to another coordinate system (e.g., plasma major radius), and to generate detailed maps of surface changes (e.g., blistering). A description is given of the geometry and procedure for measuring NSTX interior and exterior surfaces during operation, changes in vessel geometry during 350 °C vacuum bakeout and plasma operations, measuring the movement of Center-Stack (CS), Divertor, Passive Plates, and RF Faraday shield surfaces due to thermal deposition (detectability on CS ~Δ50°C), disruptions, erosion and other effects, and precision measurements of Edge Probe positions and tip erosion for comparison with magnetic equilibrium algorithms of edge position, and edge erosion models.

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Millimeter Wave Notch-Filters for Protection of Microwave Plasma Diagnostics

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Millimeter wave notch filters which provide a very high rejection of stopband, a very low insertion loss to other frequencies and passband up to 40% were developed and built for protection of microwave plasma diagnostics from radiation of high power Gyrotrons used for microwave heating of plasma. To create the notch filters we offer to use the Waveguide Dielectric Resonators (WDR) based on bellow cut-off waveguides with dielectric resonators which provide a high Q-factor up to 1800. The electrodynamic problem for these filter is solved. It allows to calculate the filters for given frequencies.

Six-resonators W-band notch filters with stopband 2.2% at 3 dB points and 0.5% at 50 dB points, the maximum attenuation up to 65 dB and insertion loss <1.5 dB over the 40% passband were developed and built for protection of ECE-radiometer. The length of the filter -50 mm, the waveguide cross section 2.54 x 1.27 mm².

The attenuation characteristic of the filter is presented in figure 1 below. The filters provide a wide tuning possibility due to mechanical adjustment of the resonators. They can handle a big power due to a big return loss at the reject frequencies and a small ohmic loss at dielectric.

Such filters can be realised at any band of centimetre or millimeter wave ranges.

![Attenuation Characteristic](image-url)
Debris Characterization Diagnostic for the National Ignition Facility

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Generation of debris and shrapnel from targets and by x-ray ablation of surrounding materials will be a matter of concern both for experimenters and the operations staff at the National Ignition Facility (NIF). Target chamber protection, for example debris shield damage, and efficient facility operation drive the interest for the NIF staff. Experimenters are primarily concerned with diagnostic survivability and data interpretation. Examples are separation of mechanical versus radiation induced test object response in the case of radiation effects tests and transport through the debris field when the net radiation output is used to validate computer simulations. In addition, radiochemical analysis of activated debris during ignition shots can provide a measure of the ablator $<pr>$. Conceptual design of the Debris Monitor and Radiochemistry Station, one of the NIF core diagnostics, is presented. Methods of debris collection, particle size and mass analysis, impulse measurements, and radiochemical analysis are given. A description of recent experiments involving debris collection and impulse measurement on the OMEGA laser is also provided.

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BP17
Diagnostic first mirrors for burning plasma experiments

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All diagnostics which use UV, Visible and IR radiation to probe reactor grade plasmas will view the plasma via a mirror. These first mirrors (FM) will have to survive in an extremely hostile environment and maintain a good optical performance. For example, for ITER-FEAT they will receive intense W radiation (typically 500 kW/m²), neutron heating (typically 8 W/cm²), particle fluxes arising from charge exchange atoms (CXA) (typically 2x10^19 particles/m²s with energies up to several keV) potentially leading to severe erosion, and will be subjected to the deposition of material eroded from the divertor and first wall. Mirrors used in present magnetic confinement experiments would not survive more than a few seconds under these conditions. For approximately the last three years, there has been an extensive, coordinated, R&D programme underway in Russia, Japan and Europe to develop diagnostic FMs. The key results of this work are summarised in the present paper. Attention is focused on the processes of erosion and deposition which are analysed separately using data obtained in simulation experiments.

Mirrors of several metals (Be, Cu, SS, Mo, Ta, W) with different microstructure (polycrystal, film, single crystal) have been bombarded for long periods (>15hrs) by deuterium ions of energy 0.1-1.5keV. Due to different sputtering rates of grains with different crystallographic plane orientations, the polycrystal mirrors develop a step structure soon after bombardment starts. They can also develop small scale micrelief inside separate grains. Both effects lead to a degradation of the mirror properties. On the other hand, the long-term bombardment of metal film mirrors (Be, Cu, Rh of ~1.5-10 μm thick), does not demonstrate the step structure or the small scale micrelief [1]. The behaviour of single crystal mirrors (Mo, W) is on the whole similar to that of thin film mirrors, i.e., their surfaces have a high mirror quality after erosion by sputtering of a layer several μm thick. From the data obtained, we estimate that Rh film mirrors of thickness ~10 μm can be used as FMs in locations where the CXA flux onto the mirror surface will not exceed 2x10^18 atom/m²s (~1/10 of the CXA flux to the first wall [2]). We also find that the single crystal tungsten mirrors can maintain good mirror quality even when subject to CXA flux similar to that at the first wall.

The optical characterization of thin film (<~1 μm) rhodium mirrors on Cu and V substrates was carried for a specific ITER diagnostic - LIDAR Thomson Scattering System (TSS). Rhodium was chosen because it has approximately constant reflectivity, R, (0.7-0.8) in the spectral range of interest (400-800nm), and because it has very low erosion. Optical performance close to that needed was obtained for Rh/Cu mirrors, while for Rh/V the achieved R was lower than expected. The optical planarity of the mirrors was close to λ/10 in the visible, while the roughness was close to 10nm RMS average. The measured hemispherical reflectivity (i.e., specular+diffuse) of Rh/Cu mirrors at 45° angle of incidence was measured as 0.7-0.8, fulfilling the requirements for the LIDAR TSS.

Measurements and calculations of the consequences of a thin contaminating film on the reflectance of a metal mirror were conducted for the films most likely to occur in fusion devices under operation (carbon or boron-carbon) and those that are likely in ITER (beryllium). SS, Mo and Cu were used as substrates. The reflectivity was measured in the UV, Visible and near IR regions at normal incidence and the data obtained were compared with calculations based on formulas given in [3] using optical constants k(λ) and n(λ) of the substrate and film measured by ellipsometry. It follows from the data obtained that even a thin film (of thickness ~10 nm) strongly affects the reflectance (R_{eff}) of film-substrate combinations. The R_{eff}(h) degradation depends strongly on λ and h. Methods for protecting and cleaning the mirror surface will be required and possible methods will be discussed in the paper.


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BP18
Optical characterization of Plasma facing mirrors for a Thomson Scattering System of a burning plasma experiment


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The general requirements for a Plasma Facing mirror (PFM) of a Thomson Scattering System (TS) for a Burning Plasma experiment are: (i) high and approximately constant reflectivity in the spectral interval $\Delta \lambda = 400-800$ nm; (ii) low spattering yield and low erosion; (iii) high power damage threshold; (iv) good thermomechanical properties to preserve quality imaging. The choice of the material for the mirror exhibiting these characteristics is among Ag, Rh, Mo (mass number ~100). Rhodium mirrors are chosen because: (i) the reflectivity of 0.7-0.8 in the spectral interval $\Delta \lambda = 400-800$ nm; (ii) high melting threshold for laser shots; (iii) low erosion, (~0.2 monolayers per discharge of 1000s are estimated to be removed[1]). A peculiarity of a PFM for TS is that it must be an imaging mirror (i.e. it collects the scattered radiation from different scattering volumes): so its optical quality should be unchanged under the heating due to the laser irradiation, and also to baking cycles. This effect must be minimal for Rhodium mirrors with Vanadium substrates, since the thermal expansion coefficients for the two metals are very close. In the work a detailed optical characterization of Rhodium mirrors with Copper (Rh/Cu) and Vanadium (Rh/V) substrates is presented: both types of mirrors being candidates as PFM of a TS system. Rh/Cu mirrors with Rhodium layer close to 1μm thickness were realized using electrodeposition of rhodium on Copper substrate previously covered by a thin layer of Nickel. The planarity of Rh/Cu mirrors resulted to be close to $\lambda/10$ in the visible spectral range, the roughness 8.41 nm RMS at center, while 8.91 nm average on the surface. The measured hemispherical (i.e. specular + diffused) reflectivity of Rh/Cu mirrors at 45° angle of incidence for s-polarization is 0.7-0.8 in the spectral interval $\Delta \lambda = 400-800$ nm. The Rh/Cu mirrors surfaces are sensitive to baking cycles. The Rh/V mirrors were obtained by electrodeposition of rhodium on polished vanadium surfaces. Layer thickness of Rhodium close to 1μm was obtained with this technique. The planarity of Rh/V mirrors is between $\lambda/8$ and $\lambda/18$ in the visible spectral range, with roughness close to 14nm RMS average on the surface. The measured hemispherical (i.e. specular + diffused) reflectivity of Rh/V mirrors at 45° angle of incidence for s-polarization is (0.55-0.75) in the spectral interval $\Delta \lambda = 400-800$ nm. The optical characterization of Rh/V and Rh/Cu mirrors can be used for the choice of a mirror suitable for a PFM of a TS system.

Physics of tokamak machines working in advanced regimes and related control diagnostics

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The advanced modes or regimes of tokamak operation have important potential advantages, like the possibility, at fixed fusion power, of reducing the volume of the tokamak reactor raising its beta value \((\beta = \text{kinetic pressure/ magnetic pressure})\), so lowering strongly the costs. The efficient control of tokamak machines working in advanced modes is an important issue, since involves the regulation of various quantities which are related to i) the MHD stability of the core as well as of the edge plasma, ii) the ITB (internal transport barrier) quality via the plasma rotation, pressure and current profile into the core plasma, iii) the edge pressure and current profile, iv) the radiative stability of the divertor. The plasma performance control becomes severe, approaching values of normalized beta \((\beta_N = \beta(\%)/(I_{P,MA}/a_n B_T))\) close or higher to 3.5, particularly if steady state plasmas with high bootstrap fraction are realized. The control of burning plasma in such conditions is a derived issue which is considered as well, bringing in evidence the measurements related to the alpha particle-fast ions transport, including their driven instabilities. A state-of-the-art review for the diagnostics related to the control of such plasmas is carried out trying to outline the perspectives that are seen from the point of view of the physics studies. A discussion of the present limits of diagnostic systems for controlling plasmas, is presented, and new directions of developments are identified, since a step forward in the physics studies implies a parallel refinement and/or new conception of diagnostic equipment.
Plasma Diagnostics for ITER-FEAT, K Ebisawa, A E Costley, A J H Donne\(^1\), G Janeschitz\(^2\), S Kasai\(^3\), A Malaquias\(^2\), G Vayakis, C I Walker\(^4\), S Yamamoto\(^2\), V Zaveriaev\(^4\), \textbf{ITER Joint Central Team, Naka} --- A full set of diagnostics, including magnetics, neutron systems, optical/IR systems, bolomeric systems, spectroscopic and neutral particle analyzing systems along with a diagnostic neutral beam, microwave systems, and plasma facing/operational systems, is planned for ITER-FEAT. The design of the systems is a substantial technical challenge because of the combination of the harsh environment with the demanding measurement requirements. The conditions are most severe for systems mounted inside the vacuum chamber where there are high neutron and gamma radiation fluxes, substantial heat loads from plasma radiation, and high neutral particle fluxes from charge exchange processes in the edge regions of the plasma. Re-deposition of material eroded from other in-vessel components is an additional hazard. Systems with complicated transmission lines and sensors located outside of the vacuum vessel have to be compatible with ITER requirements for vacuum integrity, tritium containment, and maintainability. Through a combination of careful choice of technique, materials and design, supported by dedicated R&D, a diagnostic set has been developed. In the paper the requirements for measurements are outlined and representative diagnostic designs are presented. Areas where further work is required are identified.

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\(\square\) Place in the following grouping

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BP21
Diagnostic Requirements for High Power Auxiliary Heating on NSTX

A. L. Roquemore, D. Johnson, R. Kaita, Princeton University. NSTX has recently completed its first phase of operation. The primary objective for the baseline diagnostic set during this phase has been to aid in plasma control and machine operation, which successfully led to attainment of 1 MA of plasma current and some encouraging initial results with coaxial helicity injection (CHI). This first set of diagnostics relied on techniques previously established on tokamaks and related plasma devices. In the next phase of operation, strong auxiliary heating will become available in the form of RF heating through high harmonic fast waves (HHFW) and neutral beam injection (NBI) for a combined total power of 11 MW. With intense auxiliary heating, accurate and reliable measurements of the plasma parameters for both machine operation and characterization of the plasma performance over a wide range of conditions will require an extended set of diagnostics. Profile diagnostics will be particularly important in this phase, and in some cases this capability can be achieved by upgrading existing diagnostics. However, many new diagnostic approaches must be implemented which take into account the constraints of a spherical torus device. An overview of the full complement of diagnostics planned for NSTX will be presented, and issues related to implementing each diagnostic will be discussed.


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BP22
Abstract for the 13th Topical Conference on High Temperature Plasma Diagnostics, June 18-22, 2000

**Diagnosics for a Magnetized Target Fusion Experiment**

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We are planning experiments using an FRC plasma injected into a metal cylinder, which is subsequently imploded to achieve a burning fusion plasma. Diagnosing this plasma is quite challenging due to the short timescales, high energy densities, high magnetic fields, and difficult access problems we expect to encounter. In this paper, we outline our planned diagnostic sets in both a Phase I study (where the plasma is formed and translated), and Phase II study (where the plasma is actually imploded). The pre-compression plasma is expected to have $n \sim 10^{17} \text{cm}^{-3}$, $T \sim 100-300 \text{ eV}$, $B \sim 5 \text{T}$, a lifetime of 10-20 microseconds, in a diameter of only 8-10 cm, and length of 30-40 cm. We will use visible/near IR laser interferometry across the plasma, along with a series of fiber-optically coupled visible light monitors to determine the plasma density and position. A set of excluded flux pickup coils will be placed outside the quartz tube of the formation region, but inside of the diameter of the theta-pinch formation coils. Impurities will be monitored spectroscopically, although even at the initial "low" pre-compression density, Stark broadening of all line radiation will make interpretation difficult. Fast bolometers will give us the radiated power, although their analysis can be complicated by the exhaust plasma from the axial divertor of the FRC. After the plasma translates into the thin-walled aluminum metal liner, we will have to use small cutouts in the aluminum cylinder to allow side-on access for diagnostics. A 10-Joule Thomson scattering laser beam will be introduced in the axial direction, and scattered light (from multiple spatial points) will be collected from the sides. Neutron diagnostics (activation and time-resolved scintillation detectors) will be fielded during both phases of the DD experiments. In the first phase, we expect to eliminate noise issues, but perhaps also detect a few neutrons from the pre-compression plasma due to its high density. In the second phase, as the density increases a factor of 100x, and the temperature increases a factor of 10-20x, the neutron time history and absolute levels will be essential for judging the success of the implosion, relative to code modeling. Due to the incredibly high magnetic fields expected as a result of the liner compression ($5 \text{ Tesla} \rightarrow 500 \text{ Tesla}$), we also have the opportunity to field novel magnetic field sensors.

BP23
Plasma Diagnostics for the Sustained Spheromak Physics Experiment


Lawrence Livermore National Laboratory

In this paper we present an overview of the plasma diagnostics planned for the SSPX device now operating at LLNL. The SSPX explores the relationship between helicity injection, magnetic turbulence, and energy confinement in a spheromak configuration (0.25m minor and major radius plasma stabilized by a copper shell “flux conserver”). Recent operations have shown magnetic fields of 0.2 T at the wall and up to 500 kA of plasma current. Electron density is in the range of 2 x 10^{20} to 2x10^{21} m^{-3}. Magnetic decay times of up to 1 msec are seen with titanium gettering of the tungsten-spray coated flux conserver. Gettered shots also show clear evidence of burning through carbon impurities.

A set of 46 wall-mounted magnetic probes provide the essential data necessary for magnetic reconstruction of the Taylor relaxed state. Rogowski coils measure currents induced in the flux conserver. A single-chord CO_{2} laser interferometer is used to measure electron line density. Spectroscopic measurements include an absolutely-calibrated SPRED spectrometer for obtaining time-integrated VUV spectra and two time-resolved vacuum monochrometers for studying the time evolution of two separate emission lines. Another time-integrated spectrometer records spectra in the visible range. Filtered silicon photodiode bolometers provide total power measurements, and a 16 channel photodiode spatial array gives radial emission profiles. Two-dimensional imaging of the plasma and helicity injector is provided by gated TV cameras and associated image-processing software. An array of fiber-coupled photodetectors with Halpha filters view across the midplane and in the injector region to measure neutral hydrogen concentrations.

Several novel diagnostics are being fielded including a Transient Internal Probe (TIP) developed by the University of Washington, and an Ultra-Short-Pulse Reflectometer microwave reflectometer (USPR) developed by the University of California, Davis. The TIP probe fires a very high velocity optical bullet through the plasma and will provide fairly non-pertubative internal magnetic field and current measurements to compare with an equilibrium code model fitted to wall-mounted probes. The USPR is being designed to study edge density and turbulent fluctuations. A multipoint Thomson scattering system is currently being installed to give radial temperature and density profiles. Additional chords are planned for the CO_{2} interferometer to provide a redundant density profile.

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BP24
Calibration Facilities at Bechtel Nevada - Livermore Operations

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Abstract

Since moving to a new location in March of 1999, Bechtel Nevada - Livermore Operations has established a modern laboratory for the characterization of optical and x-ray diagnostics for high temperature plasmas. Some of the facilities include a short pulse laser facility, a streak tube production facility, a microchannel plate characterization laboratory, an optical streak camera calibration laboratory, and a CCD calibration laboratory. Descriptions of the facilities will be presented as well as examples of data taken at the laboratory. Future upgrades to the facility will be discussed.
Detection of RF Perturbations Using an Ion Beam Diagnostic

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Presently, experiments are underway at the Plasma Dynamics Laboratory at Rensselaer Polytechnic Institute to demonstrate that the techniques developed for heavy ion beam probe diagnostics (HIBP) can be used to measure radio frequency (RF) fluctuations in plasmas. We hope to measure fluctuations in plasma density and magnetic and electric fields. This will provide a direct measurement of the electric and magnetic fields in the plasma during ICRF heating and thereby improve understanding of heating deposition and wave physics. In addition, the field and the density measurements will be used to determine the plasma reaction to the heating experiments. It is expected that the density measurements will be easiest to interpret, while the electric field measurement will be the most difficult to interpret. The diagnostic issues that will be important in taking data at RF frequencies include faster electronics, signal levels, and path effects. We have used a current to voltage amplifier design to measure 0-500 kHz fluctuations in several previous experiments. By reducing the gain and changing some components, a very similar design is capable of operation at RF frequencies. The modified circuit has been tested up to 15 MHz and worked well. The number of beam ions striking the detector plate in one RF period will be too small to obtain good enough statistics for fluctuation measurements, and therefore, averages over many cycles will be required. We expect to be able to achieve millisecond time resolution in the experiments. The global nature of the modes will tend to make path effects important in the HIBP signals. On the other hand, since the beam will take more than one period to cross the plasma, phase shifts may cancel some of these effects. In addition, a path effect term due to dA/dt will be much more important relative to the electric potential than in lower frequency experiments. The initial experimental plan is to do a series of measurements in which a Lithium ion beam passes through an Argon helicon plasma. The helicon plasma was chosen because its high density (of order \(10^{19}\) m\(^{-3}\)) will produce a larger HIBP signal than can be obtained from other small plasmas. The helicon plasma is formed within a solenoidal magnetic field of 1 kG on axis. The plasma is excited by an RF antenna that is a modification of the type used in Boswell's experiments [1]. The RF power source is presently a 500 Watt, 13.56 MHz generator. From calculation of final trajectories we have determined that 16 to 29 keV Li ions can be used to probe a plasma with 1 kG magnetic field on axis. If the signal levels with a lithium beam are too small, a molecular hydrogen source will be used. For testing the basic operation of the ion beam probe we will use a simple plate detector mounted on the output flange. These preliminary experiments will be used to determine the feasibility of measuring density and magnetic field fluctuations. A second set of experiments using a more traditional HIBP energy analyzer as a detector is also planned. This detector will also be able to measure electric field effects on the probing ions. It will also be less sensitive to UV noise from the plasma.

Calibration and Initial Operation of the HIBP on MST
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The application of a Heavy Ion Beam Probe, HIBP, on the Madison Symmetric Torus, MST, has presented new challenges for the diagnostic. The primary sources of difficulty are small access ports, high plasma and UV flux and a confining magnetic field produced entirely by plasma currents. The requirement to keep ports small so as to avoid magnetic field perturbations lead to the development of cross-over sweeps as was reported at this meeting in 1998. That sweep system has been installed and is operational. The effectiveness and calibration of this sweep system will be reported.

In addition, this diagnostic is operating with greater plasma loading effects than any previous Rensselaer HIBP, with the possible exception of neutral beam discharges on ISX-B. The loading is the result of plasma flow and UV flux through the MST ports. The plasma flow is greatly reduced using a magnetic suppression structure (reported on elsewhere at this conference). The UV flux appears to be the dominant cause of the remaining loading, which is substantial.

Two approaches have been used to handle this UV loading. First, the system has been modified to reduce the loading on certain key components such as the ion source. And second, the method of operation has been modified. For example, beam steering is usually done with parallel plates biased at opposite potentials. In regions of heavy loading, only one plate is biased and the other is grounded. This has resulted in more reliable operation at the price of a reduced steering capability. Tests will be presented that demonstrate that the sweep system works as expected with plasma.

The magnetic field being largely produced by the plasma makes determination of measurement locations exclusively from trajectory calculations difficult. This motivated the design of MST-wall mounted detectors for system alignment, calibration, and subsequent development of improved confining field models.

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BP27
Suppression of Plasma Electrons in the Diagnostic Ports of MST
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The recent application of a HIBP to an RFP has motivated the development of permanent magnet plasma suppression structures. Non-confined plasma at the RFP diagnostic ports, perhaps due to field errors, is free to flow out the ports and into the adjoining vacuum chambers. The HIBP utilizes two diagnostic ports, a 2-inch port for the primary beamline and a 4-inch port for the secondary beamline. Located within the HIBP vacuum chambers closest to the RFP vacuum chamber are seven pairs of high voltage, fast slew, electrostatic steering plates. Stray charged particles within this region are attracted to the biased plates, loading down the controlling power supplies, and detrimentally affecting the desired operation of the plates.

Structures comprised of steel keepers and nickel plated magnets were designed to conform to the walls of the two ports and suppress the flow of the stray plasma particles within the port region. The magnetic fields, in the region between the permanent magnets, are sufficiently strong to suppress much of the plasma that crosses the RFP plasma edge boundary in route to the HIBP chambers. In addition, the magnetic fields external to the keeper are small and fall-off fast enough with distance to avoid perturbing the RFP fields at the plasma edge.

A description of the keeper designs and magnets will be presented. Measurements of magnetic fields on-axis, off-axis, and as a function of distance from the magnet surfaces will be given. Results of suppression tests and of sweep plate operation in the presence of plasma with keepers installed will be shown. In addition, an analysis of the remaining loading of the sweep plates by residual stray particles and UV radiation, another significant driver of sweep-plate loading, will be reviewed.

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Abstract. A heavy ion beam diagnostic is being developed for the tokamak ISTTOK (R=0.46 m, a=0.085 m, B=0.5 T, I=6-9 kA), based on multiple cell array detectors (MCAD), aiming at the study of the time variation of the plasma density, electron temperature, poloidal magnetic field and plasma potential radial profiles.

This paper describes an alternative method to the traditional electrostatic energy analysers for the measurements of the plasma potential \( V_p \), based on the time-of-flight technique. The \( V_p \) profiles are obtained by measuring the times-of-flight of the secondary ions between semitransparent and solid MCADs, separated by 70 cm and placed in an auxiliary vacuum chamber connected to the tokamak exit port. Due to geometric constraints electrostatic plates should be implemented near the first detector for the adequate steering of the secondary ion trajectories. The signals provided by the two detectors are delivered, after suitable conditioning procedures using on-site developed electronic units, to the time-to-amplitude converters linked to VME recorders.

The first measurements of the changes of the average plasma potential during tokamak discharges with minor disruptions are also presented. These results have been obtained measuring the time-of-flight of the ions of a pulsed (250 ns) primary beam from the electrostatic plates of the ion gun to the primary detector. The achieved energy resolution \( \Delta E/E \approx 1.5 \times 10^{-3} \) is limited by the noise of the detector circuit, since the primary detector is placed inside the tokamak vacuum chamber.

BP29
The Modified Biased Split Detector for the HIBP Electrostatic Energy Analyser.

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Abstract. A heavy ion beam probing is known as the only method for the direct measurements of the electric potential in a hot plasmas. These measurements are realised by the energy analysis of the secondary ions which arose in collisions with the plasma electrons. In the HIBP electrostatic energy analysers the required accuracy of the measurements $\Delta E/E \leq 10^{-4}$ is provided by the differential detection of the ion beam on the split detector. Secondary electrons created on the detector surface by the analysed ions and by the UV plasma radiation exist in all HIBP experiments and strongly influence the measurements. Traditional methods of secondary electron suppression by the direct biasing of the conventional split detector and/or additional grid do not result in sufficient improvement.

This paper considers in detail the influence on the analyser operation of the secondary electrons emitted from the detector, describes the relations for the corresponding errors in the plasma potential measurements, presents the modified biased split detector which strongly diminishes these errors. The different biasing configuration of a new detector were examined by the efficacy of the secondary electron suppression simulated numerically and tested in the simultaneous experiments on test facility. The results obtained with the final version of the detector are presented and demonstrate a substantial improvement in the measurements by the electrostatic energy analyser.

BP30
Redesign of the HIBP for ITER-FEAT

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ABSTRACT

The ITER-FEAT project is oriented to H-mode operation that needs the detailed knowledge of the radial electric field in plasma.

The conceptual design of a Heavy Ion Beam Probe (HIBP) diagnostics made by international workgroup for ITER has been revised for the ITER-FEAT aiming to contribute for:

(i) understanding the external (H-mode) and internal transport barriers (ITB) by the direct measurements of the plasma potential profile,
(ii) the detailed study of the plasma periphery by simultaneous measurements of the plasma potential, density and poloidal magnetic field profile and fluctuations,
(iii) the study of the new mechanisms of the plasma rotation in ignited plasma such as the losses of alpha particles.

HIBP particle trajectories calculations have been made for a standard magnetic configuration. The measurements can be made with the proposed optimized probing scheme including the radial scan line with a single energy (for profile measurements) and coverage of some 2D area in a low field side of a vertical plasma cross-sections.

This work is supported by Russian Basic Research Foundation, Grant No 99-02-18457.
Development of Mesh-Probe for the Calibration of HIBP Diagnostic System in the JFT-2M Tokamak K.KAMIYA, Y.MIURA, T.IDO, Y.HAMADA, a) K.TSUZUKI, T.NAKAYAMA, b) JAERI, a) NIFS, b) Hitachi Ltd.

A new calibration technique for heavy ion beam probe (HIBP) system using mesh-probe is established. The mesh-probe makes it possible to calibrate the diagnostic system with the same condition of a real plasma measurement. With applying DC bias voltage ($\Phi_{bias}$) of -1.0kV to the inner mesh box and puffing He gas into the torus, it could be directly observed the location of sample volume with the spatial resolution of about 10mm. A new method of absolute calibration of the energy analyzer is also established. When an AC voltage (+/-1.0kV, 50 Hz) is applied to the inner mesh box after setting the sample volume within the inner mesh box, it is confirmed that the Normalized Difference (ND) depends linearly on the applied bias voltage. The slope of the ND to the bias voltage ($dND/d\Phi_{bias}$) shows the clear dependence on the entrance angle that is expected from the ideal analyzer model. Although the mesh transparency of the beam is about 40 %, good signal to noise ratio is obtained by the beam current of about 10 A, and the uncertainty for an absolute calibration of energy analyzer is less than 10 %.
Installation of an Advanced Heavy Ion Beam Diagnostic on the TJ-II Stellatrator.


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Abstract. An advanced heavy ion beam diagnostic has been developed for the TJ-II stellatrator based on the simultaneous utilisation of two different detection systems for the secondary ions: a multiple cell array detector and a 30° Proca-Green electrostatic energy analyser. This innovative design aims at enlarging the HIBD capabilities in order to allow the instantaneous measurements of electron density and plasma potential profiles together with their respective fluctuations.

This paper presents the detail description of the main parts of HIBD and their characteristics obtained during the first operation on TJ-II. Special attention is employed to the control and data acquisition system built in a distributed multiplatform architecture using PC-133 MHz IBM compatible running Windows 95 and one VME Motorola 68030 running OS-9. The results of the diagnostic beam carrying through the magnetic structure of TJ-II into electrostatic energy analyser are presented and compared with the trajectory calculations. The operation and calibration of 30° electrostatic energy analyser free of guard rings and with a new biased split detector are described. The problems of plasma loading of the detection systems and HX-ray excitement by the probing beam are considered together with the ways of their solution.
Development of fast response calorie meter for Neutral Beam Shine-Through Measurement on CHS
M. OSAKABE, Y. TAKEIRI, T. TAKANASHI, K. TSUMORI, S. OKAMURA, K. MATSUOKA, R. AKIYAMA, E. ASANO, O. KANEKO, T. KAWAMOTO, Y. OKA National Institute for Fusion Science (NIFS), 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan A fast response calorie-meter chip has been developed for the Neutral-Beam Shine-Through measurement. This calorie-meter has such advantages. 1) Temporal variation of the heat load onto the chip can be measured. 2) Measurement under the relatively high heat flux environment is possible, where the usual bolometer system is difficult to use to avoid the evaporation of a detector. and 3) The calorie-metric measurement under continuous and steady state heat load environment is also possible. The verification of the measurement principle was done using Neutral Beam Injection system on Compact Helical System at NIFS. It was experimentally confirmed that the time constant of the measurement is about 5ms.

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In situ Calibration of Neutral Beam Port-Through Power and Estimation of NB-deposition power on LHD


Neutral beam heating campaign has been started on Large Helical Device since September 1998. LHD-NBI system is characterized by its high energy beam based on a large negative-ion source. In estimating the beam port-through power of LHD-NBI system, many assumption, such as beam divergence, beam focal length, IT-fraction in accelerated beam current and beam uniformity are necessary. To avoid these assumption, the beam port-through power is directly measured by a Calorie-Meter array, which is installed at the counter wall of beam injection port inside the LHD vacuum vessel. The beam deposition power is also evaluated using this CM-array through NB shine-through measurement. In this presentation, we will show the evaluation process of NB port-through power and the deposition power on LHD.
A diagnostic neutral beam system has been created for the MST Reversed-Field Pinch. These beams are used (1) for Charge-Exchange Recombination Spectroscopy (CHERS) to measure impurity ion velocity and temperature, both equilibrium and fluctuating, (2) for Rutherford scattering to measure the majority ion equilibrium and fluctuating velocity and temperature, and (3) for magnetic field measurement via Motion Stark Effect (MSE). The system consists of two beam units, and two neutral particle analyzers. One beam unit creates a 20 keV, 4.5 A helium beam used for the Rutherford scattering. A second beam unit creates a 30 keV, 4 A hydrogen beam, which is used for the CHERS and MSE diagnostics. The beam ions are extracted from plasma created by an arc source and then are neutralized in a gaseous target. A low ion temperature at the plasma emission surface is achieved via the plasma expansion cooling. A hallmark of the beam design is the focusing ion optical systems that consists of four multiperture spherically curved electrodes. The geometric focusing provides a low (<1°) divergence, high neutral current (several equivalent amperes), and small size (~4 cm) on the MST axis. A beam unit is compact in size (30x10 cm) and weighs about 70 kg. The two 12-channel neutral particle analyzers measure the energy spectra of the helium beam scattered atoms from which the plasma temperature and velocity are determined. The atoms are ionized in a gaseous stripping target and then analyzed by a electrostatic 90° analyzer. We present details of the beam and analyzer design and results of their tests on the MST.

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Rutherford Scattering Diagnostics for the MST Reversed-Field Pinch*

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A Rutherford Scattering diagnostic system has been created for the MST Reversed-Field Pinch. The system consists of a diagnostic neutral beam (20 keV, 4 A equivalent current, 3 ms duration) and two electrostatic neutral particle energy analyzers. The analyzers are located at the same toroidal location as the beam and 170 poloidal degrees away, so that beam atoms which have undergone small-angle (10°) Rutherford scattering from the plasma ions are detected. The plasma majority ion temperature is deduced from the broadening of the energy spectrum of either analyzer, while the majority ion velocity is calculated from the relative shift between the two spectra. A distinguished feature of this diagnostic is the ability to locally measure properties of the bulk plasma ions. Localization of the measurement is achieved by crossing the beam line and the analyzer view. The scattering from the majority ions is well separated in energy from the scattering from impurities, due to the difference in their masses. The high beam brightness allows a time resolution of 10 μs, so that temperature and velocity fluctuations can be recorded during the 3 ms duration of the beam. Calibrations of the beam energy, energy spread, and angular spread were performed in situ by scattering from room-temperature Argon and Hydrogen gases. Results of the ion dynamics study from the MST are presented. The equilibrium ion temperature is approximately equal to the electron temperature, which suggests the presence of a heating mechanism in addition to Ohmic heating. In addition, prompt ion heating is observed at magnetic reconnection events (‘sawteeth’). These measurements confirm the presence of anomalous ion heating observed previously with the Charge Exchange and Doppler spectroscopy diagnostics.

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Atomic beam diagnostics for characterization of edge plasma in TJ-II stellarator B. Brañías, D. Tafalla, F. Tabarés, P. Ortiz. Laboratorio Nacional de Fusion. Asociación EURATOM-CIEMAT, 28040 Madrid, Spain

He and Li beams have been installed and set into operation at TJ-II stellarator with the aim of measuring electron temperature and density profiles \( (n_e(r) \text{ and } T_e(r)) \), in the edge and SOL regions of the plasma. An effusive thermal Li beam is produced from an oven which is electrically heated at temperatures of \(-600 \) °C. It penetrates up to a normalized effective radius of \( \rho=0.6-0.7 \) in typical ECH plasmas. The beam size at the measurement region is 1 cm. Radial resolution depends on detection optics and typically is a few mm. The oven design was optimized to maximize thermal inertia and avoid spurious contributions to the beam. Recording emission from the excited Li atoms is made through a multianode photomultiplier array with 16 channels. Background emission has been detected, in a first phase of diagnostic operation in equivalent discharges without Li beam. As this emission is not negligible and depends strongly on plasma conditions, the diagnostic has been upgraded to include a chopper that modulates the beam with an effective frequency of \( \sim 200 \) Hz.

The He beam is a pulsed supersonic one. A pulse length of \(<3 \text{ ms} \) and a repetition rate up to 50 Hz are typically used. Simultaneous detection of three lines (667.2, 706.5 and 728.1 \text{ nm}) is made with a set of three photomultipliers and the measurement position is scanned during the plasma shot with a oscillating mirror. The electron temperature and density are deduced from the intensity ratios of these lines. The measurement region extends from the SOL to well inside the plasma \( (\rho<0.6) \).

The measurements of \( n_e(r) \) show well known features such as the effect of limiter position or magnetic configuration. While the agreement with Langmuir probes in the outer region is good (taking into account the uncertainties of both diagnostics), the Li beam measurements show wider density profiles than the ones deduced from extrapolation of \( n_e(r) \) measured by Thomson scattering.

First He beam measurements of \( n_e \) and \( T_e \) will be presented and the agreement among results of all plasma edge diagnostics will be discussed. In particular, a comparison of results of both beams, taking into account their different response to suprathermal electrons, is made.

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BP38
Subject Classification Category: n/a

Design of the Neutral Particle Analyzer Diagnostic for NSTX*
S. S. Medley and A. L. Roquemore, Princeton University. The low value of the magnetic field in NSTX (B = 0.3 T) leads to the existence of a rich variety of energetic ion phenomena, such as high energetic particle beta, large population of super Alfvénic ions, large Larmor radii and orbit widths, large population of trapped ions even for co-beam injection, and ion distribution anisotropy induced by prompt loss of edge or counter-going beam and/or RF-driven ions. Measurements of the ion distribution will be made using an E||B charge exchange neutral particle analyzer (NPA) originally designed for application on TFTR [1]. This analyzer has an energy range of 0.5 ≤ \( E/(\text{keV}) \leq 600 \) and will provide simultaneous mass-resolved energy spectra of \( \text{H}^+ \) and \( \text{D}^+ \) ion species. The detector consists of a large-area microchannel plate which is provided with two rectangular, semi-continuous active area strips, one coinciding with each of the mass rows for detection of \( \text{H}^+ \) and \( \text{D}^+ \). Each mass row has 39 energy channels and has an energy dynamic range of \( E_{\text{max}}/E_{\text{min}} = 30 \). The energy resolution is \( 3\% \leq \Delta E/E \leq 7\% \). Time resolution, which in practice is driven by the signal-to-noise ratio, is expected to be \( \sim 5 \) ms. The system design will be described, including the support structure for the NPA which will provide horizontal and vertical scanning capability to map the ion energy distribution in space and pitch angle.


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First results of RFX vertical Time of Flight.

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The ion temperature, in addition to being an essential quantity for the determination of a fusion plasma's energetic content, constitutes a long term issue of Reversed Field Pinch (RFP) research.

In order to improve the experimental knowledge of this plasma parameter, in the Reversed Field eXperiment (RFX) a vertical Time of Flight (ToF) neutral particle analyzer has been recently installed. It sees the plasma along a vertical chord, whose impact parameter is about half radius, and it is meant to complement the other two NPAs, which are installed on the equatorial plane.

In this paper, the new vertical ToF is described in detail, with particular attention to its more delicate components. The first measurements of the ion temperature are reported, showing the reliable operation of the system and the acceptable signal to noise ratio obtained up to now. The results are also compared with the measurements of the horizontal NPAs mainly in the experimental regime of high plasma density. Possible improvements of the diagnostic and its use in combination with a neutral particle beam are also briefly described and discussed.

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TOPIC:
Time of flight

BP40
Charge Exchange Neutral Particle Analysis with a Natural Diamond Detector on LHD, M. Isobe, M. Sasao, S. Iiduka†, A.V. Krasilnikov*, M. Osakabe, T. Mutoh, S. Murakami, K. Kawahata, N. Oyabu, O. Motojima and LHD experiment group, National Institute for Fusion Science, Japan—Semiconductor detectors based on natural diamond are installed on the Large Helical Device (LHD) to measure energy distribution of charge exchange (CX) fast neutral particles from different viewing angle. In comparison with a conventional analyzer, attractive points of a natural diamond detector (NDD) are the compact size and easier handling. A NDD is also better in obtaining more continuous data points, i.e., more detailed shape of energy spectrum of fast ions. One of weak points is that there is a limit in detecting low energy ions because of finite thickness of surface electrode, thermal noise pulses coming from a preamplifier and so on. In our system, the detectable lowest energy is about 30 keV. A NDD set on a tangential port have successfully measured time-resolved energy distribution of counter-going passing beam ions in LHD. A detector was also installed on a perpendicular port to diagnose fast ion tail formation during ICRH. In the 3rd cycle of LHD experiment, fast ion tail up to ~300 keV due to ICRH was observed. The LHD neutral particle analyzer using natural diamond will be presented. The analysis with taking into account of fast ion orbit will be also presented.

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An Application of Electrically Cooled Si-detector to Fast Neutral Measurement on CHS

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A new Fast Neutral Analyzer (FNA) has been developed by using an electrically cooled Silicon-diode Detector (Si-FNA).

The Si-FNA is suitable for a spatial measurement of energy spectra for high energetic particles, which are produced by NBI and/or ICRF heating. It has following advantages; 1) wide energy range 2) compact size 3) inexpensiveness compared to the conventional FNA. On the other hand, it is not suitable for a low energy measurement and its energy resolution is rather bad. Cooling the detector allows this problem to be solved. It also suffers noises due to X-rays and visible lights emitted from plasma. With Lead collimator in front of the detector, we could reduce the effect of X-rays. With an evaporated Aluminum layer on the entrance window of Si-detector, we attempted to shield from the visible lights.

Aluminum layer causes the energy straggling to the measured particles. Energy broadening on the particles transmitting this layer plus Silicon-dead layer is calculated by using Trim code[1]. It indicates that the broadening is about 4-keV for hydrogen atoms of 40-keV, which is the typical injection energy of CHS-NBI, when it transmits the Aluminum layer of 100Å plus Silicon-dead layer of 500Å. This broadening limits the energy resolution of the detector. This range of the energy resolution is achieved by cooling the detector below 10 degrees centigrade.[2] To drop in this temperature, we adopted a Peltier module instead of liquid Nitrogen.

The prototype of the Si-FNA was constructed and the Peltier-cooling effect of the detector was tested on this prototype. Energy resolution of this prototype was examined by using ²⁴¹Amercicium X/γ-ray source. In the presentation, these experimental results of the Si-FNA on CHS and analysis will be shown.

Reference

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BP42
Development of novel ion-energy spectrometer using a semiconductor collector under a circumstance of simultaneously incident ions and electrons with x rays


Plasma Research Centre, University of Tsukuba, Japan, JAERI

For the purpose of end-loss-ion energy analyses in open-field plasma devices including the GAMMA 10 tandem mirror, a newly developed electrostatic ion-energy spectrometer using a semiconductor-detector collector is fabricated. Experiments using a test-ion-beam line verify a significantly upgraded broad ion-energy sensitivity from several tens of eV to hundreds of keV; the lowest energy limit is extended to 2 orders-of-magnitude better than that for commercially available Si-surface-barrier diodes employed for standard plasma-ion diagnostics. A signal-to-noise ratio of 2-3 orders-of-magnitude better than that for usual metal-collector detectors is demonstrated. The novel spectrometer with the sensitive semiconductor ion detector has a special triangle-grid structure so as to prevent x-ray noise emitted from ion-biasing grids due to incident electrons. The effectiveness and usefulness of the specific structured spectrometer is clearly demonstrated by an enhanced ion-spectrum signals without any appreciable x-ray noises in plasma experiments.
Simultaneous observations of spatially resolved ion and electron temperatures using a semiconductor detector array


Plasma Research Centre, University of Tsukuba, Ibaraki, Japan

A novel method for simultaneous observations of both plasma ion (T_i) and electron temperatures (T_e) is proposed using one semiconductor detector array alone. In particular, the first experimental demonstration of temporal evolution of spatial profiles of T_i using a small-sized semiconductor array provides to open a new convenient "T_i tomography" method using a limited diagnostic space. The semiconductor detector is fabricated with a novel idea of a "positive" use of a semiconductor "dead layer"; that is, an SiO_2 layer is employed as an unbreakable energy-analysis filter for low-energy charge-exchange neutral particles from plasmas ranging in T_i from 0.1 to several keV. The availability of such semiconductors for distinguishing the neutrals (for T_i) from x rays (for T_e) simultaneously emitted from plasmas into semiconductor detectors is theoretically simulated and experimentally verified using their different penetration lengths and the resultant different deposition depths and profiles in semiconductor materials.

Prefer Poster Session

☐ Prefer Oral Session

☐ No Preference

☐ This poster/oral should be placed in the following grouping:
   (specify order)
   X-ray imaging

☐ Special Facilities Requested
   (e.g., movie projector)

☐ Other Special Requests

Submitted by:

Teruji CHO

(Same Name Typewritten)
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Plasma Research Centre
University of Tsukuba
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Simultaneous observations of temporally and spatially resolved profiles of ion-confining potentials and end-loss ions
M, YOSHIDA, T. CHO, M. HIRATA, J. KOHAGURA, Y. NISHIZAWA, T. SASUGA, S. NAGASHIMA, K. YATSU, and S. MIYOSHI
Plasma Research Centre, University of Tsukuba, Ibaraki, Japan
Newly installed ion-energy-spectrometer arrays [1] in both end regions of the GAMMA 10 tandem mirror make it possible to observe two-dimensionally resolved radial-distribution profiles of end-loss-ion fluxes and ion-confining potentials \( \phi_c \). Such a relation provides one of the most essential fundamentals of tandem-mirror plasma confinement, since the confinement of tandem-mirror plasmas is characterized by efficient potential pluggings of end-loss plasmas. The experimental data show that peak-on-axis radially symmetric profiles of \( \phi_c \) make radially symmetric ion-plugging distributions. It is found that the formation of higher potentials ranging \( \phi_c/T_i > 1 \) produces hollow-shaped strong end-loss pluggings with good spatial symmetry. After the \( \phi_c \) formation period, a symmetrically shaped large amount of end-loss fluxes is released from plasma confinement region. This again indicates the effectiveness of potential pluggings. These data are consistently interpreted by the Pastukhov theory of the relation between plasma confining potentials and end-loss-ion fluxes.

An omegatron-type cyclotron-resonance mass spectrometer has been used to obtain the ion mass distribution of hydrogen plasmas in a linear, simulated divertor experiment. For typical operating parameters of magnetic field $B = 1$ kG, plasma density $n \sim 10^{11}$ cm$^{-3}$, and electron temperature $T_e \sim 15$ eV, the plasma is observed to consist of roughly comparable concentrations of H$^+$, H$_2^+$, and H$_3^+$. Additionally, the omegatron has been used as a parallel ion energy analyzer, giving ion temperatures of $T_i \sim 15$ eV. In either capacity, the omegatron performance is adversely affected by diagnostic misalignment, plasma space-charge effects, and collisions with neutrals. Additionally, the ion mass spectroscopy measurements are found to be affected by the applied RF electric field uniformity. Significant improvements in ion mass and temperature resolution have been obtained by differentially pumping the diagnostic to minimize the effect of neutral collisions, and by using closely-spaced wire meshes in the diagnostic to minimize space-charge effects.

Supported by US DOE Grant DE-FG03-95ER54301
High Temperature Plasma Diagnostics Conference

Elective Laser Induced Plasma Deposition of Diamond Like Film

Zheng Bangke, Dr. Paul Lee, Plasma Lab, Physics Division, School of Science, Nanyang Technological University, Singapore

Abstract:
In order to achieve high quality diamond like polycrystalline film, namely to increase the ratio of constitution of sp3 structure versus that of sp2 structure in the deposited film, the ions C4+, C3+(which most likely form sp3 structure) and C+(which most likely form sp2 structure), should be separated after they are evaporated by the heat of laser beam from graphite target. The separation of C4+, C3+, C+ is dominated by two factors: velocity of the ions and charge quantity of the ions, so the first stage is to use an electromagnetic velocity selector to let the ion of a certain velocity pass through. The voltage that forms the electric field of the selector can be calibrated according to the ions signal on the oscilloscope collected by the Faraday cup placed behind the aperture of the selector so as to choose a velocity interval which contain the most of the ions. The ions that pass through the selector are of the same velocity; The second stage is to use a biasing electric field to separate the ions of different charge but of almost the same velocity, which finally condense on the substrates placed at different distances from the aperture of the selector, forming the film. This thesis introduce the design of these devices.
### Tuesday Morning, June 20
X-ray Imaging and Streak Cameras - Jim Knauer, Chair

**8:30 a.m. - 10:30 a.m. Presidio Ballroom 5**

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Affiliation</th>
<th>Country</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI1</td>
<td>Landen</td>
<td>LLNL</td>
<td>USA</td>
<td>X-Ray Backlighting For The National Ignition Facility</td>
</tr>
<tr>
<td>CI2</td>
<td>Smalyuk</td>
<td>LLE</td>
<td>USA</td>
<td>Fourier-Space Image Processing For Spherical Experiments On OMEGA</td>
</tr>
<tr>
<td>CI3</td>
<td>Scott</td>
<td>LANL</td>
<td>USA</td>
<td>Radiographic Image Analysis Of Cylindrical Implosion Experiments</td>
</tr>
<tr>
<td>CI4</td>
<td>Weber</td>
<td>LLNL</td>
<td>USA</td>
<td>A Direct Electron Bombarded Charge Coupled Device For Dynamic Plasma Imaging Applications</td>
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**10:45 a.m. - 12:30 p.m. Presidio Ballroom 1-4**

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
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<th>Title</th>
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<tbody>
<tr>
<td>CP1</td>
<td>Bugrov</td>
<td>TRINITI</td>
<td>Russia</td>
<td>Advanced Plasma Diagnostics For Investigation Of Physical Processes In Laser-Irradiated Foam Targets</td>
</tr>
<tr>
<td>CP2</td>
<td>Nishikino</td>
<td>ILE Osaka</td>
<td>Japan</td>
<td>Density Profile Of The Ablating Plasma Produced By Soft X-Ray Irradiation</td>
</tr>
<tr>
<td>CP3</td>
<td>Porter</td>
<td>Sandia</td>
<td>USA</td>
<td>Development Of A Laser-Produced-Plasma X-Ray Backlighter For Z</td>
</tr>
<tr>
<td>CP4</td>
<td>Bennett</td>
<td>Ktech</td>
<td>USA</td>
<td>X-Ray Imaging Techniques Using The Z-Beamlet Laser Backlighter System</td>
</tr>
<tr>
<td>CP5</td>
<td>Kantsyrev</td>
<td>U Nevada Reno</td>
<td>USA</td>
<td>Advanced X-Ray And EUV Imaging, Spectroscopy, And Polarimetry Diagnostics For Z-Pinch Plasma Experiments At The Nevada Terawatt Facility</td>
</tr>
<tr>
<td>CP6</td>
<td>Shelkovenko</td>
<td>Cornell</td>
<td>USA</td>
<td>Point-Projection X-Ray Radiography Using An X Pinch X-Ray Source</td>
</tr>
<tr>
<td>CP7</td>
<td>Lebedev</td>
<td>Imperial Coll.</td>
<td>UK</td>
<td>X-Ray Backlighting Of Wire Array Z-Pinch Implosions Using X-Pinch</td>
</tr>
<tr>
<td>CP8</td>
<td>Workman</td>
<td>LANL</td>
<td>USA</td>
<td>One-Dimensional X-Ray Imaging Using A Spherically Bent Mica Crystal At 4.75 KeV</td>
</tr>
<tr>
<td>CP9</td>
<td>Workman</td>
<td>LANL</td>
<td>USA</td>
<td>X-Ray Yield Scaling Studies Performed On The OMEGA And TRIDENT Lasers</td>
</tr>
<tr>
<td>CP10</td>
<td>Kyrala</td>
<td>LANL</td>
<td>USA</td>
<td>Fluorescence Concerns In High Energy X-Ray Yield Scaling And Imaging Studies</td>
</tr>
<tr>
<td>CP11</td>
<td>Bullock</td>
<td>LLNL</td>
<td>USA</td>
<td>Relative X-Ray Backlighter Intensity Comparison Of Ti And Ti/Sc Combination Foils Driven In Double-Sided And Single-Sided Laser Configuration</td>
</tr>
<tr>
<td>CP12</td>
<td>Bullock</td>
<td>LLNL</td>
<td>USA</td>
<td>10 µm And 5 µm Pinhole-Assisted Point-Projection Backlit Imaging For NIF</td>
</tr>
<tr>
<td>CP13</td>
<td>Bradley</td>
<td>LLNL</td>
<td>USA</td>
<td>Development And Characterization Of A Single Line Of Sight Framing Camera</td>
</tr>
<tr>
<td>CP14</td>
<td>Landon</td>
<td>LLNL</td>
<td>USA</td>
<td>Design Of The National Ignition Facility Static X-Ray Imager</td>
</tr>
<tr>
<td>CP15</td>
<td>Oertel</td>
<td>LANL</td>
<td>USA</td>
<td>Large Format X-Ray Imager For The LANL ICF/RP Program</td>
</tr>
<tr>
<td>CP16</td>
<td>Evans</td>
<td>LANL</td>
<td>USA</td>
<td>Quantitative X-Ray Imager</td>
</tr>
<tr>
<td>CP17</td>
<td>Turner</td>
<td>LLNL</td>
<td>USA</td>
<td>Comparison Of CCD Vs Film Readouts For Gated MCP Cameras</td>
</tr>
<tr>
<td>CP18</td>
<td>Landen</td>
<td>LLNL</td>
<td>USA</td>
<td>Angular Sensitivity Of Gated Micro-Channel Plate Framing Cameras</td>
</tr>
<tr>
<td>CP19</td>
<td>Marshall</td>
<td>LIE</td>
<td>USA</td>
<td>Imaging Of Laser-Plasma X-Ray Emission With Charge Injection Devices (CID)</td>
</tr>
<tr>
<td>CP21</td>
<td>Takagi</td>
<td>NIFS</td>
<td>Japan</td>
<td>Soft X-Ray Detector Array For The Study Of MHD Instabilities In The CHS Heliotron/Torsatron</td>
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<td>Japan</td>
<td>Tangential Soft X-Ray Camera For Large Helical Device</td>
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<tr>
<td>CP23</td>
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<td>NIFS</td>
<td>Japan</td>
<td>Soft X-Ray Detector Array System On Large Helical Device</td>
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<tr>
<td>CP24</td>
<td>Stutman</td>
<td>Johns Hopkin</td>
<td>USA</td>
<td>Operation Of The Ultrasoft X-Ray System On NSTX</td>
</tr>
<tr>
<td>CP25</td>
<td>Stutman</td>
<td>Johns Hopkin</td>
<td>USA</td>
<td>Ultrasoft X-Ray Telescopes For Fluctuation Imaging In Fusion Plasmas</td>
</tr>
<tr>
<td>CP26</td>
<td>Soukhanovskii</td>
<td>Johns Hopkin</td>
<td>USA</td>
<td>Multilayer Mirror And Foil Filter AXUV Diode Arrays On CDX-U And NSTX</td>
</tr>
<tr>
<td>CP27</td>
<td>Tritz</td>
<td>U Wisconsin</td>
<td>USA</td>
<td>Design And Modeling Of The Soft X-Ray Flux Surface Shape</td>
</tr>
<tr>
<td>CP28</td>
<td>Bellan</td>
<td>Caltech</td>
<td>USA</td>
<td>Soft X-Ray Imaging For Spheromak-Like Plasmas</td>
</tr>
<tr>
<td>CP29</td>
<td>Savrukhin</td>
<td>Kurchatov</td>
<td>Russia</td>
<td>Reconstruction Of The Internal Plasma Perturbations Using Soft X-Ray Tomography And Magnetic Probes Analysis</td>
</tr>
<tr>
<td>CP30</td>
<td>Aglitskiy</td>
<td>SAI</td>
<td>USA</td>
<td>X-Ray Imaging Diagnostics For The Inertial Confinement Fusion Experiments</td>
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<tr>
<td>CP31</td>
<td>Fujita</td>
<td>ILE Osaka</td>
<td>Japan</td>
<td>Monochromatic X-Ray Imaging With Bent Crystals For Laser Fusion Research</td>
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<td>CP32</td>
<td>Pikuz</td>
<td>VNIIFRTI</td>
<td>Russia</td>
<td>Using Spherically Bent Crystals In Wide Range Of Bragg Angles For Obtaining High-Resolution, Large-Field, Monochromatic X-Ray Backlighting Imaging</td>
</tr>
<tr>
<td>CP33</td>
<td>Sewall</td>
<td>LLNL</td>
<td>USA</td>
<td>National Ignition Facility Core X-Ray Streak Camera</td>
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<tr>
<td>CP34</td>
<td>Kalantar</td>
<td>LLNL</td>
<td>USA</td>
<td>Optimizing Data Recording For The NIF Core Diagnostic X-Ray Streak Camera</td>
</tr>
<tr>
<td>CP35</td>
<td>Heya</td>
<td>ILE Osaka</td>
<td>Japan</td>
<td>Development Of Wide-Field, Multi-Imaging X-Ray Streak Camera Technique With New Image-Sampling Method</td>
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<tr>
<td>CP36</td>
<td>Bugrov</td>
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<td>Russia</td>
<td>Time- And Space-Resolved Imaging Techniques For Study Of Plasma Dynamics In Low-Density Laser-Irradiated Matter</td>
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Tuesday Afternoon, June 20
Fusion Products and Fast Ions - Ray Leeper, Chair

2:00 p.m. - 3:30 p.m. Presidio Ballroom 5

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
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<tr>
<td>DI1</td>
<td>Ericsson</td>
<td>Uppsala</td>
<td>Sweden</td>
<td>Neutron Spectroscopy On JET: Results From The MPR Spectrometer</td>
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<tr>
<td>DI2</td>
<td>Stoyer</td>
<td>LLNL</td>
<td>USA</td>
<td>Nuclear Diagnostics For Petawatt Experiments</td>
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<td>Murphy</td>
<td>LANL</td>
<td>USA</td>
<td>Nuclear Diagnostics For The National Ignition Facility</td>
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3:45 p.m. - 5:30 p.m. Presidio Ballroom 1-4

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<td>DP1</td>
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<td>IPP Garching</td>
<td>Germany</td>
<td>Fast Ion Loss Measurements At The W7-AS Stellamtor</td>
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<tr>
<td>DP2</td>
<td>Darrow</td>
<td>PPPL</td>
<td>USA</td>
<td>Fast Ion Loss Diagnostic Plans For NSTX</td>
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<tr>
<td>DP3</td>
<td>Osakabe</td>
<td>NIFS</td>
<td>Japan</td>
<td>Up-Grade Of Electrical Cooled Si-FNA For LHD Fast Ion Measurement</td>
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<td>DP4</td>
<td>Cecil</td>
<td>Colorado Sch.</td>
<td>USA</td>
<td>A Thin Film Device As A Low Energy, High Flux Charged Particle Spectrometer</td>
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<tr>
<td>DP5</td>
<td>Tanaka</td>
<td>JAERI</td>
<td>Japan</td>
<td>Diamond Radiation Detector Made Of An Ultra High-Purity Type Ila Diamond Crystal Grown By HP-HT Synthesis</td>
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<tr>
<td>DP6</td>
<td>Fisher</td>
<td>GA</td>
<td>USA</td>
<td>Measured Response Of Bubble Neutron Detectors And Prospects For Alpha Knock-On Diagnostics</td>
</tr>
<tr>
<td>DP7</td>
<td>Jaanimagi</td>
<td>LLE</td>
<td>USA</td>
<td>Neutron-Induced Background In CCD Detectors</td>
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<tr>
<td>DP8</td>
<td>Kohagura</td>
<td>U Tsukuba</td>
<td>Japan</td>
<td>Investigation Of X-Ray-Energy Responses Of Semiconductor Detectors Under Deuterium-Tritium-Fusion-Produced Neutron Irradiation</td>
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<td>DP9</td>
<td>Kaneko</td>
<td>JAERI</td>
<td>Japan</td>
<td>Time Response Measurement Of A Fusion Power Monitor Based On Activation Of Water Flow</td>
</tr>
<tr>
<td>DP10</td>
<td>Ruiz</td>
<td>Sandia</td>
<td>USA</td>
<td>The NIF Total Neutron Yield Diagnostic</td>
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<tr>
<td>DP11</td>
<td>Barnes</td>
<td>LANL</td>
<td>USA</td>
<td>High-Yield Neutron Activation System For The National Ignition Facility</td>
</tr>
<tr>
<td>-------</td>
<td>--------------</td>
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<tr>
<td>DP12</td>
<td>Wallner</td>
<td>U Vienna</td>
<td>Austria</td>
<td>Study Of The $^{27}$Al(n,2n)$^{28}$Al Reaction And Its Potential For Ion-Temperature Measurements</td>
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<tr>
<td>DP13</td>
<td>Kaschuck</td>
<td>TRINITI</td>
<td>Russia</td>
<td>Neutron Flux Monitoring System For ITER-FEAT</td>
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<td>DP14</td>
<td>Glebov</td>
<td>LLE</td>
<td>USA</td>
<td>Secondary Neutron Yield Measurements By Current Mode Detectors</td>
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<td>DP15</td>
<td>Shibata</td>
<td>Nagoya U.</td>
<td>Japan</td>
<td>Time-Of-Flight Neutron Spectrometer For JT-60U</td>
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<tr>
<td>DP16</td>
<td>Henriksson</td>
<td>Uppsala</td>
<td>Sweden</td>
<td>Fusion Reactivity Studies Of DT Plasmas With NB Heating</td>
</tr>
<tr>
<td>DP17</td>
<td>Tardocchi</td>
<td>Uppsala</td>
<td>Sweden</td>
<td>Neutron Emission Spectroscopy (NES) Diagnosis Of DT Plasmas With Ion Cyclotron Resonance Heating</td>
</tr>
<tr>
<td>DP18</td>
<td>Hjalmarssohn</td>
<td>Uppsala</td>
<td>Sweden</td>
<td>The Development Potential For Neutron Emission Spectroscopy Diagnosis Of DT Plasmas</td>
</tr>
<tr>
<td>DP19</td>
<td>Sangster</td>
<td>LLNL</td>
<td>USA</td>
<td>Calibration Of The MEDUSA Neutron Spectrometer</td>
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<tr>
<td>DP20</td>
<td>Watt</td>
<td>LANL</td>
<td>USA</td>
<td>A Neutron Spectrometer For NIF</td>
</tr>
<tr>
<td>DP21</td>
<td>Murphy</td>
<td>LANL</td>
<td>USA</td>
<td>Neutron Time-Of-Flight And Emission Time Diagnostics For The National Ignition Facility</td>
</tr>
<tr>
<td>DP22</td>
<td>Frenje</td>
<td>MIT</td>
<td>USA</td>
<td>CR-39 Track Detector Response To Charged Particles And Neutrons</td>
</tr>
<tr>
<td>DP23</td>
<td>Frenje</td>
<td>MIT</td>
<td>USA</td>
<td>Design Of A Magnetic Deuteron Recoil (MDR) Neutron Spectrometer For Fuel $^{D}_{3}$, Ion Temperature And Neutron Yield Measurements In Deuterium-Tritium Plasmas</td>
</tr>
<tr>
<td>DP24</td>
<td>Hicks</td>
<td>MIT</td>
<td>USA</td>
<td>Optimal Foil Shape For Neutron Time-Of-Flight Measurements Using Elastic Recoils</td>
</tr>
<tr>
<td>DP25</td>
<td>Seguin</td>
<td>MIT</td>
<td>USA</td>
<td>Diagnostic Use Of Secondary Proton Spectra For D-Filled ICF Targets</td>
</tr>
<tr>
<td>DP26</td>
<td>Li</td>
<td>MIT</td>
<td>USA</td>
<td>Measuring Fusion Yields, Areal Densities And Ion Temperatures Of Imploded Capsules At OMEGA</td>
</tr>
<tr>
<td>DP27</td>
<td>Morgan</td>
<td>LANL</td>
<td>USA</td>
<td>Development Of A Neutron Imaging Diagnostic For ICF Experiments</td>
</tr>
<tr>
<td>DP28</td>
<td>Delage</td>
<td>CEABruyeres l Chatel</td>
<td>France</td>
<td>SIRINC: A Code For Assessing And Optimizing The Neutron Imaging Diagnostic Capabilities In ICF Experiments</td>
</tr>
<tr>
<td>DP29</td>
<td>Berggren</td>
<td>LANL</td>
<td>USA</td>
<td>Gamma-Ray Based Fusion Burn Measurements</td>
</tr>
<tr>
<td>DP30</td>
<td>Nishitani</td>
<td>JAERI</td>
<td>Japan</td>
<td>Fusion Gamma-Ray Measurements For $D^{2}$He Experiments In JT-60U</td>
</tr>
<tr>
<td>DP31</td>
<td>Paiziev</td>
<td>Uzbek Acad.</td>
<td>Uzbekistan</td>
<td>Feature Of Positron Annihilation In High Temperature Plasma And Injection Of Positrons In A Magnetic Trap</td>
</tr>
</tbody>
</table>

Tuesday Evening, June 20  
Banquet – The Last Territory
X-Ray Backlighting for the National Ignition Facility*


Lawrence Livermore National Laboratory
P.O. Box 5508
Livermore, CA 94551

Abstract

X-ray backlighting refers to the technique of radiographing transient phenomena in high-density materials. The x-ray backlighter sources are provided by picosecond- to nanosecond-duration laser plasmas created by the interaction of high-intensity laser beams with solid or gaseous targets. Imaging is usually provided by one of three methods:

1. Pinholes (for 2D imaging) or slits (for 1D imaging) are placed between the backlit sample and detector.
2. A point source of x rays is created that casts a shadow of the sample at the detector.
3. X-ray optics such as curved mirrors and Fresnel lenses relay a backlit image at the detector.

The intrinsic spatial resolution depends on a combination of the detector resolution and the pinhole diameter, point-source size, or quality of the figure of the optic, respectively. The effective resolution, however, as limited by data noise, can be worse.

The strengths and weaknesses of the first two backlighting geometries is reviewed, especially in the context of extrapolating to NIF scale. Variants on these backlighting geometries that should improve the backlighter efficiency for some current experiments by factors of up to 100x are proposed. Recent striking results from Nova and Omega using new techniques such as backlit pinholes are presented as proof of principle. The improvements in backlighter x-ray yield using spatially distributed and broader-bandwidth sources is also discussed.

Second, the choice of detector, particularly with respect to the data signal-to-noise ratio (SNR), is reviewed. Recent results show significant improvements in data SNR by switching from film to CCD as the final recording medium and by correcting postshot for fixed pattern noise on framing camera data.

*Work performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.
Fourier-Space Image Processing for Spherical Experiments on OMEGA

V. A. Smalyuk, B. Yaakobi, T. R. Boehly, L. S. Iwan, T. J. Kessler, J. P. Knauer,

LABORATORY FOR LASER ENERGETICS
University of Rochester
250 East River Road
Rochester, NY 14623-1299

Abstract

Studies of the compressed shell integrity of spherical targets on the 60-beam, 30-kJ UV OMEGA laser system involve measurements of shell integrity using imaging of core emission at different x-ray energies. The emission from the hot core has been imaged through the cold shell at three narrow, x-ray energy bands, one absorbed and two not absorbed by the shell. The modulations in the core emission due to core areal-density and temperature nonuniformities have been measured by comparing images at the two energies that are not absorbed by the shell. The cold-shell areal-density modulations have been measured by comparing images at the two energies, one absorbed and one not absorbed by the shell. This method has been used for pure-CH shells with x-ray energies around 2.8, 4.0, and 5.0 keV and for shells with titanium-doped layers with x-ray energies around 4.0, 5.0, and 6.5 keV. Time-integrated images of the target have been obtained using a pinhole array with K-edge filters and recorded on DEF film. The spatial resolution of the imaging system was about 6-μm. Using Fourier transforms of the images, signal modulations have been distinguished from noise. Contributions of film noise, digitizing noise, and x-ray photon statistic noise to the total noise have been measured using multiple target images taken during the same shot. The dominant source of noise depends on the level of exposure and spatial frequencies of the image. The sensitivity of the imaging system has been identified using measured energy spectra of core emission and calculated spectral response of the filters and film. The noise in the images has been filtered, and the spatial response of the pinhole camera has been deconvolved using the Fourier-space Wiener filtering technique. Nonlinearities of the imaging system caused by its finite energy response have been simulated and found to be smaller than system noise for the levels of shell areal-density modulations that were measured to be about 10% to 30%, depending on shell thickness and pulse shape used during experiments.

This work was supported by the U. S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.
Radiographic Image Analysis of Cylindrical Implosion Experiments

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Radiography is a heavily used tool for diagnosing laser-based hydrodynamic experiments. A successful experiment relies on the gathering of data over a time window where the relevant physics occurs and an accurate analysis of that data. Cylindrical implosion experiments have been conducted to study hydrodynamic perturbation growth in a convergent geometry. Initially performed in an indirect drive configuration at NOVA and recently in a direct drive configuration at OMEGA, these experiments demonstrate effects not seen in planar geometry such as shell thickening and Bell-Plesset growth. The primary diagnostic of these experiments are radiographic images obtained by looking axially down the cylinder. Analysis of the experimental images yields interface location and perturbation information. Frequently, image filtering and enhancement routines are used to process the interface data from the radiographic image. These routines are necessary as an aid in selecting the location of the interface especially in images degraded by noise. In order to validate the data-reduction process, static target experiments have been performed at the OMEGA laser facility. In these experiments, a Ti disk is illuminated with five laser beams, creating x rays which backlight a static target of known configuration. No drive beams interacted with the target, hence the name "static target". The experimental data is used to benchmark a new set of image processing routines designed for edge enhancement and detection. An older image processing algorithm lacked these abilities. Comparisons of experimental images with initial target geometry are presented with discussions of the differences in the results. Simulations of the experiments have been performed, and analysis of radiographs generated from the simulation data are compared to the experiment. In addition, simulations are used to provide insight for the effects of parallax on the image data.

This work was performed under the auspices of the U. S. Department of Energy by the Los Alamos National Laboratory under contract No. W-7405-Eng-36.
A Direct Electron Bombarded Charge Coupled Device
For Dynamic Plasma Imaging Applications

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A variety of plasma physics experiments require the recording of continuous time history of x-ray emission. Many laboratories have developed x-ray streak camera technology in order to time resolve x-ray spectra or images produced by laser-driven plasma experiments. These cameras record x-rays by converting photons to electrons, which in turn are focused and swept across an electron sensitive area detector as a function of time.

X-ray photons impinging on a transmission type photo-cathode generate photoelectrons which are accelerated to energies between 10 and 20 keV and focused onto a phosphor screen. The light from the phosphor image may be intensified using a micro channel plate, and is usually optically coupled directly onto film or an optical charge coupled device.

We have designed and built a x-ray sensitive streak camera readout where we replaced the micro channel plate based intensifier and film package with a modified charge coupled device area detector to directly absorb accelerated photoelectrons emitted from the cathode. This system has been integrated into the streak tube arrangement. We will present a set of system performance data, which have been obtained from both bench top experiments on a DC source and dynamic measurements at the Nova laser facility. X-ray images at various exposure times show better spatial resolution, improved signal to noise ratio and higher dynamic range. Other advantages include instantaneous data readout, which enables fast post processing, and no increase in overall cost for an engineered system.

* This work was performed under the auspices of the U.S. DOE by LLNL under contract number W-7405-ENG-48.
Advanced Plasma Diagnostics for Investigation of Physical Processes in Laser-Irradiated Foam Targets


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Recently the low-density foam-like materials have been found very attractive for various applications in high energy-density physics. Irradiation of these materials by powerful laser pulses is the promising approach for plasma formation with parameters being of interest for inertial confinement fusion, X-ray lasers, modeling of astrophysical phenomena, etc. This report is devoted to development and application of diagnostic methods in experiments on irradiation of planar low-density (0.5-10 mg/cm$^3$) porous targets with powerful laser pulses ($10^{13}-10^{14}$ W/cm$^2$). To obtain reliable information on high-temperature dense plasma formation, plasma dynamics, and energy transfer in the target interior, we used a number of optical and X-ray diagnostics providing high spatial ($\sim 10 \mu$m) and temporal ($\sim 10$ ps) resolution. High-speed X-ray imaging, multiframe optical shadowgraphy and interferometry, as well as scattered laser light spectroscopy at the fundamental frequency and its harmonics were used in each experiment. Only being used simultaneously these diagnostic methods provide possibility to understand the complicated physical processes inside laser irradiated foam-like materials. Possibilities of the diagnostic complex are illustrated by examples of obtained results and corresponding data analysis.

This work was supported by the Russian Foundation for Basic Research (Projects No. 98-02-16600 and 98-02-16662).
Density profile of the ablating plasma produced by soft x-ray irradiation.
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Indirect/direct hybrid irradiation has been proposed for suppressing the initial imprint of the laser irradiation nonuniformities. Indirect soft x-ray irradiation of the target generates an expansion layer on the plasma surface. When the drive beam comes later, the target has a substantial stand-off distance between the ablation front and the beam absorption region, in which the thermal smoothing effect is expected to take place, and then, the initial imprint of the laser irradiation nonuniformities can be significantly reduced. Characteristics of the stand-off distance are of great importance in the imprint mitigation. We measured the preformed plasma profile by using x-ray side-on backlighting method. The preformed plasma was backlit by x-rays and imaged onto an x-ray streak camera. The scale length of the preformed plasma was found to increase with duration of the soft x-ray irradiation. The experimental results were in good agreement with 1D hydrodynamic simulations.
Development of a laser-produced-plasma x-ray backlighter for Z


Sandia National Laboratories


Lawrence Livermore National Laboratory

We are in the process of constructing a flexible x-ray backlighter diagnostic on the Z facility at Sandia National Laboratories in Albuquerque, NM. The Z backlighter (ZBL) system uses a laser-produced-plasma as the backlighter x-ray source and can be used in either point-projection or area backlighting configurations. The most demanding design criteria of the backlighter is that it provide a spatial resolution of 25 microns at an x-ray probe energy of 10 keV. The Beamlet laser system from Lawrence Livermore National Laboratory (LLNL) is being moved to Sandia to use as the laser driver for the backlighter. The final laser system at Sandia will produce a peak power of approximately 2 TW at a wavelength of 0.53 microns for pulse widths between 200 psec and 2 nsec. The laser can be focused to a spot as small as 50 microns in diameter and will be capable of generating up to 4 separate laser pulses within a 20 nsec time interval. The Z backlighter diagnostic is scheduled to be ready for use on Z early next year.

This work was supported by the U. S. Department of Energy under Contract DE-AC04-94 AL85000. Sandia is a laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.
X-ray Imaging Techniques using the Z-Beamlet Laser Backlighter System

G. R. Bennett, Ktech Corp.; J. L. Porter, L. E. Ruggles, W. W. Simpson, and C. Wakefield, Sandia National Laboratories; and O. L. Landen, Lawrence Livermore National Laboratory

The Z-Beamlet Laser Backlighter System at Sandia National Laboratories (see Porter et al. this session), which will be operational in 2001, will create a point or area source of high energy x-rays behind a Z-Accelerator [R. B. Spielman et al. Phys. Plasmas. 5, 2105 (1998)] target. With > 2 kJ in four pulses of < 2 nsec total duration in a 20 nsec interval, and > 80 % of the 2ω energy in a ~ 50 μm diameter spot, the resulting > 4×10^16 W/cm² irradiances will generate ≥ 8.950, 8.999 keV (Zinc He-α) x-rays. This source will be used directly for multiframe, point projection x-ray imaging, and will attain spatial resolutions and signal-to-noise ratios significantly better than presently possible on Z using existing methods. In combination with a few cm field-of-view, the technique will be ideally suited to the large, relatively opaque objects characteristic of Z experiments. This addition to the Z facility at Sandia will have a major impact upon the basic physics of z-pinch implosions, and therefore the ultimate x-ray powers and radiation temperatures that may be possible. Furthermore, in combination with a similar point source and a grazing incidence microscope, Z-Beamlet will allow various inertial confinement fusion and high energy density physics experiments to be enhanced significantly. Details of the planned imaging techniques and applications will be presented.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract No. DE-AC04-94AL85000.

Special note. Please arrange for this paper to be presented next to John Porter’s poster during that session.

CP4
ADVANCED X-RAY AND EUV IMAGING, SPECTROSCOPY, AND POLARIMETRY DIAGNOSTICS FOR Z-PINCH PLASMA EXPERIMENTS AT THE NEVADA TERAWATT FACILITY. V.L. KANTSYREV, B.S. BAUER, A.S. SHLYAPTEVA, D.A. FEDIN, S.B. HANSEN, D. CHAMBERLAIN, M. GHARAIBEH, A. JONES, N. OUART, University of Nevada, Reno, NV, USA - A wide variety of x-ray and extreme ultraviolet (EUV) diagnostics are being developed to study z-pinch plasmas at the Nevada Terawatt Facility (NTF) at the University of Nevada, Reno. Time-resolved x-ray/EUV imaging, imaging spectroscopy, polarization spectroscopy, and backlighting will be employed to measure profiles of plasma temperature, density, flow, and charge state and to investigate electron distribution functions and magnetic fields. These diagnostics are used to study the NTF pinch as an x-ray/EUV source for plasma spectroscopy research and to examine the early-time evolution of a current-driven wire, the formation of a plasma sheet from the explosion and merging of wires, etc. The instruments are state-of-the-art applications of glass capillary converters (GCC), multilayer mirrors (MLM), and crystals. Devices include: a novel glass-capillary-based two-dimensional imaging spectrometer, a time-resolved x-ray spectrometer, a time-resolved pinhole camera with 6 channel MCP imager, a 5-channel crystal/MLM spectrometer (Polychromator) with a transmission grating spectrometer, and a two channel x-ray/EUV polarimeter-spectrometer (to study the polarization of K- and L-shell radiation at the same time). A multiframe x-pinch backlighter, yielding point-projection microscopy with few-micron, ns resolution is under development. X-ray convex-crystal survey spectrometers, imaging spectrometers, and fast filtered x-ray diodes have observed single Ti- and W-wire z-pinch es and Ti and Fe x-pinch es. The NTF x-ray yield and x-ray pulse duration depend sensitively on the wire load. For example, K-shell emission varies from 5-10 J in 1-1.5 ns to 30-40 J in 20-30 ns for the y-pinch, while L-shell emission changes from 300-400 J in 2-3 ns to 4 kJ in 30-40 ns. There is evidence of an energetic electron beam with a complex spatial structure in the x-pinch plasma. X-ray polarization measurements will help determine the electron distribution function and the magnetic field in the z-pinch. The presented work includes experimental instrumentation and theoretical support, and a substantial part of these diagnostics can be useful for space- and time-resolved spectroscopy at the NIF. This work is supported by DOE, DOD, SNL, and UNR.
Point-projection x-ray radiography using an X pinch x-ray source


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Using an X pinch as a source of radiation for point-projection radiography, it is possible to project a high-resolution shadow image of dense plasma or test object(s) directly onto x-ray-sensitive film. The emission characteristics of X pinches composed of a wide variety of materials have been studied using several diagnostics. The pulse duration and shape of the x-ray bursts were measured in the 1.5-6 keV band using a set of fast diamond PCDS with different filters. To investigate the line and continuum radiation emitted by the X pinches, two types of spectrographs were used: a convex spectrograph using a mica or KAP crystal and a spectrograph based on a spherically bent mica crystal [1]. The spatial parameters of the intense x-ray source from the X pinch have been estimated from radiographs of test objects, including interference fringes in some images. Summarizing the data:

1. Two types of x-ray sources have been observed in X pinches, sometimes even in the same X pinch. The first is a "high-temperature" source with spot sizes from 3-10 microns, and the second is a "high-density" source with spot sizes less than about 0.5 microns.
2. The smallest spot sizes, which yield the highest quality images, are achieved using only the continuum radiation from the X pinch.
3. Wires known to have slower expansion rates and high boiling temperatures (NiCr, Ti, Nb, Mo, Pd, Ta, W, and Pt) appear to yield the smallest x-ray source sizes, i.e. yield the best spatial resolution in radiographs. All of these materials have intense continuum radiation with energy up to 6 keV.

Wires with intermediate Z (Nb, Mo, and Pd) usually yield the highest quality X pinches for radiography. Observations have been made of x-ray burst durations in the 1.5-6 keV range of less than 250 ps, the temporal limit of our diagnostic system.

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X-ray backlighting of wire array Z-pinch implosions using X-pinch.

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X-ray point-projection radiography with high temporal (~1ns) and spatial (~20 m) resolution was used to study implosion dynamics of wire array Z-pinch. As a backlighting source an X-pinch was installed in the return path of the current. Initial test experiments with 4-wire arrays have been performed on the XP pulser (450 kA, 100 ns) at Cornell University. These experiments, using two X-pinches connected in parallel, provided two backlighting images separated by 10-20 ns.

On the MAGPIE generator (1MA, 240ns) at Imperial College radiography was used to study implosion dynamics of arrays with up to 64 Al or W wires. An X-pinch was installed in place of one of the 4 return current rods. Timing of the probing x-ray pulse (120-250ns) was adjusted by varying the number of wires (2-4) in the X-pinch and their diameters (15-50 m Al). The sizes of the dense wire cores in the wire arrays, measured by radiography, were found to be significantly different for tungsten and for aluminum (~100 m and 250 m, respectively). The development of perturbations in wire cores (with ~0.5mm for Al) was observed at the time of the array acceleration. These perturbations could act as a seed for global m=0 mode of the Rayleigh-Taylor instability observed later.
Abstract submitted to
13th Conference on High-Temperature Plasma Diagnostics

One-dimensional x-ray imaging
using a spherically bent Mica crystal at 4.75 keV

Jonathan Workman*, Scott Evans and George Kyrala
Los Alamos National Laboratory1

One-dimensional imaging of static gold bars using a spherically bent Mica crystal are presented for the first time at an x-ray energy of 4.75 keV. X-rays are produced using the TRIDENT laser facility driving the He-like resonance transition in solid titanium disks. Time-integrated images of square profile parallel gold bars are recorded on DEF film with a magnification of ~10 using a 100mm radius mica crystal. Rising edge measurements of the bars demonstrate resolutions of about 6-7 μm over a 400 μm field of view.

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Abstract submitted to
13th Conference on High-Temperature Plasma Diagnostics

X-ray Yield Scaling Studies Performed on the OMEGA and TRIDENT Lasers

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The quality of an x-ray image is directly related to the flux of the x-ray source and the efficiency of the detector as well as the x-ray energy. Because the recorded x-ray signal depends on the object opacity and source strength an understanding of how to produce the desired x-ray flux at the appropriate energy is crucial in the design of an experiment. To this end we have performed experiments with planar targets on the OMEGA laser facility at the University of Rochester and the TRIDENT laser facility at Los Alamos. These experiments investigate the scaling of x-ray yield and conversion efficiency with some of the laser parameters and focusing properties for several different target materials. Work on the TRIDENT laser has concentrated on the scaling of Ti k-shell emission near 4.75 keV. Scaling of yield for Ti was investigated for a fixed laser spot-size while changing laser energy as well as fixed laser energy and changing spot-size. Changes in spot size were accomplished both by focusing into and out of the target surface. Effects of smoothed and un-smoothed beams using phase plates were also investigated. The work on the OMEGA laser concentrated on the scaling of x-ray yield at higher x-ray energies. It is expected that the conversion efficiency of laser light into k-shell x-rays will drop rapidly with higher Z targets as more energy and intensity is required to remove k-shell electrons. The experiments on OMEGA are designed to investigate the scaling with x-ray energy and to determine the feasibility of high-energy backlighters under typical irradiance geometry. The scaling of Fe emission near 6.7 keV was investigated by varying laser irradiance from $10^{14}$ to a few $10^{16}$ W/cm². The scaling of Ge emission near 10.3 keV was investigated over a range of irradiances from $10^{16}$ to $10^{17}$ W/cm². In addition, the scaling of target Z (x-ray energy) was studied at fixed laser intensity near $10^{16}$ W/cm² for Fe, Zn and Ge. Time integrated spectra as well as filtered x-ray film give absolute and relative x-ray yields. Time and spatially resolved images of the emission region are presented in addition to time resolved spectra.

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Abstract submitted to
13th Conference on High-Temperature Plasma Diagnostics

**Fluorescence Concerns in High Energy X-ray Yield Scaling and Imaging Studies**

George A. Kyrala and Jonathan B. Workman
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X-rays at high photon energies are needed to backlight and image large objects of high opacity on large lasers, such as the NIF, or large X-ray facilities, such as ATLAS. Attenuators and filters are usually used to bring the signals to scale and to filter the x-rays from un-needed low energy components. As the x-ray energy increases, the secondary effect of the interactions of the x-rays with the filter or attenuator material must be addressed. This is especially true when one considers using the very high energy x-rays from the hot electrons generated during the interaction of intense lasers with high Z materials.

We will show how these concerns can be quantified and reduced in at least one case; an experiment on the OMEGA laser facility, designed to investigate the scaling of absolute x-ray yield and conversion efficiency with laser energy and power. This investigation is part of the study to determine the feasibility of high-energy backlighters using Ge emission near 10.3 keV. We will also show how these results apply to imaging at larger x-ray energies.

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Use of multiple backlighter foils and/or double-sided laser interaction geometry with backlight imaging can result in improved backlighter efficiency. An experimental comparison of backlighter intensity for Ti foils and Ti/Sc combination foils in both the one-sided and double-sided laser-interaction configuration is presented. Spectrally-integrated framing camera images show intensity contributions of front and rear backlighter surfaces for both foil types. Analysis of x-ray spectra collected from foil targets show the relative contribution of Ti and Sc He$_a$ lines to the total backlighter intensity.

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10 μm and 5 μm Pinhole-Assisted Point-Projection Backlit Imaging for NIF*, A. B. Bullock, O.L. Landen, and D.K. Bradley, Lawrence Livermore National Laboratory, Livermore CA.

Pinhole-assisted point-projection backlighting with 10 μm and 5 μm pinholes placed a small distance of order 1 mm away from the backlighter produces images with large field of view and high resolution. Pinholes placed closely to high-power backlighter sources can vaporize and close due to x-ray driven ablation, thereby limiting the usefulness of this method. A study of streaked 1-D backlit imaging of 25 μm W wires using the OMEGA laser is presented. The pinhole closure timescale for 10 μm pinholes placed 0.45 mm and 1 mm distant from the backlighter is 0.8 ns and 1.5 ns, respectively. Similar timescales for 5 μm pinholes is also presented. Successful wire imaging prior to pinhole closure is clearly demonstrated.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.
Development and characterization of a single line of sight framing camera*

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High-speed microchannel plate (MCP) based x-ray framing cameras have been in common use at large-scale laser facilities for a number of years. However, a disadvantage of these devices is that each frame requires a separate image, each with a slightly different line of sight to the source. For experiments that use a backlighter source there can also be potentially severe parallax problems. High-speed framing cameras based on image converter tubes can give multiple frames from a single line of sight, but have traditionally suffered from degradation in spatial resolution for short gate times, and the blanking of images between frames has also been a problem. We will present data from a hybrid camera that uses an electron optic tube to produce up to four simultaneous DC images from a single image incident on the cathode and a microchannel plate based device to provide the temporal gating of those images.

*This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.
Design of the National Ignition Facility Static X-ray Imager

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Abstract
Two static x-ray imagers (SXI) will be used to monitor beam pointing on all target shots in the National Ignition Facility. These pinhole-based instruments will provide time integrated 2-D images of target x-ray emissions in the energy range between 2 and 3 keV. These instruments are not DIM based and will view along dedicated lines of sight from near the top and bottom ports of the target chamber. Beams which miss or clip the hohlraum laser-entrance holes will produce x-ray emission on the ends of the hohlraum, indicating improper beam pointing and/or target positioning. The SXI’s will also be used to quantify beam focusing and pointing by producing x-ray images of dedicated test targets irradiated by focused beams at pre-calculated positions. A proposed design is presented, along with supporting data from NOVA target experiments.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.
Large Format X-ray Imager for the LANL ICF/RP Program
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We describe a new Large Format X-ray Imaging Camera (LFC) for the Los Alamos Inertial Confinement Fusion/ Radiation Physics (ICF/RP) program. This instrument is intended as a prototype for use at the National Ignition Facility (NIF), but is capable of operating at LANL's Trident and University of Rochester's Omega laser systems. Based upon similar x-ray camera designs\(^1\) and currently in the final design stages, the LFC is based upon a large format microchannel plate (MCP) detector primarily for a larger field of view, but also for greater temporal coverage and higher magnification applications. The LFC is designed to have 30 data channels, six 13 mm wide striplines, continuous temporal coverage of 4.2 ns, adjustable electrical gate width, variable gain on each stripline and magnifications up to 20x. Detailed design information will be shown as well as supporting optimization experiment results on MCP and phosphor screens.

This work was performed under the auspices of the U.S. department of Energy by the Los Alamos national laboratory under contract No. W-7405-ENG-36.

\(^1\) P.M. Bell, J.D. Kilkenny, O. Landen, D. Ress, J. Wiedwald, D.K. Bradley, J.A. Oertel, and, R. Watt
Quantitative X-ray Imager
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We report on development of a Quantitative X-ray Imager (QXI) for the national Inertial Confinement Fusion (ICF) program. Included in this development, is a study of photocathode response as a function of photon energy, 2-17.5keV, which is related to diagnostic development on the National Ignition Facility (NIF). The QXI is defined as being a quantitative imager due to the repeated characterization. This instrument is systematically checked out, electronically as well as its photocathode x-ray response, both on a DC and pulsed x-ray sources, before and after its use on a shot campaign. The QXI is a gated X-ray imager used for a variety of experiments conducted in the Inertial Confinement Fusion and Radiation Physics Program. The camera was assembled in Los Alamos and has been under development since 1997 and has now become the workhorse framing camera by the program. The electronics were built by Grant Applied Physics of San Francisco, Ca. The QXI has been used at the LANL Trident, LLNL Nova, and University of Rochester Laboratory OMEGA laser facilities. The camera consists of a gated microchannel plate (MCP), a phosphor coated fiberoptic faceplate coupled to film for data readout, along with a high speed electronic pulsers to drive the x-ray detector. The QXI has both a two-strip and a four-strip detection mode and has the ability to individually bias the gain of each of the strips. The timing of the QXI was done at the Trident short pulse laboratory, using 211 nm light. Single strip jitter was looked at as well and determined to be < 25 ps. Flatfielding of the photocathode across the MCP was done with the Trident main laser with 150 Joules on a gold disk with a 1-ns. Spatial resolution was determined to be < 5 microns by using the same laser conditions above and a backlit 1000-lp/in grid. The QXI has been used on Cylindrical Implosion work at the Nova Laser Facility, and on Direct-Drive Cylinder Mix and Indirect-Drive High Convergence Implosion experiments at OMEGA. Its two-strip module has provided the capability to look at point backlighters, as part of technique development for experiments on the NIF. Its next use will be in March, 2000 with its Off Axis Viewer (OAV) nose at Omega, providing a perpendicular view of Rayleigh-Taylor spike dissipation.

This work was performed under the auspices of the U.S.Department of Energy by the Los Alamos National Laboratory under Contract No W-7405-ENG-36

1. High speed x-ray gating cameras for ICF imaging applications, UltraHigh-Speed Photography, Videography, and Photonics, 92,1801,1140(1992)
2. Grant Applied Physics, Inc., 101 Lombard Street, San Francisco, Ca 94111

CP16
Abstract for High Temperature Diagnostic Meeting

Tuscon, AZ  June 18-22, 2000

Comparison of CCD vs film readouts for gated MCP cameras*

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We have used a large format (4000 x 4000) high resolution (9 um pixels) CCD to record images from the rear of a gated micro channel plate (MCP) intensifier, and compared the results with conventional film recording. Measurements of linearity, dynamic range, and distortion all show that the CCD is an at-least adequate replacement for film. Furthermore, its excellent registration allows for easy flat-fielding, using data from a uniformly exposed MCP. As we increase the signal level to where the signal to noise is not dominated by photon counting statistics, we find that this flat fielding procedure produces a significant improvement in signal to noise. The small spatial scale of this noise has led to its identification as high spatial frequency variations in the MCP phosphor.

*Work performed under the auspices of the U.S. Department of Energy by the University of California's Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.
Angular sensitivity of gated micro-channel plate framing cameras

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Abstract

Gated, microchannel-plate-based (MCP) framing cameras have been deployed worldwide for 0.2 - 9 keV x-ray imaging\textsuperscript{1-4} and spectroscopy\textsuperscript{5} of transient plasma phenomena. For a variety of spectroscopic and imaging applications, the angular sensitivity of MCPs must be known in order to correctly interpret the data. Present and future MCP users either need complete information on the angle-dependent sensitivity of these MCPs at all relevant photon energies, or predictive capabilities based on modelling validated by a few select measurements, as described here. Previous characterization\textsuperscript{6-11} has addressed dc non-imaging applications under unspecified MCP gain conditions, with limited data at the multi-keV photon energies relevant to ICF. We present systematic measurements of angular sensitivity at discrete relevant photon energies. In addition, by varying the gain on the plate, we are able to confirm the transition from single surface photoelectron production at low photon energies (< 2 keV) to multiple, distributed x-ray-pore interactions at penetrating higher photon energies (> 5 keV). Finally, the relative photoelectron production efficiency between the gold conductive ends and the leaded glass matrix is inferred from the angular sensitivity. The results have been accurately modelled by using a simple 2D approximation to the 3D nature of the MCP and by averaging over all possible photon ray paths.

\textsuperscript{*}Work performed under the auspices of the U.S. Department of Energy by the University of California's Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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CP18
Imaging of Laser-Plasma X-ray Emission with Charge Injection Devices (CID)

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Abstract

This work details the method of obtaining time-integrated images of laser-plasma x-ray emission using charge injection devices (CID s) as has been demonstrated on the University of Rochester’s 60-beam UV OMEGA laser facility. The CID has an architecture similar to a charge-coupled device (CCD). The differences make them more resistant to radiation damage, and therefore more appropriate for some applications in laser-plasma x-ray imaging. CID-recorded images have been obtained with x-ray pinhole cameras, x-ray microscopes, x-ray spectrometers, and monochromatic x-ray imaging systems. Simultaneous images obtained on these systems with calibrated x-ray film, as well as laboratory measurements, have enabled determination of the absolute detection efficiency of the CID s in the energy range from 2 to 10 keV.

This work was supported by the U. S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.
Photon counting CCD detector as a tool of x-ray imaging,
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The new x-ray imaging technique to measure magnetic axis and two-
dimensional soft x-ray energy spectra for long pulse discharge has
been developed by using soft x-ray photon counting CCD camera. This
system consists of pinhole, Be filters, and 1024x1024 frame transfer
back illumination CCD detector (the imaging area has 1024x512
pixels). By choosing appropriate combinations of pinhole and Be filter,
the x-ray flux is adjusted to the level good for photon counting mode
and imaging mode, respectively. The Shafranov shift is derived from
two-dimensional soft x-ray intensity measured in the imaging mode
in CHS and LHD. Two-dimensional profiles of electron temperature are
derived from two-dimensional energy spectra of x-ray measured in
photon counting mode for CHS hot electron mode plasma.

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CP20
In heliotron/torsatron configurations, the plasma can basically be confined by the magnetic field generated by external coils, without large net plasma current. Therefore, the pressure driven magnetohydrodynamic (MHD) instabilities such as interchange or ballooning mode are most dangerous instabilities from a point of view of the plasma confinement. A twenty channel PIN-photodiode array using soft X-ray (SX) detector is installed on the Compact Helical System (CHS) heliotron/torsatron for the investigation of MHD instabilities and its internal structure. The array is installed on a top port of the CHS from which the vertically elongated section of the plasma can be seen. Each detector has a size with 12 mm x 1.5 mm and the spacing of center-to-center is 2.25 mm. The viewing aperture defined by a 2 mm thick stainless plate with 2 mm x 8 mm size slit is covered with Be filter of thickness 8μm, to eliminate visible to VUV lights (less than about 1 keV photon energy). The spatial resolution (2Δr) using this aperture is about 10 mm in the equatorial plane of the plasma (<a>~200 mm). The maximum frequency response in this experimental setup is up to about 200 kHz. Therefore, this soft X-ray detector array can detect MHD instabilities less than 200 kHz.

In neutral beam heated plasma on CHS, sawtooth oscillations induced by burst-like magnetic fluctuations are often observed in SX signals. The precursor of high frequency of 30-50 kHz has m/n=2/1 mode structure. The most characteristic feature of this sawtooth is to accompany the large amplitude postcursor of low frequency of several kHz. The sawtooth crash is initiated near the r/2π=1/2 rational surface (ρ~0.4-0.6) and typically indicated a character of off-axis or annular crash. This soft X-ray detector array is successfully employed for the study of internal structure of these sawteeth with precursor and postcursor.
Tangential Soft X-ray Camera for Large Helical Device

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A tangential viewing soft X-ray(SX) camera has many advantages for studying fine structure of magnetically confined plasma over the conventional SX diode array system. 1) It can provide 2-D image directly without uncertain assumptions in reconstruction, e.g. the solid rotation of the plasma. 2) Perturbed structures of fluctuations are usually elongated along the confined magnetic field lines. Since the sightlines of the tangential camera are parallel to the magnetic field lines, the spatial resolution for the fluctuations with higher mode number is much better than that in tomographic reconstruction where the sightlines are almost perpendicular to the magnetic field.

We plan to install a tangential SX camera on the Large Helical Device (LHD) in this fiscal year. Detailed design of the instruments will be reported. Soft X-ray radiation from the plasma is converted to visible light by a fast phosphor (P-47) screen. The light is guided by a plastic bundled fiber (5 m in length) to an image intensifier (Hamamatsu, V4440 U-mod), which is surrounded by an iron box to eliminate the stray magnetic field from LHD. The output image is amplified and recorded by a fast CCD camera whose typical framing rate is 4 kHz (can be used at 40kHz with a limited area of the CCD). Estimation of S/N ratio in measurement and the accuracy to determine the magnetic axis will be presented. The capability to detect magnetic islands related to the MHD fluctuations which we observed in LHD with conventional SX detector array system will be also discussed.

CP22
Soft X-ray Detector Array System on Large Helical Device

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Soft X-ray (SX) detector array systems are installed on Large Helical Device (LHD) to study MHD phenomena. Two types of system are in operation: (1) An 80 ch array for detailed profile measurement with adjustable Be filter and (2) two 40 ch arrays with Be foil of 15 μm installed inside the vacuum vessel suitable for fluctuation studies. An integrated PIN photodiode detectors consist of twenty channels is used in both systems. Each channel of the detector has an effective area of 12 mm x 1.5 mm with a center-to-center spacing of 2.25 mm. It detects photons with energies below 30 keV. The upper limit of the frequency response is about 300 kHz.

Arrays are installed at a vertically elongated section of LHD. Typical spatial resolution is 30 mm (80ch array) and 50mm (40ch array) at the equatorial plane.

Results from 2nd and 3rd experimental campaign of LHD will be reported; (1) Hollow profile of SX radiation which is caused mainly by the hollow density profile and partly by hollow enhancement factor profile. (2) Peaking of the enhancement factor profile suggesting contamination of metal impurities at the core region. (3) Low frequency (< 10 kHz) fluctuations which correlate well with magnetic fluctuation. The peak of the observed fluctuations is located around 1/q = 1 rational surface. Estimation of poloidal mode number (m = 2, 3 experimentally) by the measurements from one direction will be also discussed.
Operation of the ultrasoft X-ray system on NSTX, * D. STUTMAN, M. IOVEA, M. FINKENTHAL, Johns Hopkins U., R. KAITA, D. JOHNSON, L. ROQUEMORE, P. RONEY, Princeton U., AND THE NSTX TEAM - The ultrasoft X-ray imaging system on NSTX become operational and provided first data in the filtered diode (SBD) configuration. Using different band pass filters on each of three arrays allows an approximate spectroscopic estimate of the plasma impurity content, as well as of the electron temperature. MHD activity from different plasma regions is also observed. The soft X-ray emission profiles are well behaved until an Internal Reconnection Event (IRE) occurs. Examples of NSTX MHD phenomena seen in the ultrasoft X-ray emission under different operational regimes will be presented.

From a technical point of view, we point out that the industrial PC based data acquisition system was not adversely affected by stray magnetic field's due to its close proximity to the NSTX device. Also, the surface barrier diodes withstood baking to 100°C relatively well.

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Ultrasoft X-ray telescopes for fluctuation imaging in fusion plasmas.* D. STUTMAN, M. FINKENTHAL, M. IOVEA, V. SOUKHANOVSII, M. J. MAY AND H. W. MOOS, Johns Hopkins U., - We present designs for the development of a novel instrument for two-dimensional imaging of low amplitude, fast fluctuations from MCF devices. The optics are similar in principle to that of the X-ray telescopes used in recent astrophysical missions. It uses a large (10-20 cm diameter), spherical multilayer mirror to select and concentrate a bright USXR impurity line (e.g. C VI Ly at 33.7 Å, or C VI Hα at 182 Å) onto a low noise and fast, two-dimensional detector. A first version of the telescope will use a fast phosphor to convert the image into visible light, which is then guided using fiber optics to a fast-gated CCD camera outside the vacuum. Detailed signal-to-noise analysis indicates that, due to the high energy and brightness of the USXR line emission and large reflectivity of present mirrors (up to 60% above 100 Å), such an instrument would allow imaging of sub-percent amplitude fluctuations with ≤ 10 µs time resolution and sub-cm spatial resolution. At the same time, ray tracings show that quite large plasma regions (up to a few tens of cm extent) can be imaged. Another version of the telescope would use a two-dimensional array of XUV diodes at the focal plane. In this case fluctuations of less than ≈ 0.1% could be imaged.

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CP25
Abstract Submitted
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Multilayer mirror and foil filter AXUV diode arrays on CDX-U and NSTX. V. A. SOUKHANOVSII, D. STUTMAN, M. IOVEA, M. FINKENTHAL, H. W. MOOS, The Johns Hopkins University, T. MUNSAT, B. JONES, D. HOFFMAN, R. KAITA, R. MAJESKI, Princeton Plasma Physics Laboratory — Recent upgrades to CDX-U spherical tokamak diagnostics included two 10-channel 100 kHz AXUV diode arrays. The multilayer mirror (MLM) array measures the 150 Å emissivity distribution of O VI ions in the poloidal plane using the Mo/B₄C MLM's as dispersive elements. The second array has a tangential view and is equipped with interchangeable beryllium and titanium foil filters. This allows measurements of radiated power, O VI or C V radial distributions. The arrays have been used on CDX-U for impurity transport studies and fast imaging of resistive MHD phenomena, such as low m oscillations and internal reconnection events, in plasmas with Tₑ ≤ 100 eV. Based on the reliable performance of the diagnostics, a new ultra soft X-ray multilayer mirror AXUV array monitoring the 34 Å emissivity distribution of C VI will be build and installed on NSTX.
This work is supported by U.S. DoE Grants DE-FG02-86ER53214 and DE-FG02-99ER54523 at JHU and U.S. DoE Contract DE-AC02-76-CH03073 at PPPL.

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Design and Modeling of the Soft X-ray Flux Surface Shape Diagnostic on the PEGASUS Toroidal Experiment*

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Flux shape information can be used as a constraint for reconstruction of the plasma current and q profiles for shaped, low-aspect ratio toroidal devices. The coupling of flux surface shape to internal profiles is particularly strong in PEGASUS due to the extreme toroidicity of the plasma. To exploit this sensitivity of shape to plasma profiles, the magnetic equilibrium code, Tokamak, has been expanded to incorporate flux surface shape information from linearized chordal soft X-ray (SXR) measurement inputs from a 2-D tangentially viewing pinhole camera. In addition, Tokamak has been expanded to include spline parameterization of the current and pressure profiles to add flexibility in reconstructing the q profiles. Initial modeling is being used to determine the number of measurement chords needed and the required signal strength for accurate profile reconstruction. The pinhole camera consists of a 2 mm diameter pinhole projection onto a 150 mm diameter viewport coated with a high-efficiency phosphor (P43). A 40mm diameter MCP image intensifier is lens coupled to the phosphor for maximum sensitivity, resulting in a signal to noise ratio of <1% from photon statistics. The MCP is optically coupled to a fast framing CCD camera allowing for frame rates of 1000 frames/sec and exposure times < 100 μs, providing for a time evolution of the reconstructed plasma equilibrium and profiles.

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-- End of Abstract

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Soft X-Ray Imaging for Spheromak-like Plasmas

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A pinhole soft x-ray imaging camera is being developed for use on the Caltech solar prominence simulation experiment and also the Caltech spheromak experiment. The camera is based upon a commercial gated intensifier which produces an image on a phosphor screen. Moderate signal level, excellent time resolution, and reasonable imaging have been obtained, but there has not been any determination of the x-ray energy spectrum. An estimation of the spectrum is now underway using filtered AXUV diodes and it is expected that knowledge of the x-ray energy will enable further optimization of the camera.
Reconstruction of the internal plasma perturbations using soft x-ray tomography and magnetic probes analysis.

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Numerical method is designed for joint analysis of the soft x-ray images and magnetic probes data in T-10 tokamak. The soft x-ray imaging system consists of three arrays of the surface barrier diodes and two proportional counters placed in various toroidal and poloidal locations around the torus. Soft x-ray tomography is based on Cormack algorithms with SVD decomposition and additional regularization technique. Tomographic reconstruction of the soft x-ray images is used in combination with data of the magnetic probes for analysis of the internal and external modes in sawtooth crash and coupling of the modes during density limit disruptions in ohmically and ECRH heated plasma.
X-ray imaging diagnostics for the inertial confinement fusion experiments.

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We report on our continued development of the advanced x-ray plasma diagnostics based on spherically curved crystals. The diagnostics include x-ray spectroscopy with 1D spatial resolution, 2D monochromatic self-imaging and backlighting and can be extended to the x-ray collimating and 2D absorption and emission spectroscopy. The system is currently used, but not limited to diagnostics of the targets ablatively accelerated by the NRL Nike KrF laser.

A spherically curved quartz crystal (2d=6.68703 \(\mu\)m, R=200 mm) has been used to produce monochromatic backlit images with the He-like Si resonance line (1865 eV) as the source of radiation. The spatial resolution of the X-ray optical system is 1.7 \(\mu\)m in selected places and 2-3 \(\mu\)m over a larger area. Another quartz crystal (2d=8.5099 \(\mu\)m, R=200mm) with the H-like Mg resonance line (1473 eV) has been used for backlit imaging with higher contrast. Spherically curved mica (2d=9.969 \(\mu\)m in the second order of reflection, R=200mm) has been used for backlighting of the low density foam cryotargets with the backlighter energy of 1.26 keV.

Time resolution is obtained with the help of a four-strip x-ray framing camera. Time resolved, 20x magnified, backlit monochromatic images of CH planar targets driven by the Nike facility have been obtained with spatial resolution of 2.5 \(\mu\)m in selected places and 5 \(\mu\)m over the focal spot of the Nike laser.

A second crystal with a separate backlighter has been added to the imaging system. This makes it possible to use of all four strips of the framing camera. As a result we have four monochromatic snapshots of developing instabilities.

We are currently exploring the enhancement of this technique to the higher and lower x-ray energies. A progress in high energy (4.5 keV) backlighting that has been made in cooperation with the LLNL will be reported.
Monochromatic X-ray Imaging with Bent Crystals for Laser Fusion Research


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The critical issue in laser fusion research is implosion stability of micro fusion capsule irradiated with intense laser light or x rays. X-ray line spectra emitted from the imploded plasma is often used to derive temperature and density, strongly depending on implosion stability.

Monochromatic x-ray imaging for the x-ray lines has been applied to temperature distribution measurements by the use of bent crystals in collaboration with Jena University. 2-channel X-ray Monochromatic Camera (XMC) consisting of two toroidally bent crystals of Ge and Si was developed to obtain monochromatic images at wavelengths of 33.71 nm of Ar$^{16}$ 1s$^2$-1s3p (He-$\beta$) and 31.55 nm of Ar$^{17}$ 1s-3p (Ly-$\beta$). Distribution of intensity ratio of the images can provide temperature distribution of the implosion plasma having tiny amount of Ar gas [I. Uschmann et al., RSI 66, 734 (1995)].

In addition to observation of these Ar resonance lines emitted from the center region of the imploded plasma, Cl lines from outer region were also observed at the same time by 5-ch XMC [M. Vollbrecht et al., JQSRT 58, 965(1997)]. Material distributions of argon and chlorine are useful to estimate the implosion stability.

Time-resolution of 34 ps by the use of X-ray Framing Camera (XFC) using fast gate function of micro channel plate (MCP) was installed as a detector of 10-ch Monochromatic XFC (M-XFC). The M-XFC can give 2-color (Ar He-$\beta$ and Ly-$\beta$ line) images at 5 different times to obtain temporal behavior of temperature distribution.

Rayleigh-Taylor (R-T) instability occurring at inward acceleration of the capsule is essential to understand implosion stability. A new XMC for new R-T experiments in ignition or high-gain condition is under development.

CP31
Using spherically bent crystals in wide range of Bragg angles for obtaining high-resolution, large-field, monochromatic X-ray backlighting imaging

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The new advantages of a laser-produced X-ray plasma source and spherically bent crystal combination for the X-ray backlighting scheme were experimentally demonstrated and theoretically modelling by ray-tracing package SHADOW. It was shown at first time that spherically bent crystals could be sufficiently used for obtaining high-resolution (about 4-6 \(\mu\text{m}\)), large-field (few mm), monochromatic (\(\delta \lambda = 10^{-5}-10^{-3}\)) images in a wide range of Bragg angles (\(\theta = 40-90^\circ\)). Thus spherically bent crystals are universal for X-ray monochromatic backlighting in a very wide wavelength region, what is very important for many applications.
National Ignition Facility Core X-Ray Streak Camera

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Abstract
The core x-ray streak camera for the National Ignition Facility will be utilized for experiments in support of High Energy Density Science Experiments, Inertial Confinement Fusion Ignition Experiments, and basic science experiments. The x-ray streak camera system is being designed with an interchangeable family of snouts, to record the time dependent x-ray emission from NIF targets. It will provide one dimensional (1D) space and a continuous time record over selected time periods. With the addition of a spectrally dispersing crystal in the snout, it will provide spectral vs. time information. A Charge Coupled Device readout will be used to record the signal from the streak tube. The streak tube, CCD, and associated electronics will reside in an EMP/EMI protected, hermetically sealed, temperature controlled box whose internal pressure is approximately one atmosphere. The streak tube itself will penetrate through the wall of the box into the target chamber vacuum. We are working towards 40 m spatial resolution and adjustable sweep speeds from 0.30ps/mm to 1ns/mm. The camera spectral sensitivity extends from soft x-rays to 10 keV x-rays, but with varying spatial resolution and quantum efficiency based on photo cathode selection. The system will have remote control, monitoring, and Ethernet communications through an embedded controller. The core streak camera will be compatible with the instrument manipulators at the Omega and NIF facilities.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.
Abstract for High Temperature Plasma Diagnostic Meeting

June 18-22, 2000
Tucson, AZ

Optimizing data recording for the NIF core diagnostic x-ray streak camera*

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Quantitative measurements of the sensitivity, dynamic range, and image resolution of a Nova SIM-based x-ray streak camera have been made. Comparisons were made using film vs. a 4kx4k optical CCD for data readout. These tests were performed with and without an optical image intensifier tube, and with a direct electron sensitive microchannel plate. We present results from these tests and recommendations for the NIF core x-ray streak camera.

* This work was conducted under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.
Abstract submitted for the 13th Topical Conference on High-Temperature Plasma Diagnostics
Tucson, Arizona, June 18-22, 2000

Development of wide-field, multi-imaging x-ray streak camera technique with new image-sampling method, M. Heya, S. Fujioka, H. Shiraga, N. Miyanaga, and T. Yamanaka, Institute of Laser Engineering, Osaka University, JAPAN—In order to enlarge the field of a multi-imaging x-ray streak camera (MIXS) technique [1], which provides two-dimensionally space-resolved x-ray imaging with a high temporal resolution of 10-20 ps, we have proposed and designed a wide-field MIXS (W-MIXS) with a new image-sampling method, a multi MIXS imaging. In this method, multi combinations of the cathode slit and the pinhole array were used as a photocathode of an x-ray streak camera and an imaging device. The field of W-MIXS can be enlarged up to 150-200 μm (70 μm for a typical MIXS) at a sampling distance of 6 μm. A proof-of-principle experiment of W-MIXS was carried out at the Gekko-XII laser system. A cross-wire target was irradiated by four beams of the Gekko-XII laser. The data streaked with the W-MIXS system were reconstructed as a series of the time-resolved, two-dimensional x-ray images. The W-MIXS system has been established as a two-dimensionally space-resolved and sequentially time-resolved measurement.


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CP35
Time- and space-resolved imaging techniques for study of plasma dynamics in low-density laser-irradiated matter.


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Optical and X-ray time- and space-resolved imaging techniques were developed and successfully used in experimental investigation of powerful laser beam interaction with low-density porous materials. Polymer organic material (agar) of fibrous structure with the average density (0.5±10) mg/cm³ was used to fabricate the planar targets. The targets of different thickness (from 100 μm to 1000 μm) were irradiated by a Nd-laser beam (λ=1.054 μm, τ=2.5 ns, I=10¹³+10¹⁴ W/cm²). To enhance the contribution of radiative processes to energy transfer, the agar targets doped with high-Z materials (from 25% to 50% by weight) were also used. The 1.5 μm-thick Al foils were deposited on the rear surface of the targets for the diagnostic purposes.
The processes of laser light absorption and formation of high-temperature plasma region inside a low-density media were studied by registration of plasma emission in soft X-rays (hv>400 eV) with temporal and spatial resolution using the X-ray streak camera. The energy transfer from the absorption region into the surrounding regions and towards the rear surface of the target was investigated with the help of the streak camera. This camera recorded the luminosity (in visible) at the rear side of the irradiated targets with time and space resolution. The multiframe optical shadowgraphy made it possible to analyze the motion of the accelerated matter. The lateral energy transfer and pressure profile smoothing inside porous matter were also studied in special experiments: two laser beams were focused onto the target surface with the focal spot spacing being varied from 150 μm to 300 μm.
The used diagnostic methods were proved to be adequate for investigation of energy transfer processes in laser irradiated porous materials.

This work was performed under the auspices of the Russian Foundation for Basic Research under Projects No. 98-02-16660 and 98-02-16662.

CP36
Neutron Spectroscopy on JET
Results from the MPR Spectrometer

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The Magnetic Proton Recoil (MPR) neutron spectrometer has been in operation at JET since the end of 1996. Being primarily designed as a 14-MeV spectrometer, a great wealth of data has been acquired, especially, during the deuterium-tritium experimental campaign of 1997 (DTE1). This paper reports on the main features of the spectrometer and its calibration besides results obtained, illustrating different aspects of the MPR as a plasma diagnostic. The results include the first observation of the so-called alpha knock-on effect in neutron spectra, the detailed analysis of the plasma response to ICRH and NB heating and a study of the time evolution of tritium retention in the JET vessel after DTE1.

Installed in the JET Torus Hall (TH), about 10 m from the plasma center, the MPR views the neutron emission from the plasma through a collimator at the end of which is placed a thin CH₂ foil. A fraction of the impinging neutrons scatter elastically on the target's hydrogen, creating nearly same energy proton recoils in the forward direction. Protons are selected by a proton aperture, momentum analyzed in the spectrometer's magnetic field, focused and finally registered in the 37-element focal plane scintillator array. Thus, the neutron energy distribution on the CH₂ foil is converted into a proton position histogram at the detector position.

The spectrometer offers good count rate capability (MHz) combined with good resolution. A flexible system of converter foils and proton apertures ensures that the experimental settings can be changed to meet varying plasma conditions. Thus, the spectrometer's energy resolution can be varied between about 2% and 10% (FWHM), with a reference efficiency of 1.3×10⁻⁴ cm² at 4% resolution. The high count-rate capability, together with the high detection efficiency and the position of the spectrometer in the JET TH, means that the spectrometer can provide data with good time resolution, statistics permitting. Data are routinely acquired with a time resolution of 10 ms.

The spectrometer was carefully characterized before delivery to JET and was in principle turn-key ready after installation. The absolute energy calibration has an uncertainty of less than 10 keV, which has been tested and verified both with the use of radioactive sources (²⁴¹Am) and later with JET data from plasma discharges with purely ohmic heating. The precise determination of the energy calibration makes the MPR a diagnostic for plasma rotation.

Background control and corrections are done in three steps: first, by the 65-ton radiation shield (mainly concrete), second, by pulse height discrimination and, finally, by interference corrections derived by off-line analysis of recorded pulse height spectra. The sensitivity of the MPR is such that high-energy components on the level of about 10⁻⁵ of the peak amplitude can be observed. This has been exploited in a search for and the first positive identification of the so-called alpha knock-on tail in neutron spectra.

Another aspect of the diagnostic capability of the MPR is the analysis of ICRH heated plasmas, here in particular those with a deuteron minority. These data have been analyzed in a new three-component model and represents the first use of neutron emission data for high accuracy diagnosis of the response of the plasma to ICRH heating, including its time evolution over individual discharges.

A final example of the MPR versatility is the use of the neutron emission to study the time evolution of tritium retention in the JET vessel. Since the end of DTE1 in 1997, JET has been operating with D plasmas. However, even under these conditions there are trace amounts of tritium in the plasma due to the d+d → t+p reaction. In addition, tritium stored in the vessel walls after DTE1 is slowly released into the vessel during operations. With the MPR these two components can be distinguished, and the time evolution of tritium retention since DTE1 can thus be studied.
Nuclear Diagnostics for Petawatt Experiments


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With the operation of successively more intense and powerful lasers, such as the NOVA Petawatt laser with $I \sim 3 \times 10^{20}$ W/cm$^2$, several novel (to laser physics) nuclear diagnostics were used to determine the nature of the laser/matter interaction at the target surface. A broad beam of hot electrons, whose centroid varied from shot to shot, width was remarkably constant, and intensity was about 40% of the laser energy on target, was observed. New nuclear phenomenon included photonuclear reactions (e.g. $(\gamma, xn)$), photofission of $^{238}$U and intense beams of ions. Photonuclear reactions were observed and quantified in Cu, Ni and Au samples, and produced activation products as neutron deficient as $^{191}$Au (a $(\gamma, 6n)$ reaction!), requiring gamma-rays exceeding 50 MeV in energy. The spectral features of the gamma-ray source have been investigated by comparing activation ratios in Ni and Au samples, and angular distributions of higher energy photons have been measured with activation of spatially distributed Au samples. Extraordinarily intense beams of charged particles (primarily protons) were observed normal to the rear surface of the target and quantified using the charged particle reaction $^{48}$Ti(p,n)$^{50}$V, radiochromic film and CR39 plastic track detectors. Approximately $3 \times 10^{13}$ protons, with energies up to 55 MeV were observed in some experiments. Collimation of this beam increases with increasing proton energy. Correlations of activation with laser performance will be discussed.
Nuclear diagnostics for the National Ignition Facility* Thomas J. Murphy, Los Alamos National Laboratory. The National Ignition Facility, currently under construction at the Lawrence Livermore National Laboratory, will provide unprecedented opportunities for the use of nuclear diagnostics in inertial confinement fusion experiments. The completed facility will provide 2 MJ of laser energy for driving targets, compared to the approximately 40 kJ that were available on Nova and the approximately 30 kJ available on Omega. Ignited NIF targets are anticipated to produce up to $10^{19}$ DT neutrons [1].

These higher NIF yields are expected to allow innovative nuclear diagnostic techniques to be utilized. Neutron imaging, demonstrated on Nova [2] and currently under continued development at Omega, is being investigated as a routine diagnostic procedure for NIF. Techniques based on detection of recoil protons from thin plastic films [3], of limited use on existing laser facilities due to the low detection efficiency, may become useful at NIF yields.

In addition to new opportunities, NIF will produce new challenges. The stand-off distance, currently quoted as 50 cm, will prevent neutron-based burn history measurements due to the time-of-flight spreading of the neutrons. Techniques which utilize the 17-MeV gamma ray from the T(d,γ)^7He reaction are currently being developed [4,5]. These offer an advantage since the gammas exhibit no time-of-flight spreading. Success of this method also relies on the increased yields expected from NIF since the branching ratio of this reaction is small.

In this talk, an overview of the nuclear diagnostic suite as planned for NIF will be presented. Advanced techniques currently being developed will be discussed. Challenges that remain will be listed.

Future fusion reactors should have good confinement of fusion born $\alpha$-particles to sustain a self burning plasma. Thus, fast ion loss measurements are of great interest, in particular for stellarators with their additional field ripple in comparison to axisymmetric systems. Also in the case of improved field configurations like the largely drift-optimized W7-X or quasi-omnigeneous stellarators fast ions may be lost due to the interaction with MHD-perturbations. W7-AS is only a partially drift-optimized stellarator with a complex field structure, and the fast ion orbits are quite different from those of classical stellarators. Thus, the investigation of fast ions losses generated by neutral beam injection (NBI) and ion cyclotron heating (ICRH) is of particular interest with respect to heating efficiencies and to the confinement properties of W7-AS, in which fast hydrogen ions may serve as a substitute for $\alpha$-particles.

At W7-AS, fast ion losses have been detected with a scintillator based probe, which works like a magnetic spectrometer. It consists of an aperture system with a pinhole followed by a slit and a scintillator plate behind. Gyroradius and pitch angle of the lost ions can be resolved by observing the light distribution on the plate with a CCD-camera and photomultipliers. The new feature of our probe is the simultaneous measurement of both co- and counter-going losses. It has also the capability of calibrating the loss rates with measured ion loss currents using the probe as a Faraday cup.

We present ion loss data of discharges with perpendicular (diagnostic) and tangential (heating) co- and counter-NBI. The loss signals show that the slowing down of the ions has to be taken into account, that is temperature, density and the impurity content affect slowing down times and the scattering in pitch angle.

Ion losses during ICRH are found for a variety of different heating schemes such as second harmonic, minority and the so called magnetic beach heating. The energetic ion tail generated by ICRH at large perpendicular velocities has been directly observed.

Fast ion losses are found, which are induced by beam- and current-driven MHD-instabilities. In the case of beam-driven instabilities, where the parallel velocity of the injected ions matches the Alfvén velocity, trapped particle losses are increased during bursts of an intermittent Alfvén eigenmode. Strong effects were observed in the case of current-driven instabilities. After the evolution of tearing modes, which were identified by soft X-ray tomography, fast ions are expelled from the plasma on a short time scale.
Fast Ion Loss Diagnostic Plans for NSTX*

D. S. Darrow, Princeton Plasma Physics Laboratory

The National Spherical Torus Experiment (NSTX) at PPPL will be heated with up to 5 MW of 80 keV D co-injecting neutral beam (NB) power and up to 5 MW of High Harmonic Fast Wave (HHFW) heating. The HHFW system is already functioning at the 2 MW level, with 5 MW available in fall 2000. The NB system will be operational starting in October 2000.

The prompt loss fraction of NB ions from NSTX is predicted to be between 12% and 45% for plasma conditions of interest. Collisions, MHD activity, fast ion driven instabilities, non-adiabaticity, and HHFW-induced velocity diffusion will all tend to increase the loss fraction above these baseline values. In addition, some modeling results predict that the HHFW will produce a fast ion tail when the central ion temperature exceeds ~700 eV. In order to test the predictions of neutral beam prompt loss and to measure the effect of these other phenomena in producing loss, some means of measuring the loss rate and spatial distribution in NSTX is needed.

Infrared cameras will be the first diagnostic applied to measuring the fast ion loss. One will be aimed at the front face and leading edge of the HHFW antenna at the midplane, which is predicted to take a substantial fraction of the lost fast ions. Comparison of the deposition patterns and peak temperatures reached with model predictions should allow assessment of the validity of the model.

As a second diagnostic of fast ion loss, a fixed-position probe with several recessed Faraday cups will be installed in NSTX for the 2000 experimental campaign. This probe will give an integrated measure of ion flux over a range of pitch angles and energies, absolutely calibrated. Results from this diagnostic will also be compared with the modeling. In subsequent years, this probe will be upgraded with resolution by using thin foil Faraday cup stacks[1] to resolve energy and an aperture/detector strip arrangement to resolve pitch angle.

Finally, a concept is being developed to use natural diamond detectors to measure the pitch angle distribution of charged DD fusion products at the wall.[2,3] From this measurement, the fusion source profile can be inferred.


*This work supported by US DoE contract DE-AC02-76CH03073.
Upgrade of Electrical Cooled Si-FNA for LHD Fast Ion measurement


A new Fast Neutral Analyzer has been developed at NIFS, by using electrically cooled Silicone-diode detector (Si-FNA). This detector is suitable for profile measurement of fast neutral energy spectra since it is compact and inexpensive. Two Si-FNA's were newly designed and installed on LHD during the 3rd experimental campaign. Basic performances of Si-FNA were examined by using X/γ-ray sources of 57Co and 241Am. The energy resolution of about 3keV is achieved for the resolution optimum condition and that of about 5keV is done for the count-rate optimum condition. The calibration for neutral were done by using the Neutral Beam injection experiment without target plasmas on LHD, where the NB's were ionized by a collisions with residual gases in LHD vacuum vessel. The energy loss of about 40 keV and the energy broadening of about 5keV were observed in the spectra of calibration experiments. These loss and broadening are considered to be due to the effect of an evaporated aluminum layer, which is attached on the...

We are continuing our investigation of the use of stacks of electrically isolated thin metal foils as spectrometers for lost ions from tokamak fusion plasmas. Devices of this type in which the foil thicknesses were a few micrometers were installed on JET during the recent DTE-1 experiment in an effort to observe lost energetic alpha particles[1]. While there was no convincing evidence of lost alpha particles in this experiment, we did observe significant fluxes of low energy (<500 keV) charged particles[2]. In an effort to provide an instrument for the investigation of this phenomenon and of escaping relatively low energy (<100 keV) ions from other fusion plasma devices, we have developed an alternative device with very thin (few hundred nanometer) deposited layers of conductor and insulator. Such a device consisting of two layers of Al each about 400 nm separated by 100 nm of SiO2 has been tested for protons with energies between 20 and 160 keV yielding an energy resolution of better than 10% at 120 keV. At an energy of 100 keV, the device was able to operate up to a current density of about 100 microAmps/cm2, corresponding to a power density of 100 KW/cm3. Possible improvements which will allow operation at higher power densities will be discussed. *Supported in part by a grant from the Office of Fusion Energy Sciences of the U.S DOE.


Diamond radiation detector made of an ultra high-purity type IIa diamond crystal grown by HP-HT synthesis, T. Tanaka, J. Kaneko, D. Takeuchi, M. Katagiri, T. Nishitani, H. Takeuchi, T. Iida, H. Ohkushi. Japan Atomic Energy Research Institute, 1 Electrotechnical Laboratory, Osaka University --- The best natural diamond radiation detector satisfies all performance required for plasma ion temperature measurement based on a neutron energy spectroscopy; moreover, the detector has very compact size compared with other neutron detectors. Therefore, a diamond radiation detector is a strong candidate for a neutron detector used for a plasma ion temperature distribution measurement system in ITER. We have been developing synthetic diamond radiation detectors aiming for this purpose, because it is very difficult to routinely produce natural diamond radiation detectors of sufficiently good performance. It was already revealed by a previous study that there was severe trapping on electrons in a conventional type IIa synthetic diamond crystal. In order to understand influence of nitrogen and boron impurities, radiation detectors made of ultra high-purity type IIa diamond crystals whose nitrogen impurities were less than or equal to 0.1 ppm were studied. An energy spectrum of 5.486 MeV α particles from 241Am obtained by the detector with illumination of UV light of 370 nm indicated that there was superior part to the conventional type IIa diamond; because, an α peak was not affected so much by the illumination of the UV light. This result suggested a possibility that a practical diamond radiation detector will be realized by using synthetic diamond.
Abstract Submitted for the Thirteenth Topical Conference on High Temperature Plasma Diagnostics
June 18–22, 2000, Tucson, Arizona

[ ] Theory [x] Experiment

Measured Response of Bubble Neutron Detectors and Prospects for Alpha Knock-On Diagnostics* R.K. Fisher, A. Bellian,† M.L. Loughlin,‡ J.Liptac,*, S. Medley,† E. Morse,‡ P.B. Parks, and A.L. Roquemore,† General Atomics — Measurement of the neutron energy spectrum above ~16 MeV will yield information on the spatial and energy distributions of confined fast alphas in DT tokamaks.1 The energetic neutrons result from fusion reactions involving the energetic ions created by alpha-fuel ion knock-on collisions. Standard two-gas bubble neutron detectors, designed to only detect neutrons with energies above a selectable threshold determined by the gas mixture, were used in preliminary attempts to measure the knock-on neutrons from DT plasmas in TFTR and JET. Subsequent measurements at accelerator neutron sources showed an unexpected below-threshold detector response that prevented observations of the alpha-induced neutron tails. Spontaneous bubble nucleation measurements show that the majority of this below-threshold response is due to slight variations in the gas mixture, and is not present in single-gas detectors. Single-gas detectors will be tested at UC Berkeley to determine the neutron energy threshold as a function of detector operating temperature and to confirm their suitability for alpha knock-on tail measurements. An array of single-gas detectors operating at different temperatures should allow measurements of the alpha knock-on neutron tail during the proposed DTE2 experiments on JET.


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†UC Berkeley, JET, *Univ. of Washington, and ‡PPPL
Neutron-Induced Background in CCD Detectors

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Abstract

We report on measurements of the neutron-induced background levels in the CCD detectors that are replacing film as the recording medium in many ICF diagnostics. This background degrades the SNR of the recorded signals and for the highest yield shots comprises a substantial fraction of the pixel’s full well capacity. We discuss the spectrum of the deposited energy per pixel, its time history and the efficacy of shielding. To make meaningful measurements at 1.E+13 DT neutron yields on OMEGA, we have had to move our most sensitive streak camera diagnostics over 16 meters from the target chamber center, behind a 2-meter-thick (line of sight) concrete shield wall. There are also problems with using film instead of CCDs, as we have observed substantially increased fog levels on DEF film as a function of neutron yield.

This work was supported by the U. S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FG03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.
Investigation of x-ray-energy responses of semiconductor detectors under deuterium-tritium-fusion-produced neutron irradiation


Plasma Research Centre, University of Tsukuba, Ibaraki, Japan

JAERI, Japan

For the purpose of investigating fusion-produced neutron effects on semiconductor x-ray detectors, detection characteristics of x-ray tomography detectors used before and/or after fusion experiments in the Joint European Torus (JET) tokamak (n-type silicon) and the GAMMA 10 tandem mirror (p-type silicon) are studied using synchrotron radiation from a 2.5-GeV positron storage ring at the Photon Factory. Degradations of the responses after neutron exposure into the detectors are found to have functional dependence on x-ray energy. Changes in the depletion thicknesses of the detectors are investigated using an impedance analyzer. The fusion neutronics source (FNS) facility of Japan Atomic Energy Research Institute is also employed for well-calibrated D-T neutron irradiation onto these semiconductor x-ray detectors. Our theory is applied to interpret these systematically obtained properties; that is, dependence of total sensitive depths of the detectors (i.e., the depletion layer thicknesses and the diffusion lengths) on the D-T neutron fluence is analyzed.
13th Topical Conference on
High Temperature Plasma Diagnostics
18-22 June 2000, Tucson, Arizona
Abstract Submittal Form
Deadline: Monday, 6 March 2000

Subject Classification Category  Neutron Measurements  Theory  Experimental

Time response measurement on a fusion power monitor based on activation of water flow*, J. Kaneko, Y. Uno, T. Nishitani, F. Maekawa, T. Tanaka, Y. Shibata, Y. Ikeda, H. Takeuchi Japan Atomic Energy Research Institute --- As a part of development of nuclear instrumentation for ITER, a fusion power monitor based on activation of water flow was developed. The fusion power monitor determines D-T neutron yields, i.e., fusion power, by measuring 6-MeV γ-rays accompanied by disintegration of 16N nuclei which are produced by the 16O(n,p)14N reaction with 14 MeV neutrons in water. The fusion power monitor consists of a water pipe loop laid from the first wall through out side of the bio-shield and a gamma-ray detector, e.g., a BGO scintillator. This monitor has excellent features in high reliability, long-term stability, absolute measurement and free-maintenance. In an experiment for time resolution measurement with pulsed neutrons, time resolution of 50 ms that fully satisfied the time resolution of 100 ms required from plasma diagnostics was achieved. In addition, it became clear that time response of the system was described by turbulent flow model.

*This work was supported by ITER EDA under task agreement No. T-499.

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DP9
The NIF Total Neutron Yield Diagnostic*

by

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We have designed a total neutron yield diagnostic for NIF which is based on the activation of In and Cu samples. The particular approach that we have chosen to use is the “calibration factor” method in which we calibrate the entire counting system. In this method, In and/or Cu samples are exposed to known sources of DD and DT neutrons. The activated samples are then counted with the appropriate system: an HPGe detector for In and a NaI coincidence system for Cu. We can then calculate a calibration factor, which relates measured activity to total neutron yield. The advantage of this approach is that specific knowledge of such factors as cross sections and detector efficiencies are not needed. The disadvantage is that it may be difficult to mock-up in a calibration experiment the actual scattering environmental of NIF. As a result, the experimentally obtained calibration factor may have to be modified using the results of a numerical simulation of the scattering environment. In this paper, experimental results for the calibrations factors will be presented as will the overall design concept.

*This work supported by the U. S. Department of Energy under Contract No. DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy.
High-Yield Neutron Activation System for the National Ignition Facility

Cris W. Barnes, T.J. Murphy, J. A. Oertel, Los Alamos National Laboratory

The total fusion energy production from inertial confinement fusion targets at the National Ignition Facility (NIF) will be measured by a variety of fusion product diagnostics. Possibly the most accurate and precise determination of the total neutron yield over extreme dynamic range comes from radioactivity produced by threshold nuclear reactions in small samples placed near the target and then subsequently removed to count the gamma-ray activation. Such techniques have achieved ±7% (one-sigma) accuracy on magnetic fusion devices such as TFTR¹ and JET, and have demonstrated dynamic range between shots of over six-orders-of-magnitude.²

The high-yield system for NIF uses thin elemental samples ("foils") for which the gamma-ray detection efficiency can be calculated accurately from first principles. Then using dosimetric cross-sections and standard nuclear physics parameters the measured fluence can be determined and turned into total yield using neutronics modeling of the target chamber. Such a system can work down to 10⁶ neutrons/cm² which, assuming a 50-cm exclusion radius, means minimum yields of ~3x10¹⁰ neutrons/shot. By increasing the sample distance to near the target chamber wall (4 meters), reducing the sample mass and increasing the counting rate, yields up to the maximum allowable on the system can be measured. A complementary low-yield activation system³ will use larger masses to achieve higher sensitivity and will use associated particle methods⁴ at an accelerator to determine the calibration. The system design requirements will be detailed for the high-yield neutron activation system on NIF. A pneumatic transport system similar to that used on TFTR and designed for ITER⁵ will be described as well as the requirements for the irradiation ends and counting system.

This work was performed under the auspices of the U.S. Department of Energy by the Los Alamos National Laboratory under contract No. W-7405-Eng-36.

³ C. L. Ruiz, these proceedings.
A detailed measurement of the $^{27}$Al($n$,2$n$)$^{26}$Al reaction cross sections was performed in the near-threshold region ($E_{th}$=13.54 MeV), and its possible applicability for ion temperature measurements was investigated.

The production of the long-lived radionuclide $^{26}$Al ($t_{1/2}$=7.2*10$^5$ a) is of considerable interest to the fusion reactor program. Particularly long-lived radionuclides may lead to a significant long-term waste-disposal. Al-containing materials and Si carbide are candidate materials for fusion-reactor systems. The Al($n$,2$n$) reaction and the two step process $^{28}$Si($n$,np+d)$^{27}$Al($n$,2$n$) are the dominating processes for the formation of $^{26}$Al in a fusion reactor. The $^{27}$Al($n$,2$n$)$^{26}$Al reaction is expected to vary strongly with neutron energy above threshold. An accurate description of the excitation function is necessary to estimate the production of $^{26}$Al in a typical D-T fusion environment. From the existing data on cross sections it was not possible to produce an unambiguous excitation function. We started therefore a project to determine this excitation function more accurately.

It has been pointed out by Smither & Greenwood$^2$ that the $^{27}$Al($n$,2$n$)$^{26}$Al reaction can be used as a monitor to determine the ion temperature in a D-T fusion plasma. This method makes use of the neutron energy distribution as a sensitive function of the plasma ion temperature. The temperature sensitivity is most pronounced if the excitation function is strongly nonlinear and if the threshold falls within the energy region of the emitted neutrons: For the $^{27}$Al($n$,2$n$)$^{26}$Al reaction the threshold lies at 13.54 MeV and the ($n$,2$n$) reaction is expected to be a strongly varying function of the neutron energy near threshold.

Al samples were irradiated with 14-MeV neutrons generated via the T(d,n)$^4$He reaction at three different laboratories under different conditions. The produced $^{26}$Al was measured using the extremely sensitive method of accelerator mass spectrometry (AMS). $^{26}$Al/$^{27}$Al isotope ratios as low as 10$^{-15}$ could be measured with the Vienna Environmental Research Accelerator (VERA) corresponding to cross section values as low as 0.03 mb.

The results from the different neutron irradiations agree very well with each other. The absolute cross section values could be measured to 5% (mainly systematic errors). The slope of the excitation function is reproduced to better than 1% from our measurements. With this improved knowledge the sensitivity for monitoring the ion temperature in a D-T plasma was investigated. For monitoring the ion temperature of a thermal plasma a sensitivity of a few percent can be achieved by this method. In case of non-thermal plasmas with neutral beam injection (NBI) the mean neutron energy depends on the direction under which the plasma is viewed. A very high sensitivity for the case of backward viewing for NBI is obtained for the $^{27}$Al($n$,2$n$)$^{26}$Al reaction reflecting the closer distance of the mean neutron energy to the reaction threshold ($E_{th}$).

Together with the very sensitive method of AMS this reaction may serve as a useful tool in plasma diagnostics.


Neutron Flux Monitoring System for ITER-FEAT

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Troitsk Institute of Innovating and Fusion Research (TRINITI), Troitsk, Moscow reg. 142092, Russia

The concept of the neutron flux measurements for ITER-FEAT is discussed. In spite of ITER-FEAT has reduced fusion power with ITER-FDR, the requirements for neutron flux monitors are the similar — wide dynamic range (7 orders), good temporal resolution (1ms) and high accuracy (10%). It is clear that only fission chambers are most suitable detectors for this application. However high neutron intensity of the fusion plasma and hard requirements lead to more complicated detection system than ordinary fission chamber. Another problem is an absolute calibration of the detectors. We propose neutron flux monitoring system, which consist of microfission chambers, placed inside ITER vacuum chamber, 3 wide range fission chambers, placed outside vacuum chamber, multi natural diamond detectors based compact neutron monitors, placed inside channels of neutron cameras and compact neutron generator for calibration. Microfission chambers will be installed in the standard plugs with other detectors (vacuum X-ray diode, magnetic probe). $^{235}$U could be used as well as threshold fission materials ($^{238}$U, $^{237}$Np, $^{232}$Th). In the last case the fission chamber will be covered by boron shield to reduce the changes in the sensitivity. Wide range fission chambers will operate in both pulse count mode and Campbell mode. High linearity is provided by count mode. Temporal resolution 1 ms is provided by count mode at low neutron flux and by Campbell mode at high. The non-linearity of the fission chamber during switch from count mode to Campbell mode will be corrected by another fission chambers with low sensitivity operating in count mode. Compact in-neutron camera neutron flux monitors will consist of up to ten natural diamond neutron counters which sensitivity to DT neutrons will be doubled by correspondingly installed polythilen radiators. Such monitors provide DT neutron flux profile measurements with dynamic range (3 orders), temporal resolution (1ms) and accuracy (10%). Full system could be calibrated by compact moveable neutron generator with neutron yield $10^{11}$ neutron/sec which operate in continuous mode. All elements of the system are commercial available except neutron generator and diamond detector based monitors. The neutron generator and multi diamond detector based DT neutron monitors are now under development. Existing prototype of neutron generator operate with yield one order less.

Performance and major characteristics of proposed systems of neutron flux monitoring will be discussed from the point of view of their application for neutron flux measurements and control on deuterium and deuterium-tritium phases of ITER-FEAT operation.

DP13
Secondary Neutron Yield Measurements by Current Mode Detectors


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Abstract

The measurement of secondary deuterium—tritium (DT) neutrons from pure deuterium inertial confinement fusion (ICF) targets can be used to diagnose the fuel areal density. Single-hit detectors like LaNSA at LLNL or MEDUSA at LLE saturate for fairly low, secondary DT and primary DD neutron yields. They are not suitable for high-yield, direct-drive implosion experiments currently carried out on the 30-kJ, 60-beam OMEGA laser system or for future cryogenic capsule experiments on OMEGA. Current mode detectors (e.g., a single scintillator and a photomultiplier tube) for secondary neutron yield measurements on current and future OMEGA experiments are being developed. The status of current mode detectors for secondary yield measurement at LLE will be presented together with experimental results of several direct-drive implosion experiments on OMEGA.

This work was supported by the U. S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.
Time-of-Flight Neutron Spectrometer for JT-60U, Y. Shibata, M. Hoek, T. Nishitani and T. Iguchi, Nagoya University. We have developed a 2.45 MeV neutron Double Crystal Time-of-Flight (DC-TOF) spectrometer for DD plasmas in JT-60U. The DC-TOF neutron spectrometer consists of two fast plastic scintillators (50 cm$^2$ and 1800 cm$^2$, thickness 2 cm) where both detectors are located on constant TOF spheres. The TOF spheres have a radius of ~1 m which gives a neutron flight length of ~1.64 m and a TOF of ~92 ns for 2.45 MeV neutrons. The calculated spectrometer efficiency and resolution are 2.8x10^-2 cm$^2$ and 105 keV (4.3 %), respectively. The energy resolution corresponds to a time resolution of 2.0 ns. The performance of the spectrometer was tested with 14-MeV neutrons at the FNS neutron generator in JAERI Tokai. The spectrometer has been installed in the basement of JT-60U, ~10 m away from the plasma center with vertical line-of-sight. To handle higher detector count-rates, the detectors were modified and the shielding was increased. The results from these modifications showed that neutron energy distributions can be obtained when the neutron yields from the plasma are ~10^15 neutrons/s.

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Submitted By:

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DP15
Abstract
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'13th Topical Conference on High-Temperature Plasma Diagnostics',
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Fusion Reactivity Studies of DT Plasmas with NB Heating, -- H HENRIKSSON, S CONROY, G ERICSSON, G GORINI*, A HJALMARSSON, J KÄLLNE AND M TARDOCCHI, Dept. of Neutron Research, Uppsala Univ.*, Sweden; *Dept. of Physics, Univ. of Milano-Bicocca and Ist. di Fisica del Plasma**, Italy. -- The energy spectrum of the DT neutron emission was measured in experiments carried out at JET for plasmas heated with high power neutral beam (NB) injection. Heating schemes included deuterium beams at $E_0=75$ keV and/or 150 keV, as well as tritium beams of $E_0=150$ keV nominal injection energies. The spectrum was measured with the magnetic proton recoil (MPR) spectrometer which provided high quality data in which up to three spectral components, due to different ion reactions, could be distinguished.
A Monte Carlo simulation was used to model reactions involving the slowing down population of anisotropic (co and counter passing) NB ions as well as trapped NB ions. Moreover, a narrow Gaussian component due to thermal DT reactions could be resolved in some cases. Examples of results from different heating schemes will be presented including time resolved analysis.

*EURATOM-NFR Association; **EURATOM-CNR-ENEA Association

Contact: J Källne, Uppsala University; e-mail Källne@tsl.uu.se
Abstract
Submitted to
'13th Topical Conference on High-Temperature Plasma Diagnostics',
Tucson, Arizona, June 19-23, 2000

Neutron Emission Spectroscopy (NES) Diagnosis of DT Plasmas with Ion Cyclotron Resonance Heating.
-- M TARDOCCHI, S CONROY, G ERICSSON, G GORINI*, H HENRIKSSON, A HJALMARSSON AND J KÄLLNE, Dept. of Neutron Research, Uppsala Univ.*, Sweden: *Dept. of Physics, Univ. of Milano-Bicocca and Ist. di Fisica del Plasma**, Italy. The energy spectrum of the DT neutron emission was measured in experiments carried out at JET for plasmas of deuterium-tritium heated with different ion cyclotron resonance heating (ICRH) schemes. The spectrum was measured with the MPR (magnetic proton recoil) spectrometer. The data were analyzed in up to three spectral components which were ascribed to the underlying reactions involving thermal, epithermal and high energy ions. The results include time resolved information for individual discharges. Changes in the (minority) deuterium concentration in the range 9 to 20% were found to affect significantly the ICRH absorption and its perturbation of the minority velocity distribution. High energy components in the fuel ion population were found in most cases and analyzed in terms of a tail temperature. This contribution will present the first use of neutron emission spectroscopy (NES) for high accuracy diagnosis of the plasma response to ICRH in tokamak plasmas.

*EURATOM-NFR Association; **EURATOM-CNR-ENEA Association

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DP17
The Development Potential for Neutron Emission Spectroscopy Diagnosis of D plasmas. -- A Hjalmarsson, S Conroy, G Ericsson, G Gorini*, H Henriksen, J Kallne, M Tardocchi and J Thun, Dept. of Neutron Research, Uppsala Univ.*, Sweden; *Dept. of Physics, Univ. of Milano-Bicocca and Ist. di Fisica del Plasma**, Italy. -- Neutron emission spectroscopy (NES) measurements in the MHz count rate range have been performed on DT plasmas at JET using the magnetic proton recoil (MPR) spectrometer for 14-MeV neutrons. These MPR measurements have successfully demonstrated the NES diagnostic potential in DT plasmas with ICRH or NB heating, and even with Ohmic heating alone. NES diagnosis of D-plasmas requires the instruments with a neutron detection efficiency that is 10^2 to 10^3 times higher than that of the MPR and other capabilities (such as high count rate) so as to match the performance level of the MPR. The conceptual basis for such an instrument is the time-of-flight (TOF) technique optimized for rate (TOFOR). The design of a 2.5-MeV TOFOR spectrometer has been started as will be reported in this contribution. The TOFOR diagnostic mission on JET would be studies of perturbed fuel ion velocity distributions under NB and RF heating compared to those of equilibrium plasma conditions of Ohmic heating. This will also be discussed.

*EURATOM-NFR Association; **EURATOM-CNR-ENEA Association

Contact: J Kallne, Uppsala University.; e-mail Kallne@tsl.uu.se
Calibration of the MEDUSA neutron spectrometer


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1Laboratory for Laser Energetics, Univ. of Rochester, Rochester, NY

2State University of New York, Geneseo, NY

The MEDUSA array is a multi-element, scintillator-based neutron time-of-flight spectrometer designed primarily to measure primary and secondary neutron production from indirect drive DD and DT capsule implosions at the Omega Laser in Rochester, NY. The array consists of 824 identical scintillator-PMT detectors coupled to analog signal discriminators and high resolution, multi-hit time-to-digital converters (TDC's), and is located 19.4 meters from the center of the Omega target chamber. It is possible to accurately measure the neutron energy spectrum by simply measuring an adequate sample of neutron flight times to the array (the burn time width is negligible). However it is essential to understand the response of the array detectors to the fusion neutrons before an energy spectrum can be deduced from the data. This array response function is generally given in terms of a calibration constant that relates the expected number of detector hits in the array to the number of source neutrons. The calibration constant is a function of the individual detector gains, the thresholds of the discriminators and the amount of neutron attenuating material between the array and the target. After gain matching the detectors, a calibration constant can be generated by comparing the array response against a known yield of neutrons (this requires dozens of implosions) or from a first principles measurement of the individual detector efficiencies. In this paper, we report on the results of both calibrations of the MEDUSA array. In particular, we will focus on the issues and errors associated with the very different measurements required and discuss a new technique being considered for rapid in situ future calibrations.

*This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48, by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

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DP19
A neutron spectrometer for NIF
R. G. Watt, R. E. Chrien, K. Klare, G. Morgan, T. J. Murphy, D. C. Wilson
Los Alamos National Laboratory
S. Haan
Lawrence Livermore National Laboratory

We are designing a 1020-channel single-neutron-interaction time-of-flight spectrometer as a core diagnostic for the National Ignition Facility using hardware from the Nova Tion array\(^1\). This spectrometer can measure (1) capsule implosion yield (\(10^7\) to \(10^{10}\) range) and ion temperature from early NIF targets, (2) fuel density-radius product (\(pR=0.02\) g/cm\(^2\)) from secondary neutrons arising from fusion-produced tritons in D\(_2\)-filled capsules with yields up to \(10^{12}\), (3) fuel electron temperature in D\(_2\)-filled capsules in which fusion-produced tritons are thermalized in the fuel (\(pR>0.05\) g/cm\(^2\)), and (4) fuel \(pR\) in near-ignition capsules by a three-step process creating neutrons with energies up to 30 MeV. Calculated spectra for the tertiary neutrons from simulations done by both LANL and LLNL will be shown, along with a discussion of implications for the instrumental design. The photomultiplier array can also be used as a recording system for a low-yield neutron imager. A 27-m line-of-sight has been assigned on NIF and the major sources of background from inelastic neutron scattering have been identified. The time resolution will be upgraded with new time-to-digital convertor electronics, resulting in a neutron energy resolution better than 10 keV.


Poster Session

DP20
Neutron time-of-flight and emission time diagnostics for the National Ignition Facility* T. J. Murphy, J. L. Jimerson, Los Alamos National Laboratory. Current mode neutron time-of-flight (nToF) detectors have been used to measure the neutron yield [1], ion temperature [2-7], and neutron emission time [8] of ICF targets on Nova, Omega, and other large ICF facilities. A current-mode neutron time-of-flight detector typically consists of a scintillator optically coupled to a photomultiplier tube and placed at a distance from a pulsed neutron source. Neutrons are usually produced in the reactions D(d,n)3He or T(d,n)4He. Conservation of energy (mass) and momentum and the large amount of energy released in the reaction results in nearly monoenergetic neutrons being produced at energies of 2.45 MeV (DD reaction) or 14 MeV (DT reaction).

Current plans call for a system of current mode neutron detectors for the National Ignition Facility for extending the range of neutron yields below that of the neutron activation system, for ion-temperature measurements over a wide yield range, and for determining the average neutron emission time. The system will need to operate over a yield range of $10^6$ for the lowest-yield experiments (in order to maintain capabilities that were available on Nova and are currently available on Omega) to $10^{19}$ for high-yield ignited targets.

The requirements will be satisfied using several detectors located at different distances from the target. Each detector will incorporate fiducial signals for determining timing and performing pre-shot testing. Sensitivity will be adjusted for each experiment by varying the bias voltage on the tubes. Signals will be recorded on high-speed digitizing oscilloscopes.

In this paper, a conceptual design for the NIF nToF system will be presented. Required technology developments, improvements in components, and loss of commercially available items since the construction of Nova and Omega diagnostics will be discussed.

Detection of charged particles using CR-39 nuclear track detectors has become an important method for probing inertial confinement fusion (ICF) plasmas. A thorough study of the response characteristics of CR-39 to a wide variety of MeV ions is being undertaken to maximize the utility of this versatile particle detector in an ICF environment. An important aspect of this study is to investigate the response of CR-39 to ions produced by neutron interactions within the detector and surrounding sources. This leads to new ways of reducing neutron-induced noise and also to absolutely calibrated neutron measurements using CR-39.

POSTER PRESENTATION PREFERRED
DESIGN OF A MAGNETIC DEUTERON RECOIL (MDR) NEUTRON SPECTROMETER FOR FUEL <pR>, ION TEMPERATURE AND NEUTRON YIELD MEASUREMENTS IN DEUTERIUM-TRITIUM PLASMAS

J. A. Frenje, D. G. Hicks, C. K. Li, F. H. Séguin, and R. D. Petrasso*  
*Also visiting Senior Scientist at the Laboratory for Laser Energetics, Univ. of Rochester

Plasma Science and Fusion Center, Massachusetts Institute of Technology,  
Cambridge, Massachusetts 02139

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One method to determine fuel <pR> is to measure the neutron energy distribution of elastically scattered primary neutrons in high-density plasmas. However, measuring the scattered neutrons, in the energy region between the primary neutron regions, will be a difficult task. First, mechanical structures, such as vacuum chamber and diagnostic instruments, can also scatter neutrons. Second, the diagnostic instrument must have good enough resolution to distinguish the scattered from the primary neutrons. These requirements will be met by a new neutron spectrometer design for measurements of neutrons in the energy range of 10-15 MeV. Scattered neutrons will be probed in the energy range 10-13 MeV, while the primary neutrons will be used for an ion temperature and a neutron yield measurement. The spectrometer is based on a magnetic spectrometer, in combination with a nd-conversion foil for production of deuteron recoils at near forward scattering angles. The produced deuteron recoils are then detected by an array of scintillation counters, working in current mode, located at the focal plane of the spectrometer. The technique is referred to as the magnetic deuteron recoil (MDR) technique. A standoff distance of a couple meters between the nd-conversion foil and the detectors provides a time separation between the signal and the primary neutron background, allowing a high signal-to-background ratio (S/B), and a complete recovery of the detectors from the primary background neutrons. A time gate, adjustable to the specific energy of the signal deuterons, will discriminate most of the background, while the remaining background in the signal can be characterized by moving out the nd-foil of the spectrometer line of sight during data taking.

POSTER PRESENTATION PREFERRED

DP23
Optimal Foil Shape for Neutron Time-of-Flight Measurements Using Elastic Recoils

D. G. Hicks, C. K. Li, F. H. Seguin, J. A. Frenje, and R. D. Petrasso

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Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

T. C. Sangster
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The basis for a time-of-flight neutron spectrometer using recoils from a shaped scattering foil is presented. It is shown that the number of elastic recoils can be substantially increased by utilizing a scattering foil in the shape of an ellipsoid, with the shape of the ellipsoid being determined by the mass of the recoil particle. This shape allows the time-of-flight dispersion - present originally in the neutrons - to be maintained despite the large foil dimensions. The feasibility of using this design on current inertial confinement fusion experiments will be discussed.
Diagnostic Use of Secondary Proton Spectra for D-Filled ICF Targets

F. H. Séguin, C. K. Li, D. G. Hicks, J. A. Frenje, and R. D. Petrasso*

Plasma Science and Fusion Center
Massachusetts Institute of Technology


Laboratory for Laser Energetics
University of Rochester

T. C. Sangster, M. D. Cable**

Lawrence Livermore National Laboratory

S. Padalino and K. Fletcher

SUNY Geneseo

The use of measured spectra of secondary fusion protons for studying physical characteristics of D-filled ICF capsules is described theoretically and demonstrated with data from implosions in the OMEGA 60-beam laser facility. Spectra were acquired with a magnet-based charged-particle spectrometer and with a range-filter-based spectrometer utilizing filters and CR39 nuclear track detectors. Measurement of mean proton energy makes possible the study of a capsule's total areal density ($\rho R$), since that is what affects the energy loss suffered by protons as they pass through fuel and shell while leaving the capsule. Details of specific shots will be presented. It is also shown that similar techniques should prove useful for diagnosis of future experiments with cryogenic D-filled capsules.

* Also visiting Senior Scientist, Laboratory for Laser Energetics, University of Rochester.

** Currently at Xenogen Corporation.
With charged-particle spectroscopy (CPS) implemented on OMEGA, we have been able to routinely measure the particle spectra (both nuclear lines and continua) from a variety of capsule implosions. Important parameters such as fusion yields, fuel and shell areal densities, and ion temperatures can be readily deduced. We will report on details of this work with emphasis on the implosion physics.

* Visiting senior scientist, LLE at Univ. of Rochester.

† This work has been supported in part by LLE (subcontract P0410025G) and LLNL (subcontract B313975), and by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement NO. DE-FC03-92SF19460.
Development of a neutron imaging diagnostic for ICF Experiments


Los Alamos National Laboratory

L. Disdier

CEA/Bruy res le Ch tel

Pinhole imaging of the neutron production in laser-driven ICF experiments can provide important information about the performance of various capsule designs. This requires the development of systems capable of resolutions on the order of 5 microns or less for source strengths of $10^{15}$ and greater. We have initiated a program which will lead to the achievement of such a system to be employed at the NIF facility. Calculated neutron output distributions for various capsule designs will be presented to illustrate the information which can be gained from neutron imaging and to demonstrate the requirements for a useful system.

We will describe initial development work to be carried out at the Omega facility and the path which will lead to systems to be implemented at NIF. Beginning this year, preliminary experiments will be aimed at achieving resolutions of 30 to 60 microns for direct-drive capsules with neutron outputs of about $10^{14}$. The main thrust of these experiments will be to understand issues related to the fabrication and alignment of small diameter pinhole systems as well as the problems associated with signal to background ratios at the image plane.

Subsequent experiments at Omega will be described. These efforts will be aimed at achieving resolutions of about 10 microns. Proposed developments for new imaging systems as well as further refinement of pinhole techniques will be presented. Lastly, we will describe the lines-of-sight available at NIF for neutron imaging and explain how these can be utilized to reach the required parameters for neutron imaging.
SIRINC: A Code for Assessing and Optimizing the Neutron Imaging Diagnostic Capabilities in ICF Experiments

O. Delage, R. A. Lerche*, T. C. Sangster*, H. H. Arsenault**

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*Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550

** COPL Universite LAVAL, St. Foy Quebec, Canada G1K7PL

For high-density, near-ignition ICF target experiments, the only radiation to escape is the thermonuclear neutrons produced in the core. Thus it is to these neutrons that we must turn to learn of the physical processes occurring there. Shape analysis of the compressed core by imaging techniques can determine the effect of the radiation symmetry on the implosion performance. Penumbral Imaging technique has been demonstrated at the LLNL in the United States and has been used at the CEA in France to image ICF cores. Such a technique has been proved to be feasible in the case of very penetrating radiation. The information contained in a penumbral image is distorted by degradation problems caused by the aperture design and the camera. In addition, getting an estimate of the source requires specific numerical reconstruction.

The spatial resolution required on the NIF/LMJ project to diagnose high convergence targets is 5 μm. One of the major steps to achieving such a high resolution is careful analysis of all the information degradation processes.

The first prototype version of SIRINC will be presented. The degradation processes modeled and methods used for their simulation will be discussed. Particular attention will be given to the refinements brought to the reconstruction technique. Also the SIRINC presentation will be illustrated by results obtained on simulated and experimental neutron images. Besides neutrons, SIRINC analysis is also applicable to all the other imaging diagnostics of high penetrating radiation.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.


e-mail addresses:

DP28
Gamma-Ray Based Fusion Burn Measurements


Los Alamos National Laboratory

Lawrence Livermore National Laboratory

A TIM based gas Cerenkov detector has been built for use on the OMEGA laser system to record high-energy gamma-rays emitted during DT gas burn. Observation of the 16.7 MeV gamma is the primary objective. The detector first converts the gamma-rays to high energy electrons through Compton conversion and pair production. Cerenkov light is emitted by those electrons with energies greater than 12 MeV when traveling through CO₂ gas with an index of refraction set to 1.00083. The critical conversion processes (gamma to electron and electron to visible light) involve small angle processes, which take place throughout the volume of the detector leading to variable path lengths from target to recorder. A light collection system has been designed such that the inherent time resolution of the detector is ~7 ps.

Detector design, sensitivity and background studies were possible using the Integrated Tiger Series Monte Carlo code modified to include Cerenkov production, optical transition radiation, and full time history of all particles. The results of this code were iterated with the ASAP optics code to optimize the light collection system, while providing radiation shielding and stray light baffles. The detector architecture and the set of Omega experiments designed to observe the 16.7 MeV gamma-ray, while excluding possible background signals, will be discussed.

contact: Steve Caldwell, Los Alamos National Laboratory, scaldwell@lanl.gov
Fusion Gamma-ray Measurements for D-^3He Experiments in JT-60U, T. Nishitani, Y. Shibata^1, Y. Kusama, Japan Atomic Energy Research Institute. --- We carried out the preliminary D-^3He experiments with negative ion-base neutral beam injector (N-NBI) with 350-500 keV in Reversed Sear plasmas. Gas of ^3He was puffed in the plasma initiation and just before the N-NBI injection of 3.5 MW with 360 keV. The D-^3He reaction produces 3.6 MeV alpha and 14.7 MeV proton, however, has a small branch of 2.5 \times 10^{-3} which provides ^7Li and 16.7 MeV gamma-ray. The total D-^3He reaction rate can be evaluated by the measurement gamma-ray from ^3He (d, ^\gamma) ^7Li reactions using BGO (Bi_{3}Ge_{2}O_{12}) scintillator of φ3'' × 3''. The fusion gamma detector is located 15 m below the plasma center and measures the emitted gammas in a vertical line-of-sight. The detector is mounted inside the heavy collimator with polyethylene and lead. The floor penetration with 4 × 8 cm² is used as a pre-collimator. The energy calibration of the detector was done by some photo-peaks for neutron capture gammas from the structural material in D-D discharges. The detection efficiency is calculated with Monte Carlo code MCNP-4B for 16.7 MeV gammas. The pulse height analysis of the gamma-rays provides the D-^3He fusion power of 110±30 kW in this experiment.

1 Nagoya University, Nagoya, JAPAN
The diagnostic of plasma by methods of electron-positron annihilation (EPA) can be esteemed as an adding and independent way of definition and control of plasma parameters. Value of a EPA technique is the capability of the simultaneous control of two parameters of plasma (electron concentration $n_e$ and temperature $T$) within the framework of one methodical approach, and also capability of observation of local areas of plasma which one can be registered by a pair of detectors of annihilation gamma radiation (AGR). On the other hand large penetrating capability an AGR with energy 0.5 Mev allows to receive the information through walls of the chamber.

Two versions of measurement of a profile of electronic density distribution of plasma in the given local area via results of measurement of local speed of positron annihilation are offered. In first case it is similar as method of chords in microwave diagnostic of plasma each pair of detectors AGR selects in plasma a cross-sectional cylindrical volume. In an alternative version many counter system of AGR is organized analogously a principle of a tomograph. The best localization of measurements in this case is provided by the greater number of pairs detectors registering coincidence AGR. Also the way of positron injection in circuited torroidal magnetic trap (CMT) is reviewed. This method grounded on emission of positrons from micro particle of radioactive matter. This grain is entered in CMT as the disk of small radius. It is show that at radius of a grain of radioactive matter (isotope Cu$^{64}$) $R=500$ cm in CMT the concentration of positrons about $1000$ cm$^{-3}$ is reached at activity of a grain $5 \times 10^{11}$ c$^{-1}$. As demonstrate estimations this concentration of positrons is sufficient for implementation of simultaneous local probing of local areas of plasma.

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E-mail: paiziev@akmal.silk.org
Wednesday Morning, June 21
Optical (IR, Visible, UV) - Neville Luhmann, Chair

8:30 a.m. - 10:30 a.m. Presidio Ballroom 5

<table>
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10:45 a.m. - 12:30 p.m. Presidio Ballroom 1-4

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EP25 Fenzi U Wisconsin USA 2D Turbulence Imaging In DIII-D Via Beam Emission Spectroscopy
EP26 McKee U Wisconsin USA A Lyman-Alpha-Based (VUV) Plasma Density Fluctuation Diagnostic Design
EP27 Jakubowski U Wisconsin USA Electrostatic Potential Fluctuations Via Time-Resolved Turbulent Flow Analysis
EP28 Reinecke U Wisconsin USA Equilibrium And Stability Measurements Via Neutral Beam Spectroscopy For The Pegasus Toroidal Experiment
EP29 Eisner FRC U Texas USA CXRS On Alcator C-Mod
EP30 Craig U Wisconsin USA First CHERS And MSE Results From The MST Reversed Field Pinch
EP31 Bretz PPPL USA A Motional Stark Effect Instrument To Measure Q(R) On C-Mod
EP32 De Angelis Frascati Italy The Motional Stark Effect Diagnostic In FTU
EP33 Jaspers FOM Netherlands Spectra-Polarimetry Of The Motional Stark Effect At TEXTOR-94
EP34 Thomas GA USA Prospects For Edge Current Density Determination Using LIBEAM On DIII-D
EP35 Burrell GA USA Improved CCD Detectors For The Charge Exchange Spectroscopy System On The DIII-D Tokamak

Wednesday Evening June 21
Interferometry, Polarimetry, and Thomson Scattering - Robin Snider, Chair
7:00 p.m. - 8:30 p.m. Presidio Ballroom 5

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Affiliation</th>
<th>Country</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI1</td>
<td>Celliers</td>
<td>LLNL</td>
<td>USA</td>
<td>VISAR For Measuring EOS And Shock Propagation In Liquid Deuterium</td>
</tr>
<tr>
<td>FI2</td>
<td>Lanier</td>
<td>U Wisconsin</td>
<td>USA</td>
<td>Electron Fluctuation And Fluctuation-Induced Transport Measurements In The Madison Symmetric Torus Reversed-Field Pinch</td>
</tr>
<tr>
<td>FI3</td>
<td>Donne</td>
<td>FOM</td>
<td>Netherlands</td>
<td>The New Diagnostics For Physics Studies On TEXTOR</td>
</tr>
</tbody>
</table>

8:45 p.m. - 10:30 p.m. Presidio Ballroom 1-4

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Affiliation</th>
<th>Country</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP1</td>
<td>Hazleton</td>
<td>HY-Tech</td>
<td>USA</td>
<td>Holographic Measurement Of Magnetic Fields In Plasma Discharges</td>
</tr>
<tr>
<td>FP2</td>
<td>Holcomb</td>
<td>LLNL</td>
<td>USA</td>
<td>Non-Perturbing Current Profile Measurements Of A Sustained Spheromak</td>
</tr>
<tr>
<td>FP3</td>
<td>Wang</td>
<td>LANL</td>
<td>USA</td>
<td>Density And Ha Diagnostics For The Sustained Spheromak Physics Experiment</td>
</tr>
<tr>
<td>FP4</td>
<td>O'Gorman</td>
<td>RFX</td>
<td>Italy</td>
<td>The Multi-Chord FIR Polarimeter Of The RFX Experiment</td>
</tr>
<tr>
<td>FP5</td>
<td>Park</td>
<td>PPPL</td>
<td>USA</td>
<td>Status Of Far Infrared Tangential Interferometry / Polarimetry (Firetip) System On NSTX</td>
</tr>
<tr>
<td>FP6</td>
<td>Kawano</td>
<td>JAERI</td>
<td>Japan</td>
<td>Infrared Laser Polarimetry For Electron Density Measurement In Tokamak Plasmas</td>
</tr>
<tr>
<td>FP7</td>
<td>Akiyama</td>
<td>Tokyo Inst. Tech.</td>
<td>Japan</td>
<td>Faraday Rotation Densitometry For LHD</td>
</tr>
<tr>
<td>FP8</td>
<td>Brower</td>
<td>UCLA</td>
<td>USA</td>
<td>Multichannel FIR Polarimeter-Interferometer System On The Reversed Field Pinch MST</td>
</tr>
<tr>
<td>FP9</td>
<td>Brower</td>
<td>UCLA</td>
<td>USA</td>
<td>Multichannel Interferometer System For The HSX Stellarator</td>
</tr>
<tr>
<td>FP10</td>
<td>Canton</td>
<td>RFX</td>
<td>Italy</td>
<td>Spatially Scanned Two Color MIR Interferometer For FTU</td>
</tr>
<tr>
<td>FP11</td>
<td>Tanska</td>
<td>NIFS</td>
<td>Japan</td>
<td>CO2 Laser Imaging Interferometer On LHD</td>
</tr>
<tr>
<td>FP12</td>
<td>Okajima</td>
<td>Chubu U</td>
<td>Japan</td>
<td>Development Of Short-Wavelength Far-Infrared Laser For High Density Plasma Diagnostics</td>
</tr>
<tr>
<td>FP13</td>
<td>Pikuz</td>
<td>Cornell / Lebedev</td>
<td>USA</td>
<td>A Simple Air-Wedge Shearing Interferometer For Studying Exploding Wires</td>
</tr>
<tr>
<td>FP14</td>
<td>Evans</td>
<td>AWE</td>
<td>UK</td>
<td>Time Resolved Displacement Interferometry for The Characterisation Of Preheat And Free Surface Motion</td>
</tr>
<tr>
<td>FP15</td>
<td>Koch</td>
<td>LLNL</td>
<td>USA</td>
<td>X-Ray Interferometry With Spherically Bent Crystals</td>
</tr>
<tr>
<td>FP16</td>
<td>Bangke</td>
<td>Nanyang U</td>
<td>Singapore</td>
<td>Improvement Of The Interferometry Measuring The Plasma Density</td>
</tr>
<tr>
<td>FP17</td>
<td>Tokuzawa</td>
<td>NIFS</td>
<td>Japan</td>
<td>New Type Of Digital Phase Linearizer For Real-Time Interferometric Measurement</td>
</tr>
<tr>
<td>FP18</td>
<td>Hughes</td>
<td>MIT</td>
<td>USA</td>
<td>High Resolution Edge Thomson Scattering Measurements On The Alcator C-MOD Tokamak</td>
</tr>
<tr>
<td>FP19</td>
<td>Kurzan</td>
<td>IPP Garching</td>
<td>Germany</td>
<td>Improvements In The Evaluation Of Thomson Scattering Measurements Data On ASDEX Upgrade</td>
</tr>
<tr>
<td>FP20</td>
<td>Bray</td>
<td>GA</td>
<td>USA</td>
<td>Upgraded Calibrations Of The Thomson System At DIII-D</td>
</tr>
<tr>
<td>FP21</td>
<td>Lee</td>
<td>KBSI</td>
<td>Korea</td>
<td>Measurements Of The Electron Temperature By The Thomson Scattering System On The Hanbit Magnetic Mirror Device</td>
</tr>
<tr>
<td>FP22</td>
<td>Narihara</td>
<td>NIFS</td>
<td>Japan</td>
<td>Design And Performance Of Thomson Scattering Diagnostic Installed On LHD</td>
</tr>
<tr>
<td>FP23</td>
<td>Yamada</td>
<td>NIFS</td>
<td>Japan</td>
<td>Active Control Of Laser Beam Direction For LHD YAG Thomson Scattering</td>
</tr>
<tr>
<td>FP24</td>
<td>Johnson</td>
<td>PPPL</td>
<td>USA</td>
<td>APD Detector Electronics For NSTX Thomson Scattering System</td>
</tr>
<tr>
<td>FP25</td>
<td>Den Hartog</td>
<td>U Wisconsin</td>
<td>USA</td>
<td>Status Of The New Multi-Point, Multi-Pulse Thomson Scattering Diagnostic For The MST RFP</td>
</tr>
<tr>
<td>FP26</td>
<td>Pasqualotto</td>
<td>RFX</td>
<td>Italy</td>
<td>The New RFX Thomson Scattering System</td>
</tr>
<tr>
<td>FP27</td>
<td>van der Meiden</td>
<td>FOM</td>
<td>Netherlands</td>
<td>Double Pulse Multiposition Thomson Scattering On TEXTOR</td>
</tr>
<tr>
<td>FP28</td>
<td>Kondoh</td>
<td>JAERI Naka</td>
<td>Japan</td>
<td>Collective Thomson Scattering Using A Pulsed CO2 Laser In JT-60U</td>
</tr>
<tr>
<td>FP29</td>
<td>Richards</td>
<td>ORNL</td>
<td>USA</td>
<td>Advances In The CO2 Laser Collective Thomson Scattering Fast Ion / Alpha Particle Diagnostic</td>
</tr>
<tr>
<td>FP30</td>
<td>Porte</td>
<td>MIT</td>
<td>USA</td>
<td>Implementation Of Collective Thomson Scattering On The TEXTOR Tokamak For Energetic Ion Measurements</td>
</tr>
<tr>
<td>FP31</td>
<td>Zweben</td>
<td>PPPL</td>
<td>USA</td>
<td>Plasma Turbulence Imaging Using High-Power Laser Thomson Scattering</td>
</tr>
<tr>
<td>FP32</td>
<td>Hennequin</td>
<td>Ecole Polytechnique</td>
<td>France</td>
<td>Edge Plasma Turbulence Analysis By Collective Light Scattering In The Tore Supra Tokamak</td>
</tr>
<tr>
<td>FP33</td>
<td>Kantor</td>
<td>Ioffe Institute</td>
<td>Russia</td>
<td>Test of a periodic multipass-intracavity laser system for the TEXTOR multiposition Thomson scattering diagnostics</td>
</tr>
<tr>
<td>FP34</td>
<td>Kantor</td>
<td>Ioffe Institute</td>
<td>Russia</td>
<td>A Possibility Of Plasma Current Density Measurements with Soft X-Ray and Thomson Scattering Diagnostics</td>
</tr>
</tbody>
</table>
Synergy of edge multiviewing spectroscopic diagnostics on COMPASS-D

P G Carolan, N J Conway, A R Field and H Meyer

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon,
Oxfordshire, OX14 3DB, UK.

Visible spectrometers have been combined using a single collection optics system that vertically views the edge of the COMPASS-D tokamak plasma. Since the spectrometers view the same positions, cross-data comparisons can be made. The resulting synergy enhances the physics investigations of localised phenomena, typical of edge tokamak plasmas. The optics view a thermal helium jet from a nozzle in the equatorial plane. Total line intensities are obtained from a 10 chord spectrometer, HELIOS	extsuperscript{1}, from which He I line-ratios are used in determining $T_e(r)$ and $n_e(r)$ profiles. The spectral coverage also includes the Balmer $D_\alpha$ line whose absolute intensities are unfolded to give the $D_\alpha(r)$ emissivity profile. This yields the the neutral density profile, $n_\theta(r)$, using $T_e(r)$ and $n_e(r)$ in a collisional radiative model. Light from the collection optics is also routed to a 20 chord high resolution Doppler spectrometer, CELESTE	extsuperscript{23}, which incorporates a spectral lamp to provide accurate wavelength measurements. Doppler measurements of HeII and intrinsic low ionisation state impurities, for example CIII, provide impurity ion temperatures, $T_i(r)$, and poloidal velocities, $V_\theta(r)$, and associated radial electric fields, $E_r(r)$. These and the $T_e(r)$, $n_e(r)$ and $n_\theta(r)$ profiles are used in investigating L- to H-mode transition dynamics such as synchronicity of $E_r$ increase and $D_\alpha$ reduction, suppression of peeling modes and viscous damping.

This work is funded by the UK Department of Trade and Industry and EURATOM.

Results from the Modulated Optical Solid-State Spectrometer

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Plasma Research Laboratory,
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Canberra ACT 0200

The utility of fixed delay static Fourier transform spectrometers for Doppler spectroscopy of extended radiating media has been recently demonstrated [1]. Based on these results and the successful development of the MOSS (Modulated Optical Solid-State) spectrometer, we have installed in H-1NF a variety of visible spectroscopic diagnostics for applications including time-resolved perturbation studies of plasma transport, tomography of ion temperature and flow fields and detailed distribution function studies.

The simplest MOSS spectrometer is a fixed delay modulated Fourier transform spectrometer based on an electrooptic and birefringent lithium niobate plate. The system uses an interference filter to isolate the spectral line of interest, followed by a solid-state polarization interferometer with fixed path length offset and delay modulation obtained by applying a high voltage audio signal across the LiNbO₃ plate. The visibility of the resulting fringes (species temperature) and the interferometric phase (flow speed) are extracted from the amplitudes of the modulation harmonics. A LabVIEW-based software virtual instrument is used for control of fixed-delay single channel MOSS spectrometers via a National Instruments ADC/DAC PC card. The card generates the low-voltage audio drive signal as well as synchronously acquiring and processing the spectroscopic data. CAMAC-based systems are presently used for the multi-channel spectrometers. Light is typically coupled to the MOSS using high throughput optical fibres (diameter 1mm, NA=0.4).

In this paper we present the basic theoretical results underpinning this work, together with a description of the hardware and recent results. This includes

- The 55-channel, multi-view lens-coupled fibre array for tomography of ion temperature and flow vorticity in H-1NF [2];
- The multi-channel imaging MOSS camera [3];
- The multi-crystal SOFT (Spread-spectrum Optical Fourier Transform) spectrometer for tomography of ion/atom velocity distribution functions.

The coherence-based techniques presented here are also well suited to a variety of polarization spectroscopy applications, including Zeeman effect and motional Stark effect spectroscopy.

[2] Tomographic MOSS System for H-INF, F. Glass and J. Howard, these proceedings
[3] The MOSS Camera on H-INF, C. Michael, J. Howard, A. Cheetham and B. Blackwell, these proceedings
Visualization of Plasma Turbulence with Laser-Induced Fluorescence, Fred M. Levinton, Fusion Physics & Technology, Inc., Torrance CA.

Turbulence is a key factor limiting the performance of fusion devices. Plasma edge turbulence determines the boundary values of the plasma density and temperature, which in turn determines the internal gradients and controls global plasma transport. In recent years significant progress has been made in the numerical calculations for modeling turbulence behavior in plasmas and its effect on transport. Visualization of turbulence would improve the connection to theory and help validate the modeling.

Planar laser-induced fluorescence (PLIF) is a powerful technique that has been previously applied to combustion and fluid processes to visualize turbulence. We have recently applied this technique to an argon plasma to visualize turbulence and structures in this plasma. An argon plasma is generated by a helicon plasma source. The electron density is about $5 \times 10^{19}$ m$^{-3}$. The laser is an Alexandrite laser that is tunable between 700-800 nm, and from 350-400nm at second harmonic. A Raman converter can also be used to shift the laser wavelength between 400-700 nm in order to cover the entire visible spectrum. Results from several argon ion, krypton, and xenon lines have been obtained. The best signal has been obtained from an argon ion transition that is pumped with the laser at 378 nm and fluorescence observed at 488 nm. The fluorescence light is imaged onto an intensified CCD camera that is gated in synchronization with the laser. Images from the plasma show a structure in the plasma rotating about the center at about 30 kHz. We plan to demonstrate the technique on other magnetic confinement devices in the near future.
Diagnostics for Advanced Tokamak Research
K.H. Burrell, General Atomics, San Diego, California

Advanced tokamak research seeks to find the ultimate potential of the tokamak as a magnetic confinement system. Achieving this potential involves optimizing the current density and pressure profiles for stability to MHD modes while simultaneously controlling the current density, pressure and radial electric field profiles to minimize the cross field transport of plasma energy. In its ultimate, steady-state incarnation, the advanced tokamak also requires pressure profiles that have been adjusted to achieve the maximum possible bootstrap current, subject to the constraints of MHD stability. This simultaneous, nonlinear optimization of current, pressure and electric field profiles to meet multiple goals is a grand challenge to plasma physics.

Diagnostic measurements play a crucial role in advanced tokamak research. One outstanding example of this is the way motional Stark effect (MSE) measurements of the internal magnetic field revolutionized work on current profile shaping. Improved diagnostic measurements are essential in testing theories which must be validated in order to apply advanced tokamak results to next step devices.

In order to optimize MHD stability, the key issues to be confronted include 1) stability of the edge localized modes (ELM) in the H-mode, 2) stability to neoclassical tearing modes and 3) stability to resistive wall modes. Although existing diagnostics are being used to confront these issues, improvements are needed for definitive experiments. For example, to properly attack ELM stability, improved internal magnetic field measurements in the edge regions are needed to quantitatively assess the role of edge current profile in the stability of edge localized modes. Better measurements of 3D internal structure of MHD modes are also needed.

In order to optimize the pressure profile, control of heat and particle transport is needed. While significant progress has been made in the past five years in creating regions of the reduced transport in the plasma core, much remains to be done to understand transport, especially in the electron channel. One key issue here is the role of ExB shear in controlling turbulence and transport; this involves both the equilibrium electric field and the fluctuating field associated with the poloidally and toroidally symmetric zonal flows. While existing diagnostics have allowed us to investigate the role of the equilibrium electric field, zonal flow measurements are still in their infancy.

This talk will review the key MHD and transport issues in advanced tokamak research, will briefly summarize how existing diagnostics are being used and will present the opportunities for diagnostic innovation in the advanced tokamak area.

*Work supported by U.S. Department of Energy under Contract No. DE-AC03-99ER54463.
Diagnostics for Liquid Lithium Experiments in CDX-U.* R. KAITA, P. EFTHIMION, D. HOFFMAN, B. JONES, H. KUGEL, R. MAJESKI, T. MUNSAT, S. RAFTPOULOS, J. TIMBERLAKE, G. TAYLOR, Princeton U., V. SOUKHANOVSII, D. STUTMAN, M. IOVEA, M. FINKENTHAL, Johns Hopkins U., R. DOERNER, S. LUCKHARDT UCSD, R. MAINGI, ORNL, R. CAUSEY, SNL -- A flowing liquid lithium first wall or divertor target could virtually eliminate the concerns with power density and erosion, tritium retention, and cooling associated with solid walls in fusion reactors. To investigate the interaction of a spherical torus plasma with liquid lithium limiters, large area divertor targets, and walls, discharges will be established in the Current Drive Experiment-Upgrade (CDX-U) where the plasma-wall interactions are dominated by liquid lithium surfaces. Among the unique CDX-U lithium diagnostics is a multi-layer mirror (MLM) array, which will monitor the 135 Å LiIII line for core lithium concentrations. Additional spectroscopic diagnostics include a STRS grazing incidence XUV spectrometer and a filterscope system to monitor Dα and various impurity lines local to the lithium limiter. Profile data will be obtained with a multichannel tangential bolometer and a multipoint Thomson scattering system configured to give enhanced edge resolution. Coupons on the inner wall of the CDX-U vacuum vessel will be used for surface analysis. A 10,000 frame per second fast visible camera and an IR camera will also be available.

*Work supported by U. S. D. O. E. Contract DE-AC02-76-CH03073.

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EP1
Fast Ion Loss Measurement by Infrared TV in Reduced Ripple Experiment with Ferritic Inserts on JFT-2M

H. KAWASHIMA, K. TSUZUKI, T. TANI, M. SATO, JFT-2M GROUP, Japan Atomic Energy Research Institute

In the medium size tokamak, JFT-2M, the ferritic steel boards (FBs) were inserted to reduce the toroidal field ripple which causes the fast ion losses. To evaluate the effect of FB insertion, 2D infrared TV (IRTV) system with high resolutions in time and space was developed, which is quite suitable to measure the first wall temperature increment caused by the ripple ion losses in a medium size tokamak. We adopt an IR thermal imager (Mitsubishi IR-M300) that provides a field time of 1/60sec. Detectable temperature range is 0-500°C with the resolution of 0.2°C. The PtSi (26x20μm) detector being sensitive to 3-5μm IR radiation is composed of 256x256 array. The optical system to view the first wall consists of an IR-lens (f:25mm,F:2.0), a reflecting mirror and a sapphire vacuum window, in which distance from the camera position to the target wall is shortened to ~3.5m. Thus, we obtained a high spatial resolution of ~3mm. By using this system, the local hot spot due to the ripple trapped losses of fast ions was observed during NBI (36kV, 500kW) heating. The peak temperature increment ΔTs reached to ~75°C before FB insertion. After FB insertion, the ΔTs was reduced clearly. In the most optimized case, the temperature increment became negligibly small. These IRTV data make clear the effectiveness of FBs for reduction of fast ion losses.

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E-mail Address
Design of a bolometer for Hanbit magnetic mirror device

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Suwon 442-749, Korea
Suk-Jae Yoo
Korea Basic Science Institute, Taejon 305-333, Korea

A metal resistor bolometer for the Hanbit device (a magnetic mirror machine at Korea Basic Science Institute) has been designed and tested in order to measure the total radiation of the plasma in the device. Since the target plasma parameters at the central cell are 1-keV ion temperature, 200-eV electron temperature, and $5 \times 10^{12}$ cm$^{-3}$ electron density with a plasma duration of 100-500 ms, a prototype bolometer should be fast and sensitive enough to obtain the meaningful data for the plasma.

We report here our experiences in designing the structure of the bolometer and the metal resistor which were designed to obtain a maximum variation in electric resistance under a given radiation exposure, and also the test results of the prototype bolometers under Xenon lamp heating. When the electric resistance of gold grid is kept constant, a sample with the thinner or the wider grid showed a better sensitivity. The cooling time constant of the bolometer, an important factor for the time resolution, could be improved fast enough to probe the plasma in the Hanbit device by a sandwich structure, in which metal grids are printed on a Kapton substrate and covered with a spin-coated Polyimid film which was less than 1 μm thick and a radiation stopping layer was deposited on.
In the last few years a new type of imaging bolometer has been under development through a collaboration between the National Institute for Fusion Science (NIFS) (Japan) and Los Alamos National Laboratory (USA)[1,2]. This diagnostic, known as the Segmented Mask Infrared Imaging Bolometer (SIB), uses state-of-the-art infrared imaging technology to measure the temperature rise of each pixel in a two dimensional array of thin metal foil pixels. Since the temperature rise of each foil pixel results from heating by the incident radiation from the plasma collimated by a pinhole, this results in a two dimensional measurement of the plasma radiation. We have designed, constructed, installed and calibrated a version of the SIB for the Large Helical Device (LHD). This diagnostic uses a 0.8 micron thick aluminum foil which is separated into 118 channels by the 2 mm thick copper masks. It has a two dimensional view (toroidal and poloidal) of the LHD plasma from an upper port. First results will be presented at the conference including data from discharges in LHD.

In addition to the SIB, another type of infrared imaging bolometer, known as the Infrared Imaging Video Bolometer (IRVB) is also under development at NIFS. This concept differs from the SIB in that it replaces the segmented matrix of foil pixels with one large thin metal foil held in a copper frame. Instead of relying on the mask to thermally isolate each pixel as in the SIB, a numerical algorithm is used to solve for and subtract out the diffusive contribution to the signal. This concept more fully utilizes the IR camera data to provide a video image of the plasma and give calibrated two-dimensional radiated power data. In addition to the above mentioned advantages this concept avoids the problems associated with the foil mask of the SIB and in exchange provides the flexibility to choose the bolometer pixel size (trading sensitivity for temporal and spatial response) to match the experimental conditions. Assuming the same pixel size, error analysis shows that it improves on the sensitivity of the SIB by a factor of 2 — 5 with a slight improvement in the spatial resolution. The IRVB's possible disadvantage is the lack of mechanical support for the foil provided by the SIB's copper mask. A prototype of this diagnostic consisting of a 1 micron x 66 mm x 90 mm gold foil has been installed on a tangential port in LHD and its images will be shown at the conference along with information on sensitivity and calibration.

References:
Digital-image capture system for the IR camera used in Alcator C-Mod

R. Maqueda, G. A. Wurden
Los Alamos National Laboratory, Los Alamos, NM, USA

J. L. Terry
Plasma Science and Fusion Center, MIT, Cambridge, MA, USA

J. Gaffke
Engineering Design Team, Inc., Beaverton, OR, USA

An infrared imaging system is used at Alcator C-Mod to measure the surface temperatures in the lower divertor region [1]. This system employs an Amber Radiance 1 infrared camera that is optically coupled to the torus via a re-entrant, 5-m long, ZnSe based periscope. Due to the supra-linear dependence of the thermal radiation with temperature it is important to make use of the 12-bit digitization of the focal plane array of the Amber camera and not be limited by the 8 bits inherent to the video signal. It is also necessary for the image capture device (i.e., fast computer) to be removed from the high magnetic field environment surrounding the experiment. Finally, the coupling between the digital camera output and the capture device should be non-conductive for isolation purposes (i.e., optical coupling). This paper presents one solution to this problem.

The 60 Hz images from the Amber Radiance 1 camera, each composed of 256x256 pixels and 12 bits/pixel, are captured by a Windows NT computer using a digital video remote camera interface system. This system is composed of two parts, the Remote Camera Interface (RCI) that is located close to the digital camera and a Fiber Optic Interface (FOI) board that is located on the PCI bus of the Windows NT computer. The RCI module converts the digital output to a 1.25 GBd fiber optic signal for transmission over a 100-m long multi-mode fiber. The single slot PCI bus board in the computer then converts the fiber optic signal back into digital data for direct memory storage. An electrical trigger signal is given directly to the RCI module to synchronize the image stream with the experiment. The RCI can be programmed from the host computer to work with a variety of digital cameras, including the Amber Radiance 1 camera.

In addition to the new digital-image capture system, the view of the divertor region has been modified from that in Ref. [1] to allow the measurement of the surface temperatures below the outer divertor nose where the outer strike point is typically located. In agreement with this strike point position, hot-spots reaching 800 °C are observed, together with discontinuous toroidal bands. Recent results from the experiment will be presented.

This work was supported by the U.S. D.o.E. under Coop. Agreement DE-FC02-99ER54512 and Contract No. W-7405-ENG-36.

Edge turbulence measurements in NSTX by Gas Puff Imaging

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a Los Alamos National Laboratory, Los Alamos, NM, USA
b Princeton Plasma Physics Laboratory, Princeton, NJ, USA
c Fusion Physics and Technology, Torrance, CA, USA
d Columbia University, New York, NY, USA

Turbulent filaments in visible light emission corresponding mainly to density fluctuations at the edge have been observed in large aspect ratio tokamaks: TFTR [1], ASDEX [2], Alcator C-Mod [3], and DIII-D [4]. This paper reports on similar turbulent structures observed in the National Spherical Torus Experiment (NSTX) using a fast-framing, intensified, digital visible camera [5]. These filaments were previously detected mainly in high recycling regions, such as at limiters or antennas, where the line emission from neutral atoms was modulated by the fluctuations in local plasma density. However, by introducing controlled edge gas puffs, i.e. Gas Puff Imaging (GPI), we have increased the brightness and contrast in the fluctuation images and allowed the turbulent structure to be measured independently of the recycling. The 2-D structure of the edge light emission from either D2 or He gas puffs is imaged using a fast-framing camera with a typical exposure time of 10 µs and a framing rate of 1 kHz. The images in NSTX were produced by either filtered D2 or HeI (5876 Å) light, or total visible light. The views of the edge turbulence structure were of either the poloidal vs. toroidal or poloidal vs. radial planes. A set of three discrete fiber-optically coupled sight-lines also measured the frequency spectra of these light fluctuations with a 200 kHz bandwidth.

Initial results in NSTX show that the turbulent filaments are well aligned with the magnetic field which can be up to 45° from the horizontal at the outer midplane of NSTX. The dominant poloidal wavelength is ~15 cm, corresponding to a kpol ρs of ~0.2 at an assumed Te=25 eV, and the frequency spectra has a typical “power law” shape characteristic of edge turbulence extending to about 100 kHz. By imaging a He gas puff along a magnetic field line the characteristic radial scalelength is observed to be in 3-5 cm range.

The ongoing analysis of the turbulent structure and time series will be presented as well as the characteristics of the diagnostic set employed to view the edge gas puffs. The plans for the next experimental campaign in NSTX will also be outlined.

This work was supported by the U.S. D.o.E. under contracts W-7405-ENG-36 and DE-AC02-CH03073.

Applications of Visible CCD Cameras on the Alcator C-Mod Tokamak

C. J. BOSWELL, J. L. TERRY, B. LIPSCHULTZ, J. STILLERMAN, M.I.T. Plasma Science and Fusion Center — Five 7 mm diameter remote-head visible CCD cameras are being used on Alcator C-Mod for several different diagnostic purposes. All of the cameras' detectors and optics are placed inside a magnetic field of up to 4 Tesla. Images of the cameras are recorded simultaneously using two three-channel color framegrabber cards. Two CCD cameras are used to generate 2-D emissivity profiles of deuterium line radiation from the divertor. Interference filters (Dα, Dβ, or Dγ) are used to select the spectral line to be measured. The local emissivity is obtained by inverting the measured brightnesses assuming toroidal symmetry of the emission. Another use of the cameras is the identification and localization of impurity sources generated by the ICRF antennas, which supply the auxiliary heating on Alcator C-Mod. The impurities generated by the antennas are identified by correlating in time the injections seen by the cameras with measurements made with core diagnostics. Visible spectroscopic views aligned with the camera views are also used to identify the species of the impurities injected. The cameras have been able to evaluate, in situ, the performance of the antennas.

Work Supported by Coop. Agreement DE-FC02-99ER54512
Abstract for the Thirteenth Topical Conference on High Temperature Plasma Diagnostics

High resolution visible continuum imaging diagnostic on the Alcator C-Mod tokamak,


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A high resolution imaging camera system has been installed on the Alcator C-Mod tokamak to measure radial profiles of continuum emission from the high temperature and density plasmas produced in the device. The input optics includes a 3 nm bandpass interference filter, centered at 536 nm, which is a relatively line-free region of the spectrum. As a result, the detected emission from most of the plasma volume is dominated by free-free bremsstrahlung. At the extreme periphery of the plasma, where Te<20 eV, recombination continuum becomes significant, and molecular band pseudo-continuum from D2 also contributes to the signal. The detector system uses the model CL-C6-2048 camera, produced by Dalsa, Inc., which has a 2048 element linear CCD detector, with 12 bit digital output and maximum frame rate of 4.8 kHz. Data acquisition is accomplished with a PC-based framegrabber, controlled with a LabView application. As shown in figure 1, the system views the plasma tangentially, in the torus midplane. The optical train consists of a mirror, an entrance aperture, a 3 lens periscope, the interference filter, a compound lens (50 mm focal length, f/1.2) and finally the detector. The resulting resolution for chords passing tangentially near the last closed flux surface is about 1 mm (FWHM). This high resolution is particularly important for measurements of the sharp gradients in emission which are present after the plasma makes transitions into H-mode, when typical edge gradient scale lengths for the bremsstrahlung emission profile are in the range from 2 mm to 20 mm. When combined with measurements of electron density and temperature from other diagnostics (interferometry, ECE and Thomson scattering), the continuum emissivity intensity can be used to infer $Z_{eff}$ in the plasma. Figure 2 shows the time histories of the measured central $Z_{eff}$ for two discharge cases, where the majority ion species was changed from deuterium to helium. For relatively clean deuterium plasmas, with $Z_{eff}$ close to 1, the measurements can alternatively be used to monitor the evolution of electron density profile with very high spatial resolution, and measurements from L- and H-mode plasma regimes, both with and without auxiliary ICRF heating, will be described.

Fig. 1 Schematic of the instrumental view. The chords are in the horizontal midplane of the torus.

Fig. 2 Comparison of D2 (solid) and He (dashed) working gas discharges. The third panel shows the $Z_{eff}$ time histories.

Work supported by USDoE under agreement DE-FC02-99ER54512.
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Visible Bremsstrahlung Measurements in Low Density, Advanced Tokamak Discharges in the DIII-D Device, N.H. Brooks, R.J. Colchin,† W.P. West, M.R. Wade,† General Atomics — The Visible Bremsstrahlung (VB) diagnostic on DIII-D measures the continuum emission centered at 523 nm along sixteen tangential viewchords spanning the full width of the plasma column. Due to the faintness of the VB continuum at densities below $5 \times 10^{13}$ cm$^{-3}$ and the presence in L-mode of a bright halo of non-VB emission, eight new channels have been added to provide better resolution of the boundary region. Both these new channels and the existing edge channels have been outfitted with baffled, razor blade viewing dumps to suppress contamination of weak VB emission along the edge chords by scattered VB light from the bright interior of the plasma column. Together with improved calibration procedures, these steps should make it possible to obtain more reliable measurements of the VB emissivity profile and, together with measured $n_e$ and $T_e$ profiles from the the DIII-D Thomson scattering system, deduce Z-effective profiles over the full minor radius. These results will be compared with Z-effective profiles deduced from density profile measurements of the dominant impurities (carbon and neon) by the DIII-D Charge Exchange Recombination diagnostic.

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Continuum-Based Diagnostics of Weakly Nonideal Laser-Produced Plasmas

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The early-time spectral emissions from weakly nonideal laser-produced plasma (LPP) plumes in a vacuum are essentially a continuum. We have developed a novel plasma diagnostic technique, based entirely on the continuum, and present the result for aluminum plasma. Due to the presence of significant self-absorption, the analysis leading to the density and temperature profile is carried out in close coupling to plasma equilibrium calculations. It starts with the scaling relations linking the time-resolved specific continuum intensity \( I \), as defined over the spectral range of the detection system, to the local temperature \( T \) and pressure \( p \):

\[
T = S_T I^\kappa \quad \text{and} \quad p = S_p I^{\kappa + \omega}.
\]

The LPP plume is completely specified once the specific continuum intensity is found together with the scaling exponents \( \kappa \) and \( \omega \) and the scaling constants \( S_T \) and \( S_p \). Inversion of the time-resolved side-view luminosity profile (2-D) into the specific continuum intensity profile (3-D) is carried out self-consistently and assuming axisymmetry, subject to the sixteen independent measurements for aluminum. A 5-mm circular area of the aluminum target is exposed to Nd:glass laser excitation at four different energies. Attenuation of the laser beam is measured through a 0.3-mm pinhole at the center of the target at its fundamental and second harmonic frequencies. The total plasma mass as well as the total laser energy deposited into the plume is measured. The plasma calculation includes the nonideality corrections in the lowering of ionization potentials and plasma absorption coefficient. The calculated plasma mass, plasma energy which includes the cumulative radiative loss, and laser beam attenuation are compared with the measurements for each set of values for the scaling exponents and constants. An agreement to within 6.1% of the measurements overall has been achieved with \( \kappa = 0.45 \pm 0.03 \), \( \omega = 1.0 \pm 0.03 \), \( S_T = 0.190 \pm 0.003 \) and \( S_p = 340 \pm 5 \). The scaling exponents are essentially universal, only weakly dependent on the detector's spectral response, whereas the scaling constants are subject to the manner in which the luminosity values are referenced.

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EP10
Reconstruction of Time-Resolved Continuum Intensity Profile of Non-axisymmetric Laser-Produced Plasma

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A single laser pulse is used to produce weakly nonideal plasma from a metallic aluminum target immersed in a dense neutral gas. The attendant increase in plasma density due to neutral gas confinement is accompanied by interfacial instability when the gas density exceeds a threshold value. A new diagnostic method has been developed to reconstruct the plasma's cross-sectional profile in specific continuum emission intensity as a function of time. Two mutually orthogonal side-view projections of the plasma are acquired by streak photography at a fixed distance from the target surface with 3 nsec time resolution. The fact that each side-view luminosity profile results from integration along the line of sight is used to successively approximate the plasma cross-sectional profile. In the absence of axial symmetry the solution is not unique because of insufficient data available in the two side views. This is overcome by using a front-view luminosity image of the plasma as a 2-D weighting factor at time zero. The resulting profile is used as the weighting factor for the next time segment, and this is continued till the end. The algorithm was first tested with a wide range of simulated time-dependent profile functions. The time-resolved reconstructed plasma profiles clearly exhibit the near-threshold behavior of the instability of Rayleigh-Taylor type. The onset and escalation of the fluctuation in the transmitted intensity of the laser pulse are found strongly correlated with the increasing variability of the plasma structure at neutral gas densities above the threshold value.

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Abstract Submitted for the 13th Topical Conference on High-Temperature Plasma Diagnostics. 
Tucson, Arizona, June 18-22, 2000

Design and fabrication of a VUV pinhole camera based on thin phosphor screens.

A compact and highly sensitive pinhole camera has been developed for acquiring broadband VUV emission profiles of plasmas in the TJ-II. Its principal purpose is to obtain profiles with sufficiently high resolution so as to aid in the search for topological structures in stellarator plasmas. It can also be used to support experiments such as impurity injection by laser ablation.

The original and purpose-designed camera reported here provides optimum sensitivity over a broad spectral range. In the camera vacuum chamber, plasma radiation passes through a pinhole and a filter before impinging on a 5\times30 mm area of a P-46 phosphor screen. Thin screens of this material were extensively characterized using calibrated monochromatic VUV sources and it was found that their response is maximized when operated in reflection mode. Luminescent light emitted from the vacuum side of the screen is then focussed by a parabolic mirror (the pinhole is cut in its centre) onto the outside of a quartz window which is mounted on the side of camera. Finally, this intermediate image is relayed onto the surface of a gated and intensified linear photodiode array (25 microns by 25 mm) having 700 active pixels. This system is capable of obtaining radial VUV profiles every 12 ms and of recording them in \geq 100 ns.


Topic: Optical Through X-ray Spectroscopy
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A Fast Phosphor Imaging Diagnostic for Two Dimensional Plasma Fluctuation Measurements*

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A plasma imaging diagnostic is being developed using a fast time response ZnO:Zn phosphor to detect and follow plasma density fluctuations in a two dimensional region in the PISCES-A linear plasma device. The instrument is a 9.8-cm diameter phosphor coated disk enabling one to image the entire cross-section of the plasma column at one time. The disk is inserted into the plasma and electrons incident on the phosphor surface generate local excitation and emission of photons. The phosphor coating is electrically conducting and sensitive to electrons with energy $E_e > 2.5eV$. Phosphor light fluctuations are imaged using fast CCD cameras and photodiode detectors. A bias voltage may be applied to the phosphor disk increasing the brightness in situations where more light is needed for improved signal to noise ratio. The phosphor light fluctuations are then interpreted as plasma density fluctuations using sheath theory and the phosphor response function. The local intensity of phosphor light is related to the incident electron current density through the equation $I = \int R(E_e)(v \cdot a)f_e(v, t)dv$, where $R(E_e)$ is the energy dependent response function of the phosphor. Absolute radiometric calibration indicates that plasma fluctuations with a mm wavelength can be resolved to $\sim 0.25\%$ with a $2\mu s$ exposure. The phosphor persistence time is $1\mu s$ and with fast electronic camera shutter speeds enables the imaging of the plasma fluctuations with microsecond range time resolution. The broadband turbulent phosphor light fluctuations ($f < 500kHz$) have been imaged in PISCES-A and compared with local Langmuir probe measurements of plasma density fluctuations.

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EP13
Spectroscopy diagnostics of a low temperature laser ablated LiAg plasma plume

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Time- and spatially-resolved spectroscopy in conjunction with detailed modeling constitutes a powerful technique for the understanding of plasma plume dynamics. To this end, in a series of experiments performed at Sandia National Laboratories, laser-generated LiAg plasma plumes were produced by irradiation of solid targets using a 10 ns pulse duration, $1\times10^8$ W/cm\textsuperscript{2} intensity Nd laser. Time- and spatially-resolved (along a direction normal to the target's surface) optical spectra were recorded with a framing spectrograph. In order to limit gradients along a direction perpendicular to the target normal, targets with strips of LiAg coated on top of Pt were used. The Pt plume collisionally confines the LiAg, thus reducing the LiAg lateral expansion. This technique allows a better characterization of the LiAg plasma. The observed spectra consist of optical line emission in Li and Ag atoms. Evidence of ions in the plume is suggested by the presence of forbidden lines and Stark-broadened line shapes due to plasma electric microfields. A spectroscopic model based on time-dependent collisional-radiative atomic kinetics that self-consistently and simultaneously calculate the Li and Ag level populations in conjunction with detailed line shapes, and radiation transport calculations are used to interpret the data. From this analysis temperature, density and ionization in the plume as a function of time and position along the normal to the target surface are extracted.

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EP14
High Resolution Measurements of Neutral Density and Ionization Rate in the Alcator C-Mod Tokamak.\textsuperscript{1} R.L. BOIVIN, J.W. HUGHES, B. LABOMBARD, D. MOSSESSIAN, J.L. TERRY, M.I.T. Plasma Science and Fusion Center — Two new high resolution detectors have been installed on the Alcator C-Mod tokamak to measure the neutral density and ionization rate near the edge of the discharge in the main chamber. Based on a silicon detector sensitive to UV light, and a very narrow filter with a peak at 1215 Angstroms, we measure the Lyman alpha radiation emanating from neutral deuterium (and hydrogen). The detectors consist of a 20 channel array which views the plasma tangentially 12.5 cm below the outer midplane, and 10 cm above the inner midplane, through a 1mm x 3mm slit, giving a nominal radial resolution of 2 mm and 3 mm respectively. The local emissivity is obtained via a standard Abel inversion technique. Employing well-known branching ratios, and using measured local electron density and temperature, we therefore infer the neutral density and ionization rate with similar radial resolution. Details of the setup and sensitivity of the results to input parameters will be discussed.

\textsuperscript{1}Work Supported by D.o.E. Coop. Agreement DE-FC02-99ER54512.
Multi-channel spectroscopy diagnostic for Helium line intensity ratio Measurements, H. Punzmann, M. G. Shats, W. M. Solomon Plasma Research Laboratory, Research School of Physical Sciences and Engineering, Australian National University

A multi-channel spectroscopy diagnostic has been designed to measure the electron temperature and density in radiation-dominated helium plasma in the H-1 heliac. The diagnostic principle relies on the well-known technique of measuring neutral helium line intensity ratios. A 2x10 optical fiber matrix (1mm fiber diameter) is imaged into the plasma and collects light from 10 chords. Two sets of 10-fiber arrays are coupled to the input slits of two monochrometers. The output slits are coupled to photomultiplier tubes through another two 10-fiber arrays. Several pairs of neutral helium spectral lines are used to measure time and spatially resolved \( T_e \) and \( n_e \). The effect of structures and magnetic islands on the plasma profiles is investigated using this diagnostic.
Abstract Submitted for the HTPD Meeting of
The American Physical Society
Tuscon, AZ

Real-Time Measurement of Toroidal Rotation—* S.F. PAUL Princeton Univ., C. CATES, M. MAUEL, D. MAURER, G. NAVRATIL, M. SHILOV Columbia Univ.—One of the important goals in Columbia's HBT-EP tokamak program is the improvement of tokamak plasmas by controlling the bulk plasma flow relative to the conducting wall. The method for active plasma flow control in HBT-EP is the application of oscillating resonant magnetic perturbations to oppose the velocity of magnetic islands at the $q = 2$ surface. Real-time (10 kHz) feedback control without inserting a material probe necessitates the use of an optical toroidal rotation measurement whose data is available during the shot. This is being accomplished in a novel way by seeding the deuterium plasma with 5-10% helium and measuring the Doppler shift of the chord-integrated emission of the He II ($n = 4 \rightarrow 3$) line at 4686 Å. Since the electron temperature is expected to be about 30 eV at the $q = 2$ surface, helium is not fully stripped. The shift in wavelength is calculated by measuring the change in intensity as the line moves across the passband of an interference filter that varies linearly. Filters with less than 0.2% variation from a perfectly linear slope have been obtained. Fluctuations in the plasma emission are removed by having two detectors observe the same volume of plasma. This is achieved by splitting the optical view with a 'Y' composed of randomized optical fibers. One detector views the plasma through a filter whose passband has a negative slope and the other channel views through a positive-slope filter. Systematic differences such as detector sensitivity, amplifier gain, fiber losses, etc. are compensated by normalizing each signal to the signal at a particular reference time. The ratio of signals at two different times does not depend on any detector or circuit characteristic that remains constant. The Doppler shift, relative to the reference time, is a function only of the slope of the filter's transmission. The Doppler shift at the He II impurity emission line is 0.25 Å for a toroidal rotation of 3 km/sec, and the slope of the filter passband is 8-10% per Å, resulting in a 4% variation in signal level relative to the other channel.

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Prefer Oral Session

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Edge temperature and density measurements by helium line intensity ratios in

RFX with high time resolution

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In the Reversed Field Pinch RFX the electron temperature and density at the edge are measured from the intensity ratio of selected lines emitted by an atomic helium beam injected into the plasma. Helium is injected through a single 30 mm long microtube, 150 μm in diameter and then through a diaphragm of 200 μm diameter placed at 300 μm from the tube end. The optical detection system consists of four beam splitters that deviate the light to a CCD camera for a direct observation of the beam inside the plasma and to three interference filters coupled with linear array cameras or with photomultipliers. In particular the application of photomultipliers as detectors has recently increased the time resolution of the diagnostic up to 50kHz, that is up to the limit imposed by the characteristic times of the atomic processes involved. This allows following the time evolution of edge density and temperature during non-stationary processes, typically observed in RFPs. For example, the values of Te and ne at the edge may be compared in time with the toroidal angle at which the magnetic modes are phase-locked when a rotating external m=0 perturbation is applied in order to rotate toroidally the locking position.

Moreover, the enhanced time resolution increases the capability of the diagnostic as to the measurement of the edge Te and ne fluctuations, that are relevant to the edge electrostatic transport studies.

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TOPIC:
Edge Diagnostics
A Multi-Channel Spectroscopic System for Measuring Impurity Ion Temperatures and Poloidal Rotation Velocities in TJ-II Plasmas. 


In this paper, we report on the hardware and software of an eight channel, high resolution, spectroscopic diagnostic system that has been built for the TJ-II flexible heliac. This system is currently being used to measure, using passive emission spectroscopy, ion temperatures and poloidal rotation of impurity ions that emit at $\rho \geq 0.5$ in plasmas created in this device. The principal features of the diagnostic include independent focusing of its channels, high sensitivity for performing Doppler measurements in low density ECR heated plasmas as well as a flexible and fast in-house developed software program for performing data reduction and analysis.

The system is based on a 1 m image corrected spectrometer equipped with a 3600 g/mm grating and an eight channel fiber optical bundle that relays the light emitted by impurity ions along different plasma chords to the input slit of the spectrometer. At its output slit, a refrigerated and shuttered CCD detector records eight line profiles during integration times of a few tens of milliseconds. The CCD data are recorded on a personal computer before being transferred to a Digital Alpha Server for analysis. The software developed for this consists of a visual and interactive program for fitting line shapes required by a model for deducing local plasma parameters.

Also, we outline calibration procedures, some results obtained from TJ-II plasmas, as well as some details of future upgrades to the system.

Topic: Optical Through X-ray Spectroscopy
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Full Aperture Back Scatter Diagnostic for the NIF Laser Facility

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Abstract
The current schemes for achieving ignition on the National Ignition Facility (NIF) require efficient coupling of energy from 192 laser beams to the Deuterium-Tritium fuel capsule. Each laser beam must propagate through a long scalelength plasma region before being converted to x-rays (indirect drive) or being absorbed on the capsule (direct drive). Laser-plasma instabilities such as stimulated Brillouin and stimulated Raman scattering (SBS and SRS) will scatter a fraction of the incident laser energy out of the target leading to an overall reduction in the coupling efficiency. It is important to measure the character of this scattered light in order to understand it and to develop methods for reducing it to acceptable levels. We are designing a system called the Full aperture backscatter diagnostic (FABS) with the capability to measure the time-dependent amplitude and spectral content of the light which is backscattered through the incident beam focusing optic. The backscattered light will be collected over about 85% of the full beam aperture and separated into the SBS wavelength band (348-nm to 354-nm) and the SRS wavelength band (400-nm to 700-nm). Spectrometers coupled to streak cameras will provide time-resolved spectra for both scattered light components. The scattered light amplitude will be measured with fast and slow diodes. The entire system will be routinely calibrated. Analysis of the data will provide important information for reducing scattered power, achieving power balance and finally achieving ignition.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.
Near to Back Scattered Light Imaging Diagnostic on the National Ignition Facility

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Abstract

The National Ignition Facility is being built at LLNL for the DOE Stockpile Stewardship Program. It will perform experiments for Inertial Confinement Fusion (ICF) ignition, High Energy Density (HED) science, and basic science. A target diagnostic is being developed for the NIF that will image nearly all the light scattered near the laser axis, just outside the laser focusing lens. It is required to measure stimulated Brillouin (SBS) and stimulated Raman (SRS) scattering for backscatter fraction with a goal of 5% uncertainty, and SBS and SRS temporal response with 100 ps resolution. It will also provide an option to measure temporally resolved spectrum with 50 ps and 1 nm resolution. The diagnostic will obtain SBS and SRS scatterplate images with a retro-viewing optical digital camera placed inside the target chamber. Optical diodes will be placed to obtain the temporal data throughout the scatterplate image, and fibers will be placed near the diodes to make the spectral measurement. An in situ calibration will be performed with a low power laser, used to illuminate a series of points on the plate while recording the plate image with an external camera system.

*This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

EP21
Fiber-coupled streaked optical spectroscopy for the National Ignition Facility

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Time-resolved optical spectroscopy is critical to understanding laser-plasma scattering processes for the National Ignition Facility (NIF), and for other laser-plasma experiments. Optical fibers are used to couple light into spectrometers for many applications, and are planned to be used for the backscatter diagnostics on NIF. Here several issues arise that can seriously limit the system performance, such as the wavelength dependent group delay, and intramodal dispersion.

These issues are investigated in 10-m length fibers using either a 400-μm core step index or graded index fiber. For the group delay measurement, a 1-ps pulse from a Ti:Sapphire laser is used to produce a short, broadband (400-700 nm) light source via self phase modulation in fused-silica. The broadband source is injected into the fiber, and the fiber output is measured using a spectrometer coupled to a streak camera. Streak records are obtained to determine the relative group delay versus wavelength for the fibers. A narrow band 1-ps pulse is used to study intramodal dispersion in these fibers. The narrow band source is injected into the fibers with various coupling schemes. The fiber output illuminates a diffuser at the streak camera slit to record the time-resolved output angle from the fiber. This allows a determination of which modes contribute most to temporal dispersion for the various input coupling schemes.

Finally, a conceptual design is proposed for multi-channel streaked optical spectroscopy for NIF using 100μm core graded index fibers. Designs appropriate for a high spectral resolution instrument (Brillouin scattering), and a low spectral resolution instrument (Raman scattering) are presented. The fiber dispersion issues are discussed in the design of these diagnostics.
Spectral Catalogue of Optical Lines for the Development of Diagnostics for Fusion Plasmas

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Spectroscopic data of neon, argon and krypton is of particular interest for fusion plasma following the development of radiative cooling scenarios and, more recently, using these gases to control the edge condition to sustain the high performance. Optical transitions offer excellent opportunities for diagnostics given the range of temperature and densities of the edge region and the state-of-the-art of optical instruments that may include light fiber optics, laser tagging, and solid-state optical elements. Unfortunately, the atomic data for optical transitions, especially for ions with charge higher than 3+, are largely unknown. In fact, most lines have never been identified. Using our fully equipped spectroscopic facilities on the LLNL EBIT device, we plan to establish a catalogue of spectral line emission of neon, argon and krypton in the optical region. As a first part of this project, we used a Steinheil prism spectrograph and a scientific grade CCD camera to perform broad band (3700 — 6000 Å) spectral surveys with moderate resolution. With fine energy steps, the electron beam energy was varied from about 150 eV to 17 keV. Because of the continuous flow of neutral gas from the gas injector, many lines from low ionization stages have been observed together with a number of magnetic dipole transitions from higher charge states. Large fraction of the lines, for example over 70% for krypton, has not been recorded in literature. These measurements establish a baseline for the optical emission for future extensions using spectrometers with high resolution, such as transmission grating spectrometers with a resolving power of about 14000. As a test case, we measured the Kr spectra at region from 3450 Å to 3900 Å with wavelength accuracy of 0.01 Å, and a greater number of new lines have been discovered.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.
An eight-channel beam-emission-spectroscopy (BES) system has been installed on the Alcator C-Mod tokamak, intended for use with a diagnostic neutral hydrogen beam (DNB). Capable of localized measurements from the plasma edge to the plasma core, the BES diagnostic collects light from the first Balmer transition (H\text{\(\alpha\)}) resultant from beam/plasma collisions. The H\text{\(\alpha\)} line splits into several components whose central wavelengths depend on the viewing geometry, the magnetic field, and the beam energy. This is due to the Doppler shifts from viewing the beam off perpendicular, the different velocities of the three mass components of the beam (H, H\text{\(2\)}, H\text{\(3\)}), and the large motional Stark effect. Optimal signal-to-noise requires collecting these components while attenuating all other emission: primarily bremsstrahlung and D\text{\(\alpha\)} radiation (from plasma D\text{\(0\)}/e\text{\(\text{-}\)} collisions). Tunable bandpass filters are thus required. A BES simulation code has been developed that calculates the brightnesses (bremsstrahlung, D\text{\(\alpha\)}, H\text{\(\alpha\)}) versus wavelength using plasma profile data from the C-Mod MDSplus database, a computation of the beam penetration, the viewing and DNB geometries, and bandpass filter characteristics. The model was first used to estimate signal levels and choose the optimal BES bandpass filters; its ultimate purpose is to determine the shot-to-shot tuning requirements of the filters for different discharge conditions. Comparisons of measured and predicted background bremsstrahlung and D\text{\(\alpha\)} brightnesses are presented, as are first measurements and calculations of the beam emission. The code is written in the IDL programming language utilizing the "widget" graphical user interface. Designed for geometrical and spectral flexibility, it can be modified to simulate other beam diagnostics such as motional-Stark-effect (MSE) plasma current measurements and charge-exchange recombination spectroscopy (CXRS), as well as passive diagnostics measuring chord-averaged spectral emission.

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3 IDL is a registered trademark of Research Systems, Inc.
2D Turbulence Imaging in DIII-D Via Beam Emission Spectroscopy

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Turbulence in a toroidally confined tokamak is fundamentally 2D in nature. Hence, fully 2D measurements are needed for obtaining the relevant $S(k, k_0)$ wavenumber spectrum and a realistic representation of the turbulence structures for comparison to theory, to provide time-averaged and possibly time-resolved visualization of the turbulent eddy structures, obtain high spatial resolution fluctuation velocity and velocity shear measurements, and ultimately characterize the turbulence growth and nonlinear energy transfer rates for more direct comparison to nonlinear theory. In DIII-D, the Beam Emission Spectroscopy diagnostic\(^1\) has been installed to measure spatially localized, long wavelength density fluctuations. The diagnostic presents 32 spatial channels which can be deployed to provide simultaneous access to both radial and poloidal directions. The 2D motorized fiber mounting array can be scanned radially to observe different spatial regions of the plasma. The 1 cm radial and vertical resolution allows for observation of long wavelength modes with wavenumber $k \leq 3 \, \text{cm}^{-1}$, which are typically associated with anomalous transport in the edge and core plasma regions. The signals are digitized at 1 MHz and the use of a cryogenically cooled amplifier circuits provide photon-noise limited current detection. A 2D fiber mount array allows for such 2D measurements. Spatial channels are arranged to image a $5 \times 6 \, \text{cm}$ (radial x poloidal) region in the plasma cross section at the nominal 1 cm spatial resolution and spatial separation. This provides an ensemble averaged $S(k, k_0)$ spectrum, and provides visualization of 2D structures in turbulence. Data have been acquired during L to H-mode transitions near $r/a = 0.9$-1.0. Spatial correlation analyses as well as 2D nonlinear analysis algorithms are being developed to further characterize the measured turbulence and associated structures. In addition, biorhogonal decomposition techniques are being developed to identify and characterize coherent, large scale structures, as has been done with Langmuir probe measurements in the SOL of the ASDEX tokamak\(^2\). It allows for the simultaneous analysis of the space and time dependencies of fluctuation data, and should lead to a more detailed characterization of the DIII-D edge turbulence.


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A high spatial resolution, high sensitivity, long-wavelength density fluctuation diagnostic that observes collisionally-induced Lyman-alpha emissions (\( \lambda_\alpha = 121.6 \text{ nm} \)) from neutral beam atoms is being designed. A conceptually similar diagnostic based on Balmer-series emission (visible \( D_\alpha \); \( \lambda_\alpha = 656 \text{ nm} \)), the Beam Emission Spectroscopy (BES) system, has proven to be very successful at characterizing long-wavelength density turbulence in tokamak plasmas. One drawback to the visible BES system has been reduced sensitivity in high-confinement modes of operation and near the plasma core due to nature of turbulence and reduced beam penetration. One solution that offers the potential to dramatically improve sensitivity is to observe the \( L_\alpha \) emissions in the vacuum-ultraviolet (VUV) spectral region rather than the more accessible visible emission at \( D_\alpha \). The photon flux at \( L_\alpha \) is estimated to be 30-50 times higher than \( D_\alpha \) due to atomic transition rates and the neutral beam excited-state population densities in typical tokamak plasmas. This dramatically increases the photon-noise-limited signal-to-noise ratio. Previously, a \( L_\alpha \) based system has not been developed due to the technically difficult problem of designing a high throughput, high efficiency, low-noise VUV optical system. Recent developments in high quantum efficiency detectors at \( L_\alpha \), improvements in holographic diffraction grating manufacturing technology, and high-reflectivity coated and multilayer mirrors suggests that such a design is now feasible. The system must meet several requirements to be a viable system: spectral resolution of \( \Delta \lambda = 0.5 \text{ nm} \) at \( L_\alpha \), to isolate the Doppler-shifted beam emission from the bright edge \( L_\alpha \) emission; near unity quantum efficiency detectors; high transmission (\( \tau \geq 25\% \)); high optical throughput (\( E \geq 5 \times 10^{-3} \text{ cm}^2 \text{-ster} \)); and multichannel, 2D capability in the radial and poloidal directions. The imaged plasma volume should be \( \leq 1 \text{ cm} \) in the radial and poloidal directions for each channel in order to access fluctuations in the wavenumber range \( 0.1 \leq k_r, k_\theta \leq 3 \text{ cm}^{-1} \). System designs based on Seya-Namioka, Czerny-Turner, and Monk-Gillieson monochrometers, as well as multilayer spectral-filtering reflecting surfaces are being considered. The conceptual design will be presented.

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ELECTROSTATIC POTENTIAL FLUCTUATIONS VIA TIME-RESOLVED TURBULENT FLOW ANALYSIS

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Beam Emission Spectroscopy (BES) measures localized density fluctuations in fusion plasma turbulence. A wavelet-transform-based spectral analysis is applied to BES data to extract poloidal rotation velocity fluctuations from the density data. Cross correlation analysis is used to obtain preliminary wavenumber spectra of DIII-D plasma potential fluctuations on the assumption that the poloidal velocity flow, and fluctuations therein, are dominated largely by ExB flow. This study quantifies the data signal-to-noise requirements for electrostatic potential fluctuation measurements via BES by simulating turbulent velocity fluctuations. Frequency transfer functions for the wavelet extraction method are calculated. Furthermore, low-noise autopower spectra of potential fluctuations are obtained by applying two methods. First, numerical noise is reduced by eliminating phase jumps due to >1 period time delay phase differences in rotation measurements. Second, aspects of the wavelet spectral analysis are exploited to allow extraction of the plasma turbulence autopower spectrum from background incoherent noise.

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Equilibrium and Stability Measurements via Neutral Beam Spectroscopy for the PEGASUS Toroidal Experiment*

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An optical neutral beam spectroscopy system is being designed to provide plasma pressure profiles and internal MHD measurements for the PEGASUS Toroidal Experiment. This system will be able to measure plasma density, local ion temperature, the internal structure of large-scale MHD instabilities, and, possibly, the total magnetic field intensity. Time resolved, spatially localized measurements of the plasma density are provided by the intensity of the collisionally induced neutral beam fluorescence. Spectrally resolved measurements of the charge-exchange recombination emission of impurities can be used to determine the local ion temperature. Plasma stability will be studied with localized MHD measurements via the beam emission spectroscopy (BES) technique. Present efforts are focused on refurbishing the neutral beam hardware (25 kV, 4 A) and evaluating the feasibility of magnetic field intensity (mod-B) measurements via motional Stark broadening of deuterium beam emission. In principle, the internal pressure profile and mod-B measurements can constrain the current density profile, j(R), in magnetic equilibrium reconstructions. The accuracy of j(R) determination and beam performance requirements are under evaluation.

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-- End of Abstract

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The optical systems for charge-exchange recombination spectroscopy (CXRS) on Alcator C-Mod have been developed and installed. They will provide measurements of $T_i$, $v_\phi$, and $v_\psi$. With the addition of the MSE diagnostic to determine $B_\phi$, $E_r$ can be inferred from the ion pressure balance equation, $E_r = (\langle Z e n_z \rangle)^{-1} \nabla \varphi + v_\theta B_\theta - v_\phi B_\phi$. The optical systems are simple and have high throughput. In particular, the toroidally-viewing systems must be designed for invessel installation close to the plasma where they are subject to large forces and are inaccessible between vacuum vents. Two optical systems, located invessel, provide 20 channels of $T_i$ and $v_\phi$ data from $67.4 \text{ cm} < R < 88.8 \text{ cm}$. A third system, located in air and viewing the plasma through a window, provides 10 channels of $T_i$ and $v_\phi$ data from $60 \text{ cm} < R < 95 \text{ cm}$. Simulations of the expected performance are presented and will be compared with initial results, if available. An extension of the CXRS system for measurement of ion temperature modulation in transient transport experiments, and perhaps for ion temperature fluctuations, will also be discussed.

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First CHERS and MSE Results from the MST Reversed Field Pinch

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The plasma in the Madison Symmetric Torus (MST) is characterized by low magnetic field (~ 1-5 kG), moderate temperature and density (< 1 keV and 10^{19} m^{-3}), and large levels of both magnetic and electrostatic fluctuations. Localized measurements of core ion dynamics and magnetic fields have never before been made in a large hot reversed field pinch. We report on the first results of Charge Exchange Recombination Spectroscopy (CHERS) and Motional Stark Effect (MSE) measurements in the MST. A 30 keV, 4A neutral H beam is used in combination with visible and UV spectroscopy to make the measurements. For CHERS, a survey of species and transitions has been made to find the best candidate for the measurement. It appears that the C VI line at 343.4 nm yields the brightest beam signal and is most clearly resolved from other nearby lines. The background emission is large, presumably due to the large neutral hydrogen pressures in the core. We observe a clear decrease in background and increase in charge exchange signal during high confinement discharges when core neutral density drops sharply and electron temperature increases. A new high resolution, high throughput spectrometer is being constructed to do fast measurements of core impurity flow and temperature.

MSE measurements are made via the Doppler shifted H_{a} emission from the beam with a CCD imaging spectrometer. The low magnetic field in MST makes this measurement challenging but we have observed some separation of the Stark manifold. Preliminary analysis shows the magnetic field on axis to be roughly consistent with that predicted by equilibrium modeling. Currently the precision of the measurement is limited by broadening of the individual Stark components due to finite beam temperature and divergence, slight temporal variations in beam energy, and finite collection volume. Modifications to the existing hardware are underway to include a lower noise CCD detector and to limit the spatial extent of the beam and light collection cone.
A Motional Stark Effect Instrument to Measure q(r) on C-Mod


A Motional Stark Effect (MSE) instrument to measure q(r) using the TEXT neutral beam on C-Mod has been designed and installed. The neutral beam is on the midplane, aimed perpendicular to the magnetic field. The MSE optics view the outer half of the plasma -0.3<(R-R)/a<1.05. This geometry results in a spatial resolution of 1 (edge) - 2.5 (center) cm, respectively, from a beam apertured horizontally to 2 cm and significantly reduces the observed Stark polarization angle Bp/Bt near the plasma boundary. Estimates of the signal levels from the 50 keV beam indicate that statistical errors in the measurement of Bp/Bt can be less than 0.2% for ne0<2.0x10^14 cm^-3 similar to other MSE instruments. The collection optics reside within the vacuum chamber reflecting and imaging the neutral beam through a vacuum window in the neutral beam port. The optics are designed so that Beam Emission Spectroscopy can be carried out simultaneously with MSE measurements. Optical signals are transmitted to remote detectors by fiber optics. Low Verdet glass and dielectric mirrors are used to minimize polarization changes. Polarization is measured by conventional techniques using photoelastic modulators, optical filters, and photomultipliers.

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The Motional Stark effect diagnostic in FTU - R. De Angelis, S. Segre, N. Tartoni, V. Zanza - Associazione EURATOM-ENEA sulla Fusione- C.R.Frascati C.P. 65, 00044 Frascati, Rome, Italy

This paper reports the description of a Motional Stark Effect diagnostic in FTU. Estimates of the attenuation and emissivity of a 40 keV hydrogen beam in typical plasmas, \(10^{20} \, \text{m}^3\) average density, lead to the possibility of polarimetric measurements with a spatial resolution of 3cm over a 30mm central plasma region. The neutral injector can deliver an equivalent neutral current of 1A. Due to the geometrical constraints the beam direction and the polarimeter lines of sight lie on a vertical plane on the same horizontal port. This layout has the advantage of a more convenient projection of the polarization vector on the line of sight, which increases the sensitivity of the measure. Two different kinds of polarimeters are compared and discussed. The first one makes use of photo elastic modulators and a linear polarizer. The second is a new conception and performs the modulation by means of fast rotating half wave plates. The signals are acquired at a 5 M/s rate and Fourier analyzed to determine the polarization direction of the incoming light. A particular effort has been devoted to the development of the relay optics to avoid optical components which can perturb the polarization angle.
Spectra-polarimetry of the Motional Stark Effect at TEXTOR-94


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The Balmer-α light emitted by neutral particles injected into tokamaks is polarized with respect to the Lorentz electric field experienced by these atoms: \( E_L = v \times B \), known as the Motional Stark Effect (MSE). Measuring this polarization thus directly provides the direction of the magnetic field. Application of the Motional Stark Effect to determine the current distribution generating the poloidal magnetic field has been satisfactory demonstrated on different devices. All these setups use a narrow band interference filter to select one of the Stark lines and determine the polarization by using two crossed photo-elastic modulators (PEMs). On TEXTOR-94, a medium sized, circular limiter tokamak (major radius \( R_0 = 1.75 \) m, minor radius \( a = 0.46 \) m) a new MSE system is under development which exploits the full spectral information, along with its polarization.

The advantages of exploiting the full spectral information are obvious: i) the system is insensitive to variations in beam velocity or magnetic field, ii) the Doppler shift is measured as well, allowing to determine the observation volume directly from the spectrum, iii) the polarization is measured at several lines simultaneously, increasing the accuracy of the deduced direction of the magnetic field and finally iv) if in addition to \( E_L \) a radial electric field is present in the plasma this can, albeit with limited accuracy, be determined as well by comparing the polarization direction of two different energy components of the neutral beam.

The TEXTOR-94 MSE system is optimized for good spatial resolution. It consists of 30 radial channels covering the plasma from the center to the edge, with a radial variation of less than 5% over the full profile. This is accomplished by inserting all the optical components inside the vessel looking towards the beam at different angles for different channels. The polarization is obtained by introducing a polarizing beam splitter (Glan-Laser a-BBO crystal) in the optical path. With fiber optics the light is transferred out of the vessel towards a Littrow spectrometer. The use of a spectrometer limits the time resolution to 50 ms. For that reason a provision is made to couple the optical fibers also to a narrow band interference filter followed by a linear array. This increases the time resolution to less than 1 ms, at the cost of loosing the spectral information.

The accuracy of the measurements for deducing the polarization angle is estimated to be 0.3°. Together with the spatial resolution this leads to an accuracy for determining the safety profile factor \( q \) (defined as the number of toroidal orbits of a field line to complete one poloidal orbit) of 10-15%. The accuracy in measuring the radial electric field in the plasma is estimate to be 15-20 kV/m.

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*Partner in the Trilateral Euregio Cluster (TEC)*
Prospects for Edge Current Density Determination Using LIBEAM on DIII-D, D.M. Thomas, K.H. Burrell, T.H. Osborne, L.L. Lao, General Atomics, D.G. Nilsen, B.W. Rice, Lawrence Livermore National Laboratory — The specific size and structure of the edge current profile has profound effects on the stability and ultimate performance of many advanced tokamak (AT) modes. This is true for both bootstrap and externally driven currents that may be used to tailor the edge shear. Absent a direct local measurement of \( j(r) \), the best alternative is a determination of the poloidal field, \( B_\theta \). Measurements of the precision \(-0.1^\circ\) in magnetic pitch angle and \(1-10\) ms) necessary to address issues of control and provide constraints for EFIT are difficult to do in the region of interest \((\rho = 0.9-1.1)\). Using Zeeman polarization spectroscopy of the \(2S-2P\) lithium resonance emission from the DIII-D LIBEAM, measurements of the various field components may be made to the necessary precision in exactly the region of interest to these studies. Because of the negligible Stark mixing of the relevant atomic levels, this method of determining \( j(r) \) is insensitive to the large local electric fields typically found in enhanced confinement (H-mode) edges, and thus avoids an ambiguity common to Motional Stark Effect (MSE) measurements of \( B_\theta \). Key issues for utilizing this technique include good beam quality, an optimum viewing geometry, and suitable optical filters to isolate the polarized emission line. A prospective diagnostic system for the DIII-D AT program will be described.

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Abstract Submitted for the Thirteenth Topical Conference on High Temperature Plasma Diagnostics
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Category Number and Subject: [ ] Theory [x] Experiment

**Improved CCD Detectors for the Charge Exchange Spectroscopy System on the DIII-D Tokamak,** K.H. Burrell, P. Gohil, R.J. Groebner, D.H. Kaplan, D.M. Thomas, General Atomics, D.G. Nilson, Livermore National Laboratory — Charge exchange spectroscopy allows determination of ion temperature, poloidal and toroidal velocity, impurity density and radial electric field $E_r$ in high temperature tokamak plasmas. Charge exchange spectroscopy has been one of the workhorse diagnostics on the Doublet III and DIII-D tokamaks since 1983. The ability to determine the $E_r$, for example, has been essential in testing the model of EB shear suppression of turbulence. For the 2000 experimental campaign, we have replaced the intensified photodiode array detectors on the edge portion of the system with advanced CCD detectors mounted on faster ($f/4.7$) spectrometers. The combination has improved the photoelectron signal level by about a factor of 20 and the signal to noise by a factor of 2 to 8, depending on the absolute signal level. A major portion of the signal level improvement comes from the improved quantum efficiency of the back-illuminated, thinned CCD detectors (70% to 85% for the CCD versus 10%-20% for the image intensifier) with the remainder coming from the faster spectrometers. The CCD camera also allows shorter minimum integration times: 320 $\mu$s while archiving to PC memory and 150 $\mu$s using temporary storage on the CCD chip. The PC memory option allows up to 4096 spectra per tokamak shot, limited only by available memory, while the faster on-chip storage is limited to 254 spectra. Results from tokamak plasma shots will be presented.


[x] Prefer Poster Session Submitted by: [ ] Prefer Oral Session K.H. Burrell
[ ] No Preference
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EP35
Abstract prepared for submittal to the
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VISAR\textsuperscript{1} for measuring EOS and shock propagation
in liquid deuterium\textsuperscript{*}.

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Initial laser-driven equation of state (EOS) experiments on liquid deuterium employed x-ray radiography to track the shock and particle speeds in the shock compressed sample. With the high pressures available with laser drivers we found that it is also possible to track the shock front directly with a velocity interferometer (VISAR\textsuperscript{1}) because the shock front reflects light across the visible spectrum with reflectance around 50\% for shocks stronger than 50 GPa in liquid deuterium. We have observed similar reflectances in other dielectric samples, such as diamond, LiF and water. The pressure required to produce a reflecting shock varies with each material. This phenomenon allows us to design impedance-matched EOS experiments using velocity interferometry to measure the propagation speed in the transparent shocked materials, and step breakout measurements to determine the speed in the pusher. In a different kind of experiment we have observed double shock compression in liquid deuterium by impacting a shock in liquid deuterium at a LiF anvil placed in the liquid sample. VISAR can be used to track the shock in the deuterium as well as the motion of the deuterium-LiF interface subsequent to impact. This allows us to diagnose double-shock states using the VISAR technique. As a final example VISAR can be used to track shock overtake events such as produced by shaped pulse compression or shock reverberation effects in the accelerating pusher. This capability is directly applicable to shock timing experiments needed to tune the drive pulse for inertial confinement fusion capsules on the National Ignition Facility.

\textsuperscript{1}Velocity Interferometer System for Any Reflector
\textsuperscript{*}Work performed under the auspices of the U.S. D.O.E. by LLNL under contract number W-7405-ENG-48.
Electron Fluctuation and Fluctuation-Induced Transport Measurements in the Madison Symmetric Torus Reversed-Field Pinch

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University of California – Los Angeles

Abstract:

A recent study investigating the role of electron density fluctuations in particle transport has been conducted on the Madison Symmetric Torus Reversed-Field Pinch. Three diagnostics enabled this experiment: a high-speed multi-chord Far-infrared (FIR) laser interferometer, a 64-position magnetic coil array, and a Doppler spectrometer measuring impurity ion flow fluctuations. Correlation analysis is used to elucidate the relationship between density, magnetic and impurity ion flow fluctuations. We observe that the electron density fluctuations are highly coherent with the magnetic fluctuations resulting from core-resonant resistive tearing modes. Moreover, the fluctuation-induced particle transport, obtained from the correlation between electron density and flow fluctuations, indicate that the core resonant tearing modes do not drive significant particle transport in the plasma edge. We will address the three primary diagnostics, details of the analysis techniques, and principal results from this study.
The New Diagnostics for Physics Studies on TEXTOR (Invited)


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After the end of the Rijnhuizen Tokamak Project (RTP), the work of the plasma physics department of the FOM-Institute has concentrated on the medium-sized TEXTOR tokamak. The main emphasis of the FOM-team will be a natural continuation of the work that has been done on RTP. The highlights of the RTP programme were the study of internal transport barriers located near rational q-values, as well as the study of plasma filaments. To continue these studies at a larger sized tokamak, TEXTOR is presently being equipped with Electron Cyclotron Resonance Heating. Simultaneously, the diagnostics set of TEXTOR, which was traditionally heavily biased towards the plasma edge, has been extended with a number of advanced plasma core diagnostics. This paper will describe the new diagnostics that have been recently installed by the FOM-team, along with some first results.

High-resolution measurements of the electron temperature and density profile along a vertical chord are done with a double-shot multi-position Thomson scattering system. The complete vertical chord of 900 mm length is resolved into 120 spatial positions of 7.5 mm each. The spectrum at each position is resolved into 80 wavelength channels. To measure the electron temperature profile as a function of time, the present set of ECE diagnostics is extended by a 16-channel frequency tunable heterodyne radiometer as well as by a 14-channel ECE-Imaging system. Both of these systems have the possibility to measure microscopic temperature fluctuations with frequencies up to several hundreds of kHz. The default position of the vertical chord of ECE Imaging is right on top of the Thomson scattering laser chord, which simplifies the comparison between the two diagnostics as well as calibration of the Imaging system. An already existing 4-channel third harmonic ECE system has been extended with four second harmonic channels to study supra-thermal electrons. The electron density profile at the low field side is measured by a fast (2 MHz) 10-channel pulsed radar reflectometer (18 - 57 GHz). Two additional frequency tunable channels can be used for fluctuation correlation measurements up to 10 MHz. It is planned to operate a prototype microwave imaging reflectometer before summer.

An already existing Motional Stark Effect system has recently been extended to 30 viewing channels. Simultaneously, the spatial resolution has been drastically improved. The new MSE system measures the spectrally resolved polarization state of the beam emission offering a number of advantages.

A five-camera ultra-soft x-ray tomography system will be employed to study impurity transport processes. The cameras feature multi-layer mirror / pinhole assemblies to create plasma ultra-soft x-ray images in selected spectral lines on a phosphor. Light from the phosphor is guided by fiber optics to Electron Bombarded CCD tubes. Each camera resolves a poloidal cross section of the plasma in at maximum 100 separate viewing chords of 1 cm width. The highest temporal resolution that can be achieved by this system is 1 ms in burst mode or 20 ms in continuous mode.

Fast ion populations can be studied by an ion collective Thomson scattering system using a 110 GHz, 400 kW, 200 ms gyrotron as a source. The scattering system can measure the perpendicular component of the fast ion distribution in a range of radial and, to some extent, poloidal locations on a shot-to-shot basis.

Other systems that are already existing at TEXTOR, but that are also operated by the FOM team are an infrared camera to observe synchrotron radiation and a Charge Exchange Recombination Spectroscopy system.
Holographic Measurement of Magnetic Fields in Plasma Discharges *
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The measurement of magnetic fields in hot, dense plasmas such as those produced by a z-pinch is problematic because standard probe techniques such as $B\text{d}t$ loops are not compatible with such an environment. In the past, the measurement of the Faraday rotation of a laser beam has been used to infer the distribution of magnetic fields in a plasma. The main drawback of this approach can be seen in the defining equation for the observed rotation, $\Delta \Phi \propto n_e B \text{d}z$. The rotation, $\Delta \Phi$, is a product of the magnetic field and the electron density. In order to deconvolve the magnetic field distribution one must also have a map of the electron density distribution. Using standard methods to measure the Faraday rotation, the electron density profile must be determined separately.

Looking more deeply into the process, Faraday rotation arises because the right circularly polarized (RCP) and left circularly polarized (LCP) components of a linearly polarized laser beam have slightly different phase velocities in a magnetized plasma and therefore experience a relative phase shift while traversing the plasma. In our approach, we record simultaneous, but separate, holograms of the RCP and LCP waves, which, upon reconstruction can be interfered to give a 2D phase map which is proportional to the Faraday rotation. By recording a third hologram prior to the introduction of the plasma, one can also deduce the 2D electron density by interfering this hologram with one of the Faraday holograms. By recording all three holograms on a single plate with separate reference beams, the Faraday rotation and electron density distributions can be independently determined and are perfectly registered.

Initial measurements have been carried out z-pinches produced by a 250 kA, 150 ns pulse generator. Although the anticipated magnetic fields are not high, preliminary analysis of the holographic data indicate the presence of measurable and reasonable magnetic field profiles.

The described system has a number of unique and highly desirable features. First and foremost, both the Faraday rotation and electron density profiles are recorded simultaneously on the same holographic plate providing perfect registration of the images. Second, the use of multiple, independent reference beams allows the implementation of sophisticated phase stepping reconstruction techniques which give us phase resolutions on the order 10 degrees. Third, the holographic plate has a high dynamic range (up to 6ND), which makes it highly immune to incoherent background light. Finally, since the wavefronts are permanently recorded on the holograms, various analysis techniques can be employed at the leisure of the researcher.

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Non-Perturbing Current Profile Measurements of a Sustained Spheromak


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In this paper we discuss the measurement of the current profile in the SSPX spheromak. In the spheromak, magnetic fluctuations arise when the current and field profiles deviate from the Taylor-relaxed-state. We have built a Transient Internal Probe (TIP) diagnostic to measure the internal field profile in a SSPX plasma sustained by DC coaxial helicity injection. TIP is a diagnostic that makes a spatially resolved (ie not chord averaged) measurement of the local magnetic field using Faraday rotation. A 1-cm by 4-mm diameter verdet probe is fired through the plasma at about 2 km/s by a two-stage light gas gun. The probe is illuminated by an Argon Ion laser throughout the traverse of the plasma – the retro-reflected light is then analyzed with an ellipsometer to determine the field at each location. The speed, small size of the probe, and the probe cladding make this measurement possible even in hot (100’s of eV) plasmas. The plasma flow past the probe is Knudsen rather than Hydrodynamic, meaning that frozen in field lines are not warped by its presence - thus the true field is measured. Based on its trajectory through the plasma, we will measure $F(R)=RB_z$ in the spheromak. We will use the LLNL code CORSICA to solve the Grad Shafranov equation by fitting to this data and edge probe measurements. The measurement is accurate enough (1 Mhz, ± 7 Gauss, 1 cm spatial resolution) to map out MHD mode amplitudes from the flux conserver to the magnetic axis. Using all this data, we hope to learn more about how the spheromak equilibrium is affected by being driven with a helicity injector; how it relaxes and decays when this is turned off; and to what extent mode activity is responsible for current redistribution.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

FP2
Density and Hα Diagnostics for the Sustained Spheromak Physics Experiment

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Abstract

The Sustained Spheromak Physics eXperiment (SSPX) is designed to achieve electron and ion temperatures of a few-hundred electron volts in a spheromak plasma sustained by DC magnetic helicity injection. We have built a multi-chord CO₂ interferometer at 10.6-μm laser wavelength that measures line-integrated plasma density and an Hα array that monitors the light emissions in the magnetized plasma injector and spheromak mid-plane. Details of both diagnostics are described. The interferometer signals are free of vibration for the several millisecond duration of the plasma, but often exceed 8 fringes (2.1×10^{20} m^{-2} per fringe) over a 1.53-m total pathlength. The ratio of the current over density J/n is within the range of a few times 10^{15} to 10^{14} A-m. Observation of Hα emission in the injector and voltage on the magnetized plasma injector raised issues about location and timing of breakdown that have been addressed and improved by operating changes to the gun bias flux and gas injection. More work is underway to address the breakdown and density issues to achieve the design goals of the SSPX.

This work was performed under the auspices of the U. S. Department of Energy by the Los Alamos National Laboratory under contract No. W-7405-Eng-36.

(Please put with posters by McLean and Holcomb)
The multi-chord FIR polarimeter of the RFX experiment

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The design, construction and the first operating results of the multi-channel FIR polarimeter for the RFX experiment are reported. Following a preliminary, single-chord experiment, a multi-chord FIR polarimeter has been designed, built and used to perform measurements on the RFX experiment, with the purpose of measuring the poloidal magnetic field profile $B_\theta$. The polarimeter uses a CO$_2$-pumped, FIR laser (100 mW output power, $\lambda = 118.8$ $\mu$m) whose beam is transmitted to the machine via a 31 m long, N$_2$ filled beamline. Faraday rotation measurements are made along five parallel chords crossing the 1-m diameter RFX plasma on a poloidal cross section. As the density profile is known from a CO$_2$ interferometer, the diagnostic implements a simple polarimetric technique by measuring the intensities of two mutually perpendicular polarization components of the beam emerging from the plasma. Low noise DLATGS detectors with responsivity of 3 V/W and $2 \times 10^{-8}$ W/Hz$^{1/2}$ NEP at 3 kHz chopping frequency provide a 0.2$^\circ$ accuracy in the measured Faraday rotation angle, sufficient to estimate the characteristics of the $B_\theta$ profile. Systematic removal of the noise induced by mechanical vibrations and a careful sensitivity calibration allowed measurements of Faraday rotation angles consistent with external magnetic fields measurements.

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TOPIC:
Laser Diagnostics 
FIR Diagnostics 
Interferometry and Polarimetry

FP4
Measurement of the core $B_T(r,t)$ value is essential in NSTX, since effects of paramagnetism and diamagnetism in Spherical Torus are expected to be considerably greater than that in higher aspect ratio tokamaks. Therefore, plasma parameters dependent upon $B_T$ such as the $q$-profile and local $q$ value can not be evaluated without independent measurement of $B_T(r,t)$. The multi-chord Tangential Far Infrared Interferometer/Polarimeter (FIReTIP) system currently under development for NSTX will provide temporally and radially resolved toroidal field profile [$B_T(r,t)$] and 2-D electron density profile [$n_e(r,t)$] data. The seven channel system is based on three FIR lasers including Stark tuned FIR laser operating at 119 $\mu$m which is an optimum wavelength for NSTX plasma parameters. The optical system is configured as a Michelson system using retroreflectors. The final system design is completed and initial two channels will be installed this fiscal year to support NSTX operation.

The channel spacing of FIReTIP system is optimized via data analysis with various expected electron density and magnetic field profile shapes. In simulation study, the solution of self-consistent MHD equilibrium was used to project diamagnetic effect on the toroidal magnetic field. The detail inversion process based on assumed profiles of the electron density and self-consistent toroidal field is exercised to estimate the source of errors for both local density and local magnetic field. The outcome of the proposed system is crucial to the study of confinement, heating and stability of NSTX plasmas.

* This work is supported by the U.S. Department of Energy under contract Nos. DE-AC02-76-CHO-3073 and DE-FG03-95ER54295.
Infrared Laser Polarimetry for Electron Density Measurement in Tokamak Plasmas

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In order to establish the reliable electron density measurement in long time and steady operation of tokamak fusion devices, the feasibility of infrared CO₂ laser polarimetry (λ=9.27 μm) for the tangential Faraday rotation measurement has been verified in JT-60U [1]. Afterwards, the original polarimeter has been upgraded to the dual CO₂ laser polarimeter (λ=9.27 and 10.6 μm) under the two-color polarimeter concept to eliminate the Faraday rotation component arisen at vacuum windows [2,3]. At the present, electron density is measured by the 9.27- and 10.6-μm polarimeters individually (Fig. 1), and by the application of the two-color polarimeter concept [4]. Recently, the high reliability of the infrared polarimetry is well demonstrated by the results from pellet injection experiments (Fig. 2). In Fig. 2, good resolution of the Faraday rotation angle (α₂7μm) of ~0.01° is shown with sufficient temporal response. (On the other hand, failure of interferometry is observed at t=3.9 s.)

A system stability for long time operation up to ~10 hours has been confirmed with baseline fluctuation of polarimeter signals of 0.4~0.7°[4]. Substantial fractions of this fluctuation should be attributed to the mechanical rotation of optical systems. The new multi-color polarimeter concept is proposed to eliminate the mechanical rotation components.

An application of the diamond window has been proposed for not only the reduction of the Faraday rotation at vacuum windows but also the broadband windows of optical diagnostics in tokamaks [3,4]. The optical properties of diamond plates for the infrared polarimetry is now under examined.

Fig. 1  Fig. 2

References
Faraday Rotation Densitometry for LHD

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Interferometry, which has high resolution, needs a time history, so that a “fringe jump” error reduces its reliability. The Faraday rotation would enable us to monitor the electron density of plasma, where the confining magnetic field can be calculated at least for low β operation in Large Helical Device (LHD). Since polarimetry is free from the miscount of fringes, it is suited for long-pulsed operation. Hence, complementing the interferometer by a polarimeter can make the electron density measurement system more accurate and reliable.

CO₂ laser was selected to avoid the refraction effects of plasma. The Faraday rotation angle along toroidally tangential chords in LHD is about a degree. The polarimeter utilizes the frequency-shift heterodyne technique with the use of acousto-optic modulators (AOM) for high resolution. Two counter-rotating circularly polarized beams are recombined with the same path length, so that this polarimeter is insensitive to the FM noise of laser. This system is designed for 3-channel measurement using polarization insensitive beamsplitters.

We fixed retro-reflectors inside the vacuum vessel in July, 1999 and installed two optical tables on the stage for measurement in August. We put off fixing the reflector for ch1 which is the nearest to the plasma, so that 2 channels (ch2: tangent radius 3.72 m, ch3: 3.90 m) were measured in the third LHD operation cycle in 1999.

We have succeeded preliminary measurements of the Faraday rotation angle from LHD plasmas and its waveform was similar to the time evolution of the line averaged electron density from interferometry. The accuracy of the polarization angle is 0.01 deg. with a time resolution of 16 ms by digital complex demodulation. In the case of long-pulsed operations we could also get the traces of the Faraday rotation, while the rotation angle sometimes fluctuated with amplitudes up to 0.05 degrees in several seconds. The line averaged density evaluated from the Faraday rotation was found that the data of ch2 was close to the one from the interferometer while that of ch3 was about 30% larger even if using the actual density profile calculated from the interferometer data. We’re going to present more detailed results re-evaluating the calibration of the Faraday rotation and so on.

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FP7
Abstract Submitted for the Thirteenth Topical Conference on
High-Temperature Plasma Diagnostics
June 18-22, 2000
Tucson, Arizona

MULTICHANNEL FIR POLARIMETER-INTERFEROMETER SYSTEM ON THE REVERSED FIELD PINCH MST.* D.L. BROWER, Y. JIANG, S.D. TERRY, N.E. LANIER† D. HOLLY† Electrical Engineering Department, University of California, Los Angeles. †Physics Department, University of Wisconsin-Madison. The multichannel far-infrared heterodyne polarimeter-interferometer system on MST is now operational. The combined system consists of 11 channels with variable radial and toroidal spacing. The poloidal magnetic field is determined by measuring the Faraday rotation of the FIR laser beam after propagation through the plasma by use of a phase technique. The polarimeter has 3 mrad rms noise level and 1 msec temporal resolution while the interferometer resolution is $n_{dl} = 10^{-17}$ cm$^2$ with time response of 1 μsec. Absolute calibration of the polarimeter system is described. Initial 11 channel measurements from MST will be presented. Future plans to increase the polarimeter time response from 1 msec to 10 μsec will also be detailed. This will allow direct measurement of magnetic fluctuations associated with global resistive tearing on MST. The effect of these modes on density is already clearly resolved and provide insight into the dynamics of these structures. Improving the time response will also result in lower phase noise for both the polarimeter and interferometer. *Supported by USDOE under grant DE-FG03-86ER-53225, Task III.

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FP8
Abstract Submitted for the Thirteenth Topical Conference on
High-Temperature Plasma Diagnostics
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Tucson, Arizona

MULTICHANNEL INTERFEROMETER SYSTEM FOR
THE HSX STELLARATOR.* D.L. BROWER, C. DENG, D.
ANDERSON*, W. MASON*, Electrical Engineering Department,
University of California, Los Angeles, †Electrical Engineering
Department, University of Wisconsin-Madison. A multichannel far-
infrared interferometer system has been designed, fabricated and
installed on the quasi-helical stellarator HSX. The interferometer system
will view the plasma cross section along 9 adjacent chords with 1.5 cm
spacing. With this arrangement, coverage will span from the low-field
side plasma scrape-off layer to well past the magnetic axis. For the
plasma densities anticipated on HSX, a solid-state source operating at
288 GHz will be utilized. At this frequency refraction will be
manageable, being less than the channel spacing. The source will be
bias-tuned and modulated with a sawtooth waveform at 750 kHz in order
to generate the intermediate frequency necessary for the heterodyne
detection scheme. The signals will be measured using Schottky-diode
corner-cube mixers. The interferometer will have sensitivity $n_{dl} = 10^{11}$
cm$^{-2}$. Initially, the phase will be evaluated using analog electronics with
bandwidth <10 kHz providing real-time line-integrated output. A digital
phase comparator scheme will also be implemented whereby the
measured waveforms are directly digitized and the phase evaluated using
a software-based algorithm. This will increase the time response up to
the modulation frequency of 750 kHz. Improved time response will
permit measurement of high-frequency density fluctuations along with
the equilibrium profile. †Supported by USDOE under grant DE-
FG03-86ER-53225, Task III.

Prefer Poster Session
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   (e.g., movie projector)
☐ Other Special Request

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FP9
Spatially scanned two color MIR interferometer for FTU

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The design of a scanning beam two-color Mid-Infra-Red interferometer is presented. The diagnostic is being developed for the FTU Tokamak in Frascati, which calls for a new interferometer to perform detailed study of advanced confinement regimes in D-shaped plasmas. After successfully performing a feasibility study and a prototype test, we designed a scanning interferometer providing more than 40 'virtual' chords of \( \approx 1 \) cm diameter and a full profile every 62 \( \mu \)s. Besides compactness and simplicity, the new diagnostic promises significant advantages compared to present systems in terms of immunity to fringe-jumps. Three main factors contribute to that: the high critical density associated to MIR beams, the large bandwidth provided by 40 MHz heterodyne detection and, most important, the fact that each scan provides 'self-consistent' profile.

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Interferometry

CO₂ laser imaging interferometer on LHD

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A CO₂ laser imaging interferometer is designed for electron density profile and electron density fluctuation measurements. On LHD, an FIR laser (wavelength 119μm) interferometer is routinely working and provides density profile information. However, in the case of pellet injection, the FIR laser interferometer sometimes suffers from fringe loss due to the steep density gradient in the plasma edge. In addition, the FIR laser interferometer measures the steep density gradient region with 2-3 channels, and detailed edge density profile is not clear. The CO₂ laser Mach-Zehnder type interferometer is planned on LHD for high density operation like pellet injection and precise measurements of the edge density profile. Also, measurements of micro turbulence are tried.

Three slab-like beams are used and the phase variations of the beam due to the plasma density and density fluctuations are projected on the image plane and detected by using linear detector arrays. The spatial resolution and number of the channels are planned to be 5mm and 150 respectively. This fine spatial resolution is to measure micro turbulence as well as edge density profiles. However, measurements are line integrated, therefore, in order to get localized information of micro turbulence along beam axis, cross-beam technique with additional beams or magnetic shear technique are considered.

The second color interferometer is installed simultaneously in order to account for the phase shift due to the mechanical vibration.

The particularities and basic characteristics of the diagnostics are considered. The results of the bench top experiment are reported.

FP11
Development of short-wavelength far-infrared laser for high density plasma diagnostics S.OKAJIMA, K.NAKAYAMA, H.TAZAWA, College of Engineering, Chubu University, Kasugai-shi 487-8501, Japan, K.KAWAHATA, K.TANAKA, T.TOKUZAWA, Y.ITO, National Institute for Fusion Science, Toki-shi 509-5952, Japan, K.MIZUNO, Research Institute of Electrical Communication, Tohoku University, Sendai-shi 980-8577, Japan

We have developed powerful and stable 119-μm CH3OH laser system to measure the electron density profile of LHD-plasmas in National Institute for Fusion Science. For future high density operation of LHD and for large plasma machine such as ITER, far-infrared lasers of from 40 to 70 μm in wavelength may be useful rather than the 119-μm CH3OH laser and 10-μm CO2 laser from view points of refraction and vibration effects and fringe shifts in the interferometer. For the purpose, a 57.2-μm CH3OD laser pumped by 9R(8) CO2 laser, the detectors and the optical elements are under development. The CO2 laser is of intra-cavity type and FIR laser is of twin type of about 2m in length. The FIR laser power of about 150 mW for 80 W pumping and the video sensitivity of about 3 V/W on GaAs Schottky barrier diode detector with corner cube reflector have been submitted.
A simple air-wedge shearing interferometer for studying exploding wires


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A new type of shearing interferometer using an air wedge is described. This interferometer is based on a beam splitter constructed using two 90° prisms. The first prism is oriented so that its long side is slightly rotated from the angle of total internal reflection. A small air gap, which varies in spacing from top-to-bottom, separates the second prism from the first and forms the air wedge. The single incident laser beam is focused near the gap, and the two primary reflections from the long sides of each prism form the two virtual sources necessary for interferometry. The shift between the two images of the object, as well as the orientation and frequency of the fringes, can be independently adjusted by altering the air gap thickness and angle and the position of the laser focus. The beam splitter does not perturb the laser beam significantly. The spatial resolution of this diagnostic is determined by the apertures and aberrations of the optical components in the complete system. This interferometry scheme is easily aligned, and has been successfully and reliably used to study exploding wire experiments. Using x-ray radiography to obtain independent, simultaneous measurements of vapor, plasma ion and inferred plasma electron densities, the interferometry data have been used to determine refractive indices and the polarizabilities of metal vapors created during wire explosions.

This research was supported by Department of Energy Grant No. DE-FG03-98DP00217 and Sandia Contract BD-9356.

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Time Resolved Displacement Interferometry for the Characterisation of Preheat and Free Surface Motion. A M Evans, S D Rothman, P Graham, AWE Aldermaston, Reading, UK.

We report results from two separate experiments fielded on the AWE Helen laser facility both diagnosed by interferometry. In the first experiment, measurements were made on preheat in flat targets indirectly driven by 1.8 mm and 2.2 mm (length and diameter) hohlraums heated by two 0.53 μm, 3 ns duration shaped laser pulses, each of 400 J. The rear surface of the target acts as one mirror of a Michelson interferometer, and the fringe pattern produced is temporally resolved using an optical streak camera. Motion of the fringes prior to the arrival of the shock at the rear surface enables expansion due to preheating to be measured.

In the second experiment spallation measurements were made on pure Al. Cylindrical targets (800 μm dia. x 500 μm long) were directly driven with one beam of 0.53 μm, 200 ps duration laser pulses of 3 - 15 J. A time resolved Michelson interferometer recorded the motion of the free surface. Pull back, elastic precursor and spallation signatures were observed and strain rates of $3 \times 10^6 \text{s}^{-1}$ and spall strengths of 33 kbar were measured.
X-ray Interferometry with Spherically Bent Crystals* 

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Recent progress in manufacturing high-quality spherically bent crystals allows highly monochromatic x-ray beams to be produced, and allows efficient x-ray imaging with μm-scale resolution. This paper explores some of the constraints for x-ray interferometry utilizing spherically bent crystals and laser-produced plasma sources, and discusses several shearing interferometer concepts which might be experimentally investigated.

*This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

FP15
Abstract:
Wollaston prism is often used in measuring plasma density by the means of interferometry, in this procedure the polarized probing laser beam pass the detected object and is separated by wollaston prism into ordinary and extraordinary light that travel through the polarizer and interference with each other to form a fringe pattern, from which the phase shift caused by density gradient of the plasma can be observed. In this thesis, the design of the writer is to replace the wollaston prism with a biprism, so that the polarizer can be exempted, the loss of probing light can be lessened, and image of higher resolution can be achieved.
New type of digital phase linearizer for real-time interferometric measurement.

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A new type of digital phase linearizer has been developed for real-time measurement of multi channel FIR interferometer. The phase linearizer can measure phase shifts up to 640 fringes. The size of internal memory is 16bits - 2Mwords and the sampling frequency of the waveform data is up to 1MHz. Internal clock is able to be chosen 100 or 200MHz and the frequencies of the input signals; i.e. reference and probe signals, are around 1MHz. The resolution of the phase components is 1/100 fringes, which corresponds to the line integrated density of $9.0 \times 10^{16} \text{m}^{-2}$, when the internal clock is 100 MHz and the difference of the beat frequency is 1 kHz. For real-time measurements the phase linearizer has digital-to-analog (DAC) output. The resolution of DAC output is 12bits and the amplitude is ± 5V. It has been utilized the density feedback system on the Large Helical Device (LHD).
High Resolution Edge Thomson Scattering Measurements on the Alcator C-MOD Tokamak

J.W. HUGHES, D. MOSSESSIAN, M.I.T. Plasma Science and Fusion Center, D. JOHN-SON, D. SIMON, Princetion Plasma Physics Laboratory — A high resolution Thomson scattering diagnostic is in operation on the Alcator C-MOD tokamak, measuring radial profiles of electron temperature and density at the plasma edge. Photons are scattered from an Nd-YAG laser beam pulsed at 30 Hz, and are measured by a filter polychromator. Signals from four spectral channels give reliable measurements of $T_e$ in the range of 20–800 eV. Sixteen scattering volumes are located about the last closed flux surface, closely spaced for a nominal resolution of 1.3 mm in midplane radial coordinates. High resolution is essential for measuring edge $T_e$ and $n_e$ profiles on C-MOD, since these quantities exhibit gradient scale lengths as small as 2 mm when in H-mode. The steep profiles at the H-mode edge are readily fit to a parameterized pedestal function, and we examine pedestal parameters (e.g. height and width) for correlations with global plasma parameters. Highly resolved profile measurements also allow us to analyze the evolution of $T_e$ and $n_e$ gradients prior to the formation of H-mode, in order to improve understanding of the L-H transition mechanism.

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Prefer Poster Session
Improvements in the Evaluation of Thomson Scattering Data on ASDEX Upgrade

BERND KURZAN, HEINDIETER MURMANN, HANS SALZMANN. ASDEX UPGRADE TEAM. Max-Planck-Institut für Plasmaphysik, EURATOM-IPP Association, 85748 Garching, Germany — High performance plasma discharges with large neutron rates produce a high background noise in the avalanche diodes used as light detectors in the Thomson scattering diagnostic. This often made it impossible to determine the electron temperature from the ratios of the signal amplitudes of the different spectral channels. Due to the high noise level they were often no longer in the allowed range of the temperature look-up table. A weighted least square fit of the theoretically expected signals for electron temperature $T_e$ to the measured signals of the spectral channels was implemented. With this $T_e$ can now also be determined in the presence of high background noise. The direct application of the non-linear characteristics in the determination of the electron temperature from the detector signals produces for very noisy detector signals asymmetric error distributions of the electron temperature. This makes a further statistically correct treatment of the data difficult. Therefore these characteristics are now linearized around a gliding working point to secure normally distributed errors for the evaluated temperatures.
Upgraded Calibrations of the Thomson System at DIII-D,*
B. Bray, C. Hsieh, T.N. Carlstrom, C. Makariou, General Atomics — The DIII-D Thomson system measures electron density and temperature with eight pulsed ND:YAG lasers along three paths through the plasma vessel. The components of the Thomson system are absolutely calibrated so the measurements can be combined into a single profile from a normalized radius of about 0.1 to beyond the edge of the plasma. A monochromator calibration and opto-electronic calibration measure the detectors' absolute sensitivity to background and pulsed light. A Rayleigh scattering calibration and transmission calibrations measure the transmission of light to the detectors. The calibration systems are being upgraded to reduce the effect of systematic errors on the temperature and density measurements. The systematic errors can be checked by a comparison of overlapping channels and estimated from fits to the profiles. The contributions of the background and scattered light to the systematic and statistical uncertainties of the measurement are discussed through simulations and experimental data.

*Work supported by U.S. Department of Energy under Contract DE-AC03-99ER54463.

[x] Prefer Poster Session
[ ] Prefer Oral Session
[ ] No Preference
[ ] This poster/oral should be placed in the following grouping:
   (specify order)

[ ] Special Facilities Requested
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[ ] Other Special Requests

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Measurements of the electron temperature by the Thomson scattering system on the Hanbit magnetic mirror device.* H. G. Lee, S. G. Lee, B. C. Kim, J. Hong, W. C. Kim, K. K. Choh, J. H. Choi, J. G. Yang, H. K. Na, C. J. Doh, S. M. Hwang, and M. Kwon National Fusion R & D Center, Korea Basic Science Institute. Y. H. Won Department of Physics, Ajou University. A Thomson scattering system on the Hanbit magnetic mirror device has been installed to measure the electron temperature and density of the plasma at the central cell. The configuration is based on a standard 90-degree scattering scheme and the optical system consists of a Q-switched Nd:YAG laser, input optics, collection optics, spectrograph optics, detectors, and a data acquisition system. Although the laser beam-path is about 50 m long and the background emissions are not low, the electron temperature measurements have been made at a single point by a shot-to-shot average, in which the stray light was considerably suppressed by using a beam dump, a view dump, and baffles. The obtained electron temperature is about 50-70 eV in the experiments for plasma production and heating by ICRF of 200 kW rf power using a slot antenna. The schemes of the installed system and the experimental results are presented.

* Work supported by the Ministry of Science and Technology of the Republic of Korea under the Hanbit Project Contract.
Design and Performance of Thomson Scattering Diagnostic installed on LHD
K. Narihara, J. Yamada, K. Yamauchi and H. Hayashi
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We describe the design and performance of the Thomson scattering system installed on the Large Helical Device (LHD). A toroidal vacuum chamber, winded by a pair of helical coils, locates deeply inside of a cryostat which keeps the super conducting coils at liquid helium temperature. This fact makes it difficult to equip two ports for a conventional 90 scattering configuration. We were, thus, obliged to adopt an obliquely back scattering configuration: Laser beams are injected from a window set at the center of an outer port along a major radius, and the backward scattered (-170 deg.) light quanta are collected through an window (0.6 x 0.4 m²) set on the same port and focused by a 1.5 x 1.8 m² mosaic mirror onto the tips of arrayed optical fibers of 2 mm in diameter and 45 m in length. The other end of fibers are connected to five-filter polychromators to analyze the scattered light. This back scattering system enables us to obtain Te and ne profiles of the entire plasma region along a major radius with spatial resolution of 1.5-3 cm. The scattering position, which is critically dependent on the beam pointing stability, is kept within -0.5 cm variation by using an active beam direction control system. With this system, we observed the evolution of an island shape formed by an error field with repetition rate of 50 Hz.

Prefer Poster Session

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FP22
Active Control of Laser Beam Direction for LHD YAG Thomson Scattering

I. Yamada, K. Narihara, K. Yamauchi, H. Hayashi, and LHD G1 and G2 groups, National Institute for Fusion Science, Toki 509-5292, Japan

We have developed a YAG Thomson scattering system for the measurements of electron temperature and density profiles on the Large Helical Device (LHD).

The system is composed of four YAG lasers (repetition rate of 50 Hz and pulse energy of 0.5 J), photon collection optics and two hundreds polychromators. Flexible operational modes are possible with the four YAG lasers, for example, 1) High power mode: The pulse energy can be increased up to four times by firing the four lasers simultaneously. This mode is suitable for low density plasmas, 2) High reputation mode: When firing the lasers at the intervals of 5 msec, the lasers work as a 200 Hz laser. The laser beams are transmitted to LHD by several beam steering mirrors. The first mirror is real-time feedback-controlled for precise beam transport. Thomson scattered photons are collected with a large (1.5x1.8 m²) Au-coated spherical mirror, and analyzed by using five channel polychromators.

We will report on the details of the multilaser system for the LHD YAG Thomson scattering, together with its application to the measurements of electron temperature and density profiles of LHD plasmas.
APD detector electronics for NSTX Thomson scattering system

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Princeton Scientific Instruments, Princeton, NJ, USA

A Thomson scattering system is being installed on NSTX which uses Nd:YAG lasers and avalanche photodiode detectors (APD’s). The system is being designed to accommodate up to 40 spatial channels, each with a filter polychromator selecting up to 6 spectral bands. This paper describes the design philosophy and implementation of the detection circuitry, and initial test results.

The goal is to measure low level, short duration pulses (~10 ns) in the presence of background plasma light emission using discrete EG&G 3 mm dia. APD’s. The preamplifier design is similar to that developed for the DIII-D Thomson system [1], having pulse and background outputs. Both use a low noise, transimpedance amplifier front end, and a “delay line” technique which subtracts a signal delayed by ~100 ns from the undelayed signal to form the pulse channel output. A factor of two reduction in the photoelectron equivalent noise has been achieved in the new design. Other features of this design include individual remote control of APD diode voltages, first order temperature compensation of the APD gains using the bias voltages, and auto-zero DC offset compensation. The preamplifier is housed with the APD in a box attached at each polychromator output.

The pulse and background outputs from the 6 preamplifiers in each polychromator are inputs to sample and hold, multiplexer (S/H-MUX) modules. Signals are sampled at trigger times derived either from laser pulses or from CAMAC. Trigger timing is determined by matching optical path lengths with cable lengths, and delays can be swept under CAMAC control in 2 nsec steps. The 12 sampled signals from a polychromator are multiplexed into a single output, which is clocked into a 12 bit CAMAC digitizer channel.

Photographs, block diagrams, and circuit details of these components and their interface to CAMAC will be presented, as well as modeling and performance test results.


This work was supported by the U.S. D.o.E. under contract DE-AC02-76CH03073.

FP24

We are building a new Thomson scattering diagnostic system to measure electron temperature and density on the MST Reversed-Field Pinch experiment. This system has been designed to produce accurate single-shot measurements for $10 \, \text{eV} < T_e < 2 \, \text{keV}$ at electron densities $\geq 10^{14} \, \text{m}^{-3}$. Scattered light will be simultaneously recorded from 20 radial locations across the 50 cm minor radius of the plasma. Multipulse capability will be provided by two identical Nd:YAG pulsed lasers whose trigger timing can be independently varied. This will allow several combinations of input energy and pulse timing during an MST discharge, ranging from one 4 J pulse for increased accuracy during low density operation to 1 J pulses at 100 Hz for temporal evolution measurements. Scattered light will be collected by a custom deep-focus lens and coupled by optical fiber to 20 identical filter polychromators. These polychromators are being manufactured by General Atomics and use silicon avalanche photodiode detectors. Each polychromator contains three wavelength channels to allow determination of $T_e$, plus one channel at the laser wavelength to allow calibration using Rayleigh scattering for measurement of $n_e$. System control and data acquisition will be done with dedicated personal computers.

*This work is supported by the U.S. Department of Energy.

Submitted by:

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The present Thomson scattering system at RFX is insufficient to accurately determine the changes in electron temperature and density profiles in various modes of operation and only provides a single profile of each discharge. The new system will use a Nd:YLF laser providing measurements every 20 ms. A new 20 position detection system based on filter spectrometers and avalanche detectors has been built. The higher throughput of the spectrometers and the higher quantum efficiency of the detectors give an improvement of signal to noise levels of almost two orders. The system is novel in the way data are recorded using transient recorders with multiplexing of two channels on each input. To improve dynamic range the output is AC-coupled. The effective accuracy and dynamic range of this system is compared to charge integrating systems. The full system will be described with particular emphasis on the methods of calibrations, accounting for possible differences in AC and DC methods. With a look to the future we have investigated the possible use of multi-element APDs. The characteristics of some of these detectors and their use will be discussed.

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TOPIC:
Laser Scattering
Double pulse multiposition Thomson Scattering on TEXTOR

H.J. van der Meiden, C.J. Barth, and T. Oyevaar,
FOM-Instituut voor Plasmafysica Rijnhuizen, Associatie EURATOM-FOM, Partner in the Trilateral Euregio Cluster, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, e-mail: meiden@rijnh.nl

Based on the experience with the multiposition Thomson Scattering (TS) system of RTP and with a similar but improved TS system for the TJ-II stellarator, presently a high resolution TS system has been installed on the TEXTOR tokamak. This paper will give a description of the complete TS system together with first temperature and density profiles. The outline of the TS system includes the laser, laser beam line optics, and detection branch optics.

Light from a Q-switched double pulse ruby laser (25 J, or 2×12.5 J) is injected vertically into the plasma, 90 mm outwards with respect to the geometrical centre. This corresponds with more or less the average value of the Shafranov-shift, such that the laser beam goes through the plasma centre. Stray light is suppressed by placing entrance and exit windows ~ 4 m remote from the plasma centre, together by using a set of baffles. Scattered light is collected along a chord of 900 mm with f/22 optics and imaged onto a fiber array with a bundle length of 28 m. Fibers are sorted such that 300 sampling elements of 3 mm can be used along the laser chord and 3 elements of 1.5 mm perpendicular to the scattering plane. The output head of the fiber array is imaged onto the entrance slit of a Littrow spectrometer, which is similar to the ones in use on RTP and TJ-II. The spectrally resolved light is detected by the GaAsP cathode of a generation III image intensifier. Recording of the intensified image is performed by two intensified CCD cameras, which enable double pulse detection. Data analysis is done using a VME based SUN work station.

The overall transmission of the system was found to be 15%. As a result, the relative statistical errors on the electron density ($n_e$) and temperature ($T_e$) are expected to be 3 and 5 %, respectively, for a laser energy of 10 J, a scattering volume of 7.5 mm and $n_e = 2.5 \times 10^{19}$ m$^{-3}$ in the $T_e$ range of 100 eV upto 2 keV.

First $T_e$ and $n_e$ profiles for different plasma conditions will presented.
Collective Thomson scattering using a pulsed CO$_2$ laser in JT-60U

T. Kondoh, S. Lee

Naka Fusion Research Establishment, Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken, 311-0193, Japan

A collective Thomson scattering (CTS) system using a pulsed CO$_2$ laser and a heterodyne receiver has been developed to measure ion temperature and fast-ion velocity distribution in JT-60U. The pulse laser (10J in 1μs at 10.6 μm) and the heterodyne receiver with a stray-light notch filter have been developed by Dr. D. Hutchinson and Dr. R. Richards et al. of Oak Ridge National Laboratory (ORNL). The CO$_2$ laser is focalized into the center of the JT-60U plasma and the scattered light of 0.5 deg. is collected by molybdenum mirrors. A notch filter with hot CO$_2$ gas provides absorption of about 50000 at a bandwidth of less than 500 MHz to reduce stray light from the scattered signal. Noise-equivalent-power (NEP) of a quantum-well infrared photodetector (QWIP) is below 9 x 10$^{-19}$ W/Hz up to a frequency of 6 GHz. A six-channel filter bank analyzes spectrum of the scattered light in the frequency range from 0.4 GHz to 4.5 GHz. Calculation of the scattered power spectrum from a high-performance reversed shear plasma in JT-60U shows that the contribution from electrons is small and a good S/N value is expected up to 2 GHz for the bulk-ion temperature measurement. In order to prove the possibility of fast ion diagnostic, negative-ion based neutral beam heating experiments will be studied in JT-60U. Observation of scattered spectrum by the fast ions may be expected using a bandpass filter with a wide bandwidth of 2GHz.

Measurement of velocity distributions of confined-alpha particles will be essential in diagnosing fusion plasma and studies of alpha-particle confinement will be an important physics program for ITER experiments. Demonstration of the ion tail diagnostic for JT-60U will contribute to alpha-particle and ion-temperature measurement program for ITER. Installation of the CTS system in the JT-60U tokamak has been completed and measurement in the JT-60U plasma started in this year.

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Advances in the CO$_2$ Laser Collective Thomson Scattering Fast Ion/Alpha Particle Diagnostic

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richardsrk@ornl.gov

A collective Thomson scattering diagnostic is being developed for the measurement of confined fast ions in hot, dense plasmas. This includes such measurements as the ion tail in JT-60U and the alphas produced in a burning reactor or the upgraded JET device. The diagnostic also has the capability of measuring the isotopic ratio of the core ions such as the D/T ratio (required in optimizing a burning plasma experiment.) The advances under development for this diagnostic include improvements in the high power source laser, increased bandwidth and reduced noise in the receiver, and the development of an IF electronic filter bank. Such improvements are designed to permit the temporal measurement of the fast ions and improve the accuracy in determining their velocity distribution. Modeling of the expected scattered signals produced by these improvements and the diagnostics capability to measure the velocity distribution and isotopic ratio are presented.

Implementation of Collective Thomson Scattering on the TEXTOR Tokamak for Energetic Ion Measurements

L. Porte1, H. Bindslev2, F. Hoekzema3, J. Machuzak1, P. Woskov1, D. Van Eester4

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2 FOM Institute voor Plasmaphysica, EURATOM-Association, The Netherlands
3 Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Germany
4 Laboratory for Plasma Physics, École Royale Militaire, Belgium

Partners in the Trilateral EUREGIO Cluster

Knowledge of the energy spectrum of fast ions in magnetically confined fusion plasmas is important and fundamental for achieving fusion energy production. Collective Thomson Scattering of high power electromagnetic radiation (CTS) has been shown to be one of the most promising diagnostic methods for measuring the energy spectrum of confined fast ions.

A CTS diagnostic is being implemented on the TEXTOR tokamak for the study of ICRH generated fast ions. It uses a 400kW, 200ms, 110GHz gyrotron source as probe and a high-resolution heterodyne radiometer as receiver.

The receiver antenna is a center fed parabolic reflector of focal length 50mm and diameter 100mm. The feed horn, and its location w.r.t. the antenna, have been designed to produce an asymmetric beam pattern in the center of the plasma. A length of fundamental waveguide at the neck of the feed horn selects the received polarization. The antenna can be rotated in the toroidal and poloidal directions.

The transmission line has been kept as short and straight as possible to minimize power losses and reduce cost. Incorporated into the transmission line are two narrow band (=400MHz) high attenuation (=60dB) notch filters to remove stray gyrotron light. Also in the transmission line is a RF PIN switch that prevents radiation reaching the receiver while the gyrotron switches on and off. These measures ensure reliable, safe operation of the receiver.

The radiometer incorporates a fixed frequency, free running local oscillator at 100.5GHz that pumps a balanced millimeter-wave mixer. The intermediate frequency (IF) signal passes through low noise amplifiers and then is sent to frequency filter channels that resolve the expected TEXTOR scattered spectrum. These filter channels include a series of narrow width (80MHz) and wide width (750 MHz) bandpass filters that will measure the lower energy and higher energy ions, respectively. The radiometer’s noise temperature is 0.7eV and this is much lower than the expected ECE background noise temperature of (5-13)eV.

First results from the system will be obtained in the TEXTOR operational run from April through June. It is expected operation will be established in the first portion of the campaign and contributions to the TEXTOR physics campaign will begin thereafter. The system details and initial results will be presented.

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FP30
Plasma Turbulence Imaging Using High-Power Laser Thomson Scattering - S. J. Zweben, D.W. Johnson, B. LeBlanc (PPPL), J. Caird (LLNL); We propose a new diagnostic to measure the 2-D structure of plasma density turbulence in NSTX based on a Thomson scattering system made from components of the Nova laser of LLNL. The laser would form a 10-30 cm wide sheet beam passing vertically through the plasma along a major radius of the torus, and the scattered light would be imaged by a CCD camera viewing the radial vs. poloidal plane along a direction parallel to the magnetic field. The laser energy required to make 2-D images of density turbulence is in the range 1-3 kJ, which can potentially be obtained from a set of frequency-doubled Nd:Glass amplifiers with diameters in the range of 208-315 mm. The laser pulse width of \( \leq 100 \) nsec is short enough to capture the highest frequency components of the expected density fluctuations. Possible configurations for the laser amplifier, imaging detector, and machine interface will be described, along with calculations of the expected signal/noise and backgrounds.

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Edge Plasma Turbulence Analysis by Collective Light Scattering in the Tore Supra Tokamak

P. Hennequin, C. Honore, F. Gervais, A. Quemeneur, A. Truc, R. Sabot*, C. Fenzi**, P. Ghendrih*, G. T. Hoang* & D. Thouvmin*

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Turbulence studies in magnetic confinement fusion devices are essential since plasma microturbulence is a potential source of anomalous transport. Although a weak turbulence level is required in the plasma central regions, a turbulent diffusion across the magnetic field lines is favorable at the edge, since it broadens the particle and energy loads on the plasma facing components.

In the Tore Supra tokamak, the far infrared coherent scattering diagnostic ALTAIR is dedicated to turbulence and transport studies. The measured signal is proportional to the density fluctuations located along the plasma volume crossed by the laser beam, where the scattering wavevector is perpendicular to the magnetic field lines. The safety factor profile thus determines the signal spatial localization in a poloidal plane. Taking into account safety factor and density profiles, it is possible to extract the relative density fluctuation profile along the measurement chord. When the scattering volume is set to measure the edge, density fluctuation frequency spectra exhibit typically a double hump shape, attributed to opposite Doppler shifts, due to the sign reversal of the radial electric field at the plasma edge. This property allows to discriminate between fluctuations located on both side of the radial electric shear layer. A specific spectral analysis then yields to the determination of amplitude and phase of each component of the complex signal, the latter being representative of the fluctuation poloidal velocity. Statistical analysis of phase derivative moments or temporal correlation function can provide information on turbulent transport.

We present here time correlation analyses of edge fluctuation amplitude and poloidal velocity, as well as cross-correlations performed between fluctuations located on both side of the radial electric shear layer. Data have been acquired during various plasma operating modes: LHEP modes, ITB modes, steady state ohmic plasmas with various edge configurations (limiter(s) and ergodic divertor configurations), and ohmic plasmas with density scans. For all these different modes, the density profile at the edge is different and we show how the associated density regimes influence the density fluctuation level as well as the fluctuation correlation times at the edge of the plasma.

(**)Presently at Department of Engineering Physics, University of Wisconsin, Madison WI 53706
Test of a periodic multipass-intracavity laser system for the TEXTOR multiposition Thomson scattering diagnostics

M.Yu. Kantor, C.J. Barth*, D.V. Kouprienko, H.J. van der Meiden*

*Ioffe Institute, RAS, 26 Politechnicheskaya str., 194021, Saint-Petersburg, Russia.
*FOM-Instituut voor Plasmafysica 'Rijnhuizen', P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands.

Test results of a laser probing system for the TEXTOR Thomson scattering diagnostics are presented in this paper. The main goal of the test was to study laser operation in a burst mode at high repetition rate. This regime is to be used for the study of fast transient processes and filament dynamics in the TEXTOR plasma. The tested system is based on using a multipass intracavity ruby laser system, which was found to be an efficient tool in small tokamak experiments. This work shows that this concept can be successfully used also for middle size tokamaks, which require more elongated multipass systems and intracavity resonators.

The multipass intracavity probing system has been built in a geometry suitable for the TEXTOR tokamak. A pulse repetition rate of 30 kHz has been recorded, in combination with average pulse energy up to 50 J using 14 passes. Special care was taken to minimize the laser beam divergence to less than 0.5 mrad (containing ~ 70% of the pulse energy). As a result the beam cross section parallel to the scattering plane varies between 12 and 19 mm at the plasma centre and edge (r=400 mm), respectively. The beam cross sections perpendicular to the scattering plane amount to 2 and 4 mm, at r = 0 and 400 mm, respectively. These beam cross sections are thought to be small enough for the study of transport barriers and filaments in the TEXTOR tokamak.
A POSSIBILITY OF PLASMA CURRENT DENSITY MEASUREMENTS WITH SOFT X-RAY AND THOMSON SCATTERING DIAGNOSTICS.

M.Yu.Kantor

Ioffe Institute, RAS, 26 Politechnicheskaya str., 194021, Saint Petersburg, Russia.

A new way to determine the density of plasma current driven by a longitudinal electric field is proposed and discussed in the report. The method is based on the measurements of the electron distribution function distortion caused by the electric field. The electron energy region of interest is that where the electrons are nearly Maxwellian. The distortion reveals itself as a difference between electron temperatures measured by soft X-ray and Thomson scattering diagnostics. The soft X-ray spectra distortion has been derived from the electron kinetic equation with the linear Landau collisionality and nonrelativistic Bremsstrahlung cross-section. The obtained expressions allow the determination of the longitudinal electric field from the measured soft X-ray spectra, electron temperature and density. The local plasma current density is found from this field using Ohm’s law.
### Thursday Morning, June 22
X-ray Spectroscopy and Diffraction - Robert Kauffman, Chair

**8:30 a.m. - 10:00 a.m. Presidio Ballroom 5**

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Affiliation</th>
<th>Country</th>
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<tbody>
<tr>
<td>GI1</td>
<td>Smith</td>
<td>Harvard SAO</td>
<td>USA</td>
<td>X-Ray Observations And Analysis With The Chandra X-Ray Observatory</td>
</tr>
<tr>
<td>GI2</td>
<td>Nash</td>
<td>Sandia</td>
<td>USA</td>
<td>Diagnostics On Z</td>
</tr>
<tr>
<td>GI3</td>
<td>Bourgade</td>
<td>CEA Bruyeres</td>
<td>France</td>
<td>Soft X-Ray Spectrometer Designed For MJ Class Laser Produced Plasmas</td>
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**10:15 a.m. - 12:00 p.m. Presidio Ballroom 1-4**

<table>
<thead>
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<tr>
<td>GP1</td>
<td>Duorah</td>
<td>U Tokyo</td>
<td>Japan</td>
<td>Multi Layer Mirror Based Soft X-Ray Spectrometer As A High Temperature Plasma Diagnostic</td>
</tr>
<tr>
<td>GP2</td>
<td>Lanier</td>
<td>U Wisconsin</td>
<td>USA</td>
<td>A Low Cost, Robust, Filtered Spectrometer For Absolute Intensity Measurements In The Soft X-Ray Region</td>
</tr>
<tr>
<td>GP3</td>
<td>Bogatu</td>
<td>Fastech, Inc.</td>
<td>USA</td>
<td>X-Ray Ross Filter Method For Impurity Transport Studies On DIII-D</td>
</tr>
<tr>
<td>GP4</td>
<td>Minami</td>
<td>U Tsukuba</td>
<td>Japan</td>
<td>Simultaneous Observations Of Temporally And Spatially Resolved Electron Temperatures Of Both Circular Central-Cell And Elliptical Anchor-Region Plasmas In GAMMA 10</td>
</tr>
<tr>
<td>GP5</td>
<td>Shmaenok</td>
<td>Phystex</td>
<td>Netherlands</td>
<td>A Novel Instrumentation For Spectrally Resolved Soft X-Ray Plasma Tomography: Development And Pilot Results At TEXTOR</td>
</tr>
<tr>
<td>GP6</td>
<td>Stoeckl</td>
<td>LLE</td>
<td>USA</td>
<td>Hard X-Ray Detectors For OMEGA And NIF</td>
</tr>
<tr>
<td>GP7</td>
<td>Seeley</td>
<td>NRL</td>
<td>USA</td>
<td>Hard X-Ray Spectrometers For NIF</td>
</tr>
<tr>
<td>GP8</td>
<td>Bentley</td>
<td>AWE</td>
<td>UK</td>
<td>Spectral Response Calibrations Of X-Ray Diode Photocathodes In The 50-eV To 5.9-keV Photon Energy Region</td>
</tr>
<tr>
<td>GP9</td>
<td>Eagleton</td>
<td>AWE</td>
<td>UK</td>
<td>Soft X-Ray Characterisation Of A Silicon P-N Photodiode Using A Laser Produced Plasma Source</td>
</tr>
<tr>
<td>GP10</td>
<td>Palmeirinha</td>
<td>Euratom/IST</td>
<td>Portugal</td>
<td>High Count Rate Pulse Height Analysis Spectroscopy On The TCV Tokamak</td>
</tr>
<tr>
<td>GP11</td>
<td>Muto</td>
<td>NIFS</td>
<td>Japan</td>
<td>Construction And Performance Of X Ray Pulse Height Analyzer Assembly With Radial Scanning System For LHD Diagnostic Arrangement On S-300 Generator</td>
</tr>
<tr>
<td>GP12</td>
<td>Blinov</td>
<td>Kurchatov</td>
<td>Russia</td>
<td>Hohlraum Temperature Inference Via Measurement Of Aluminum Shock Velocity And Time- And Spatially- Resolved X-Ray Emission</td>
</tr>
<tr>
<td>GP13</td>
<td>Olson</td>
<td>Sandia</td>
<td>USA</td>
<td>Characterization Of Axially-Directed X-Rays Generated From A Target Within A High-Power Z-Pinch</td>
</tr>
<tr>
<td>GP14</td>
<td>Sanford</td>
<td>Sandia</td>
<td>USA</td>
<td>Wire Array Z Pinch Source Power, Energy And Spectrum Characterization With A Transmission Grating Spectrometer Measurement Of The Efficiency Of Gold Transmission Gratings In The 100 To 5000 eV Photon Energy Range</td>
</tr>
<tr>
<td>GP15</td>
<td>Cuneo</td>
<td>Sandia</td>
<td>USA</td>
<td>An Imaging Diode Array Soft X-Ray Diagnostic For Z Plasma Diagnostic For X-Ray Driven Foils At Z Analysis Of Radiatively-Heated Thin Foils In Z-Pinch Hohlraum Experiments</td>
</tr>
<tr>
<td>GP17</td>
<td>Simpson</td>
<td>Sandia</td>
<td>USA</td>
<td>Direct Spectroscopic Observation Of Multicharged MeV Ions In Plasma, Heated By Intense Femtosecond Laser Radiation</td>
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<td>GP23</td>
<td>Paenov</td>
<td>VNIIFRI</td>
<td>Russia</td>
<td>X-Ray Spectromicroscopy Investigations Of Fast Ions And Hot Electrons In Plasmas, Heated By Nanosecond Laser Radiation With Different Wavelengths</td>
</tr>
<tr>
<td>GP24</td>
<td>Yasuike</td>
<td>LLNL</td>
<td>USA</td>
<td>Hot Electron Diagnostic In A Solid Laser Target By K-Shell Lines Measurement From Ultra-Intense Laser-Plasma Interactions (3x10^18 W/Cm², &gt;400 J)</td>
</tr>
<tr>
<td>GP25</td>
<td>Shlyaptseva</td>
<td>U Nevada Reno</td>
<td>USA</td>
<td>X-Ray L-Shell Spectropolimetry Of High-Temperature Plasmas</td>
</tr>
<tr>
<td>GP26</td>
<td>Hake1</td>
<td>U Nevada Reno</td>
<td>USA</td>
<td>X-Ray Line Polarization Spectroscopy Of He-Like Si Satellite Line Spectra</td>
</tr>
<tr>
<td>GP27</td>
<td>Baranova</td>
<td>Kurchatov</td>
<td>Russia</td>
<td>High Resolution X-Ray Spectrograph For 1.5-400 KeV With Combined Cauchois-Johansson Crystal</td>
</tr>
<tr>
<td>GP28</td>
<td>Lee</td>
<td>KBSI</td>
<td>Korea</td>
<td>X-Ray Imaging Characteristics From A Large Spherically-Bent Mica Crystal</td>
</tr>
<tr>
<td>GP29</td>
<td>Brown</td>
<td>LLNL</td>
<td>USA</td>
<td>Thin-Window High-Efficiency Position Sensitive Proportional Counter For The Vacuum Flat Crystal Spectrometers On The LLNL Electron Beam Ion Trap</td>
</tr>
<tr>
<td>GP30</td>
<td>Peacock</td>
<td>Oxford</td>
<td>UK</td>
<td>Ionisation Balance In EBIT And Tokamak Plasmas</td>
</tr>
<tr>
<td>GP31</td>
<td>Golovkin</td>
<td>U Nevada Reno</td>
<td>USA</td>
<td>A Spectroscopy Diagnostic Of Plasma Gradients In ICF Imploded Cores</td>
</tr>
<tr>
<td>GP32</td>
<td>Hei</td>
<td>Tsinghua U</td>
<td>China</td>
<td>Time And Space Resolved Soft X-Ray Spectroscopy Diagnosis Of Dense Plasma Focus</td>
</tr>
<tr>
<td>GP33</td>
<td>Boehly</td>
<td>LLE</td>
<td>USA</td>
<td>Measurements Of Shock Heating Using Al Absorption Spectroscopy In Planar Targets</td>
</tr>
<tr>
<td>GP34</td>
<td>Kalantar</td>
<td>LLNL</td>
<td>USA</td>
<td>Dynamic X-Ray Diffraction To Study Compression Of Si And Cu Beyond The Hugoniot Elastic Limit</td>
</tr>
<tr>
<td>GP35</td>
<td>Krasilnikov</td>
<td>TRINITI</td>
<td>Russia</td>
<td>Time Of Flight Electron Spectrometry On TIR-1 Using Natural Diamond Detector</td>
</tr>
<tr>
<td>GP36</td>
<td>Weaver</td>
<td>NRL</td>
<td>USA</td>
<td>Time Resolved, Absolutely Calibrated Observations of Soft X-rays with the Transmission Grating Spectrometer at the Nike Laser Facility</td>
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X-ray Observations and Analysis with the Chandra X-ray Observatory

Randall Smith
Chandra X-ray Observatory Center

The Chandra X-ray telescope has 4 separate detectors, 2 CCD and 2 microchannel plates, behind a set of 4 highly polished, nested mirrors. The on-orbit performance of the imaging system is $< 1$ arcsec, a dramatic improvement from the 5-8 arcsec previously available. In addition, two transmission gratings can be placed in the system, which for point sources can reach resolutions of 300-1000+ over the range $\lambda=1.5-160\mbox{Å}$. The entire system was calibrated pre-launch at NASA/MSFC in Huntsville, AL. The results have been dramatic: the first light image of the supernova remnant Cas A showed a never-before-seen point source near the center of the remnant that may be the neutron star left over after the explosion. Even the calibration image of a distant quasar (taken for focusing purposes) showed an X-ray emitting jet extending out from the nucleus for more than 20 kpc, which challenges current theories about jet propagation.

The grating observations done by Chandra take X-ray astrophysics out of the photometry era into the spectroscopic age. Astrophysical plasmas reach conditions far out of the reach of any terrestrial laboratory, and astronomers are just beginning to understand the diagnostics of these plasmas; Chandra observations may even someday provide the best measurements of certain atomic rates. However, before that point is reached the astronomical community must gain a much better understanding of the existing and ongoing work in X-ray diagnostics from other fields. The general state of X-ray diagnostics for astronomical plasmas will also be discussed.
Diagnoses on Z


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ABSTRACT

The 100 ns, 20 MA pinch-driver Z is surrounded by an extensive set of diagnostics. There are nine radial lines-of-sight set at 12 degrees above horizontal and each of these may be equipped with up to five diagnostic ports. Instruments routinely fielded viewing the pinch from the side with these ports include x-ray diode arrays, photoconducting detector arrays, bolometers, transmission grating spectrometers, time-resolved x-ray pinhole cameras, x-ray crystal spectrometers, calorimeters, silicon photodiodes, and neutron detectors. A diagnostic package fielded on axis for viewing internal pinch radiation consists of nine lines-of-sight. This package accommodates virtually the same diagnostics as the radial ports. Other diagnostics not fielded on the axial or radial ports include current B-dot monitors, filtered x-ray scintillators coupled by fiber optics to streak cameras, streaked visible spectroscopy, VISAR, Bremmstrahlung cameras, and active shock breakout measurement of hohlraum temperature. The Data Acquisition System (DAS) is capable of recording up to 500 channels and the data from each shot is available on the Internet. A major new diagnostic presently under construction is the BEAMLET backlighter. We will briefly describe each of these diagnostics and present some of the highest quality data from them.

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000
DMX: an absolutely calibrated time resolved broad band soft X-ray spectrometer designed for MJ class laser produced plasmas

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abstract: In high flux ($10^{13-15}$ W/cm²) laser plasmas interaction a large part of the incoming laser energy is radiated into soft X-rays. To determine both the shape of this spectrum and the conversion efficiency we have designed and tested an absolutely calibrated broad band soft X-ray spectrometer with a high temporal resolution (100 ps). The detector in this spectrometer is a new coaxial X-ray diode coupled with a fast single shot oscilloscope (French IN7100 with 7GHz frequency response cutoff). Both absolute calibrations (X-ray response of diodes) and relative calibrations (filters and mirrors) have used the French synchrotron beam lines at LURE in Orsay. The initial version of this instrument has been first successfully implemented on laser plasmas experiments at Phébus facility in France and an improved version is now operating at Omega laser facility at Rochester in USA. The emitted X-ray spectrum is absolutely measured in 18 broad bands from 50 eV up to 20 keV. The softer bands (< 1.5 keV) combine mirror and filter responses coupled with the coaxial diode response to improve hard X-ray rejection. Intermediate energy channels (1.5 keV < hv < 5 keV) used only a filter and coaxial diode. For the hardest channels (> 5 keV) we replace the X-ray diode (not enough sensitive) by a photoconductive detector (n damaged GaAs). A detailed description of this new instrument operating on the Omega facility, the main characteristics of the new coaxial X-ray diode, and the calibration process will be presented. Results on Omega laser shots and a comparison with simultaneous DANTE spectrometer measurements will be shown.

An equivalent instrument will be designed in the future for Mega Joule laser facility class: NIF in USA and LMJ in France.
Multi Layer Mirror based Soft X-ray spectrometer as a high temperature plasma diagnostic


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Abstract

A fully calibrated multi layer mirror (MLM) based soft X-ray spectrometer has been developed and installed on the Compact Helical System (CHS). This MLM based spectrometer is a new approach to devise a soft X-ray spectrometer with medium time and energy resolutions. The advantages lie in the use of this spectrometer for studying fast time events as well as for spectroscopic measurements.

The spectrometer mainly consists of a MLM as the dispersive element and a 20 channel PIN diode array for the detection of the soft X-rays. Both the MLM and the PIN diodes have been calibrated at the KEK (High Energy Accelerator Research Organization) Photon Factory for an energy range of 300 eV - 1200 eV. The reflectivity of the mirror was found to increase from 3% [photon energy of 335 eV] to 25% [photon energy of 1050 eV]. The PIN diodes were found to have almost 100% efficiency for creating electron-hole pairs in the calibrated energy range. The spectrometer also includes a pinhole of dimensions 2mm x 5mm and a beryllium foil of thickness 8 μm. The energy range of measurement of the spectrometer is from 600 eV ~ 1500 eV.

The spectrometer was installed on the CHS with the aim of fast electron temperature measurement and study of fast MHD events occurring in plasmas. The experiments show that in the energy range of measurement, the electron ‘temperature’ determined from the slope of the soft X-ray spectrum is much lower than that measured by the Thomson scattering diagnostic. Analysis showed that the soft X-ray spectrum is highly contaminated by impurity emission. Therefore it should be possible to measure electron temperature with this diagnostic if we choose another energy range where we can measure the continuous spectrum.

The present time resolution of the system is of the order ~ 0.1 ms which has made it possible to study the behavior of the plasma during fast MHD events. Modulations in the soft X-ray intensity were observed during MHD events in CHS plasmas. Analysis of these shows that these may be due to modulations in the temperature or the impurity concentration.
A Low Cost, Robust, Filtered Spectrometer for Absolute Intensity Measurements in the Soft X-Ray Region

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Abstract:

We have developed a low-cost, robust, multi-foil filtered spectrometer to provide absolute measurements of impurity concentrations in the Madison Symmetric Torus reversed-field pinch. The spectrometer utilizes an array of six thin-film coated soft-x-ray diodes. Each multi-layered coating is specifically tailored to isolate the K-shell emission lines of H-like and He-like oxygen, carbon, and aluminum. With calibrations obtained via a synchrotron source, absolute measurements of photon flux are possible. We address the technical aspects of this diagnostic and present impurity data from both standard and high-confinement plasma discharges.

*This work supported by U.S. DOE.
X-RAY ROSS FILTER METHOD FOR IMPURITY TRANSPORT STUDIES ON DIII-D

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The injection of Ar into the region of DIII-D divertor is a promising technique for energy dissipation (through radiation and collisions) and consequently for reduction of the heat load on the plates. An important problem related to this technique, is the inherent poisoning of the core plasma by migrating Ar. The Ar core contamination seems also to improve the thermal transport in an advanced operating mode of the tokamak. It is therefore of great importance to measure the evolution of the impurity concentration profile within the core plasma. This goal could be achieved by using the Ross filter method in conjunction with the existing X-ray diagnostics on DIII-D. A basic Ross filter system consists of two identical detectors placed behind two different X-ray absorbing foils looking at the same plasma volume. The foils are made of different elements or compounds with adjacent or nearly adjacent atomic numbers. Their accurate thickness makes the X-ray transmission curves of the two foils to be effectively identical over the entire energy range except within the narrow region between their absorption edges. Since the transmission characteristics of the foils above and below their absorption edges are the same, any difference in the two detected signals is proportional to the total X-ray power of the emission spectrum between these two edge energies. An X-ray Ross filter with its energy pass band centered on the Ar XVII K$_\alpha$ line at 3.14 keV has been designed. This allows for the discrimination of the Ar K$_\alpha$ line only, regardless of Ar ionization state, against any background radiation with energies outside the energy pass band. The Ross filter was installed in front of two of the fan shaped poloidal X-ray arrays on DIII-D. The first measurements showed very good discrimination against Ne, another injected impurity.

Emissivity profile evolution of the K$_\alpha$ lines and Ar enhanced continuum within the energy pass band of the Ross filter can be determined from the X-ray brightness signals by inverting techniques and by using the T$_e$, n$_e$, and Ar$^{16+}$ profiles as measured by other diagnostics. The transport code MIST(1) can be used to calculate both the emissivity profiles of the K$_\alpha$ of all the ions and their concentration profiles when the measured T$_e$, and n$_e$ are used as input. The Ar$^{16+}$ profiles as measured by Charge Exchange Spectroscopy can be used as a constraint for the MIST code to accurately calculate Ar$^{16+}$ profile and thus unfold all the Ar ions K$_\alpha$ emissivity profiles. From these one can determine the Ar concentration profile evolution and the particle diffusion coefficient.

In conclusion, using the Ross filter method with the existing X-ray imaging systems results in a powerful and cost-effective diagnostic for impurity transport studies.

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Simultaneous observations of temporally and spatially resolved electron temperatures of both circular central-cell and elliptical anchor-region plasmas in GAMMA 10

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The first results of simultaneous observations of temporally and spatially resolved electron temperatures \( (T_e) \) of both circularly shaped central-cell and elliptically shaped anchor-region plasmas are reported in the GAMMA 10 tandem mirror. The data set is provided using novel matrix-type x-ray semiconductor detectors. The detector has seven “matrix columns” for the measurements of plasma x-ray profiles along with six “matrix rows” for the simultaneous analyses of six different x-ray-energy ranges by the fabrication of six different thicknesses of \( \text{SiO}_2 \) semiconductor surface layers from 1 nm to 500 nm as ultra-thin and unbreakable “x-ray absorption filters”. Such a matrix idea enables us to analyze x-ray tomography data in the \( T_e \) region down to a few tens eV. A simultaneous application of the x-ray detectors in the central cell and the anchor region gives information on individual electron behavior and the relation between these two regions. A role of magneto-hydrodynamic plasma stability in the anchor region is confirmed by the data from these detailed electron observations.
A novel instrumentation for wavelength and time resolved plasma emission tomography in the range 0.1 - 4 keV has been demonstrated in experiments at TEXTOR. The system (indicated in the list of FOM diagnostics at TEXTOR as USXT - ultra-soft x-ray tomography) is intended for reconstruction of local emission coefficients for particular spectral lines of impurity ions. With additional data on electron density and temperature, the USXT diagnostics will enable to reconstruct spatial distributions of impurity ions at corresponding ionization states.

The experimental approach is based on the use of miniature wavelength-resolving pinhole cameras, which create plasma cross-section images in selected spectral lines of impurity ions. The advanced feature of spectral selectivity is achieved by adding a flat multilayer mirror (MLM) to the pinhole-imaging scheme. The MLM coating can be made graded to collect radiation from a perfectly plane cross-section in a large viewing angle. The imaging resolution in this plane is equivalent to measuring radiation integrals along up to 100 chords. The x-ray image is converted to a visible one in a phosphor layer on the entrance surface of a 1 m fiber image conduit, which couples the pinhole/MLM camera with an Electron Bombarded CCD camera. The tomography system is built of identical sets of the above mentioned elements (imaging modules). The images are generally recorded at a 50 Hz repetition rate during the whole plasma discharge, synchronically at several locations around the plasma. Intensity distributions along the imaged spectral lines serve as initial data for the computerised tomography analysis.

The multilayer mirrors and pinholes are changeable in vacuum for selection of spectral intervals and resolution parameters to optimise the USXT diagnostics for various experimental tasks and conditions. Due to compactness of the pinhole/MLM cameras and remote location of the EBCCD cameras, the installation of the system with at least 5 imaging modules at TEXTOR is feasible.

The whole diagnostics system is controlled by a PC, used also for initial procession of imaging data.

Currently first three modules have been installed and are operational at a TEXTOR poloidal cross-section.

Pilot results on tomography reconstruction of local emission coefficient distributions will be presented, associated with ions of intrinsic and seeded impurities (oxygen, carbon, neon, argon) at different plasma regimes, including RI mode discharges.

The work is conducted under the Euratom-FOM association agreement with financial support of Euratom and NWO.


GP5
Hard X-ray Detectors for OMEGA and NIF

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Abstract

Laser—plasma instabilities that produce an unacceptably high level of hot electrons are potentially dangerous for both direct-drive and indirect-drive inertial confinement laser fusion. The hot electrons preheat the fuel and prevent compression of the capsule to the requisite conditions for ignition.

Fast-electron generation can be inferred from the hard x-ray radiation generated by the interaction of the hot electrons with the target and surrounding material. On OMEGA, time-resolved hard x-ray detectors have been operating in an energy range from 10 keV to 500 keV. The first results for the yield and spectrum of the hard x-ray radiation will be presented. The concept used on OMEGA can be easily extended to NIF conditions to infer the amount of laser energy coupled to suprathermal electrons and to the target for both direct- and indirect-drive implosions.

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A NIF core diagnostic instrument has been designed and will be fabricated to record x-ray spectra in the 1.2-20 keV energy range. The High-Energy Electronic X-Ray (HENEX) instrument has four reflection crystals with overlapping coverage of 1.2-10.9 keV and one transmission crystal covering 8.6-20 keV. The spectral resolving power varies from approximately 1000 at low energies to 315 at 20 keV. The spectrum produced by each crystal is recorded by a modified commercial dental x-ray CCD detector. The scintillators on the CCD detectors are optimized for the energy ranges. A one-channel x-ray spectrometer, using one transmission crystal covering 12-60 keV, will be fabricated for the OMEGA laser facility. The transmission crystal spectrometers are based on instruments originally designed at NIST for the purpose of characterizing the x-ray flux from medical radiography sources. Utilizing one of those instruments and a commercial dental x-ray CCD detector, x-ray images were recorded using a single pulse from a laboratory x-ray source with a peak charging voltage of 200 kV. A resolving power of 300 was demonstrated by recording on film the Kα1 and Kα2 characteristic x-ray lines near 17 keV from a molybdenum anode. The continuum radiation from a tungsten anode was recorded in the 20-50 keV energy range. The transmission crystal spectrometer has sufficient spectral resolution and sensitivity to record the line and continuum radiation from high-Z targets irradiated by the NIF laser and the OMEGA laser.
Spectral Response Calibrations Of X-Ray Diode Photocathodes In The 50ev To 5.9kev Photon Energy Region  C D Bentley & A C Simmons  
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X-ray Diode photocathodes are commonly employed in diagnostic instruments on the Helen laser at AWE Aldermaston, U.K. The photocathodes are mainly used in the Dante fast diode array and Flat Response Diodes (FRDs). These diagnostics enable the soft x-ray spectral emissions of laser irradiated targets to be determined. To derive quantitative spectral information, the quantum efficiency of the photocathodes must be known over the range of x-ray energies of interest. The photocathodes were manufactured in 1982, and were initially calibrated at that time. Since then further measurements have been performed in 1988 and 1999. The photocathodes have been exposed to a wide range of conditions during their lives, ranging from use in experiments to storage in a dry nitrogen environment.

Reported here are the results of calibrations performed in 1999 at the soft x-ray calibration facility EXCALIBUR at AWE Aldermaston and the National Synchrotron Light Source (NSLS) at Brookhaven. An assessment of their current condition and an evaluation of the change in their response over time, and the possible reasons for these changes, is made.
Soft x-ray characterisation of a silicon p-n photodiode using a laser produced plasma source  R T EAGLETON, AWE Aldermaston, Reading, UK., L E RUGGLES, Sandia National Laboratory, Albuquerque, NM. Silicon p-n diodes have proved to be excellent soft x-ray detectors due to their high sensitivity, nominally flat response and long term stability. Advances in fabrication techniques have overcome many of the limitations of older silicon diodes by minimising the thickness of the surface dead layer which would otherwise absorb low energy x-ray photons. Silicon photodiodes with extremely thin (80Å) surface dead layers are now available 1. One of these diodes has been characterised for spectral sensitivity at x-ray photon energies of 163 eV and 1.4 keV using a laser produced plasma soft x-ray source. Measurements have also been made to characterise the impulse response using fourth harmonic laser light from a short pulse (80 ps FWHM) NdYAG laser.

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HIGH COUNT RATE PULSE HEIGHT ANALYSIS
SPECTROSCOPY ON THE TCV TOKAMAK

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Abstract - A count rate optimized X-ray Pulse Height Analysis diagnostic, with time resolving capabilities is described and data presented and analyzed. This device is installed in the TCV tokamak. The diagnostic is based on a liquid nitrogen cooled 50 mm², 5 mm thick Ge detector, and presents a energy resolution of about 300 eV (at 5.9 keV, Mn Kα line) when operating in its maximum throughput of 70 kcounts/s (signal processing module limitation). The data, pile-up and timing signals were encoded into a single data stream acquired by a single digitizer channel. This data is analyzed after the plasma discharge to obtain PHA analyzed spectra which, for a Maxwellian velocity distribution, are interpreted as a plasma electron temperature. A numerical pile-up model will be presented for studies on the influence/correction of this effect in the data obtained. Experimental results will be shown from plasmas with only ohmic heating and in the presence of high power EC. With EC heating, the Maxwellian approximation remains valid, but with EC current drive, the presence of superthermal electrons was detected. These observations together with aluminum ablation and foreign body events (UFOs) are compared to other diagnostics installed on TCV, including the filtered diode array and Thomson diffusion diagnostic.
Construction and Performance of X ray Pulse Height Analyzer assembly with radial scanning system for LHD

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A radial profile of x ray energy spectrum has been successfully observed in Large Helical Device (LHD). The profile has been measured by a pulse height analyzer assembly which has been constructed and installed on the lower port of LHD. The assembly is equipped with a large rectangular swing valve, a ceramic break with bellows, a large rectangular duct with an evacuating system, an x-ray filter exchanging system controlled by a computer, an automatic liquid nitrogen transfer system, three Si(Li) semiconductor x-ray detectors to be arranged along the major radial direction of LHD with a spacing of 300 mm. The most important part of the assembly is the radial scanning system which makes it possible to measure radial profile of x-ray spectrum. The design philosophy of the assembly and some results on the performance tests are also presented.

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Diagnostic arrangement on S-300 generator.


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In recent time some experiments on X-ray and neutron generation were carried out at S-300 facility (400 kV, 3.5 MA, 100 ns). S-300 diagnostic arrangement is presented here. Plasma radiation parameters in VUV and soft X-ray range of 20-500 eV were obtained by polychromator with time resolution being better than 1.5 ns and energy resolution of 5-20%. Smoothing filters equipped vacuum diodes and semiconductor diodes with various filters were used for radiation power measurements in the range from 0.1 to 10 keV. Power level of such measurements approaches 1.5 TW. Bend crystal spectroscopic X-ray techniques with two-dimensional spatial resolution were used to evaluate plasma density, ion and electron temperatures. Plasma dynamics was studied by frame photography with electron image converters in optical and X-ray spectrum ranges and streak-camera photography in axial and radial directions. An information about periphery plasma dynamics was obtained by shadow and schlieren photography. Activation and time of flight methods determined total neutron yield and energy of generated neutrons. This work was supported by Russian Foundation for Basic Research under Grants No. 98-02-17616, No. 99-02-16658.
Hohlraum temperature inference via measurement of aluminum shock velocity and time- and spatially- resolved x-ray re-emission


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The radiation field in a cylindrical, x-ray driven hohlraum with gold walls and dimensions of 4 mm diameter x 4 mm length has been simultaneously measured by two independent techniques. An active shock breakout technique utilizing a step witness plate to measure radiation-driven shock velocity in aluminum indicates a peak radiation field with incident flux equivalent to a Planckian distribution with a temperature of 146 ± 3 eV. In the same experiment, a time- and spatially- resolved measurement of x-ray re-emission from the gold hohlraum wall indicates a peak radiation field with flux equivalent to a Planckian brightness temperature of 145 ± 5 eV. The inference of radiation temperature via a passive measurement of aluminum shock velocity is a standard technique used in laser-driven hohlraums with temperatures above ~130 eV. The present experiment, however, utilized a hohlraum driven by x-rays from a z-pinch with an active, laser probe shock measurement technique that is usually only successful for hohlraum temperatures below ~120 eV. The time- and spatially- resolved x-ray re-emission temperature measurement technique has been developed over the past few years in z-pinch hohlraum experiments. In the present work, the two temperature measurements were done simultaneously in a single x-ray driven hohlraum experiment at the Z facility at Sandia National Laboratories. It is anticipated that these diagnostic techniques will eventually be used in the National Ignition Facility.


*Sandia is a multi-program laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.
Characterization of Axially-Directed X-Rays Generated from a Target within a High-Power Z-Pinch


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X-ray powers on the order of 10 TW over an area of 4.5 mm² are produced in the axial direction from the compression of a low-density foam target centered within a z-pinch on the Z generator [1]. The x-rays from this source are used for high-energy-density physics experiments, including the heating of hohlraums for ICF studies [2]. In this paper, detailed characteristics of this radiation source measured using an upgraded axial-radiation-diagnostic suite [3] together with other on- and off-axis diagnostics are summarized and discussed in terms of Eulerian and Lagrangian radiation-magnetohydrodynamic code simulations. The source, characterized here, employs a nested array of 10-mm-long tungsten wires, at radii of 20 and 10 mm, having a total masses of 2 and 1 mg, and wire numbers of 240 and 120, respectively. The target is a 14 mg/cc CH₂ foam cylinder of 5-mm diameter.

The codes take into account the development of the Rayleigh-Taylor instability in that r-z plane, and provide integrated calculations of the implosion together with the x-ray generation.

The radiation exiting the imploding target through the 4.5 mm² aperture is measured primarily by the axial diagnostic suite that now includes diagnostics at an angle of ~30 degrees to the z axis. The near on-axis diagnostics include: (1) a 7-element filtered silicon-diode array [4], (2) a 5-element filtered XRD array [5], (3) a 6-element filtered PCD array [6], (4) a 3-element bolometer [7], (5) time-resolved and time-integrating crystal spectrometers, and (6) two fast-framing x-ray pin-hole cameras having 11 frames each. The filtered silicon-diodes, XRDs, and PCDs are sensitive to 1-200, 140-2300, and 1000-4000 eV x-rays, respectively. They (1) establish the magnitude of the prepulse generated during the run-in of the imploding wire arrays, (2) measure the Planckian nature of the dominant thermal, and (3) non-thermal component of the emission. The bolometers and XRDs mounted on the near-normal and 30-degree LOS (line-of-sight) measure the total power and check the Lambertian nature of the emission. Additionally, a suite of filtered fast-framing x-ray pinhole cameras and silicon-diode arrays behind a transmission grating, mounted on LOSs nearly normal to the z axis, quantify the plasma plume exiting the aperture. The hard bremsstrahlung generated is estimated with both on- and off-axis shielded scintillator photomultiplier diagnostics.


*Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-94AL85000.
Wire array z pinches on the Z accelerator at Sandia [1] are the most intense laboratory source of soft x-rays in the world. Tungsten wire array z pinches on Z have generated powers and energies of more than 150 TW and 1.5 MJ with a 100 ns, 20 MA current drive. Rapid progress has been made on a variety of applications involving radiation interaction with matter, including Inertial Confinement Fusion [2]. A transmission grating spectrometer (TGS) has been developed to observe the stagnated z pinch with higher spectral resolution and coverage than previously possible. This instrument is similar to those designed to make hohlraum wall re-emission temperature measurements [3]. The x-ray emission from the pinch is measured in 16 energy bins distributed from 250 eV to 2450 eV, with a ΔE/E varying from -2% at 250 eV to -14% at 2450 eV. The instrument has a ns response time. The grating efficiency and PIN diode detector sensitivity were pre-characterized in an x-ray calibration facility [3]. Higher order corrections to the grating signals are removed by an iterative technique. The spectral data is analyzed via a non-linear, two-parameter Planckian fit to the pinch spectral power as a function of time. The two fitting parameters are blackbody temperature and emission area.

This instrument has been used to observe z pinches from tungsten, stainless, molybdenum, and titanium/nickel wire array loads in various configurations fielded on the Z accelerator. Average pinch surface temperatures of 150 to 200 eV and effective FWHM at peak temperature of about 1 to 3 mm have been observed. The FWHM calculated from the fitted emission area is approximately what is measured with a time-resolved pinhole camera near peak compression. Pinch power is calculated by directly integrating the power distributions and assuming a Lambertian pinch emitter to scale the detector power to total pinch power. The z pinch x-ray energy and power measured by the TGS are within experimental uncertainty of those measured by ns-response bolometers [4], and filtered x-ray diode arrays [5]. Although the spectra are largely Planckian at and after peak, particularly for tungsten, there are non-Planckian features that may be useful in determining some features about pinch structure and opacity with more sophisticated analysis.


*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-4AL85000.

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Measurement of the efficiency of gold transmission gratings in the 100 to 5000 eV photon energy range.
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Three x-ray spectrometers, each with a transmission grating dispersion element, are routinely used at the Z soft x-ray facility to measure the spectrum and temporal history of the absolute soft x-ray power emitted from z-pinch and hohlraum radiation sources. Our goal is to make these measurements within an accuracy of ±5%. We periodically characterize the efficiency of the gratings used in the spectrometers by using an electron-impact soft x-ray source, a monochromator, grazing-incidence mirrors, thin filters, and an x-ray CCD detector. We measure the transmission efficiency of the gratings at many photon energies for several grating orders. For each grating, we calculate efficiency as a function of photon energy using published optical constants of gold and multiple-slit Fraunhofer diffraction theory and fit the calculation to the measurements using the physical parameters of the grating as variables. This article describes the measurement apparatus and calibration techniques, discusses the grating efficiency calculation and fitting procedure, and presents recent results.

*Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000. *leruggl@sandia.gov
An Imaging Diode Array Soft X-ray Diagnostic for Z

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Measurements of the hohlraum wall temperature in Z-pinch driven hohlraum experiments require looking through small (2-4 mm dia.) diagnostic holes that undergo some degree of hole closure. The existing soft x-ray diagnostics on Z measure the total flux exiting this diagnostic hole and are therefore affected by this hole closure. To avoid having to measure the effective diagnostic hole area we have designed and constructed an Imaging Diode Array (IDA) that incorporates pinhole imaging and an array of filtered silicon diodes to measure the absolute x-ray intensity from a spatially resolved region of a target. The instrument uses silicon diodes with sub-nanosecond time response that are sensitive to soft x-rays in the range 100-3000 eV. An image of the target area is projected onto the silicon diodes using pinholes. Between each pinhole and its respective diode is a soft x-ray filter. The material and thickness of the filter are selected to allow unfolding of spectral information in the 100-3000 eV spectral region. We plan to insert a set of grazing-incidence mirrors between each of the filter/diode pairs in a future version of this instrument to better define the spectral bandpass of each diode channel.

Radiation from the target region is monitored by a gated microchannel-plate-intensified image recording device that is located immediately behind the diode array. A small shadow in the recorded image corresponds to the specific area of the target that is imaged onto each silicon diode.

We are presently fielding this instrument in experiments on the Z facility located at Sandia National Laboratories in Albuquerque, NM. The instrument is located on the same line-of-sight and measures the same spatial region as a filtered fast-framing x-ray pinhole camera and a transmission grating spectrometer. This paper describes the design of the IDA diagnostic and presents the results of measurements obtained in hohlraum experiments conducted on Z.

*Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

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GP17
PLASMA DIAGNOSTICS FOR X-RAY DRIVEN FOILS AT Z

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We report the development of a set of techniques to diagnose plasmas produced by X-ray photoionization of thin foils placed near the Z-pinch on the Sandia Z Machine. The development of 100+ TW X-ray sources and thin film deposition technologies enables access to novel plasma regimes, such as the photoionization equilibrium. To diagnose these regimes one must simultaneously measure the foil density, temperature, emission and absorption, as well as the pinch power, temperature, spectrum and 2-D spatial uniformity. The desired plasma regime is only reached transiently for a 2-ns window, placing stringent requirements on diagnostic synchronization. To maximize the photon flux on the sample we place the sample as close as 1.55 cm from the pinch. We must then discriminate between the 120 TW pinch emission and the much weaker foil emission, with diagnostics viewing the target from 4+ meters away. We are able to meet these requirements by adapting existing Sandia transmission grating and crystal spectrometers, pinhole cameras and streak cameras and installing an additional gated 3-crystal Johann spectrometer with dual lines of sight. We present sample data from experiments in which 1 cm, 180-eV tungsten pinches photoionized foils composed of 200Å Fe and 300Å NaF co-mixed and sandwiched between 1000Å layers of Lexan (CHO). Future work will analyze these results to test divergent astrophysical models for photoionized astrophysical plasmas found in accretion-powered objects such as active galactic nuclei and x-ray binaries. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract no. W-7405-Eng-48.
Analysis of Radiatively-Heated Thin Foils in Z-Pinch Hohlraum Experiments

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Z-pinch experiments are performed at the Z pulsed-power facility at Sandia National Laboratories to study physics issues related to high energy density plasmas and inertial confinement fusion (ICF). In recent Z experiments, time-resolved x-ray crystal spectroscopy has been used [Bailey, et. al., Bull. Am. Phys. Soc. 44, 227 (1999)] to record inner-shell Ka spectra from thin CH-tamped foils located in a slot in the return current can (i.e., at the hohlraum boundary). Using the pinch as a backlighter, the spectrograph views the tungsten pinch x-ray radiation through the foil. To date, experiments have been performed using foils composed of pure elements (e.g., Al) and mixtures (Mg, Al, and F). In some experiments, an Al foil was backed by a thin Au foil. Spectral diagnostics of this type can be used to help constrain measurements of the pinch radiation power, the hohlraum radiation temperature, and can also be used in experiments to measure radiation flow in various materials. We discuss recent simulations of these experiments, in which we perform a combination of 3-D view factor, 1-D radiation-hydrodynamics, and 1-D collisional-radiative equilibrium (CRE) simulations.

This work is supported in part by U. S. Department of Energy Grant No. DE-FG03-98DP00250.
Axially resolved z-pinch density, electron temperature, and K-shell-emitting mass estimates from CCD-based diagnostics

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Timely estimates of z-pinch plasma conditions can aid in the optimization of plasma radiation source K-shell emission. For example, a shell on shell argon gas puff has many parameters, such as the axial gas density profile, inner to outer shell mass ratio, total mass, and pinch load length, which can be varied on a shot by shot basis. At the Double-EAGLE facility at Maxwell Physics International, CCD cameras have been implemented to routinely record pinhole images, x-ray spectra, and axially resolved streak images. (One of the cameras has also been used to record x-ray spectra at the SATURN facility at Sandia National Laboratory.) Using the approach proposed by Apruzese [Aruzese, et al. JQRST 57, 41 (1997)], a parameterized computer algorithm has been implemented to take as input the CCD data (pinch diameter, Ar Ly$_\alpha$ to He$_\alpha$ line ratio, and K-shell power) and output the estimated plasma parameters (density, electron temperature, and K-shell-emitting mass) as a function of z-pinch axial location. We describe the algorithm and present results for a number of different z-pinch loads.

* Work sponsored by the Defense Threat Reduction Agency

GP20
Design and implementation of a high resolution, high efficiency, transmission spectrometer for precision optical measurements of highly charged ion transitions

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Due to the availability of materials and tools that can transport, image, and record visible light, atomic transitions with optical wavelengths are regularly used as indicators of plasma parameters such as temperature and density in a variety of plasma devices. Precision measurements require instrumentation which can efficiently collect and disperse this radiation, while remaining uncomplicated and versatile. Here we present the design, testing, and implementation of a high-efficiency, high-resolution transmission grating spectrometer for measurements from the near ultraviolet into the visible region of the spectrum. The system consists of two f/4.6 achromatic lenses, a 3500 groove-spaced grating ion-beam etched in fused silica, and a thinned, back-illuminated CCD detector. The simple design minimizes the number of optical components, each with optimal throughput and high efficiency. The 6" diameter grating has a transmission efficiency of about 94% in the -1 order at near 4000 Å. The spectrometer has been tested using standard spectral lamps shined through a 30 μm slit. In this way a resolving power (λ/Δλ) of 15000 at 3800 Å has been measured. Initial tests have been made with the Livermore electron beam ion trap including precision measurements metastable transitions within the ground state of highly charged Kr (Si-like Kr_{22+} 3s^23p^2 3P_1 → 3P_2), as well as a series of high Z Ti-like ions (W_{52+}, Pt_{56+}, Au_{57+}, and Ti_{34+} 3s^23p^6 3d^2 J = 2 → 3). A summary of instrumental features and limitations, plans for design improvements, and the results of these measurements will be discussed.

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GP21
Direct spectroscopic observation of multicharged MeV ions in plasma, heated by intense femtosecond laser radiation.

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Experimental and theoretical investigations of multicharged ions acceleration by an intense femtosecond laser radiation with different flux densities will be presented. By Focusing Spectrometers with Spatial Resolution (FSSR) we have observed blue wing of He⁺, He⁹ and Lyα lines of fluorine, which shows a feature of the Doppler-shifted spectrum due to the self-similar ion expansion. Such wings were interpreted as an evidence of the emission of energetic He- and H-like ions of fluorine with energy more than 1 MeV, produced from solid target irradiated by intense l=(1-4) · 10¹⁸ W/cm² (UHI-10 laser facility, 60 fs, λ=800 nm), obliquely incident p-polarized pulse laser. Using a collisional particle-in-cell simulation, which incorporates the nonlocal-thermodynamic-equilibrium ionization including OFI, it were obtained the plasma temperature, line shapes, hot electron spectra and maximal energy of accelerated ions, which agree well with those determined from experimental hot electrons and ions spectra. Obtained X-ray spectra with 3D spatial distribution for Heα - Kα lines of Al, Ca and Cu targets, show that the size of emission zone of Ka radiation on the target surface in 2-5 times large, than the size of emission zone of Heα lines and their satellites. On the contrary, the size of zone emission in the direction of laser-plasma expansion were equal for all lines.
X-ray spectromicroscopy investigations of fast ions and hot electrons in plasmas, heated by nanosecond laser radiation with different wavelengths.


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Space resolved X-ray spectroscopy was used for investigation of fast (up to MeV) ions generation in plasma, heated by laser radiation with different wavelengths (λ=308 nm, 800 nm, 1.06 μm, 10.6 μm). The simultaneous use of mass spectrometry showed reasonable agreement for both methods of measurements. Non-Maxwellian X-ray spectroscopy enabled us to investigate the generation of fast ions and hot electrons by means of space resolved spectroscopy in plasma areas, where the interaction with the laser beam takes place.
Hot electron diagnostic in a solid laser target by K-shell lines measurement from ultra-intense laser-plasma interactions \((3 \times 10^{20} \text{ W/cm}^2, \geq 400 \text{ J})\)

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Abstract

Characterization of hot electron production (efficiency) in ultra intense laser-solid target interaction, using 1.06 μm laser light with an intensity of up to \(3 \times 10^{20} \text{ W cm}^{-2}\) and a laser energy of \(400-700 \text{ J}\), has been done by observing \(K_\beta\) as well as \(K_\alpha\) emissions from a buried Mo layer in the targets, which were same structure as in the previous 100 TW experiments, \([1, 2]\) but these experiments have done under more laser intensity and energy conditions \((\leq 4 \times 10^{19} \text{ W cm}^{-2} \text{ and } \leq 30 \text{ J})\). The conversion efficiency from the laser energy into the energy, carried by hot electrons, has been estimated to be \(-40\%\), which in the same order of the previous less laser energy \((\sim 20 \text{ J})\) experiments, yet the x-ray emission spectra from the target has change drastically, e.g., gamma flash.


This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.
X-ray L-shell spectropolarimetry of high-temperature plasmas.
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- X-ray spectropolarimetry is a powerful new tool for investigating the anisotropy of high-temperature plasmas. It is sensitive to the energetic electron distribution function and magnetic field, which, in general, have not been measured adequately. This diagnostic brings together space- and time-resolved x-ray spectroscopy and polarimetry. Specifically, it is based on the theoretical modeling of X-ray line polarization-dependent spectra measured simultaneously by spectrometers with different sensitivities to polarization. Development of time-dependent L-shell spectroscopic monitoring of high-temperature plasmas has lead to the necessity to account for, first, the non-maxwellian electron distribution function and then for polarization properties of L-shell lines. Moreover, the influence of the magnetic field on polarization of X-ray L-shell line radiation is large enough to be measured. This diagnostic can be applied to a broad range of plasmas, from low-density astrophysical plasma to the dense z-pinch plasma. This work shows how x-ray spectropolarimetry compliments the usual spectroscopic monitoring of hot plasmas and demonstrates the importance of accounting for x-ray line polarization in plasma diagnostics. The present work is supported by DOE, SNL, and UNR.

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GP25
Laser-produced plasmas driven by high-intensity, femtosecond-duration pulsed lasers have been recognized as sources of short-duration X-ray line emissions. Electron kinetics simulations of these transient and non-equilibrium plasmas predict non-Maxwellian electron distribution functions and even the presence of electron beams. X-ray line polarization spectroscopy is a diagnostic that can be used to study directionality in the electron distribution function and thus test simulation results with measurements. To this end, we use a time-dependent, collisional-radiative atomic kinetics model of magnetic sublevels to understand the underlying processes and mechanisms leading to the formation of polarized X-ray line emission in Si plasmas with anisotropic electron distribution functions. We focus on the polarization properties of the He-like Si satellites of the Ly_α line. In the situations under consideration significant emissions last less than 1 ps during which the plasma undergoes a rapid development. We identify suitable polarization markers, which are sensitive to the anisotropy of the electron distribution function and can be used for diagnostic applications.

This work was supported by NATO grant CRG 971588. PH and RCM were also supported by LLNL contract B503614.
High resolution X-ray spectrograph
for 1.5-400 keV
with combined Cauchois-Johannson crystal.

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We have designed and built wide-band, high resolution X-ray crystal spectrometer for application to high temperature plasma diagnostics. The new feature of this device is thin cylindrical quartz crystal with optical radius R. 10(-1)0 crystal planes with 2d=0,85 nm have radius 2R. They focus the softer X-rays in reflection ('Johansson') geometry on the Rowland circle of radius R. At the same time the same crystal focuses the harder X-rays in transmission ('Cauchois') with 0001 crystal planes, 2d=0.36 nm on the Rowland circle with radius R.

0001 planes are perpendicular to the crystal surface and to the 10(-1)0 planes. In contrast with usual Cauchois scheme we fabricated optical radius of crystal surface being equal to radius of Rowland circle. It is shown that for this type of transmission crystal position of line does not depend on position of the source and width of line does not depend on source size. Paper contains theoretical analysis of the instrument and corresponding calibration with x-ray tube.

Such calibrated spectrometer can be successfully used for heavy ions velocity measurements through Doppler shift, simultaneous measurements of Bremsstrahlung and line emission from hot dense plasmas. Besides reflection and transmission off the crystal planes parallel and perpendicular to the crystal surface we also analyzed various inclined cuts of the same crystal. 3-400 keV energy range is provided with 0001 cut and inclined 10(-1)2, 10(-1)3, 10(-1)4, 10(-1)5, 10(-1)6 cuts in transmission geometry.

To enlarge energy range of device we offer to use the same crystal in Johansson geometry with corresponding inclined cuts 20(-2)1, 30(-3)1, 40(-4)1, 50(-5)1. Spectra of X-ray tube is presented, obtained in reflection regime as simple illustration for the fact that single quartz crystal can provide 1.5-400 keV energy range.
X-ray imaging characteristics from a large spherically-bent mica crystal.* S. G. Lee, J. G. Bak and M. Kwon National Fusion R. & D Center, Korea Basic Science Institute, M. Bitter Princeton Plasma Physics Laboratory. A high vacuum x-ray crystal spectrometer was fabricated utilizing a large spherically-bent mica crystal (2 cm x 7 cm) and a x-ray sensitive CCD camera to observe helium-like neon spectra in the wavelength range from 13.4474 to 13.6980 and helium-like spectra of other low-Z elements, such as Mg and Al. The spectrometer was specifically designed for use at a low x-ray intensity magnetic mirror machine. The x-ray imaging characteristics of the large spherically-bent mica crystal have been tested in the laboratory with a x-ray source, using the Bremsstrahlung continuum. The results of these calibration measurements will be presented.

* Work supported by the Ministry of Science and Technology of the Republic of Korea.
Thin-window high-efficiency position sensitive proportional counter for the vacuum flat crystal spectrometers on the LLNL Electron Beam Ion Trap

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We have mounted 1 μm thick aluminized polyimide windows onto the position sensitive proportional counters employed by the wide-band flat crystal spectrometers at the Lawrence Livermore National Laboratory Electron Beam Ion Trap experiment. The aluminized polyimide, supported by thin wires across the short axis of the window, is used to isolate the detection chamber of the proportional counters, which operate at a pressure of 760 torr, from the vacuum chamber of the spectrometer. The windows are modified versions of those developed for the proportional counters which were used during ground calibration of the Chandra X-ray Observatory. The transmission properties of these windows are, therefore, well known. The increased transmission efficiency of the polyimide windows relative to the 4 μm thick polypropylene window material previously employed by our proportional counters has extended the useful range of the spectrometer from roughly 20 to 30 Å at energies below the carbon edge, as well as increasing detection efficiency at wavelengths beyond the carbon edge. Using an octadecyl hydrogen maleate (OHM) crystal with \(2d = 63.5\) Å, we demonstrate the increased wavelength coverage by measuring the resonance, intercombination, and forbidden lines in helium-like \(\text{N VII}\) in two different density regimes. The thin polyimide windows have also increased the efficiency of the spectrometers entire wavelength range. To demonstrate the increased efficiency we compare the Fe XVII spectrum in the 15-17 Å band measured with the 1 μm aluminized polyimide windows to the 4 μm aluminized polypropylene windows. The comparison shows an average increase in efficiency of \(\sim 40\%\). The polyimide windows have a significantly lower leak rate than the polypropylene windows making it possible to achieve approximately an order of magnitude lower pressure in the spectrometer vacuum chamber which reduces the gas load on the trap region.

This work was performed under the auspices of the U. S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 and was supported by the NASA High-Energy Astrophysics Supporting Research and Technology Program work order W-19127.

The equilibrium state in Tokamak core plasmas has been studied using the relative intensities of resonance x-ray lines e.g. Ly-α (H-like), “w” (He-like) and “q” (Li-like) from test ions such as Ar*. The analysis depends on comparison of ion diffusion calculations, including atomic rates from ADAS, with the data collected from a Johann configuration spectrometer with a CCD detector. Since the lines are nearly monoenergetic, their intensities are independent of the instrument sensitivity and are directly proportional to the ion abundances. This method has recently been applied to Ar in the Oxford EBIT with a beam energy in the range 3 - 10 keV. Taking into account the ADAS cross sections for monoenergetic electron collisions and polarisation effects model calculations agree with the observed line ratios at 4.1 kev beam energy. This work will be expanded to provide nomograms of ionisation state versus line intensity ratios as a function of EBIT beam energy.

1 N J Peacock, R Barnsley, I H Coffey et al., Fusion Engineering and Design 34-35, 171- 174 (see refs. within) [1997].

*Diagnostic development supported by UKAEA-Fusion.
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A SPECTROSCOPY DIAGNOSTIC OF PLASMA GRADIENTS IN ICF IMPLODED CORES

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X-ray spectroscopy of laser-driven imploded ICF cores has proved to be a powerful diagnostic of spatially-averaged temperature and density plasma conditions at the collapse of ICF implosion experiments. Temperature and density time-histories can be extracted from the analysis of time-resolved X-ray line spectra using the temperature and density sensitivity of line intensities and Stark-broadened line shapes. The next step in the spectroscopy of imploded cores is the bracketing of core plasma gradients as a function of time. To this end, we discuss a spectroscopy diagnostic which is based on the self-consistent and simultaneous simulation and analysis of time-resolved X-ray line spectra and X-ray monochromatic images. Abel inversion of X-ray monochromatic images provide line emissivity spatial profiles; this information is critical for the determination of gradients in the core. We apply this technique to the analysis of data recorded in Ar-doped ICF implosion experiments driven with the GECCO XII laser system at Osaka University. In these experiments, time-resolved X-ray line spectra and X-ray monochromatic images were simultaneously recorded for the Ar He$\beta$ and Ly$\beta$ spectral features. From the analysis of the data we can extract the time-history of temperature and density gradients in the core through the collapse of the implosion.
Time and Space resolved Soft x Ray Spectroscopy Diagnosis of Dense Plasma Focus

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A Four-stripline gated microchannel plate framing camera is used as detector in a multi-crystal spectrometer. Ellipse concave OHM and TAP crystal are used simultaneously to give a broad range spectrum from 200eV to 1200eV. Stripline gates are 5ns width and delayed 10ns successively. By using four 1mm width spatially imaging cross slits, the spectrum of 15mm width bulk plasma is measured. 2\textmu m thin polyester film is stick on the slit to separate detector from poorer vacuum of DPF device, and permit soft x ray penetrated. The output image of framing camera is record by a synchronous CCD camera. The spectrometer is used on DPF-200 device. lines of He-like O and Na-like Cu are measured.
MEASUREMENTS OF SHOCK HEATING USING AL ABSORPTION SPECTROSCOPY IN PLANAR TARGETS


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Abstract

In direct-drive laser fusion, the trade-off between stability and overall efficiency requires precise control of the implosion isentrope. Most target designs use the temporal shape of the drive pulse to create shocks that slightly preheat the capsule shell and establish the isentrope for the rest of the implosion. Also, the use of foam overcoatings has been proposed as a means to reduce laser imprinting. These foams can alter the structure and intensity of the initial shock. To ensure that our hydrocodes adequately model these effects it is important that shock heating of targets be measured and understood. We report on measurements of shock heating in planar targets irradiated with the OMEGA laser system.

Planar 20 μm-thick CH targets were irradiated with 6 UV beams at intensities of \( \sim 2 \times 10^{14} \text{ W/cm}^2 \) with temporally square and ramped pulses. Some targets also have low-density foam (30mg/cc) on the irradiated surface. A thin (0.5 μm) Al layer, imbedded in the target, is probed with x rays from a Sm backlighter. The 1s-2p absorption lines in the Al are observed with a streaked x-ray spectrometer. The absorption lines from the F-like to Ne-like ion populations provide a measure of the temperature of the target as a function of time. We present data on measurements that show the relative shock heating by square and ramp pulses. We also present results of atomic physics calculations of the absorption spectra that are used to infer the target temperature and show results from hydrodynamic simulations of the experiments.

1 D. J. Hoarty, et. al, Phys. Rev. Lett. 78, 3322 (1997)
Dynamic x-ray diffraction to study compression of Si and Cu beyond the Hugoniot elastic limit*

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We have conducted shock experiments in thin Si and Cu crystals at pressures above the Hugoniot Elastic Limit (HEL). The 40 μm thick Si crystals are shock compressed using an x-ray drive generated with an internally shielded hohlraum on Nova at peak pressures of up to 330 kbar. Diffraction signatures from the (400) and (040) lattice planes (parallel and perpendicular to the shock propagation direction) were recorded as a function of time. The diffracted signals from the planes parallel to the shock direction show compression of up to ~10% in 1-dimension, while the diffraction from the orthogonal direction shows no evidence of compression. The thin Cu crystals (8 μm) are shock compressed by direct laser irradiation at OMEGA. In this case, diffraction signatures from the (400) and (040) lattice planes both showed compression, indicating that the crystal has undergone plastic deformation by compressing in three dimensions. We will describe the simultaneous diffraction measurements and present results of the Nova and OMEGA experiments.

* This work was conducted under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.
Time-of-Flight Electron Spectrometry on TIR-1
Using Natural Diamond Detector

Troitsk Institute for Innovating and Fusion Research

Time-of-flight (TOF) technique [1] is now frequently used for determination the fuel ion temperature in
a laser driven inertial confinement fusion (ICF) experiments. Charged particle spectrum in the range 1+30.8 MeV provides information about fuel and pusher Pr.

Developed for the application in pulse height analysis mode for deuterium-tritium (DT) neutron, fast ion and atom spectrometry in high power tokamak experiments [2,3], natural diamond detectors (NDDs) [4,5] also have been successfully used for fast UV and x-ray flux dynamic measurements in laser light - target interaction experiments [6].

An NDD is a metal-semiconductor-metal structure, with Au, or Ti/Pt/Au metal contacts and very pure natural diamond semiconductor. High energy band gap, resistivity and breakdown fields, large carrier saturation velocity and mean free drift time are crucial for materials used as radiation sensors. 100% charge collection efficiency of the best (type IIa) selected natural diamonds makes it possible to use them for creating small detectors with high sensitivity. Negligible NDD sensitivity to visible light, relatively low sensitivity to x-rays, and high radiation resistance (up to 3×10^14 n/cm^2 [7]) provide an opportunity to apply it for fast particle TOF spectrometry in laser light — target interaction and ICF experiments.

Special NDD with current response duration ~ 1 ns was developed for TOF electron measurements at TIR-1 installation [8].

In TIR-1 experiments plasma was created by lead target irradiation using CO_2 laser (λ=10.6 μm) of 80-85 J energy with 20-ns pulse duration. NDD was installed 30 cm far from target plasma behind 1.5 μm aluminum foil and so measured x-ray and fast electron flux. Separation of the signals induced by x-ray and electrons was provided by magnetic field creating infront of the detector. The shape of electron induced NDD current response provided the information about the energy distribution of electrons, generated during laser light - target interaction. Analysis of these data will be reported.

An ultra fast NDD, similar to used in this work, with current response ~ 0.3 ns, can provide charge fusion products TOF spectrometry in ICF experiments.


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GP35
Time Resolved, Absolutely Calibrated Observations of Soft X-rays with the Transmission Grating Spectrometer at the Nike Laser Facility

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A new transmission grating spectrometer has been commissioned at the Nike laser facility to provide absolutely calibrated, time-resolved spectra in the wavelength range from 10 to 150 Å. Currently, the system has measured the spatially integrated soft x-ray flux for various target materials (CH, BN, Kapton, Au, and W) with different laser powers and laser spot sizes. This new spectrometer is distinguished from previous transmission grating instruments by its use of two 2500 l/mm transmission gratings with two separate detector systems: a soft x-ray streak camera and a detector system that combines absolutely calibrated Si photodiodes and a CCD camera with a phosphor scintillator. The photodiodes provide modest temporal resolution (~1 ns), high sensitivity over discrete wavelength bands ($\Delta \lambda = 6.2$ Å), and an absolutely calibrated responsivity. The CCD camera is used to determine the location of each photodiode and the relative (time-integrated) intensity distribution over the photodiode array. The spectrometer components have been calibrated at the National Synchrotron Light Source at Brookhaven National Laboratory. The transmission grating spectrometer complements a set of filtered photodiodes also in use at Nike to measure the soft x-ray flux.

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4 Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375
5 SAIC, McLean, VA 22102
6 Artep, Inc., Columbia, MD 21045

GP36
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