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THE TEXAS EXPERIMENTAL TOKAMAK:
A PLASMA RESEARCH FACILITY

THE FUSION RESEARCH CENTER
The University of Texas at Austin
Austin, Texas 78712

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The Texas Experimental Tokamak: A Plasma Research Facility

**A proposal submitted to the Department of Energy
in response to Program Notice 95-10:
Innovations in Toroidal Magnetic Confinement Systems**

PROJECT DESCRIPTION

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MASTER

SUMMARY

1. Goal of the experiment

The Fusion Research Center (FRC) at the University of Texas will operate the tokamak TEXT-U and its associated systems for experimental research in basic plasma physics. While the tokamak is not innovative, the research program, diagnostics and planned experiments are. The fusion community will reap the benefits of our success in completing the upgrades (auxiliary heating, divertor, diagnostics, wall conditioning), developing diverted discharges in both double and single null configurations, exploring improved confinement regimes including a limiter H-mode (Fig. 1), and developing unique, critical turbulence diagnostics (Fig. 2). With these new regimes, we are poised to perform the sort of turbulence and transport studies for which the TEXT group has distinguished itself and for which the upgrade was intended. TEXT-U is also a facility for collaborators to perform innovative experiments and develop diagnostics before transferring them to larger machines (e.g. to TPX).

Our general philosophy is that the understanding of plasma physics *must* be part of any intelligent fusion program, and that basic experimental research is the most important part of any such program. The emphasis of the proposed research is to provide well-documented plasmas which will be used to suggest and evaluate theories, to explore control techniques, to develop advanced diagnostics and analysis techniques, and to extend current drive techniques. Up to 1 MW of electron cyclotron heating (ECH) will be used not only for heating but as a localized, perturbative tool.

2. Synopsis of the experimental program plan

The experimental program will be performed in circular limited discharges and in diverted discharges with 600 kW of ECH at 56/60 GHz and an additional ≈ 500 kW at 110 GHz. All the regimes of operation currently available on TEXT-U will be utilized - Ohmic, IOC (improved Ohmic confinement), L mode, limiter H mode, biased H mode, and detached plasmas. Continued systematic pursuit of the diverted H-mode -- which continues to elude us though conditions seem appropriate -- should provide important information regarding the physics requirements of the H mode. The program is organized approximately by year as below (in order of priority):

Year 1.

- Continue studies of improved confinement transition physics (limiter H-mode, diverted H-mode: effect of fueling asymmetries and use of 2nd harmonic ECH).
- Identify relative roles of magnetic and electrostatic turbulence in the core.
- Continue exploration of non local transport effects.
- Explore the region of exceptionally good confinement near the magnetic axis.
- Initiate documentation of core turbulence asymmetries.
- Continue exploration of edge turbulence: role of curvature and wall conditioning, feedback control.
- Initiate studies of Alfvén modes suitable for current drive.
- Complete measurements of current ramp phenomena (Ejima coefficient, resistivity).
- Initiate MHD feedback control via intra-island heating.
- Install, test, and document proposed TPX density diagnostic.

- Begin development of new techniques for turbulence analysis.

Year 2.

- Continue study of transitions to improved confinement (investigation of fueling asymmetries, addition of 110 GHz ECH).
- Explore and document the effects of higher beta on turbulence and transport.
- Use perturbation techniques to investigate turbulent drives in the core.
- Investigate impact of turbulence asymmetries on transport.
- Continue exploration of edge turbulence: role of wall materials and control via shear in the poloidal rotation.
- Extend low power Alfvén wave studies to higher toroidal mode number.
- Complete development of MHD feedback control via intra-island heating.
- Continue development of turbulence analysis techniques: contact with theory and application to numerical code results.
- Install, test, and document the Thomson scattering fluctuation diagnostic.

Year 3.

- Continue study of transitions to improved confinement (employing 110 GHz ECH, E_r and turbulence changes during L-H transitions).
- Continue studies of core turbulence asymmetries, comparisons with measured transport.
- Continue transient transport studies with comparisons to theory and to transport measurements based on profile analysis.
- Complete studies of turbulence control via sheared poloidal rotation.
- Continue development and application of new statistical techniques for the study of the non-linear character of fluctuations. Extend to edge.
- Benchmark Alfvén wave current drive against electron cyclotron current drive.

3. Deliverable results expected

The outcome of the above experimental program will be published papers documenting:

- the physics requirements for a diverted H-mode
- an understanding of whether local or nonlocal effects govern confinement, whether critical gradients play a role, and the importance of these phenomena for other machines
- the relative roles of magnetic and electrostatic turbulence at different beta values, and the importance of these phenomena for other machines
- the excellent confinement region near the axis, and its relevance to other machines
- a comparison of experiment and theory of the transition to improved confinement
- the physics and utility of MHD sensing and ECH control techniques
- the physics and utility of edge turbulence and transport control (either stabilizing or destabilizing turbulence)
- the role of curvature, material surface selection and material conditioning in determining edge characteristics and edge turbulence
- the development of a density diagnostic for TPX, a general utility ECE imaging diagnostic, a Thomson scattering fluctuation diagnostic, and various high order analysis techniques
- the physics and utility of various Alfvén wave current drive techniques
- the plasma resistivity, V-s consumption, etc., during current ramps

4. Adequacy of the facilities

The TEXT-U tokamak currently operates routinely with all the major hardware required for the proposed research program except that required for the AWCD. Power and space are available for the AWCD equipment. All diagnostics exist and work routinely except those proposed for development as part of the research program. All operating regimes required are currently available. The engineering and physics team at the FRC are demonstrably capable of operating TEXT-U, as attested by its publication record. As in the past, approximately 25 graduate students will be involved in the experiments.

5. Adequacy of the budget

More than 14 years of operational experience with TEXT and TEXT-U allow us to be precise in the personnel and funding requirements necessary to achieve given objectives. That TEXT-U took longer than expected to bring to fruition is explained by the reduced funding which has been provided. The table below outlines the funds necessary to successfully complete the schedule.

Items	FY 1996	FY 1997	FY 1998
Total Base Level	\$4,254,000	\$4,018,172	\$4,091,741
Construction	\$476,360	\$345,000	\$455,000
Total	\$4,730,360	\$4,363,172	\$4,546,741

6. The impact for the prospects of toroidal magnetic fusion power plants

The cost of proposed toroidal magnetic fusion experiments is large: TPX at > \$0.7B and ITER at > \$3B (perhaps \$15B including design, construction, operation, and decommissioning). Clearly we cannot afford to build a fusion reactor, or improve upon prototype fusion reactors, by trial and error. We must base such machines on understanding first principles of plasma physics. This research proposal is aimed at providing that. In addition, it will continue to provide education and training of physics and engineering students.

7. Elucidation of physics principles

The physics principles of the equilibrium and macroscopic stability of fusion plasmas have a sound basis in both theory and experiment. The equivalent understanding in other important areas, most notably transport, requires much additional work. Some aspects require innovative devices and configurations for their exploration, but many innovative experiments require instead a configuration which is well understood and diagnosed. The unique set of TEXT diagnostics for profile and turbulence measurements has furthered our understanding of fusion physics and provides the opportunity for additional advancements, including those listed under 'deliverables'. These sort of experiments are essential to developing a fundamental understanding of the complex nonlinear physics of fusion plasmas, an understanding which will be necessary for development of the physics base required to go beyond an ignition demonstration machine.

Figure 1. Phenomenology of the transition to improved confinement in an ECRH, limited discharge. Shots 218116 (no transition) and 218117 (with transition) are shown. OH1 and OH2 represent ohmic phases. L represents L-mode. H and HOH represent H-mode-like and ohmic H-mode-like regimes, respectively. See section IIID of the proposal for details.

Figure 2. Poloidal asymmetry in the power spectra of turbulent electron temperature fluctuations. A novel 2-D result using a unique ECE diagnostic developed by FRC staff and operated in collaboration with Auburn. Proposal section IIIA describes the 2-D turbulence measurements.

PROJECT DESCRIPTION

I. OVERVIEW OF THE TEXT-U PROJECT

I. Overview of the TEXT-U Project

The Fusion Research Center (FRC) at the University of Texas will operate the tokamak TEXT-U and its associated systems for experimental research in basic plasma physics. While the tokamak is not innovative, the research program, diagnostics and planned experiments are. The fusion community will reap the benefits of our success in completing the upgrades (auxiliary heating, divertor, diagnostics, wall conditioning), developing diverted discharges in both double and single null configurations, exploring improved confinement regimes including a limiter H-mode, and developing unique, critical turbulence diagnostics. With these new regimes, we are poised to perform the sort of turbulence and transport studies for which the TEXT group has distinguished itself and for which the upgrade was intended. TEXT-U is also a facility for collaborators to perform innovative experiments and develop diagnostics before transferring them to larger machines (e.g. to TPX).

Our general philosophy is that the understanding of plasma physics *must* be part of any intelligent fusion program, and that basic experimental research is the most important part of any such program. The emphasis of the proposed research is to provide well-documented plasmas which will be used to suggest and evaluate theories, to explore control techniques, to develop advanced diagnostics and analysis techniques, and to extend current drive techniques. Up to 1 MW of electron cyclotron heating (ECH) will be used not only for heating but as a localized, perturbative tool.

The physics principles of the equilibrium and macroscopic stability of fusion plasmas have a sound basis in both theory and experiment. The equivalent understanding in other important areas, most notably transport, requires much additional work. Some aspects require innovative devices and configurations for their exploration, but many innovative experiments require instead a configuration which is well understood and well diagnosed. The unique set of TEXT diagnostics for profile and turbulence measurements has furthered our understanding of fusion physics and provides the opportunity for additional advancements. These sorts of experiments are essential to developing a fundamental understanding of the complex nonlinear physics of fusion plasmas.

The cost of toroidal magnetic fusion experiments currently under design is large. TPX will cost more than \$700,000,000. ITER will cost approximately \$3,000,000,000. Including design, construction, operation, and decommissioning, the cost could be \$15,000,000,000. Clearly we cannot afford to build a fusion reactor, or improve upon a first prototype fusion reactor, by trial and error. We must base such machines on understanding first principles of plasma physics. This research proposal is aimed at exactly that.

The remainder of this section will cover the following

- Historical perspective: previous work
- TEXT-U device and plasma summary
- TEXT-U experimental program and goals (deliverables)
- Schedule and cost summary
- Site issues and cost effectiveness
- Collaborations

RECENT HISTORY

Approximately two years ago, a major upgrade to the machine was completed. Hardware additions include

- divertor coils to produce double null or equatorial single null discharges, (described in section II)
- electron cyclotron heating (ECH) systems (approximately 600 kW at 56 and 60 GHz and approximately 500 kW at 110 GHz), These are described in section II and section III.
- two new motor generator sets,
- two new power supplies (for the vertical field and for the divertor coils),
- new coils to produce magnetic islands and stochastic regions in the edge (these stochastic field experiment (SFX) coils are described in section II),
- a boronization system (described in section II).

All this hardware works and is used routinely, except for the 110 GHz ECH. The 110 GHz gyrotron has just (March 1995) completed successful testing at General Atomics (GA); all components exist at TEXT for implementation without any additional cost.

In addition to the machine hardware, new diagnostics have been developed. In the last two years the following diagnostics have been brought on line by the Fusion Research Center group, and all work routinely:

- a multi-point Thomson scattering system to measure the radial electron temperature profile,
- a Mach probe system to measure edge flow velocities,
- an electron cyclotron emission (ECE) diagnostic to measure temperature fluctuations,
- a D_α array diagnostic for fluctuation measurements in regions of the plasma that are otherwise inaccessible,

- a charge exchange system for measuring the current density profile,
- a diamagnetic loop that provides energy confinement time as a function of time for every discharge,
- a vertically viewing ECE system which is used with ECH to infer magnetic fluctuation levels.
- a microwave scattering system for ECH beam diagnostics and for edge turbulence measurements

Our collaborators have also brought new diagnostics to TEXT-U. In particular

- The RPI group has developed a new heavy ion beam probe (HIBP) system which accesses 90% of the poloidal cross section, provides full radial profiles in 5 ms, or less, and can provide spatial resolution of 5 mm and temporal resolution of 1 μ s.
- The UCLA group has developed a Faraday rotation polarimeter which now provides full profiles of the plasma current density and safety factor profiles with cm spatial and sub-millisecond temporal resolution.
- The MIT group has improved the three soft X-ray array detectors.
- The Auburn group has developed an ECE system.
- The Hampton group is developing an impurity pellet injection system.

In addition to the new hardware and diagnostics now working, many standard operational regimes have now been developed for TEXT-U. These are

- the L-mode,
- a limiter discharge with clear H-mode signatures including dithering and elm-like phenomena,
- detached plasmas (naturally occurring and induced with carbon or neon),
- improved Ohmic confinement regimes,

- biased probe/biased limiter H modes.

We are now in a position to apply the standard TEXT-U diagnostics, together with those outlined above (all of which work routinely), to the various operational modes and transitions between modes outlined above. That is, if continued TEXT-U operation will allow the benefits of the Upgrade to be brought to the fusion community. The work already done with these diagnostics, machine modifications, and regimes is described in sections II and III.

TEXT-U DEVICE AND PLASMA SUMMARY.

Here we list typical conditions achieved in TEXT-U plasmas. Boronization and helium glow are used to achieve our cleanest plasmas, and to allow access to the limiter H-mode.

EXISTING CONDITIONS
$R_0 = 1.05 \text{ m}$ $a = 0.30 \text{ m}$ $\kappa \text{ (elongation)} = 0.9 \text{ to } 1.3$ $\delta \text{ (triangularity)} = -0.2 \text{ to } 0.2$ $I_p \text{ max} = 0.35 \text{ MA inductive}$ $B_{T\text{max}} = 2.8 \text{ T @ } R = 1.05 \text{ m}$ $\bar{n}_e = 0.1 - 1.0 \times 10^{20} \text{ m}^{-3}$ $T_e(0) = 0.5 - 3 \text{ keV (latter with ECH)}$ $T_i(0) = 0.25 - 1.5 \text{ keV}$ $\tau_E = 5 - 20 \text{ ms}$ Pulse = 500 ms at $B_{T\text{max}}$, longer at reduced field $\approx 0.6 \text{ MW of } \approx 60 \text{ GHz ECH, (200 ms pulse length)}$
PROPOSED ADDITIONS
$\approx 0.5 \text{ MW of } \approx 110 \text{ GHz ECH, 200 ms (paid for)}$ $\approx 0.5 \text{ MW Alfvén wave current drive, } > 100 \text{ ms}$

TEXT-U EXPERIMENTAL PROGRAM AND GOALS (DELIVERABLES)

Program Plan

The experimental program will be performed in circular, limited discharges and in diverted discharges with up to 600 kW of 56 to 60 GHz electron cyclotron heating (ECH) and in addition, approximately 500 kW of 110 GHz ECH. All the regimes of operation currently available on TEXT-U (Improved Ohmic Confinement, L mode, limiter H-mode, biased electrode H mode, detached plasmas) will be used. The program is subdivided into the following areas each of which is described in section III

- IIIA. Core Turbulence and Transport
- IIIB. Edge Turbulence and Transport
- IIIC. Turbulence Analysis
- IIID. Improved Confinement
- IIIE. ECH Physics
- IIIF. Alfvén Wave Current Drive (AWCD)
- IIIG. The Role of TEXT-U in Diagnostic Development

The following is a summary of the main goals and hardware modifications and additions for the next three years. Note that the physics goals are prioritized. In comparing with the milestones and work plans in section III, note that entries in this list typically summarize groups of milestones and abbreviate others.

Year 1.

Prioritized physics goals

- Continue studies of improved confinement transition physics (limiter H-mode, fueling asymmetries, 2nd harmonic ECRH, inside launch).
- Complete documentation of the relative roles of electrostatic and magnetic turbulence in the core.
- Continue exploration of non local transport effects with perturbative transport techniques.

- Explore the mechanism for observed turbulence modification due to ECH and determine whether they are local or non-local.
- Complete definitive wave number measurements in the core.
- Begin construction of a 2-D map of core turbulence with particular emphasis on documenting asymmetries.
- Search for turbulence drives in the scrape-off layer (SOL) (curvature drive, atomic drives). Measure parallel flow velocity in the SOL.
- Initiate studies of Alfvén modes which will lead to current drive experiments.
- Complete measurements of current ramp phenomena (Ejima coefficient, plasma resistivity).
- Initiate development of MHD feedback control via intra-island heating.
- Explore and document the core region of exceptionally good confinement.
- Install, test and document proposed TPX density diagnostic.
- Continue exploration of edge turbulence and transport control through both boronization and feedback control.
- Continue development of higher order statistical techniques for the study of the non-linear character of fluctuations in the core.

Hardware Modifications and Additions

- Add ECRH inside launch to be used for ECRH at higher density, H-mode experiments, and in later years for current drive.
- Add x-point fueling for fueling asymmetry experiments and for divertor experiments.

- Install tiles for biased divertor and x-point fueling. Preparation for turbulence control experiments in the next year and modifications for x-point fueling.
- Acquire transmitters to be used for Alfvén wave mode studies and current drive.
- Install automated glow cleaning for wall conditioning.

Year 2.

Prioritized physics goals

- Continue study of transitions to improved confinement (impact of inside launch, effect of fueling asymmetries, effect of additional ECRH at 110 GHz).
- Explore and document the effects of higher beta on turbulence.
- Use perturbation techniques to investigate turbulence drives in the core
- Continue 2-D studies of core turbulence, and compare to transport measurements via profile analysis. Infer electrostatic particle flux.
- Continue search for turbulence drives in the SOL (complete curvature drive experiments, initiate search for conducting wall drive).
- Continue studies of turbulence control in the SOL via experiments to control shear in the poloidal rotation.
- Extend low power Alfvén wave studies with improved toroidal mode number resolution.
- Complete development of MHD feedback control via intra-island heating.
- Initiate electron cyclotron current drive (ECCD) studies at 56/60 GHz and at 110 GHz to provide a benchmark for Alfvén wave current drive.

- Continue development and application of new statistical techniques for the study of the non-linear character of fluctuations. Look for contact with theory. Apply to numerical code results.
- Install, test and document the Thomson scattering fluctuation diagnostic.

Hardware Modifications and Additions

- Acquire transmitters to be used for Alfvén wave mode studies and current drive.
- Acquire and install biased divertor power supplies for turbulence control experiments.

Year 3.

Prioritized physics goals

- Continue study of transitions to improved confinement (110 GHz, document and compare electric field structure and turbulence changes during L-H transition).
- Continue 2-D studies of core turbulence, comparison with measured transport, and begin theory comparisons.
- Continue measurements of electrostatic particle flux in core and compare to transport measurements based on profile analysis.
- Continue transient transport studies with comparisons with new theories and with transport measurements based on profile analysis.
- Complete studies of turbulence control via sheared poloidal rotation
- Continue development and application of new statistical techniques for the study of the non-linear character of fluctuations. Extend to edge.
- Continue Alfvén wave experiments with improved poloidal mode number resolution.

- Benchmark Alfven wave current drive against ECCD.

Hardware Modifications and Additions

- Acquire transmitter for Alfven wave current drive experiments

Deliverables

The outcome of the above experimental program will be published papers that document:

- the physics requirements for a diverted H-mode
- an understanding of whether local or nonlocal effects govern confinement, whether critical gradients play a role, and the importance of these phenomena for other machines
- the relative roles of magnetic and electrostatic turbulence, at different beta values, and the importance of these phenomena for other machines
- the excellent confinement region near the axis, and its relevance to other machines
- a comparison of experiment and theory of the transition to improved confinement regimes
- the physics and utility of MHD sensing and ECH control techniques
- the physics and utility of edge turbulence and transport control (either de-stabilizing or stabilizing turbulence)
- the role of curvature, material surface selection and material conditioning in determining edge characteristics and edge turbulence
- the development of a density diagnostic for TPX, a general utility ECE imaging diagnostic, a Thomson scattering fluctuation diagnostic, and various high order analysis techniques
- the physics and utility of various AWCD techniques
- the plasma resistivity , V-s consumption, etc., during current ramps

SCHEDULE AND COST SUMMARY

More than 14 years of operational experience with TEXT and TEXT-U allow us to be precise in the personnel and funding requirements necessary to achieve given objectives. That TEXT-U took longer than expected to bring to fruition is a consequence of the reduced funding which was provided. The table below outlines the funds necessary to complete the schedule successfully and on time.

Items	FY 1996	FY 1997	FY 1998
Total Base Level	\$4,254,000	\$4,018,172	\$4,091,741
Hardware additions	\$476,360	\$345,000	\$455,000
Total	\$4,730,360	\$4,363,172	\$4,546,741

SITE ISSUES AND COST EFFECTIVENESS

The TEXT-U tokamak currently operates routinely with all the major hardware required for the proposed research program except that required for the Alfvén wave current drive (AWCD). There are both power and space available for the necessary AWCD equipment. Additional hardware required for fueling, wall conditioning, and bias are either modifications to existing hardware or are similar to hardware previously used in TEXT-U experiments. All diagnostics except those proposed specifically for development as part of the research program operate routinely. All operating regimes required are currently available.

The engineering and physics team at the Fusion Research Center are demonstrably capable of operating TEXT-U. That the team is capable of producing results is demonstrated by its publication record. At present, we employ 17 physicists. We propose to continue to employ approximately 25 graduate students on TEXT-U. Our collaborators now have the following personnel on site:

Institution	physicists	students
UCLA	3	
Auburn University	1	
MIT		1
RPI	2	2
Caltech		1

COLLABORATIONS

We propose to continue an important role that TEXT-U has played in the past, that of providing an opportunity for outside groups to perform experiments on a well-diagnosed machine that otherwise could not be done. Here we summarize some of the work which we and our existing collaborators hope to continue and include some new initiatives.

Experimental

Auburn University. (Staff on site)

The Auburn group have designed, built, and now operate a sophisticated ECE system on TEXT. It is capable of measuring electron temperature fluctuations at the 0.1% level. The group intend to continue their fluctuation studies, in particular to understand the relevance of the results for tokamak transport. The diagnostic is capable of observing fluctuation changes within a sawtooth cycle, and providing information on whether critical gradient phenomena exist. The group also intends to initiate measurements of locked modes, and tearing modes.

California Institute of Technology. (Graduate student on site)

The CalTech group have installed and successfully initiated operation of their compact torus injector on TEXT. The work is under the direction of Dr. P. M. Bellan. The objective is to understand the usefulness of this as a fueling source. We intend to use the system to control fuel deposition location in our studies of improved confinement regimes.

Department for Controlled Fusion Research, Association EURATOM-CEA, Cadarache, France

Gerardo Giruzzi has been a pioneer in the development of methods to understand the generation, transport, and more general role of suprathermal electrons in tokamaks. He is performing comprehensive Fokker-Planck and radiation transport simulations as part of a continuing successful effort to diagnose the level of interior magnetic fluctuations in TEXT-U.

General Atomics

The GA group has assisted the TEXT group by providing both advice and hardware for our ECRH experiments and by providing the means to condition the 110 GHz gyrotron. They intend to continue this help. In addition, the GA group (under Dr. W. P. West) has been developing a Li beam diagnostic using TEXT as a test bed. This work is expected to come to a close soon.

Hampton University (Propose to have graduate students on site)

A new collaboration is starting between Hampton and the TEXT group. It is expected that both a postdoc and students from Hampton will become involved with the TEXT experiment. An impurity (e.g., Li) pellet injector was loaned to the Hampton group. It will be upgraded before reinstallation on TEXT. On the theoretical side, Dr. V. A. Punjabi has started the analysis of TEXT data obtained with the SFX coils.

MIT (Graduate student on site)

Working under the guidance of Dr. R. D. Petrasso, a graduate student is studying the asymmetries of impurity concentrations in TEXT both with divertor and with ECH. This is a continuation of the collaboration which was initiated with the work of Dr. K. Wenzel.

NIST

The goal of this long-standing collaboration is the identification of energy levels in highly-ionized species. The work is done under the guidance of Dr. Jack Sugar.

ORNL

The feedback studies in the SOL are in collaboration with T. Uckan and B. Carreras of ORNL. T. Uckan will visit several times each year to participate in experiments.

RPI (Staff and graduate students on site)

This group and their diagnostic, the heavy ion beam probe (HIBP), help make TEXT a unique facility. The HIBP is the only diagnostic which can directly provide the plasma potential profile, the potential fluctuation

profile, the turbulence induced particle flux profile, or the internal low-wave vector magnetic mode structure. An upgraded system is now on line and operating routinely. The group intends to fully participate in all aspects of the TEXT program, in particular the improved confinement transition physics.

University of California, Davis

This group, under Prof. N. Luhmann, together with Dr. G. Cima of the TEXT group, is developing an ECE imaging system for installation on TEXT.

University of California, Los Angeles (Staff on site)

The UCLA group participates in all aspects of the TEXT program, by providing scattering measurements of fluctuations, and 2-D density profiles. Their scattering measurements still remain the standard by which other diagnostics are compared. They have successfully implemented a Faraday rotation polarimeter system that is now providing current density profiles during fast current ramps. These ramps are being used in an attempt to create reversed shear discharges for transport studies. The group intends to continue their work, with the addition of a reflectometer system, and a prototype of a TPX density system diagnostic.

University of Wisconsin at Madison

The group, under Dr. R. J. Fonck, installed the BES system on TEXT. They provided data on ion turbulence features and used TEXT as a facility to develop detectors for their General Atomics system. They intend to continue their role as advisors for the TEXT BES diagnostic and in investigating turbulence and transport mechanisms.

Theoretical studies

Columbia University

The Columbia experimental group is assisting the TEXT group with MHD stability studies, in particular the importance of conducting wall placement. In addition, Dr. A. Sen is involved with the edge turbulence control studies.

LANL

The code DCON, written by A. Glasser, is being used for MHD studies.

The Institute for Fusion Studies

This group at the University of Texas is providing assistance with Alfvén Wave Current Drive experiments and probe/plasma coupling studies (Dr. Swadesh Mahajan), conducting wall turbulence drives (Dr. H. L. Berk), impurity transport studies, edge turbulence studies (Dr. W. A. Horton)

The Fusion Research Center Theory Program

The FRC Theory Program at the University of Texas supports the TEXT-U experiments in the areas of equilibrium and MHD-stability calculations (E. R. Solano), fluctuation-data interpretation and transport theory and modeling of both core and edge plasma (D. W. Ross, J. C. Wiley, W. H. Miner), diagnostic development (P. M. Valanju), and Alfvén wave propagation and absorption (P. M. Valanju, D. W. Ross, with S. M. Mahajan of IFS).

Lodestar

The Lodestar group, under Dr. R. E. Aamodt provides theoretical assistance for the radio frequency heating, current drive and edge feedback experiments.

International

Institute of Physics, Chinese Academy of Sciences, Beijing, PRC

A long standing collaboration with Dr. Shao Bai Zheng of this institute continues with divertor concept studies tokamaks, and energy confinement studies during ECRH in TEXT.

Max Planck Institute for Plasma Physics, Garching

Two of the TEXT staff routinely visit IPP Garching for extended (up to 3 month) periods, participating in both data taking and analysis. Prof. K. Gentle is concerned with perturbative transport studies, and Prof. R. Bengtson is concerned with edge turbulence studies.

Institute of Plasma Physics, Hefei, PRC

Our 10 year collaboration with this institute continues, with the present focus being tokamak engineering studies.

Han Yang University, Korea

Dr. Kyu-Sun Chung is presently on a 1 year visit to TEXT. He is designing edge probes, operating them and analyzing data.

Korean Advanced Institute of Science and Technology

We continue our collaboration with this institute, who now operate the tokamak PRETEXT. Staff from TEXT have and will continue to visit and advise the KAIST staff on operations.

PROJECT DESCRIPTION

II. TOKAMAK AND PLASMAS

II. Tokamak and Plasmas

TEXT is a medium scale tokamak with

- auxiliary heating,
- diagnostics for complete turbulence and transport measurements,
- wall conditioning systems,
- systems for application of perturbations in electric field, rotation, impurity concentration, turbulence, and electron temperature
- diverted, poloidally limited, or toroidally limited configurations.

The basic physical parameters of the device are major radius of 1.05 m, minor radius ≤ 0.29 m, toroidal field ≤ 2.8 T, plasma current ≤ 400 kA and pulse length of 0.5 s.

This section contains a description of the present capabilities of TEXT-U. The plasmas are described first. This is followed by descriptions of the electron cyclotron resonance heating (ECRH) systems, the divertor, wall conditioning, diagnostics, and computer systems. The major, planned modifications described in this section are

- Installation of a 500 kW, 110 GHz gyrotron for high density ECRH
- Installation of inside launch antennas for high density ECRH
- Additional hardware and experiments to improve wall conditioning

Plasmas

Tokamak plasmas are produced in diverted or limited configurations in a boronized vacuum vessel and can be heated with 600 kW of ECRH. There are two basic open divertor configurations. In one of these, the equatorial single null (EQS), (see Figure II.1), the x-point is located on the midplane and on the high field side of the plasma. The other is a double null (DN) with both x-points on the high field side of the plasma. This particular configuration can be shifted up to produce a continuum of x-point configurations ranging from the double null to the upper x-point configuration shown in Figure II.2. The configuration in this figure is called a biased double null (BDN). Two basic limited configurations are also possible. One is poloidally limited on rail limiters as illustrated in Figure II.3. The other is toroidally limited on the tiles on the high field side of the vacuum vessel as shown in Figure II.4.

Figure II.1. The TEXT-U equatorial single null configuration. The measured distribution of D_α emission is shown as a false color image superimposed on a flux surface reconstruction for the discharge.

Figure II.2. The TEXT-U biased double null configuration. The measured distribution of D_α emission is shown as a false color image superimposed on a flux surface reconstruction for the discharge.

Figure II.3. Flux surface reconstruction for a TEXT-U poloidally limited configuration superimposed on a vacuum vessel drawing.

Figure II.4. Flux surface reconstruction for a TEXT-U toroidally limited configuration superimposed on a vacuum vessel drawing.

An example of plasma profiles is in Figure II.5. In this discharge, ECH power was deposited at the center of the plasma using two 60 GHz gyrotrons and one 56 GHz gyrotron. Each gyrotron generates up to 200 kW. For this same discharge, some time series traces are shown in Figure II.6. These traces were typical of operation prior to extensive boronization.

Figure II.5. Electron temperature and density profiles for an ECH heated BDN plasma in D with $B_T = 2.1$ T. Profiles are shown both before and during ECH.

A Hugill plot of TEXT-U data is shown in Figure II.7. It contains H, D, and He discharges in both diverted and limited configurations. The range of TEXT discharges appear to fall short of the Greenwald limit. TEXT discharges are usually tailored to the physics needs of an experiment so the graph reflects where we typically do experiments rather than machine capabilities. Recently though, as we began to investigate high confinement regimes, there has been an interest in obtaining high density discharges so that we can look more closely at Ohmic confinement saturation. After

boronization, we found that we could produce Greenwald limit discharges with little effort. The first observed is shown in Figure II.7. We are confident now that we can obtain routinely the Greenwald limit.

Figure II.6. Temporal traces for the discharge of Figure II.5.

Figure II.7. TEXT discharges in H, D, and He. Note that the Greenwald limit discharge indicates a major increase in discharge range.

ECRH Systems

At present, the TEXT-U plasma can be heated with three gyrotrons operating in the range of 56 to 60 GHz and generating a total of 600 kW. An example of an ECH heated discharge is in Figures II.5 and II.6. All three gyrotrons are configured for launch from the low field side thus limiting the density at which heating can occur. ECRH heating is used for experiments in H-mode, transient transport, and the transport effects of magnetic turbulence. We plan to add inside launch in order to achieve heating at higher density. We also plan to add a 110 GHz gyrotron that generates 500 kW. This gyrotron will be used for current drive experiments and additional heating for H-mode experiments. All of the equipment for the 110 GHz

system exists and is already paid for. The inside launch hardware was acquired as surplus from General Atomics.

At present, three gyrotrons are used to heat the plasma, two operate at 60 GHz and generate 200 kW each while the third operates at 56 GHz but also generates 200 kW. The typical pulse length is 50 to 70 ms. Overmoded waveguide transmission lines deliver the 56-60 GHz power to the TEXT-U vessel with typically 85-90% efficiency. A concise description of ECRH capabilities is in Table II.1.

Inside TEXT-U, the 56-60 GHz power is coupled to the plasma via two focused launchers (~6 cm spot size on axis; with one launcher toroidally steerable and the other poloidally steerable) and one unfocused launcher (~16 cm spot size). All 56-60 GHz launchers are located at the same toroidal location on the low-field side. Coupling of this power is by ordinary-mode heating at the fundamental cyclotron resonance ($B_T = 2.1$ T). Refraction, scattering, and absorption of the beam from the toroidally steerable launcher is viewed by a poloidal array of antennae located on the high-field side of the vessel directly opposite the toroidally steerable launcher.

gyrotron	1	2	3	4
frequency	56 GHz	60 GHz	60 GHz	110 GHz
max power	200 kW	200 kW	200 kW	500 kW
status	operational	operational	operational	start-up in 1996
launcher	focused toroidally steerable	unfocused	focused poloidally steerable	unfocused
spot size	6.0 cm, θ 7.0 cm, ϕ	5.0 cm, θ 6.5 cm, ϕ	17.0 cm, θ 15.0 cm, ϕ	5.0 cm, θ 5.0 cm, ϕ
heating mode at $B_T = 2.1$ T	O-mode fundamental	O-mode fundamental	O-mode fundamental	X-mode and 2nd harmonic
density limit	$3.8 \times 10^{13} \text{ cm}^{-3}$	$4.4 \times 10^{13} \text{ cm}^{-3}$	$4.4 \times 10^{13} \text{ cm}^{-3}$	$7.4 \times 10^{13} \text{ cm}^{-3}$

Table II.1. Gyrotrons for the ECRH heating system. The θ and ϕ in the spot size row refer to poloidal and toroidal extent.

Figure II.8. In-vessel configuration for the inside- and outside-launch systems

56/60 GHz Inside Launch X-Mode Improvements

Surplus inside launch waveguide hardware was obtained from D-III-D and will be used to provide TEXT-U with three inside-launch X-mode antennas for use with the three 56/60 GHz gyrotron systems. These antennas utilize a longitudinally split section of waveguide which is biased to suppress electron-cyclotron breakdown where the waveguide crosses the resonant electron-cyclotron surface. This technology was proven to work on

D-III-D for pulse lengths of up to 700 ms at full gyrotron power levels. Therefore, we expect that the waveguides should work with the 100 ms pulses that the TEXT-U 56/60 GHz ECH system can produce. The antennas will illuminate a focusing mirror mounted on the back wall of TEXT-U which will refocus the microwave beam and direct it back into the center of the plasma. The existing outside launch antenna systems will remain intact and can be reconnected without venting the tokamak. The in-vessel configuration for the inside- and outside-launch systems is shown in Figure II.8.

110 GHz Outside X-mode System Improvements

The 110 GHz gyrotron has long been considered critical to the H-mode program. After repeated delays in the development of the tube by Varian, the tube and all of the equipment required for installation are now available and paid for. Our original plans would have made the tube operational by the end of 1995, but uncertainties caused by the DOE decision to stop and reissue grants has caused us to reconsider our schedule. We need at least one year to install and make effective use of the gyrotron. This will not begin until this grant is accepted at the end of 1995.

A 500 kW, 110 GHz Varian gyrotron will be transferred from General Atomics to the University of Texas in 1995, along with a Vlasov mode converter and mode converter tank. This system was tested by General Atomics with the assistance of Fusion Research Center engineers in January 1995 at power levels up to 400 kW and at pulse lengths up to 500 ms. Installation of this gyrotron is scheduled to start in the fall of 1995, and RF operation should commence by late 1996. The system uses an optimized Vlasov mode converter designed by the University of Wisconsin, and is coupled to the tokamak by an evacuated 3.17 cm I.D. corrugated waveguide system. A vacuum window isolates the tokamak and waveguide/mode converter vacuum systems. Measurements by General Atomics indicate that this system should be able to launch a focused microwave beam with 350 kW of power into the tokamak. The outside launch X-mode antenna will be provided with a mirror system to facilitate both heating and current drive experiments. The power supply for this system is a modified MFTF-B neutral beam power supply connected to a transformer/rectifier set and powered by a motor generator system. It should be capable of producing the

design goal of 200 ms pulses, limited primarily by the thermal capacity of the waveguide vacuum window.

Once this gyrotron is in place the pulse lengths and power options will be as in Table II.2. Note that the first two rows list what is available now.

pulse length (ms)	power (kW)	gyrotrons	power supply
70	600	(1) 56 GHz (2) 60 GHz	capacitor bank
100	400	(2) 60 GHz	capacitor bank
200	500	110 GHz	motor generator

Table II.2. Pulse length and power options. The pulse length for each gyrotron is limited by the power supply. The pulse length of the 60 GHz tubes is further limited by heating of the tokamak window.

Work plan

- Install inside launch systems for 56-60 GHz
- Install 110 GHz gyrotron

The TEXT-U Divertor

TEXT was originally designed for operation with a full aperture poloidal limiter. It was modified to produce diverted plasmas in single or double null configurations or circular plasmas limited by either a toroidal limiter or by poloidal rail limiters. A cross section of the vacuum vessel is shown in Figure II.9.

Figure II.9. A cross section of TEXT-U showing the location of the divertor coils. The configuration sketches indicate the two basic divertor configurations, SN for single null and DN for double null.

The divertor coils are installed on the high field side between the vacuum vessel and the toroidal field (TF) coils and can be used to produce either double or single null configurations with high-field-side x-points. The currents in the upper and lower divertor coil sets are always parallel and both are antiparallel to that in the midplane coil. A single null (double null) configuration is produced if the current in the midplane coil is parallel (antiparallel) to the plasma current. Vertical stacks of tiles were added to the high field side of the vacuum vessel to control the concentration of metallic wall constituents in the plasma for diverted or toroidally limited

configurations. Each tile is made of graphite and coated with TiC to be sputter resistant for the range of plasmas that can be produced in a TEXT-sized device. The tiles are stacked vertically to extend from the bottom to the top of the vacuum vessel. For the most part, each stack is located beneath a TF coil and subtends a toroidal angle of 15° . This leaves a shadowed space (4° toroidally) between each of the coil stacks for diagnostics. As the stacks are toroidally discrete, the tile ends are contoured in the toroidal direction to accept the heat load.

Particular sets of tiles can and have been modified for specific purposes. One stack of tiles is instrumented with thermocouples, black body cavities, and tile probes. Thermocouples and black body cavities are added for IR camera calibration. The tile probes are needed to improve the scrape-off layer (SOL) measurements near the divertor tiles. The capability for biasing the tiles is also being added for turbulence control experiments described in section IIIB. Finally, there will be a capability for fueling through the x-point using fueling ports in the tiles. This is needed for fueling asymmetry experiments described in the section on Improved Confinement, IIID.

Wall Conditioning

Four techniques are used for wall conditioning: pulsed discharge cleaning, glow discharge cleaning, boronization, and tokamak shots. Through trial and error, we have assigned wall conditioning roles to each of these. We plan a series of experiments with the goal of completely understanding the relation between the boronization technique that we currently use and the resulting plasma properties that it affects, recycling and impurity concentration. This will allow us to improve conditioning techniques.

From the inception of operations on TEXT through 1994, it was the custom to use pulsed discharge cleaning in H or D for 12 hours each evening. On occasion, the pulse rate, or D/H pressure, and Ohmic heating current were reoptimized for the production of water vapor. During 1994, experiments demonstrated that glow discharge cleaning resulted in more rapid reduction of water vapor following vents. In early 1995, boronization using trimethyl boron was added.

The present conditioning regimen was optimized primarily by comparing several characteristics of the tokamak discharges after the particular technique was applied. These include loop voltage V_L , recycling at the vacuum vessel wall and the ratio of radiated power to chord averaged electron density. The lowest values of loop voltage and radiated power are achieved following boronization. The effects of boronization last for about 300 shots. Typical shot by shot progressions of V_L between boronizations is shown in Figure II.10. Immediately after boronization, V_L is approximately 1.2. The range for V_L before boronization was used on TEXT was 1.8 to 2.2. The hatched region in Figure II.10. V_L is allowed to increase to a value near 2 before the next boronization session. Between boronizations, glow cleaning in He is used to reduce water vapor that may result from changing of vacuum hardware or minor vacuum accidents. Pulsed discharge cleaning is now used only immediately after a vent or in those cases when it is necessary to completely strip the vacuum vessel walls after a failed boronization experiment.

Figure II.10. V_L versus tokamak discharge number following boronization. Prior to boronization the normal range for V_L was the hatched region

We plan to conduct experiments in wall conditioning. The goal is to understand the wall conditioning in TEXT and perhaps contribute to its understanding at large. There are three major components to this study:

- Characterize the glow discharge plasma and look for correlation between the glow parameters and the rate of deposition on the wall and the layer thickness. We have begun measurements of the glow cleaning plasma with Langmuir probes and with spectroscopy. We will supplement this work with measurements of the rate of deposition of the boron layer and with measurements of the layer thickness. The goal is to find the most efficient way to deposit boron on an unheated wall.
- Investigate the wall fueling problem observed during the first twenty tokamak discharges following boronization. Wall fueling is

uncontrollable during this interval. The principal problem with boronization of an unheated wall is that uncontrolled recycling sometimes follows. By correlating the physical parameters of the tokamak discharge such as neutral density, recycling rate, and edge n_e and T_e with the rate of deposition of the boron layer and with measurements of the layer thickness, it may be possible to make progress toward understanding this problem.

- Look for correlation between properties of the boron coating and the impurity concentration in tokamak discharges. It is clear that the correlation exists. In this study, the limits of discharge improvement due to boronization are actually being sought. Intensive study is required during the period immediately after boronization. Periodic observation is required thereafter to assess the degradation of the boronization effect.

Milestones

- Measure the properties of the glow discharge used for boronization and correlate with deposition rate and layer thickness.
- Correlate the deposition rate and the layer thickness with the recycling characteristics, impurity characteristics, and SOL parameters of tokamak discharges following the boronization. Measurements in tokamak discharges should continue throughout the full boronization cycle of one to two weeks.
- Add computer controlled glow cleaning to facilitate its use between shots and to improve the consistency of boronization with trimethyl boron.

Diagnostics

TEXT has excellent diagnostic access. It has a complete set of turbulence and transport diagnostics for the support of investigations of the physics of turbulence, to look for correlations between transport and turbulence, to conduct simple transport survey experiments, and for the validation of new diagnostics. The diagnostics layout is in Figure II.11. In the diagnostics context, TEXT offers inexpensive implementation of sophisticated diagnostics with a plasma that is relevant to plasma physics research in general and fusion research in particular. Table II.3 summarizes the available diagnostics and the region with which they are most closely associated in present experiments.

Figure II.11. Diagnostics Layout

Table II.3. The TEXT Diagnostics Set

measurement	technique	region
$T_e(r)$	Thomson scattering	confinement
$T_e(r)$	High res. ECE	confinement/edge
$T_e(r)$	ECE	confinement
$T_e(r)$	Langmuir probes	edge
$\tilde{T}_e$	Langmuir probes	edge
$\tilde{T}_e$	High res. ECE	confinement
$n_e(r)$	Thomson scattering	confinement
$n_e(r)$	FIR Interferometry (TEXT)	confinement
n_e	2mm μ wave interferometer.	confinement
$n_e(r)$	Langmuir Probes	edge
$n_e(r)$	Li beam (GA)	edge
$n_e(r)$	FIR Interferometry (UCLA)	confinement/edge
$\tilde{n}_e$	HIBP (RPI)	confinement
$\tilde{n}_e$	FIR Scattering (UCLA)	confinement
$\tilde{n}_e$	BES (with UW)	confinement
$\tilde{n}_e$	Langmuir probe	edge
$\tilde{n}_e$	Reflectometer (UCLA)	confinement
$\tilde{n}_e$	Phase Contrast Imaging	confinement
$\tilde{n}_e$	Li Beam (GA)	edge
$\tilde{n}_e$	D_α emission	edge
$\tilde{n}_e$	μ -wave scattering	edge
$T_i(r)$	passive spectroscopy	confinement/edge
$T_i(r)$	active CEX	confinement
$T_i(r)$	passive CEX	confinement

Table II.3. The TEXT Diagnostics Set
(continued)

measurement	technique	region
Z_{eff}	passive spectroscopy	confinement
$n_z(r)$	passive spectroscopy	confinement
$n_z(r)$	active charge exchange	confinement
$\Gamma(r), \tau_p$	passive spectroscopy	edge
$\Gamma(\tilde{n} \ \tilde{\phi})$	HIBP	confinement/edge
$\Gamma(\tilde{n} \ \tilde{\phi})$	Langmuir Probes	edge
$v_\theta(r)$	passive spectroscopy	confinement/edge
$v_\phi(r)$	passive spectroscopy	confinement/edge
$v_\theta(r)$	Mach probe	edge
$v_\phi(r)$	Mach probe	edge
$\phi(r)$	HIBP	confinement/edge
$\phi(r)$	Langmuir Probes	edge
$\tilde{\phi}$	HIBP	confinement/edge
$\tilde{\phi}$	Langmuir probes	edge
P_{rad}	Bolometry	confinement/edge
shape	magnetics	LCFS
shape	soft x-ray	confinement
β_θ	diamagnetic loop	LCFS

Table II.3. The TEXT Diagnostics Set
(continued)

measurement	technique	region
broadband soft x-ray	SBD array	confinement
$j\phi(r), q(r)$	FIR Polarimeter (UCLA)	confinement
$j\phi(r), q(r)$	active CEX	confinement
$j\phi(r), q(r)$	impurity pellet injection	confinement
f_e , superthermal	vertical ECE	confinement
f_e , superthermal	impurity pellet injection	confinement
$\tilde{b}_r$	impurity pellet injection	confinement
$\tilde{b}_r$	HIBP (RPI)	confinement
$\tilde{b}_r$	VECE	confinement
ionization	H α /D α monitor	edge

Perturbation Systems

On TEXT, there are a number of perturbative systems that are used in the transport and turbulence studies. These include ECH, a biased electrode, an active probe, an ergodic magnetic limiter, laser injection, modulated gas feed, and impurity pellets. The active probe is described in section IIIB, Edge Turbulence and Transport. ECH has already been described. The others are described below.

The Stochastic Field Experiment (SFX)

The ergodic magnetic limiter (EML) was pioneered on TEXT by a team from General Atomics working with TEXT staff. When the tokamak vacuum vessel was changed to accommodate diverted configurations, the external coils that generated this perturbation required redesign with consequent changes in the induced radial magnetic field structure. To avoid confusion, the new experiment was given a new name, SFX.

The stochastic field experiment uses external coils to produce a radial magnetic field perturbation which is spatially resonant with the pitch of equilibrium magnetic field lines on rational surfaces near the plasma edge. Because of the resonant behavior, the SFX is a low current, low cost technique for perturbing edge thermal and particle transport. When the coils are run at low current, they produce isolated magnetic islands. At higher current, the islands overlap producing stochastic regions. By appropriately adjusting the spatial phase of the perturbation, intrinsic tearing modes can be spun down into disrupting and non-disrupting locked modes.

SFX's have several applications. First, the SFX can be used as a limiter or divertor. An example is the Tore Supra ergodic divertor which

Table II.3. The TEXT Diagnostics Set
(continued)

measurement	technique	region
broadband soft x-ray	SBD array	confinement
$j\phi(r), q(r)$	FIR Polarimeter (UCLA)	confinement
$j\phi(r), q(r)$	active CEX	confinement
$j\phi(r), q(r)$	impurity pellet injection	confinement
f_e , superthermal	vertical ECE	confinement
f_e , superthermal	impurity pellet injection	confinement
$\tilde{b}_r$	impurity pellet injection	confinement
$\tilde{b}_r$	HIBP (RPI)	confinement
$\tilde{b}_r$	VECE	confinement
ionization	H α /D α monitor	edge

Perturbation Systems

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SFX's have several applications. First, the SFX can be used as a limiter or divertor. An example is the Tore Supra ergodic divertor which reduces impurity influx, and lowers the edge temperature. Secondly, the SFX can be used as an edge perturbation tool for transport studies, as the ergodic magnetic limiter (EML) was used on TEXT. We've seen previously on TEXT that the edge radial electric field and rotation velocity shear are affected. Shear and radial electric field are both thought to play an important role in determining plasma confinement. We also found that the SFX enables us to partially decouple thermal and particle transport since thermal transport is enhanced in stochastic regions, whereas particle transport is

increased by isolated magnetic islands. Finally, the coils can be used to study locked mode physics, and the attendant discharge control issues for locked-mode prone larger machines.

Figure II.12. Isometric drawing of the current-carrying elements of an individual coil. The feeds to the power supply have been omitted for clarity. Arrows indicate direction of current flow.

The new SFX coils are shown in Fig. II.12. The 3 coils, located under TF coils, each have 6 current loops producing a broad poloidal mode spectrum from 2 to 9, with a dominant mode number of 3. The lower m than on TEXT allows a deeper penetration of the perturbing field since

$$b_r \propto r^{-(m-1)}$$

There are 2 types of coils which approximately impose a toroidal mode number n of 2; however, significant $n = 1$ modes are driven as well. The SFX coils will be used with all magnetic configurations of TEXT-U: circular, single, and double null plasmas. The existing power supply can drive up to 10 kA in the coils which produces a poloidally and toroidally averaged radial field of $(3 \times 10^{-4}) B_\phi$. Because of

the resonant perturbation, this low field will produce islands and stochastic regions in the plasma. If we apply the SFX to a diverted plasma as in this magnetic puncture plot for a typical diverted plasma (Fig. II.13), we produce a highly stochastic region in the vicinity of the separatrix. This will have application in studying the L-H transition. With the SFX and excellent

turbulence diagnostics on TEXT-U, we have a unique combination of knobs on the transport driving terms, and specialized diagnostics for understanding tokamak transport, as well as locked mode physics.

Figure II.13. Poincaré sections taken for an equatorial single null plasma with $I_p = 135$ kA, $B_0 = 2$ T, $I_d = 21$ kA and $I_{SFX} = 8$ kA. Sections are taken for 9 different initial conditions integrated 150 times around toroidally. Minor radius is taken from machine center at $R = 1.05$ m. Poloidal angle is taken increasing upwards from the outside mid plane, thus $\theta = 180$ corresponds to inside midplane.

Impurity pellet injection

Impurity pellet injection has proved to be a useful and economical technique for studying tokamak plasmas. Impurity pellets can be used as a

perturbation tool, as a plasma diagnostic, for wall conditioning, and in improving our understanding of pellet ablation for fueling applications. We constructed a new single stage pneumatic injector for TEXT-U. Limited port allocations have prompted us to construct a small injector which can be installed on restricted port space in any orientation. The new injector utilizes fast shutters rather than long guide tubes to block the propellant gas. The injector is capable of injecting pellets of any solid material, e.g. Li, LiH, B, C, with radii of 70–300 μm , at velocities ranging from 30–700 m/s. Pellet penetration can be varied from a few cm to complete penetration, with a density perturbation ranging from $0.05\text{--}6 \times 10^{19} \text{ m}^{-3}$. This will provide a flexible tool for impurity and thermal transport studies, for q profile and suprathreshold electron diagnostic applications, for wall conditioning using Li and B, and for fueling studies involving LiH and plasma accelerated pellet injection. The responsibility for this equipment has been transferred to Hampton University as the first of the UT/Hampton collaborations on TEXT-U.

Laser Injection

The laser injection systems are well standardized so this description will be brief. A 5J Q-switched ruby laser is used to inject small quantities of impurities into the plasma. In the course of atomic physics and plasma physics experiments, essentially all of the elements with $Z < 70$ have been successfully injected. As a result of injection, the density perturbation can be as small as 1% with essentially no noticeable effect on T_e . At the other extreme, the density perturbation can be as much as 50% near the plasma edge. The normal use for the laser injector is in support of impurity transport measurements. It has been used extensively to inject heavy elements for measurement of energy levels of highly ionized species. A particularly interesting experiment, cold pulse propagation, is described in section IIIA on Core Turbulence and Transport.

Biased Electrode

A biased electrode was successfully used in TEXT-U experiments and proved to be a convenient means for perturbing E_r . The tip of the electrode is pyrolytic graphite and is shaped to minimize the local heat flux. The electrode is 6.3 cm in the toroidal direction, 2.5 cm in the poloidal direction

and 1.4 cm radially. A boron nitride sleeve insulates the stainless steel electrode support so that the support does not short out the electric field. Experiments are typically conducted with the bottom of the electrode tip (the innermost side) at a minor radius of 24 cm while the outer rail limiter is set at 27 cm. The power supply is adequate to supply up to 150 A for biases that range from -500 to +300 volts with respect to the vessel. Cleaning techniques have been developed to minimize impurity contamination from the probe during the tokamak discharges.

Computer Systems for Data Acquisition and Analysis.

The TEXT computer systems consist of a VAX cluster, a UNIX cluster, and a large number of desktop computers. The VAX cluster is used for data acquisition and analysis. The UNIX cluster is used primarily for computation intensive activities in simulation and analysis. A few desktop computers are used for control of individual experimental apparatus, but the majority reside on the desks of the experimental staff.

The VAX cluster consists of three computers, an 11/785 with 48 MBytes of memory, an 8350 with 28 MBytes of memory and 2 processors, and a 6430 with 192 MBytes of memory and 3 processors. These share 10 GBytes of storage on 11 disk drives. These computers are used for data acquisition and analysis. Currently, we are limited to a data acquisition rate of 2.5 MBytes/Minute by the CAMAC configuration. By January 1996, this will be increased to 5 MBytes/Minute. These computers also provide support for the TEXT data archive. Typically, 3500 shots are on disk and available for analysis at any one time. The remainder are readily accessible from tape.

The Fusion Research Center (FRC) owns (2) IBM RISC 6000s which are part of a cluster that is shared with FRC-theory and with the Institute for Fusion Studies. These computers are used primarily to run the equilibrium code, EFIT, the predictive transport code, CHAPO, and to act as server for MATHEMATICA.

Each staff member and student in the FRC has access to a desktop computer. The typical configuration for a staff member is a Macintosh IIsi with 9 MBytes of memory and an 80 MByte disk. Seven physicists have Power Macintosh 6100 class desktop computers. All physicists will be

provided with this class of machine during fiscal year 1996. The typical configuration for a student is a Macintosh Plus with 4 MBytes of memory and a 40 MByte disk. Two Power Macintosh 6100 and four Macintosh IIsi class machines are available to the students for shared use.

The major commercial software packages that are available include INGRES for database management and IDL and IMSL for data analysis. The major packages acquired from the community include the Oak Ridge CAMAC Device Driver Interface Software, EFIT and MAGDAT for equilibrium analysis, B2 for divertor plasma simulation, EIRENE for neutral transport, ASTRA for transport simulation, TORCH for simulation of ECRH, LOCUS for data analysis, and NCAR for graphical display. Software created locally to support specific aspects of our own work include CHAPO (transport simulation code tailored to our work in turbulence) and NUT, a fast 3-D neutral transport code.

PROJECT DESCRIPTION

III. PROPOSED RESEARCH

III. Proposed Research

<u>Research Area</u>	<u>Section</u>
Core Turbulence and Transport	IIIA
Edge Turbulence and Transport	IIIB
Turbulence Analysis	IIIC
Improved Confinement	IIID
ECH Physics	IIIE
Alfven Wave Current Drive	IIIF
Diagnostic Development	IIIG

PROJECT DESCRIPTION

III. PROPOSED RESEARCH

IIIA. CORE TURBULENCE AND TRANSPORT

IIIA. Core Turbulence and Transport

The first confinement measurements on tokamaks demonstrated that transport was anomalous in the sense of being far more rapid than neoclassical predictions. A plethora of small-scale instabilities existing under typical tokamak conditions provided a natural rationale for this behavior, and the advent of fluctuation diagnostics in the early 1980's offered the possibility of explaining transport. This was, in fact, a primary motivation for the original TEXT project. Transport was, and continues to be, the one crucial aspect of tokamak performance whose basic physics is not understood.

Subsequent research has greatly illuminated the subject, especially in revealing the complexity and subtlety of turbulence and transport, but the goal of explaining transport will require further significant theoretical and experimental advances. The problem is both most important and most severe in the plasma core (interior to the particle source region, i.e., $r/a < 0.8$ in TEXT). Although both density and electron temperature fluctuations have now been observed in the core and many intriguing associations with transport uncovered, causal and quantitative relations are not yet established. The specific instabilities and drives for the observed fluctuations are also unknown.

TEXT is the ideal device for continuing this work because it has both adequate profile diagnostics to measure local transport coefficients and a unique complement of existing and planned interior fluctuation diagnostics: far-infrared (FIR) collective scattering (both vertical and horizontal views),¹ a 2-MeV heavy-ion beam probe (HIBP),² correlation radiometry of electron cyclotron emission (CRECE),³ a helium beam-emission spectroscopy (BES) system,⁴ Thomson scattering (under development - see Appendix A), and microwave reflectometry¹ (planned), our experience with inferring internal magnetic fluctuation levels,⁵ and our studies of *fluctuation-induced* transport.^{5,6,7,8}

Work on TEXT has shown that magnetic fluctuations are not important for transport (at least for thermal particles at low β).^{5,9} We propose to extend this work to higher β and continue studies of the effects of magnetic turbulence on superthermal and runaway electrons. However, the main thrust will be directed to the alternative – electrostatic turbulence.

Electrostatic Turbulence and Transport

The particle and electron energy fluxes driven by *electrostatic* fluctuations are given by

$$\Gamma_e^{ES} = \langle \tilde{n}_e \tilde{v}_E \rangle = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B,$$

$$Q_e^{ES} = \frac{3}{2} \langle \tilde{p}_e \tilde{v}_E \rangle = \frac{3}{2} n_e \langle k \tilde{T}_e \tilde{E}_\theta \rangle / B + \frac{3}{2} k T_e \Gamma_e,$$

where $\tilde{n}_e$, $\tilde{T}_e$, and $\tilde{p}_e$ are the fluctuating parts of the electron density, temperature, and pressure, respectively, and $\tilde{v}_E = \tilde{E}_\theta / B = -\nabla_\theta \tilde{\phi} / B$ is the radial component of the fluctuating $\mathbf{E} \times \mathbf{B}$ velocity. The brackets indicate ensemble (time) averages. The ion energy flux is analogous to that of the electrons, but we have concentrated on the particle and electron energy channels because of better diagnostics.

If one could measure the required averages locally and average over a flux surface, one could make a purely empirical comparison of turbulent fluxes with transport. (This program has been carried out with some success in the edge.) Although this would be an experimental *tour de force* in the core, it would not, by itself, suffice to provide fundamental understanding. That will require an interaction of theory and experiment. These equations certainly indicate the important quantities that must be compared with theory. We have a variety of diagnostics to characterize $\tilde{n}_e$, new measurements of $\tilde{T}_e$, and evolving measurements of $\tilde{E}_\theta$ from the HIBP. Specific theories or theoretical relations, e.g. the Boltzmann relation $e\tilde{\phi}/kT_e \sim \tilde{n}_e/n_e$, can reduce the number of quantities that need to be measured independently.

There are a number of theoretical ideas and models, but none has reached a stage of development suitable for classical experimental "verification," for which a clear, precise experimental program could be proposed. Rather, the role of experiment now must include characterizing the phenomena as a guide to theory as well as critical tests of key ideas in various theoretical models. Experiments must supply assistance and direction for the development of good theory. We propose a broad experimental program with many elements to provide this information.

A major element in this program is an assessment of the extent to which the observed density fluctuations could account for the total fluxes of particles and electron energy in the core. Estimates of these fluxes in TEXT have been plagued by an apparent discrepancy between the 500-keV HIBP and FIR scattering measurements of the poloidal wave-number spectra.^{8,10} The HIBP, using the two-point correlation technique, found the fluctuations to be of long wavelength ($\bar{k}_\theta \lesssim 0.5 \text{ cm}^{-1}$) and high phase velocity ($\gtrsim 6 \text{ km/s}$), while the scattering system indicated $k_\theta \gtrsim 2 \text{ cm}^{-1}$ and lower phase velocity ($\lesssim 3 \text{ km/s}$). The computed quasilinear fluxes were found to be negligible for the low- k mode seen by the HIBP while in adequate agreement with the observed fluxes for the drift-wave-like fluctuations seen by FIR scattering.⁸ However, the latter statement cannot be made with certainty, since scattering could not determine the absolute power in the drift-wave feature. Therefore, characterization of the core turbulence is of utmost importance on TEXT-U.

The $\tilde{n}_e$ spectrum is measured, now fairly routinely, by FIR scattering, the 2-MeV HIBP, and most recently, BES. The $\tilde{T}_e$ spectra is measured by ECE correlation radiometry. Since BES, the HIBP, and CRECE perform two-point correlations which can be difficult to interpret when there exist more than one mode, most of the data have been taken at low densities, where the influence of an ion feature seen by FIR scattering at higher densities¹¹ is minimized. The following is a brief review of the status of these measurements, followed by interpretation and future work.

ECE Correlation Radiometry

Tremendous progress has been made during the past twelve months in measuring electron temperature fluctuations using correlation radiometry of electron cyclotron emission (CRECE) in the core of the TEXT-U tokamak. (Descriptions of the technique and system are contained in Appendix B.) The measurement technique has been proven,¹² and work has begun to more fully characterize the measured turbulence. As of April, 1994, the relative amplitude of these fluctuations, $\tilde{T}_{e,rms}/T_e$, and the associated power spectrum over most of the plasma minor radius had been measured. The relevance of these fluctuations to electrostatic heat transport had been investigated, with the conclusion that long wavelength modes do not significantly contribute to anomalous heat conduction.^{9,12} During the past year this work has been further extended to include measurements of ℓ_r and fluctuations off the equatorial midplane. This work necessitates a thorough understanding of both the spatial and minimum signal level resolution capabilities of the CRECE diagnostic.

Poloidal asymmetry of electron temperature fluctuations

Spectra of the turbulent electron temperature fluctuations have now been measured on both the top of the plasma and the inside midplane in addition to the outside midplane. Measurements at the top of plasma are accomplished by shifting the entire CRECE antenna system vertically. The ECE resonance is placed on the vertical plane through the plasma magnetic axis, and the plasma is shifted vertically to scan the minor radius. This configuration has the additional benefit that the CRECE sample volumes are aligned such that maximum resolution is obtained in the poloidal direction.

As is clear from Fig. IIIA.1, there is considerable asymmetry in the spatial distribution of the temperature fluctuations. Plotted are the power spectra of the turbulent electron temperature fluctuations for three different locations in the plasma, with the sample volumes at roughly the same minor radius. Data from the outside equatorial plane show the largest power in these fluctuations, while the inside midplane shows almost an

FIG. IIIA.1. Power spectra of electron temperature fluctuations for a "standard" TEXT-U limiter discharge indicating the poloidal asymmetry in the turbulence.

order of magnitude less. Some of this attenuation is due to the larger emission volumes on the inside as a consequence of being beyond the focus of the lens; however, experiments have shown that defocusing affects only the high frequencies.¹² The spectrum from the plasma top is intermediate in intensity. The data presented refer to a "reference" limiter discharge of 27-cm minor radius, toroidal field of ~ 2 T, plasma current of ~ 200 kA, and chord-averaged electron density of $\sim 2 \times 10^{19} \text{ m}^{-3}$.

A cohesive understanding of these results has yet to emerge. The most obvious interpretation is that the fluctuations have a ballooning character. However, several details still need to be investigated:

- Is the ballooning nature due simply to a drop in fluctuation amplitude on the inside, or is it due to a shift of the turbulence to shorter wavelengths beyond the resolution of the CRECE diagnostic? One might expect somewhat larger wave numbers on the high-field side for two reasons: $k_\theta \sim 1/\rho_s \sim B_T$ scaling; and $k_\theta \sim \omega/v_\theta$, where ω is poloidally constant but $v_\theta = v_\theta(\text{plasma frame}) + |E_T/B_T|$ is smaller on the high-field side. However, the amplitude on the inside is reduced over the entire frequency band, rendering this explanation at best incomplete.

- Is the attenuation at the top relative to the outside due simply to a drop in fluctuation amplitude, or is it due to the poorer radial resolution on top, implying a significant mean radial wave number (or wave-number spread).
- It is notable that the power in the fluctuations at the top is significant out to the Nyquist frequency of the acquisition system. Is this additional power due to enhanced k_θ resolution when the tall-but-thin emission volumes are located at the plasma top?
- Measurements to date have only been made on the midplane and in the upper plasma. What is the nature of the change in the fluctuation spectra as one progresses around the plasma at the same minor radius?

An intensive investigation is underway and planned for the next grant period to answer these questions.

Correlation lengths, propagation, and emission-layer thickness

As a next step in understanding the temperature fluctuations, considerable effort has been made in measuring both ℓ_r and ℓ_θ . We have been particularly successful in measuring ℓ_r .¹³

For the same reference discharge condition, the cross correlation of a 200-MHz wide fixed-frequency filter in conjunction with a 200-MHz wide YIG filter was measured for separations ranging from 3 to 30 mm. The measured cross coherence as a function of radial separation for each of the 32 frequency bands was fit to a smoothly decreasing function. The lower frequency data were best fit by a Lorentzian, while the higher frequencies were best fit by a Gaussian. The half-width at half-maximum, which characterizes the radial correlation length of the temperature fluctuations, is plotted as a function of frequency in Fig. IIIA.2 at three radial locations on the outer midplane.

There appears to be a frequency band (highlighted by open symbols in the figure) that exhibit longer correlation lengths (~ 2 cm) than the remainder (~ 1 cm). For $r/a = 0.4$, the longer correlation lengths and large scatter

FIG. IIIA.2. Measured radial correlation length of electron temperature fluctuations.

at the lower frequencies are caused by the persistent sawtooth activity. Data above 170 kHz are in the noise region of the spectrum and show a random distribution. In addition, this longer correlation length increases with decreasing radius. The frequency band corresponds to the persistent feature seen in the temperature fluctuation spectra,^{9,12} which is localized to the gradient region of the electron temperature profile. Results of these measurements may seem counter-intuitive, since one might expect high frequencies to have shorter correlation lengths. The results, however, are consistent with similar measurements of density fluctuations by BES.

These data have provided an unexpected result. The measured ~ 1 cm correlation length can only be taken as an upper-limit estimate of the true ℓ_r , since the calculated width of the emission volume of the ECE radiation

is of this order.¹⁴ Conversely, this measurement can be viewed as an upper limit on the true emission volume width, and represents the first experimental determination of the ECE resonance layer width.

The mean phase shift between the signals from the two emission volumes provides information on the radial propagation of the turbulence. For the data above, no phase shift was seen over the entire frequency band, i.e. $\overline{k_r} \approx 0$.

Heavy-Ion Beam Probe (HIBP)

The 2-MeV HIBP has been operated at energies up to 1.9 MeV using two injection beam lines and two energy analyzers. In contrast to the previous 500-keV HIBP on TEXT which had access only to the upper outside quadrant of the plasma, the present 2-MeV system has access to approximately 70% of the plasma cross section, including low- and high-field sides and top and bottom regions of the plasma. Further details of the system are contained in Appendix C. This added capability has resulted in the observation of a ballooning structure in the density fluctuation spectra,¹⁵ as shown in Fig. IIIA.3. A broadband mode with average frequency around 150 kHz, also observed earlier by the 500-keV HIBP, is not evident in the high-field region of the plasma. In addition, the mode amplitude is reduced at higher densities and upon application of ECRH. Initial analysis of this ballooning structure shows that it has many of the characteristics of trapped-electron modes.

Two-point correlation measurements to characterize propagation of the mode (as well as the remainder of the spectrum) are complicated by the ballooning asymmetry and the separation, size, and orientation (with respect to flux surfaces) of the sample volumes in different regions of the plasma. In most regions, the sample volumes are oriented in such a way that the measurements are sensitive to both radial and poloidal propagation. Interpretation of the data with respect to the finite sample-volume formalism of Ross et al.¹⁶ are ongoing. For example, taking $\overline{k_r} = 0$ and values for the radial and poloidal correlation lengths ℓ_r and ℓ_θ of 0.5 cm and 1 cm,

Plasma

$$B_t = 2.1 \text{ T}$$

$$I_p = 200 \text{ kA}$$

$$n_e = 2 \cdot 10^{13} \text{ cm}^{-3}$$

FIG. IIIA.3. Ballooning structure (at ~ 150kHz) seen in the density fluctuations by the 2-MeV HIBP on the low-field side of a reference TEXT-U limiter discharge.

respectively (consistent with BES data, to be presented later), HIBP data from the upper plasma is consistent with propagation in the electron diamagnetic direction at a phase velocity v_θ of $\lesssim 3$ km/s ($\bar{k}_\theta \gtrsim 2$ cm $^{-1}$). This interpretation is by no means unique, however, since $\bar{k}_r$, $\bar{k}_\theta$, and correlation lengths may all be poloidally nonuniform.

The installation of the new upper analyzer will allow a 2-D mapping of turbulence over $\sim 90\%$ of the plasma in terms of mode location, amplitude, and propagation, hopefully shedding light on the radial/poloidal propagation question. Similarly, an array detector for density fluctuation measurements, being developed in cooperation with InterScience, Inc., will allow detailed measurements of density fluctuation power in both frequency and wave number space and will provide information about beam modulation.

The 2-MeV HIBP measures larger wave numbers than the 500-keV system. Some of the differences might be instrumental; the sample volumes using the lower analyzer of the 2-MeV system are somewhat closer together, which better enables detection of features having shorter wavelengths and correlation lengths. The higher beam energies, in turn, reduce any beam attenuation-modulation effects which tend to lower the apparent wave numbers.^{16,17} However, it should be stated that the instrumental limitations of the 500-keV system were investigated theoretically and found not to be serious.^{17,18} Experiments specifically investigating this question will be performed before the new upper analyzer is installed by derating the accelerator to < 500 keV and using the old upper energy analyzer (simulating the old 500-keV system).

To interpret the phase velocity of the turbulence (measured in the lab frame), one needs to know the equilibrium radial electric field E_r in order to compute the poloidal velocity in the plasma frame (moving at the $\mathbf{E} \times \mathbf{B}$ velocity $v_E = -E_r/B$). In the past year, a major effort of the HIBP research team was directed towards preparing, testing, calibrating, and understanding the response of the lower analyzer for plasma potential and electric field profile measurements. A potential profile obtained by using the standard multi-shot method where profiles are obtained by combining data col-

lected during several similar shots is shown in Fig. IIIA.4 for the reference TEXT-U limiter discharge defined earlier. (The profile is uncertain by a small additive constant, usually provided by a Langmuir-probe measurement in the edge.) The analyzer geometric parameters have been modified several times in order to improve its performance.

FIG. IIIA.4. Plasma space potential profile measured by the 2-MeV HIBP for a reference TEXT-U limiter discharge.

Recently, attempts at measuring plasma potential profiles in a single shot by sweeping the beam across the plasma have been very encouraging. This method will be very useful during perturbation experiments in which profile information is needed before and after the perturbation in a single shot. In addition, a fast sweep system (~ 100 kHz) using a single detector set is being considered for local electric-field measurements. The fast sweep allows probing two positions in the plasma within a time interval in which the plasma potential distribution doesn't change significantly.

Plasma-potential fluctuations $\tilde{\phi}$ have so far been observed with the 2-MeV system only in the plasma core during large sawteeth induced by ECRH. The apparent correlation, observed using both spectral and wavelet analysis, between $\tilde{\phi}$ and the sawteeth will be studied further. The data sampling rate allows detection of changes within 1 μ s.

Beam-Emission Spectroscopy (BES)

Since the last progress report (July, 1994), performance of the BES system has been dramatically improved using new cryogenically cooled detectors and hydrogen as the neutralizer gas in the diagnostic neutral beam. Further details of the system are described in Appendix D. The improved signal-to-noise ratio (SNR) allows measurements in to $r/a \approx 0.5$. Shown in Fig. IIIA.5 are the cross power and phase between two observation volumes at $r/a \approx 0.65$ and separated poloidally by 1 cm for a reference discharge defined earlier.

In contrast to data at $r/a \approx 0.9$ (Fig. 1 of Ref. 9) there is an apparent lack of clear propagation in the ion diamagnetic direction of the feature at low frequencies (≤ 25 kHz) and the appearance of two "electron features" at ~ 75 and ~ 125 kHz. The phase shifts measured for all three features are very small. The remainder of the spectrum propagates in the electron diamagnetic direction at a phase velocity of ~ 3 km/s (accounting for finite emission-volume effects), consistent with electron drift waves and FIR scattering results,¹⁹ and exhibits a poloidal correlation length of $\ell_\theta \approx 1$ cm. At the time of writing, the fluctuations at low frequencies appear to be dominated by noise on the DNB during this run, and perhaps sawteeth, consistent with the observed zero phase and long poloidal correlation lengths. This noise may dominate any ion feature that might exist. Although they also exhibit near-zero phases, the features at ~ 75 and ~ 125 kHz do not appear to be due to DNB noise by virtue of their relatively small values of $\ell_\theta \approx 1.5$ cm. Future experiments will address these issues.

FIG. IIIA.5. Cross power (top) and phase (bottom) measured between BES channels at $r/a \sim 0.65$ spaced poloidally by 1 cm. Discharge condition: reference TEXT-U limiter discharge.

Similar correlation measurements were performed in the radial direction. Although the orientation of the emission volumes was not optimum, the inferred correlation length of the background electron feature was $\ell_r < 1$ cm and no appreciable radial phase was observed ($\bar{k}_r \approx 0$).

FIR Scattering

The UCLA far-infrared scattering system is presently operational in either vertical- or horizontal-view mode. Data taken on TEXT-U was found to be very similar to that obtained by the vertical-view system on TEXT.¹⁹ Of particular relevance to the previously presented data is the observation of "inverse ballooning," manifested by a "quasi-coherent mode"²⁰ residing only on the *high-field* side of the plasma and characterized by relatively narrow spectra (as low as $\Delta\omega/\omega \sim 0.1$, $\Delta k_\perp/k_\perp \sim 0.35$) and high mean wave number $\bar{k}_\perp \sim 5\text{-}8$ cm⁻¹).

Discussion and Future Plans

Perhaps as expected, the additional fluctuation diagnostics and spatial coverage of the plasma have created additional questions rather than resolving those already existing. Nevertheless, there are significant similarities among the diagnostic observations -

- The HIBP, CRECE, and FIR scattering observe a rather broad "feature" in the spectrum centered about 100 - 150 kHz (depending on radius and plasma condition) on the low-field side. This feature propagates in the electron diamagnetic direction (HIBP, FIR scattering).
- Both BES and CRECE measure similar correlation characteristics - the correlation length of the "background" turbulence just below ~ 75 kHz is short (≤ 1 cm) while that of a feature above ~ 75 kHz is longer (1.5 - 2 cm). Furthermore, there is no clear net radial propagation ($\bar{k}_r \sim 0$).

Questions yet to be resolved

- Are the poloidal asymmetries in the T_e fluctuation amplitude seen by CRECE (lent credence by the HIBP results) and in phase measurements by the HIBP real, or simply consequences of sample-volume shape and orientation? If real, the asymmetries must be characterized before estimating the electrostatic fluxes.
- How does one reconcile the ballooning structure seen by the HIBP and CRECE on the low-field side with the quasi-coherent mode seen on the high-field side by FIR scattering? Is the answer that the quasi-coherent mode is of wave numbers above the resolution of the other diagnostics, while the scattering cannot localize the low-k fluctuations?
- What are the natures of the features seen by BES at ~ 75 and ~ 125 kHz? Although they both exhibit much faster phase velocities than the background turbulence, do either have any connection to the broader feature centered about 100 - 150 kHz seen by the other diagnostics on the low-field side?

In light of the apparent poloidal asymmetries observed by the HIBP and the CRECE system, resolution of the above questions is made difficult by the lack of overlap in the spatial coverage of some of the diagnostics, e.g., BES is only on the plasma bottom, CRECE - the inside and outside mid-planes and top. Furthermore, the sample volumes of the HIBP pick up both radial and poloidal components of the turbulence, preventing unambiguous determination of either at a specific location. Poloidal correlation length and propagation data from the CRECE system, which would add further information, is not yet available.

The bimodal structure seen by BES near the edge,⁹ i.e., with the low-frequency mode propagating in the ion diamagnetic direction, is similar to the spectra seen in the far edge ($r/a \gtrsim 0.9$) of TFTR.²¹ Nothing can be said presently about an ion feature deep in the core plasma of TEXT-U until the issue of DNB noise is sorted out. The ion mode seen by BES near the edge and its density scaling are similar to the ion feature which was observed at higher wave numbers by FIR scattering on TEXT. In fact, they may be the same mode; future work will investigate this conjecture. However, the clear propagation of the low-frequency mode in the ion diamagnetic direction seen by BES is not evident in HIBP data, raising the specter of some instrumental effect (e.g. beam modulation by fluctuations in the SOL). Understanding this difference is a subject of future work, as is obtaining independent data from the CRECE system with poloidally separated emission volumes.

As for the electron mode, new data from the 2-MeV HIBP appears to be more consistent with drift-wave expectations and FIR scattering measurements of $\bar{k}_\theta$ and phase velocity, but as pointed out earlier, this is only an interpretation based on certain assumptions ($\bar{k}_r \sim 0$) which have not been unambiguously verified. The features seen by BES at ~ 75 and ~ 125 kHz at its innermost locations ($r/a \sim 0.5$) are significantly faster than, and dominate, the background electron feature. It must be understood why they are not evident in HIBP and CRECE data, requiring a coordinated effort by all

the diagnostics on the same discharge condition in as close to the same plasma location as possible.

FIR scattering, in turn, will contribute to this effort by attempting to localize its low-wave number channels to the interior. These efforts include correlating two sample volumes (at the same k) at different positions in the plasma and using local perturbations (EML, MHD islands, sawteeth, etc.) to help localize the measurements. Perhaps the most promising technique is to cross-correlate the signals from horizontal and vertical views, for which the correlated signal is presumed to come from the overlapping scattering volumes. These studies can be performed during diagnostic commissioning in the background and therefore do not need dedicated run time.

The "quasi-coherent mode" seen by FIR scattering on the inside mid-plane has potentially important implications for transport. The new horizontal-view scattering system will elucidate the k_r - k_θ composition of the mode, important for the transport estimates. It is doubtful that the HIBP, BES or CRECE can achieve the requisite high- k sensitivity to contribute to the fluctuation studies (not to mention that BES is dependent on the diagnostic neutral beam which passes vertically through the plasma center). However, the HIBP can contribute by measuring plasma potential to determine the $\mathbf{E} \times \mathbf{B}$ velocity of the mode.

The culmination of all these efforts would be characterization of the turbulent mode(s) operative in the plasma core, including amplitude, propagation, and any poloidal asymmetries. In the context of the quasilinear estimates, a verdict could then be reached on the relevance of electrostatic fluctuations to core transport. A parallel effort would be made to identify the modes with respect to theory.

In principle, the particle flux defined earlier can be directly measured by the HIBP since it can also measure (in principle) the fluctuating plasma potential $\tilde{\phi}$ in the plasma interior, unique among fluctuation diagnostics. The SNR of the old system was insufficient for core measurements although a new type of detector with higher $\tilde{\phi}$ sensitivity is under develop-

ment at RPI and will be tested on the 2-MeV system during the next grant period. Once established, these measurements would be accompanied by particle source and density profile measurements to determine the actual particle flux. A successful culmination of these measurements would be a benchmarking of the quasilinear theory, and more importantly, a definitive statement on the relevance of electrostatic fluctuations to core *particle* transport.

As mentioned earlier, the CRECE system has determined that long wavelength modes do not significantly contribute to anomalous heat conduction. If future data from the fluctuation diagnostics indicates that insignificant power exists at higher wave numbers, electron heat conduction due to electrostatic fluctuations could be judged insignificant. If, however, there is significant power, knowledge of the phase between $\tilde{T}_e$ and $\tilde{\phi}$, obtained from quasilinear calculations or in principle by cross-correlating CRECE signals with HIBP potential-fluctuation signals, would be required. Since the two diagnostics are toroidally separated and therefore cannot view the same point in the plasma, they must take data on the same flux tube, taking advantage of the very long parallel correlation lengths. Although difficult and requiring dedicated machine time, such flux-tube correlation measurements have been performed before in the TEXT plasma edge using Langmuir probes. A successful outcome of these experiments would be a definitive statement on the relevance of electrostatic fluctuations to core electron energy transport.

The experiments discussed previously will be performed in low-density plasmas to minimize three effects: 1) attenuation of the HIBP beam, 2) electron collisionality (in order to apply quasilinear theory in the dissipative trapped-electron (DTE) limit⁸), and 3) an ion feature in the fluctuation spectrum, which would confuse two-point correlation measurements. Access to the trapped electron regime $v_e^* \ll 1$ is aided on TEXT-U by the availability of 600 kW of ECRH power which allows for higher electron temperatures and therefore lower collisionalities.

The higher collisionality regimes on TEXT-U, specifically higher densities, will not be ignored, however. Better beam penetration will allow the 2-MeV HIBP to examine the "ion feature" seen by FIR scattering at the higher densities, put forward as evidence of ITG turbulence (a.k.a. η_i modes).¹¹ This feature appears as the density is raised, reaching an amplitude comparable to the ubiquitous electron feature coincident with a degradation in energy confinement. The relevance of this feature to transport will be examined in the context of an improved quasilinear theory being developed, valid for finite v_e^* and generalized (e.g., two-mode) turbulence spectra. Of course, if the HIBP is successful with $\tilde{n}_e$ and $\tilde{\phi}$ measurements and the CRECE systems with $\tilde{T}_e$ measurements at higher densities, the electrostatic fluxes could be determined directly, as discussed earlier, although special care will be required in modelling the two-featured spectra. The culmination of these experiments would be a definitive statement on the relevance of the ion feature to interior transport.

Electromagnetic Transport

So far we have discussed only electrostatic turbulence and transport because, as mentioned earlier, previous work on TEXT has suggested that transport from electromagnetic fluctuations is insignificant at low β .^{5,9} A reactor-like plasma will most likely be of high β and therefore have significant magnetic fluctuations. By reducing the toroidal field to ~ 1 T and applying 600 kW of ECRH power (second harmonic), we expect β in the confinement region of the plasma to approach $\sim 1\%$, leading to $\tilde{b}/B \sim 2 \times 10^{-4}$ (from drift waves), enough to yield $\chi_{e,R-R}$ (Rechester-Rosenbluth) = $\pi q R (\tilde{b}/B)^2 \sim 1$ m²/s, a typical power balance value. The importance of electromagnetic transport in finite- β plasmas will be assessed by first, computing the electron heat flux from inferences of the magnetic fluctuation level (via techniques outlined in Ref. 9). This would then be compared to the total electron heat flux (via power balance) and the *electrostatic* heat flux (via the quasilinear theory or, hopefully, directly).

These experiments would be performed on low-density plasmas for two reasons: i) to simplify determination of the electrostatic heat flux and ii) to ensure enough supra-thermals or runaways to infer $\tilde{b}$. Because of the specialized discharge condition and the extensive data required, these experiments will obviously require dedicated machine time.

Turbulent-Drive Experiments

The experimental program just outlined is directed at determining if the particle and/or electron energy transport is driven by the observed turbulence, whether it be electrostatic or electromagnetic in origin. A positive verdict would then logically lead to efforts to determine the specific turbulent drive(s) (dn_e/dr , dT_e/dr , dT_i/dr , dj/dr , $j_{bootstrap}$, etc.) and ultimately the mechanism(s) (e.g., electron or ion drift waves, η_e modes, magnetic "percolation," etc.) (A negative verdict would render such studies of academic interest only.)

The most efficient means to search for turbulent drives is through perturbative experiments, in which the fluctuations are monitored during naturally occurring perturbations or while plasma profiles are externally perturbed (ideally one at a time). Locality can also be examined in sensitive null-experiments by looking at the turbulence in regions where the perturbation is arranged to be very small. Natural perturbations include sawteeth, MHD islands, and transitions to improved confinement modes. External perturbations which have been used successfully are pulsed or modulated ECRH, modulated gas feed, impurity injections, current ramps, biased electrode, etc.

The "cold-pulse" experiments²² using impurity ablation have revealed significant non-local behavior in electron thermal transport that poses a great challenge to our understanding of thermal conductivity. The reduction in core transport associated with rapid edge cooling is not anticipated in any present theory or model of tokamak transport. The critical data that

led to this conclusion is shown in Fig. IIIA.6. The figure demonstrates that after injection of an impurity at 301 ms, the edge temperature decreases immediately, but the core temperature begins to *rise*. The subsequent finding of similar behavior on TFTR²³ and the observation of non-local effects in JET²⁴ confirms the generality of this novel aspect of transport.

FIG. IIIA.6. $T_e(t)$ measured by ECE radiometry at various $\rho = r/a$ are shown in heavy lines. The fit from a nonlocal model is shown dashed. The vertical dotted line indicates the time of impurity injection.

More generally, these results confirm the utility of perturbations as a technique for exploring transport with the potential for continued surprises! Since we do not even have a conceptual model for the state of turbulence (e.g. a stationary nonlinear saturated state vs. intermittent turbulence near marginal stability), it is essential to search experimentally for behavior which might suggest the dominant physical mechanisms. These studies, involving perturbations, would require dedicated machine time. We propose a number of perturbation experiments:

"Cold-pulse" phenomena

Having discovered the nonlocal behavior, we must search for the mechanisms and causes. The changes in turbulence associated with the transport changes require much careful investigation. A related result from modulated ECRH and gas feed experiments on TEXT was that the HIBP-measured $\tilde{n}_e/n_e$ in the plasma interior was more closely correlated with edge parameters than local interior parameters. This non-local character of the turbulence was either due to a path-integral contamination, or was real, rendering a search for local drives misdirected. The former interpretation has been investigated and found to be unlikely.^{16,17} The physical parameter that determines the effect is not yet known. Transport changes are certainly not triggered by slow changes in edge temperature or radiation. The effect also has a threshold in perturbation amplitude and disappears with strong auxiliary heating.

Experiments must decide whether merely larger perturbations are needed at larger power or whether the effect completely disappears when auxiliary heating decouples j and T_e . We have already discovered that the current profile seems an important consideration. In experiments inverse to the cold pulse - a fast current ramp - which raises the edge temperature and edge current density, causes a transient *decrease* in temperature near the center until the current penetrates. Experiments with ECRH will distinguish among these hypotheses.

ECRH

Recent experiments with very localized central ECRH show that the electron confinement is better in the sawtooth region than in the "confinement region", at least until a sawtooth crash occurs.²⁵ This is consistent with the observation on TEXT that the changes (both amplitude and shape) in $T_e(r)$ are not reflected in the density fluctuations measured by the 500-keV HIBP, providing compelling evidence against dT_e/dr as a drive.¹⁰ We propose to study the fluctuations, the plasma profiles, and the power balance in the inner core of the plasma to identify turbulent drives and to elucidate any differences with the adjacent confinement region. In addition to the TEXT-U high-power-density ECRH auxiliary-heating system, we intend to employ the following high-resolution diagnostics: Thomson scattering and ECE for temperature measurements, FIR interferometry and polarimetry for density and plasma current, and the HIBP and BES for plasma potential and density fluctuations.

The use of modulated ECRH for inferring χ_e is well established, but much work remains. With modulated ECH at various frequencies and deposition radii, a variety of T_e and dT_e/dr can be realized with no other perturbations. In high- q , non-sawtooth discharges, we have found temperature responses quite different from the usual diffusing heat pulse. For modulation periods short compared with the sawtooth period, we have observed complex interactions with sawteeth which may provide information on transport within the $q = 1$ surface and sawtooth mechanisms. Even in the normal cases described by diffusion, careful analysis suggests that the amplitude of the response differs from predictions based on the known power input. This may imply transport anomalies of the sort observed by Stroth on Wendelstein.²⁶

Modulated density

Similar experiments can also be done with density, although they are not as clean because some temperature perturbations accompany the density changes. Density modulation experiments as a technique for measuring

particle transport coefficients were pioneered by the TEXT group.^{27,28} With a permanent multi-chord interferometer, the subject warrants a reprise to obtain results over a wider range of parameters with auxiliary heating at higher radial resolution. The experiments will include radial scans of the turbulent density fluctuations, an important aspect because density fluctuations are more directly coupled to particle transport than to energy transport. Another aspect with important theoretical implications will be a careful comparison of the transport coefficients for perturbations with those for the equilibrium as obtained from the equilibrium density profile and particle confinement time from $H\alpha$ measurements, which are more accurate in toroidally symmetric diverted and belt-limited discharges.

Modulated gas-feed experiments on TEXT indicated that the quasilinear DTEM theory could not predict the level or phase of the perturbed particle flux.²⁸ This conclusion was independent of the choice of $\bar{k}_\theta$ (unlike the equilibrium results), but did depend on the modulation of $\bar{k}_\theta$ and a number of other terms which were not measured. In addition, the results provided strong evidence against dT_e/dr (but weak evidence for dn_e/dr) as the turbulent drive.¹⁰ These results need to be reexamined in future experiments on TEXT-U.

Sawteeth

Although the CRECE measurement technique in general requires significant time averaging in order to extract temperature fluctuation information, some degree of temporal resolution is possible by synchronizing the analysis technique with the quasi-periodic sawtooth oscillations.²⁹ By binning data into eight phases relative to the sawtooth crash we are able to extract the evolution of the temperature fluctuations during a sawtooth cycle, as shown in Fig. IIIA.7. Readily apparent is that at the sawtooth crash there is a significant increase in the temperature fluctuation power. The increase at low frequency (< 50 kHz) is almost wholly attributable to the discontinuous change in the temperature (the Fourier spectrum of the sawtooth itself). However, at higher frequency (the "bump" region which is

FIG. IIIA.7. Evolution of the temperature fluctuation power spectrum during a sawtooth cycle. Phase A is at the crash. The gray line is the spectrum average over the entire sawtooth cycle.

localized to the electron temperature profile gradient region), the increase is an enhancement of the turbulence.

In an attempt to quantify this, in Fig. IIIA.8 the integrated temperature fluctuation amplitude in the "bump" is plotted against the temperature gradient scale length $\alpha_T = |T_e / (dT_e/dr)|$. There is a clear global linear scaling ($\text{const} - \alpha_T$) of temperature fluctuation amplitude with α_T . In addition, during a sawtooth crash (hollow symbols), the temperature fluctuations increase while the gradient scale length decreases (not so clear, however, for the data at $\alpha_T/a \sim 0.12$ and 0.2). This decrease reflects the steepening of the electron temperature profile as the sawtooth heat pulse propagates outward. Presently it is unclear within the error bars whether the increase in fluctuations during the sawtooth crash adheres to the global linear relation, or whether the increase is more dramatic, as marginal stability theories would predict.

These results provide compelling evidence for dT_e/dr as a turbulent drive, in contrast to those from ECRH and modulated-gas-feed experiments on TEXT.¹⁰ Of course, the results there were for *density* fluctuations, im-

FIG. IIIA.8. Electron temperature fluctuation amplitude versus temperature gradient scale length α_T .

plying that the fluctuations in T_e and n_e have different drives. However, density profiles mimic T_e profiles, especially during sawteeth, so the scaling shown in Fig. IIIA.8 could just as well be with *density* gradient scale length, implicating dn_e/dr as the drive. Then again, some modes, e.g., DTEM, have multiple drives. Further work is proposed to better identify the drive(s) by also monitoring the density profiles and density fluctuations.

Off-diagonal terms in the transport matrix

Perturbative experiments are the only technique for isolating off-diagonal elements. Examples include density perturbations to find the diffusion coefficient D and the convective velocity V as well as the coupled temperature and density perturbations in sawteeth to find a $\partial T_e / \partial r$ term in the density equation in JET.³⁰ The experiments are subtle and ambiguities

are hard to avoid, but the terms demand exploration. One experiment is the examination of density perturbations associated with ECRH modulation to find T_e and $\partial T_e / \partial r$ terms in particle transport. The experiment would require rather low modulation frequencies. At the frequencies usually used for thermal transport experiments, one can easily show that even quite strong dependencies would not lead to observable density changes. Similarly, density perturbation experiments have already noted associated temperature oscillations. The transport implications remain to be evaluated.

Tests of theories

Several new theoretical ideas are evolving: renewed interest in various forms of marginal stability, diffusion subject to additional constraints (e.g. Refs. 31,32), etc. Comparison of theories with equilibrium data bases is at best a rough screen. Theories must be evaluated with well-designed, critical tests; perturbation experiments are often ideal. These are not experiments that can be proposed in advance, but we have devised these tests whenever possible. Examples include the $E \sim 0$ tests of resistivity-gradient driven edge modes³³ and comparisons of quasi-linear drift-wave theories with particle and thermal transport.^{8,28} We shall continue to test theories whenever they reach a state susceptible to experimental comparison.

Stabilizing influences

In addition to a search for the turbulent drives, it is clearly relevant to search for stabilizing influences. There have recently evolved on DIII-D two interpretations of interior confinement scaling – one pointing to gradients in the radial electric field E_r , the other favoring a steep current density profile $j(r)$. The former is based on the observed drops in interior fluctuations and χ_e as the steep dE_r/dr region propagates inward after the L-H transition.³⁴ The other is based on the improvement in confinement with increasing internal inductance ℓ_i (narrowing $j(r)$).³⁵ (In fact, the latter may be the same effect as the first - increased ℓ_i leads to increased B_{pol} , leading to increased $E_r \propto v_{tor} \times B_{pol}$, and hence, increased velocity shear.) How-

FIG. IIIA.9. FIR polarimetry measurements of the toroidal current density profile during a fast current ramp from 150 - 240 kA during the time interval 200 - 220 ms.

ever, recent experiments involving regions of reversed shear in the q profile (broader $j(r)$, lower ℓ_i) *also* indicate improved confinement.

The significance of these observations will be examined systematically on TEXT-U using perturbative experiments. The radial electric field, measured directly by the HIBP, can be perturbed not only by an H mode, as done on DIII-D, but also using our biased electrode or the SFX coils. A number of techniques to perturb $j(r)$ will be utilized, such as ECRH, current ramps, intrinsic MHD islands, etc. A number of diagnostics of $j(r)$ exist on TEXT-U, namely, FIR polarimetry, active charge exchange, and the HIBP. The capabilities of FIR polarimetry are exemplified by measurements of $j(r)$ during a fast current ramp, shown in Fig. IIIA.9, in which transient wings on the $j(r)$ profile are clearly discernible. Being perturbative in nature, these experiments will require dedicated machine time. The culmination of these experiments would be definitive statements on the relevance of dE_r/dr and $j(r)$ to the stabilization of interior turbulence.

Summary of Objectives

- Characterization of all turbulent mode(s) in the plasma core - amplitude, correlation lengths, propagation characteristics, poloidal asymmetries, etc.
- Determination of transport (quasilinear estimates or direct measure) from each mode
- Statements on relevance of electrostatic particle and energy transport
- Statement on relevance of electromagnetic energy transport at high- β
- Identification of turbulent drive(s) - dn_e/dr , dT_e/dr , etc.
- Identification of stabilizing influences - dE_r/dr , dq/dr , etc.

Appendix A – Electron Temperature Fluctuation Measurements using Thomson Scattering

The Thomson-scattering fluctuation diagnostic may add two improvements on the CRECE data with a few significant difficulties. The present TEXT Thomson scattering system is a 5 (spatial) $\times$ 11 (wavelength) channel detector array. In normal operation these five channels cover most of the plasma profile with 9-cm separation. These locations can be shifted between shots to six intermediary positions, allowing detailed profiles to be built up over a number of shots. The system can also be set up in a high resolution mode (HRTS) where all five channels cover only 3.5 cm of the plasma. Each spatial channel covers 5 mm $\times$ 7 mm of the plasma. This 3.5-cm viewing length of the laser beam can be located anywhere within $-22 \text{ cm} < z < +22 \text{ cm}$ and $100 \text{ cm} < R < 110 \text{ cm}$.

The spatial resolution of the HRTS (5 mm $\times$ 7 mm) is better than or equal to that of the CRECE system over the entire plasma viewing range (except at large major radii where the CRECE resolution in major radius approaches that of HRTS). In addition, Thomson scattering is not sensitive to non-Maxwellian tails. The major difficulty is that only one sample interval ($< 50 \text{ ns}$) is observed in one shot. Also, the basic statistical noise level of the diagnostic for a multi-shot data set is anywhere from 5 to 10 % depending on plasma density. Obviously a direct measure of the fluctuation level is impossible. However, we can collect a set of many identical shots for the same 3.5 cm of the plasma and then look for correlations between the five points. Shot-to-shot variations in plasma parameters (current, density, etc.) would result in variations in the temperature profile. This would lead to completely correlated changes in temperature and density between the closely spaced channels. However, fluctuations due to photon statistics of the scattering data would be completely uncorrelated. The channel spacing of this system just matches the measured turbulent correlation lengths (~ 1 to 2.5 cm).

A preliminary data set has been collected which may indicate it is possible to obtain information about the turbulent fluctuation levels in electron temperature. Figure IIIA.A1 shows the temperature data set at $R = 100$ cm, $z = -9$ cm, which is near to the maximum gradient in the temperature profile, for 38 similar discharges. Averaging over this data set gives the local gradient in temperature, shown in Fig. IIIA.A2.

FIG. IIIA.A1. Temperature data at $R = 100$ cm, $z = -9$ cm from five channels ("Te1" - "Te5") separated by 2.8 cm for 38 similar discharges.

We examine the correlation coefficient,

$$r_{xy} = \frac{\sum_{i=1}^n (T_{x_i} - \bar{T}_x)(T_{y_i} - \bar{T}_y)}{\sum_{j=1}^n (T_{x_j} - \bar{T}_x)^2 \cdot \sum_{k=1}^n (T_{y_k} - \bar{T}_y)^2},$$

where T_{x_i} is set to channel 1 and T_{y_j} represents the other four channels ($j = 1, 4$). The correlation coefficient r_{Ij} is calculated for each of the channels and shown in Fig. IIIA.A3. The first channel is obviously completely correlated with itself, and channels 3 and 4 are very near the noise level. The slightly higher correlation of channel 2 probably represents crossover from the adjacent channel 1. Only channel 5 is significantly different from the rest. The error bars about zero represent the expected range of correlation for a finite set (38 samples) of gaussian distributed data with the same standard deviation as the measured data. In order to resolve a correlated signal ($\text{SNR} \sim 2$) from this data it would require approximately 100 similar shots.

FIG. IIIA.A2. Average temperatures for the five-channel data in Fig. IIIA.A1.

FIG. IIIA.A3. Correlation coefficient with channel 1 for the five-channel data in Fig. IIIA.A1.

One significant advantage of TEXT is that it can produce a large number of nearly identical shots in a single run (>100 shots per day routinely taken). This data may also be improved by observing in a region of stronger turbulence, e.g., nearer the edge, or on the low-field side of the machine. HIBP and CRECE have observed significantly higher fluctuation levels in these regions.

HRTS data also has density information that can be processed in a similar manner. Correlation between density and temperature can then be investigated, although we must be careful in this analysis since the density includes the temperature information. This will be explored further with additional data.

The TEXT Thomson scattering system also has the ability to measure temperature and density twice in one discharge. A second laser is available, and only minor electrical and optical modifications are necessary to the existing set-up to implement this feature. This two laser system would allow investigations of the fluctuations in the time domain. The short laser pulse would allow studies of frequencies > 10 MHz. A direct comparison with the CRECE data would then be possible. In addition the scattering region could be expanded if the correlation lengths are found to be longer than 2 cm.

Appendix B – Correlation Radiometry of Electron-Cyclotron Emission

The electron-cyclotron emission (ECE) systems employed on TEXT-U serve two main functions: measurement of the “quasi-steady-state” electron temperature profile, including low frequency MHD oscillations, and measurement of high frequency turbulent electron temperature fluctuations.

ECE theoretical background

When emitted by an optically thick plasma in thermal equilibrium and detected by a suitable radiometer, the electron-cyclotron emission power is proportional to the plasma electron temperature at the EC resonance layer, but only to within a random error which depends on the radiation statistics. This error, here referred to as “wave noise” (alternatively thermal noise or Johnson noise), is small with respect to other systematic errors and ignored in most applications of ECE. However, an exception must be made when attempting to measure electron temperature fluctuations induced by high frequency turbulence in tokamaks because of the considerable spectral width and limited amplitude of the turbulent fluctuations.³⁶

The amplitude of the thermal noise fluctuations, which in these experiments accounts for virtually all of the signal noise, can be expressed in terms of the radiometer RF bandwidth $\Delta\nu_c$ and the sampled video bandwidth of the turbulent phenomenon $\Delta\nu_{\text{turb}}$:³⁷

$$\frac{\delta P_{\text{rms}}}{P} = \sqrt{\frac{2\Delta\nu_{\text{turb}}}{\Delta\nu_c}} \quad (\text{B1})$$

where P is the output signal of the single-mode radiometer, proportional to the detected power input. δP_{rms} is the amplitude (root mean square) of the fluctuations of P . In the TEXT-U experiment we observe the above high frequency ECE signal fluctuations as seen in previous experiments.^{38,39} The experimentally determined amplitude of these fluctuations in the band from

25 to 225 kHz is very near ($\pm 5\%$) to the value one obtains from Eq. (B1) using the measured IF filter bandwidth: $\delta P_{\text{rms}}/P = 6.3\%$.

Experimental technique description

Because the ECE thermal noise completely obscures the measured coherent high frequency temperature fluctuations, the actual time history of the T_e fluctuations is not accessible. However, we can still measure their *average* amplitude through correlation analysis of two suitably chosen ECE signals whose turbulent temperature fluctuations are correlated while the thermal radiation fluctuations are uncorrelated.⁴⁰ In the absence of systematic errors the measured cross-correlation of the two signals will yield the correlated signal power.

A radiometer channel output produces a signal proportional to the instantaneous collected power $S(t) \propto (\bar{T} + \tilde{T}(t))(1 + \tilde{N}(t))$, where $\bar{T}$ and $\tilde{T}(t)$ are the average plasma temperature and its fluctuating component, respectively, and $\tilde{N}(t)$ is the radiation wave noise. The observed (zero time-delay) cross-correlation $R_{12} = \overline{\tilde{S}_1 \tilde{S}_2}$, where $\tilde{S}$ is the measured signal minus the mean $\bar{S}$, between two radiometer channels identifies the common normalized electron temperature fluctuations,

$$\frac{\tilde{T}_{e,\text{rms}}}{\bar{T}_e} = \sqrt{\frac{R_{12}}{\bar{S}_1 \bar{S}_2}}. \quad (\text{B2})$$

The method does not require that the radiometers be absolutely calibrated. However, it does require an appropriately long integration time to reduce the statistical error to well below the coherent temperature fluctuation amplitude, particularly if one is seeking spectral information through suitable analysis. To this end, the limit of statistically meaningful information ("noise level") ε can be determined for R_{12} by:

$$\varepsilon(R_{12}) = \frac{\sigma_1 \sigma_2}{\sqrt{N}} \quad (\text{B3})$$

where σ is the standard deviation in S and N is the number of independent samples. This limit has been well verified both by numerical simulations of random data and bench tests using a calibrated noise source.

The CRECE (correlation radiometry of ECE) method implemented on the TEXT-U tokamak correlates the signals from two disjoint RF bands which, because of the cyclotron frequency gradient in TEXT-U and the finite width of the emission layer, overlap in space. The principle is shown schematically in Fig. IIIA.B1. Because wave noise arises from the beating of waves only within the selected frequency band, the wave noise in the two separate bands is uncorrelated. (A quantitative thermodynamic argument is presented in Ref. 36). However, the overlapping sample volumes ensure that the temperature fluctuations (with wavelengths the order of or greater than the emission volume size) will be common to both signals.

Experimental apparatus

The radiometer optics are designed to maximize poloidal spatial resolution. Poloidal resolution is of paramount importance, since the turbulent spectrum is believed to consist of abundant short-wavelength components. Two optical systems are employed, denoted below as TEXT and AU. The

FIG. IIIA.B1. Schematic of the CRECE method used on TEXT-U. The two correlated ECE signals are disjoint in frequency space, but overlap in real space.

multi-channel heterodyne radiometers are tuned to the 2nd harmonic X-mode electron-cyclotron frequency viewing along a tokamak major radius in the equatorial plane from the low-field side. In both cases the focusing element is a metallic lens of 11 cm (TEXT) and 18 cm (AU) diameter. Due to the dispersion of the lenses, the optimum focus is a function of the frequency of the detected radiation. Three frequency bands were used with the lenses positioned at three radial locations for a total of nine different focal positions in the plasma.

The lenses are fed by scalar corrugated horns to produce an output Gaussian beam of waist diameters between 1.3 (TEXT) and 2.2 cm (AU) in the 95 to 130 GHz radiometer frequency range. This beam waist increases by less than 10% over a range of about 12 cm along the beam line. Refractive effects do not affect the size of the viewing spot for the frequency and density ranges under investigation. With these systems we are thus able to cover most of the plasma minor radius with nearly optimum focus.

The horns feed TE_{1,0}-mode waveguide which is isolated from the vacuum by a mica window. The signal is downshifted by a heterodyne radiometer to a frequency range between 2 and 18 GHz with a local oscillator frequency of either 95 GHz (AU) or 108 GHz (TEXT).

Measurement of $\tilde{T}_{e,rms}$ is obtained from cross-correlation between pairs of ECE signals selected using narrow-band IF filters in a multi-channel system. A sketch of the system is shown in Fig. IIIA.B2. The signal from the radiometer is separated into four equal-width frequency bands by a multiplexer covering the 2 to 18 GHz range. These signals are amplified with broadband (2-18 GHz) intermediate frequency (IF) amplifiers with a nominal gain of 32 dB. The amplified signal is selected by the IF filters and then detected using square-law diode detectors. These crystal detectors convert the RF power into proportional dc voltages in the 10 MHz to 18 GHz range.

Schematic of Signal Detection

FIG. IIIA.B2. Schematic of the ECE system for measurement of electron temperature fluctuations.

The majority of our measurements have been obtained using 100-MHz-wide, five- and six-stage Chebychev bandpass filters with typical selectivity of 6 dB/octave per stage. Experiments with tunable filters verify the transition from complete correlation, in the case of overlapping frequency intervals, to nearly absent correlation ($< 0.5\%$) for separations greater than ~ 1.5 times the filter bandwidth. For the majority of the data presented here the stop-band between the two channels is 100 MHz. For TEXT-U field gradients this corresponds to a distance of ~ 1 mm in the cold EC resonance position along the major radius. This separation is less than the emission layer thickness, which is on the order of 0.5-1 cm,¹⁴ as verified by data presented in Ref. 13. The system allows for a radial resolution of $\bar{k}_r < 6 \text{ cm}^{-1}$.

The location of the resonance layer in the plasma is determined by the magnetic field in conjunction with the frequency of the detected radiation.

For these experiments three sets of fixed filters were chosen with resonant frequencies at (7.8; 8.0), (10.6; 10.8), and (13.2; 13.4)GHz. Thus for the AU system the cyclotron resonance is in the 103 to 108 GHz range, while for the TEXT system the resonance is in the 116 to 121 GHz range. A scan of the minor radius is accomplished by varying the magnetic field from 16.0 to 22.8 kG in increments of about 0.5 kG.

For the radial correlation studies we use a single 100-MHz-wide fixed filter in conjunction with a tunable YIG filter 30 MHz wide, and a 200-MHz-wide fixed filter in conjunction with a 200-MHz-wide YIG. The filter separation is varied over the range of ± 30 mm by shifting the resonant frequency of the YIG with respect to the fixed filter.

Output from the crystal detectors is routed to a set of video amplifiers which provide lowpass filtering in addition to a gain of 20 dB to the signal. Measured core turbulence in TEXT-U suggests that no extra information is gained by increasing the video bandwidth above 250 kHz. We therefore digitize the signal at 500 kHz.

FIG. IIIA.C1. Elevation view of the 2-MeV heavy-ion beam probe on TEXT-U.

Status

The 2-MeV heavy-ion beam probe diagnostic system is operational at full energy with two parallel plate energy analyzers, one of which analyzes beams with energies up to 2 MeV (lower analyzer) while the second (upper analyzer) can analyze beams with energies up to 600 keV. The present configuration allows coverage of ~70% of the plasma cross section. The present upper analyzer will be replaced by a second 2-MeV beam analyzer within this grant period. The combination of the 2-MeV analyzers and the two injection beamlines will allow coverage of ~90% of the plasma cross section.

Appendix D – Beam-Emission Spectroscopy

The Beam-Emission-Spectroscopy (BES) diagnostic is based on measurements of fluctuations in the intensity of the fluorescent emission from neutral atoms injected into the plasma by a neutral beam.⁴¹ The process of neutral atom excitation by plasma particles can be described by

where a fast neutral atom H^0 experiences impact excitation by a plasma electron e or proton p . Radiative decay of the atom results in line emission, with an intensity proportional to local fluid density in the plasma. The Doppler shift of the beam fluorescence due to the large velocity of the beam neutrals is used to distinguish it from the strong unshifted emission from the edge of the plasma.

Shown in Fig. IIIA.D1 is a top view of the location of the BES system with respect to TEXT-U and the Diagnostic Neutral Beam (DNB). The DNB is a 45-kV, 5-A neutral-beam injector with a pulse length of ~80 ms. The beam of diameter 5 cm is injected vertically through the plasma. A high-throughput optical system composed of a 16-cm diameter, $f/4$ objective lens of 30-cm focal length, collects light from the sample volume defined by the intersection of the optical sight line and the beam. The collected light is focused on eight fiber-optic channels located on a positioner that allows for a radial scan of the sample volume from shot to shot. The fiber-optic bundle is coupled to an 8-channel interference-filter spectrometer, which detects only the light at the Doppler-shifted wavelengths and discriminates against unshifted edge emission.

The TEXT-U DNB is injected from the bottom of the tokamak to the top. A Doppler shift of the beam emission is large enough for measurements at the bottom part of the plasma but decreases sharply toward the plasma center. To minimize the effect of signal contamination by edge H_α radiation, a helium beam is injected into a hydrogen/deuterium plasma. A

small amount of helium contaminates the plasma during injection, although due to the fast pump-out rate of the helium between shots, it is possible to keep a low level of the residual helium in the plasma, thus reducing the emission from the edge neutral helium. This is much better than using a hydrogen beam and dealing with the emission of the neutral hydrogen (H_{α}). Initial experiments with a hydrogen beam allowed measurements only at the edge of the plasma, while the helium beam allowed measurements in to $r/a \sim 0.5$.

Figure IIIA.D2 illustrates the view of the neutral beam as seen by the BES system along the tangential line of sight. As a rule, seven out of eight fiber-optic channels are distributed on the vertical positioner to provide poloidal and/or radial correlation measurements. One channel with a sample volume located far from the others is used for determining beam noise.

Each fiber-optic channel, containing 19 fibers, collects light from a roughly rectangular plasma volume of dimensions 7 mm (poloidal) $\times$ 15 mm (radial) $\times$ 50 mm (toroidal). This implies an ability to resolve fluctuation wave numbers $k_\theta \lesssim 5 \text{ cm}^{-1}$ and $k_r \lesssim 2 \text{ cm}^{-1}$. The radial and poloidal separations of the volumes are ~ 17 mm and 10 mm, respectively. The location of the fiber-optic channels shown in Fig. IIIA.D2 is for a poloidal correlation measurement. In case of radial correlation experiments, the fiber-optic channels are rotated by 90° to improve radial spatial resolution.

The BES diagnostic uses the 5876 Å line of metastable He (2^3s). A series of gases has been recommended in the literature for use in the neutralizer chamber to increase the metastable population of the beam neutrals.⁴² Hydrogen is used in the TEXT DNB, because it does not lead to additional plasma contamination and gives an additional 30-50 % increase of the SNR.

Two types of cryogenically cooled detectors were tested on TEXT-U: EG&G FFD 040B detectors cooled to -150° C (four channels) and Advanced Photonix APD 197-70-72-521 avalanche detectors cooled to -50° C . A dramatic improvement in performance has been found using these two types of new detectors. The signal-to-noise ratio has been increased by almost a factor of ten in the 1 - 200 kHz frequency band. The resulting improved SNR allows the new BES system to extend measurements in to $r/a \sim 0.5$ and to distinguish the low-level fluctuation in the plasma core.

A major problem is the high sensitivity of the cryo-cooled detectors to hard X-ray radiation. An extremely low-level of hard X-ray radiation was achieved in the described series of experiments, but it may be not be possible to obtain such low X-ray levels in routine operation. Possible solutions of this problem are under consideration.

FIG. IIIA.D2. Poloidal cross-section of the BES view.

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PROJECT DESCRIPTION

III. PROPOSED RESEARCH

IIIB. EDGE TURBULENCE AND TRANSPORT

IIIB. Edge Turbulence and Transport

Understanding of the plasma periphery is critical. Two obvious reasons are that the periphery provides the link with the wall, and the H-mode is very much an edge phenomenon. In our previous work, we have shown that the turbulence has a dominant influence in this region of the plasma, and we have investigated its characteristics. Recently we began to investigate turbulence drives and to attempt control of the turbulence using feedback, and these are the principal areas in which work is proposed here. In this introductory section, the proposed work and our historical results which lead to these proposals are briefly reviewed. Detailed descriptions of proposed experiments then follow. The final section contains a description of the diagnostics.

We have made progress in understanding the role of turbulence in the scrape-off layer (SOL). A selection of results follows. Particle transport¹ and energy transport² in the plasma periphery are now known to be due to electrostatic turbulence. In the experiments that led to these two important results, turbulent transport flux was inferred from both fluctuation amplitude and phase information and was not well correlated with amplitude data alone. This means that turbulence measurements require diagnostics that provide a complete view of the turbulence. The notable structural feature of turbulence in the plasma edge is a region of high shear in the poloidal phase velocity of the turbulence that appears to separate the region of closed field lines from the region of open field lines.³ In this naturally occurring shear region, there is a correlation between transport reduction and high velocity shear.⁴ Turbulence was thought to be Boltzmann prior to repeated experiments on TEXT (see refs. 5, for example). In fact, we find that

$$\frac{e\tilde{\phi}}{T_e} > \frac{\tilde{n}_e}{n_e} \text{ in the SOL}$$
$$\frac{e\tilde{\phi}}{T_e} < \frac{\tilde{n}_e}{n_e} \text{ inside the last closed flux surface.}$$

The TEXT measurements⁶ that led to the conclusion that $\bar{k}_{||} \ll k_{\theta}$ may eventually be seen as critical observations because this inequality has the effect of shifting the search for turbulence drives to the material surfaces on

which the field lines in the SOL terminate (see below). This sampling of the turbulence phenomenology from TEXT results is now widely observed and has served to demonstrate the importance of turbulence measurements. The problems now are in understanding the drives for turbulence.

There are some clues to the turbulence drives that will be pursued in this proposal. Because turbulence is largest in the plasma edge, a region rich in atomic processes, it is tempting to consider atomic processes as the source for the turbulence. Two mechanisms are proposed for study, ionization drive⁷ and radiation drive⁸. The magnitude of $k_{\parallel}$ may suggest a spatial location for these and other drives. Since parallel wave numbers for the turbulence are small, the turbulence drives may be well separated from the point of observation -- as far away as the divertor plates or the limiter. Taking this as a clue to look at the effects of divertor plates, sheath related phenomena become additional possibilities. These are sometimes called sheath instabilities although more recent theoretical developments suggest that they result from rotation relative to conducting end plates.⁹ Here, we simply call them conducting wall drives. This turbulence drive depends on the material properties of the limiter or divertor surface. Curvature drives¹⁰ are also a possibility in situations where magnetic field lines in the edge pass through regions of unfavorable curvature. Detailed studies of all of these are included here. Other experiments will concentrate on testing some suggestions about general turbulence properties that can be used for turbulence control. While turbulence control is interesting in itself, these studies are intended to probe the properties of turbulence and thereby contribute to our study of turbulence drives.

More direct means of turbulence control employ feedback techniques. In these unique and ongoing TEXT experiments, the SOL turbulence is sensed and then fed back into the edge to reduce or enhance the turbulence. These experiments will continue along with an additional experiment that they spawned. Specifically, we had problems with interpretation of the early turbulence feedback experiments until we realized that our results violated the prevalent theories of plasma-probe coupling. In this proposal, we describe experiments to understand this anomalous effect which will impact interpretation of diagnostic probes as well as design and modeling of divertors.

The previously-mentioned turbulence phenomenology is now observed on many tokamaks, but it may be that more information can be extracted from this data than is done at present. We will attempt to identify non-linear interactions among turbulent modes through application of higher order statistical techniques to our data. We made some initial attempts in these areas. In an early experiment,¹¹ nonlinear interactions among modes were identified and shown to lead to energy cascades. In another experiment,¹² the turbulence frequency spectrum at rational q-surfaces was shown to contain strong quasicohherent features. Detailed correlation measurements demonstrated that these do not lead to transport, but spectral bicoherence studies showed that transport related small scale turbulence activity does interact with this mode. These studies were interesting but they also led us to believe that we needed better analysis tools. Our first steps in providing these tools are described as a separate section, IIIC. It is expected that this work will impact plasma theory perhaps to the extent of supplying fundamental constraints. The results of this work may eventually come back to us in the form of better theories of turbulence and thereby contribute to our understanding of turbulence drives.

As these tools are only just being developed, their application will require a specialist. From turbulence experiments in the plasma core,¹³ we learned that some measurements are deceptively complex and correct analysis requires complete consideration of the interaction between diagnostic and plasma. In the present context, this last lesson simply means that the best approach to application of the new statistical tools is to form a close working relationship among the experimentalist who took the data, the statistical specialist and plasma theorists. This is how we will approach the problem. We are fortunate that this combination of talent is available at the FRC.

The divertor will play a critical role in the turbulence experiments. We also plan some divertor modeling as a means for unfolding the transport fluxes from equilibrium data. These fluxes are important in determining the role of the observed turbulence. We will attempt to use and test simple analytical SOL models. We will also apply the more complex numerical models widely used in the divertor community.

In summary then, this is the edge turbulence and transport program. This listing is prioritized.

- Investigate predictions for those turbulence drives which have an immediate impact on the SOL in diverted plasmas (atomic drives, curvature drives, and conducting wall drives).
- Investigate plasma-probe coupling, verify discrepancies with theory, and understand the impact on diagnostic interpretation and divertor modeling.
- Continue experiments to control turbulence, but specifically to help identify the properties of turbulence. These include feedback and shear stabilization. Special attention is given to measurement of flow velocity, a diagnostic that has not yet been intensively used.
- Investigate the impact of boronization on turbulence in the plasma edge. This work is an additional feature of the wall conditioning program, and is described in the section II under Wall Conditioning.
- Apply higher order statistical techniques to our data in an attempt to understand non-linear interactions among turbulence modes. This work is described in section IIIC rather than here because extensive development work is required before application to edge data.

Experiments to Identify the Turbulence Drives

Atomic Drives: Ionization

Until recently, atomic drives were viewed as strong candidates for the critical turbulence drive. The reasons were immediate; fluctuations tended to peak in the region dominated by atomic processes, and there was an easily understandable mechanism for the drive. For the ionization drive, early experiments¹⁴ in poloidally limited plasmas demonstrated that the local ionization rate of neutral hydrogen was larger than the critical level predicted for growth of the instability only in the vicinity of the limiter. Even there, the predicted transport⁷ due to the resulting turbulence was quite small compared to the measured transport. This caused no immediate concern because the theory was relatively primitive. Using the recently developed D_α fluctuation diagnostic,¹⁵ correlations were sought between increases in ionization rate and increases in turbulence.¹⁶ This produced negative results. Finally, a theoretical study brought into question the basic theory of the original work.¹⁷

Given this situation, it appears that the ionization drive does not play a role in tokamaks and may not exist at all. We do plan one additional experiment. The measurements will be repeated in toroidally limited and in diverted discharges. We will be surprised if the drive appears, but the problem of toroidal asymmetry was so insidious during the original work that we would prefer to redo the experiments before leaving this problem.

Atomic Drives: The Radiation Drive

Plasma radiation has been proposed as a turbulence drive mechanism.⁸ If the radiated power, P_{rad} , is represented in terms of the electron density, n_e , the impurity density, n_z , and the cooling rate, I_z , in the usual way as

$$P_{\text{rad}} = n_e \sum_z (n_z I_z),$$

then the growth rate for the instability is

$$\gamma = \frac{2 n_z}{3} \left(\frac{2 I_z}{T_e} - \frac{\partial I_z}{\partial T_e} \right).$$

The second term is the obvious (but not the only) source of an instability. The cooling rate has been calculated in coronal models (ref. 18, for example) to decrease with increasing electron temperature in the plasma edge. This being the case, the instability will grow. There is a particular motivation to study this drive mechanism because it is quite similar to proposed mechanisms for a widely observed macroscopic instability, the MARFE.¹⁹ Thus, at least intuitively, the drive is an interesting possibility.

We have studied this mechanism for microscopic turbulence, but questions remain within the community which we will resolve. A critique¹⁷ pointed out that the original theory assumed that there was a separation of time scales between the approach to equilibrium and the growth of the instability. This separation did not exist because the time scale for the growth of these modes is the same or longer than that for the transport or the approach to equilibrium. Generalizing and at the same time making the argument intuitively accessible, it was noted in the critique that this is common to all instabilities driven by sources which also contribute to the equilibrium particle or energy balance. In experiments,²⁰ we used modulated ECH to vary the electron temperature in the plasma edge. The plasma radiation appeared to be in phase with the temperature at the plasma edge, hence the second term of the above equation is not destabilizing. This might almost have been expected because the destabilizing influence of that second term is based on a coronal model for impurities which, of course, omits transport. With this type of information at its disposal,²¹ a Transport Task Force Workshop concluded that the following measurements are still of interest before concluding that the radiation drive is not relevant:

- phase shift between $\tilde{T}_e$ and $\tilde{n}$ (A π phase shift is expected for a radiation drive)
- ratio of temperature to density fluctuations
- phase shift between $\tilde{T}_e$ and $\tilde{P}_{\text{rad}}$. (A π phase shift is expected for a radiation drive)

In the last of these, the influence of the second term in the above equation is still sought, but in a plasma unperturbed by ECRH.

We have measured the temperature and density fluctuations²² in the past and found the correlation between them to be low. We also measured the ratio of density to temperature fluctuations and found $\frac{\tilde{T}}{T} = 0.4 \frac{\tilde{n}}{n}$. Interestingly, our results were confirmed in a stellarator²³. We plan to continue these experiments using a new type of probe, the time domain triple probe, which provides a promising means for improving our measurements of $\tilde{T}$ while permitting simultaneous measurement of $\tilde{n}$.

The next major area for us to look at is correlation of $\tilde{T}_e$ with $\tilde{P}_{rad}$. The goal is to look directly at the second term in the equation above for the growth rate. In this experiment, the radiated power will be measured with a fast X-UV photodiode array that is benchmarked against a bolometer at lower frequency. (This application for the X-UV photodiode array is sufficiently novel to require frequent benchmarking.) The temperature fluctuations will be measured with a Langmuir probe. Correlating the two measurements is difficult because one is a chord integral and the other is a point measurement at a different toroidal location, but these problems can be overcome.²⁰ We will also continue the ECH modulation experiments. The radiation drive will be sought over the range of TEXT densities and with variation of the edge impurity content. We note in passing that we are able to change the shape of the radiation distribution by changing the major edge impurity from carbon to boron (via boronization). This may change the dependence of P_{rad} on T_e .

Experiments

- Perturb the electron temperature with ECH and observe the response in the radiated power. Vary the electron density, the principal edge impurity, and the impurity concentration.
- Measure the coherence and phase between radiation and electron temperature fluctuations.
- Use the time domain triple probe (a critical new diagnostic described below under Langmuir Probe Diagnostics) to measure local T_e , n_e and their fluctuations in the SOL and edge plasma.

Curvature Drive

The toroidal curvature of the magnetic field lines may be a source for turbulence in tokamaks.^{24,25} On the open field lines in the SOL, some fluid modes may be unstable for the appropriate average curvature of the magnetic field lines with respect to the pressure gradient. In a tokamak, curvature is stabilizing on the inner side of the torus (on the high field side of the poloidal cross section) and destabilizing on the outer side (on the low field side). The fact that curvature can be destabilizing is certainly not new, but the recent development of theory²⁵ for open field lines which seems to describe some well-known properties of turbulence is the motivating factor for this work. In the SOL, this drive is all the more interesting because field lines intercept material surfaces which prevents averaging over regions of favorable and unfavorable curvature as might occur on the closed field lines inside the last closed flux surface.

This mechanism has promise as a turbulence drive for several reasons. As noted by Garbet,²⁵ it predicts previous TEXT observations^{26,27} including turbulence scale lengths, phase shifts, and phase velocities. In more recent experiments on TEXT-U,²⁸ turbulence amplitudes on the low field side of a double null configuration were found to be larger than on the high field side. In the double null configuration, the SOL on the high field side is effectively isolated from that on the low field side. The plasma region on the high field side has favorable curvature. The average curvature on the low field side is unfavorable. In ASDEX,²⁹ the turbulence amplitudes were measured to be larger on the high field side of a single null configuration than on the high field side of a double null configuration. Double null curvature effects in ASDEX are as described above for TEXT-U. For the single null case in ASDEX, the curvature on the high field side is favorable but the high field side is connected to the low field side, a region of unfavorable curvature. This evidence suggests that curvature may drive turbulence, but it is indirect and incomplete.

On TEXT-U, curvature drives can be studied by directly varying the fraction of an open field line that has unfavorable curvature. The three basic TEXT configurations chosen for this experiment are shown in Figure IIIB.1.

Figure IIIB.1. Cartoons of TEXT-U configurations for the curvature drive experiment. From left to right, double null (compare Figure II.2), toroidally limited (compare Figure II.4), equatorial single null (compare Figure II.1).

All three are axisymmetric to avoid obvious analysis uncertainties. The hatched region in the double null cartoon of Figure IIIB.1 should itself be free of curvature drive and also isolated from the region of the SOL with unfavorable curvature. From existing experiments, we already know that the turbulence amplitudes are significantly different in these two regions of the double null. The outer section of the toroidally limited discharge (center, Figure IIIB.1) is most unstable to curvature drive. The equatorial single null discharge is also unstable (right, Figure IIIB.1), but it does have an x-point which results in interesting curvature on the high field side. The toroidally limited discharge can be compared with the equatorial single null discharge to determine the effect of an x-point on the curvature drive. The growth rate, γ , for the curvature instability at $k_{||}=0$ in each of the three configurations can be estimated using a simple model.²⁵ The results are shown in Table IIIB.1.

Configuration	$\gamma \frac{R}{V_{thi}}$
double null, hatched region	---
toroidal limiter	2.5
equatorial single null	2.5*
double null, unhatched region	4.0

Table IIIB.1. Growth rate versus configuration. γ is growth rate, R is major radius, and V_{thi} is ion thermal velocity. *The effect of the x-point is unknown.

In this experiment, the curvature drive can be varied over a wide range. Because there are likely several processes acting simultaneously,

turbulence driven by the curvature will be varied against an already turbulent background. Changes in $k_\theta, \tilde{n}, \tilde{\phi}$, the phase angle between $\tilde{n}$ and $\tilde{\phi}$, and the scale lengths of the averaged quantities will be measured. This will allow characterization of the portion of the turbulence due to curvature and estimation of the resulting electrostatic transport.

The instability is stabilized³⁰ by increasing $\frac{T_i}{T_e}$. The stabilizing influence can be checked in TEXT-U. ECRH and variation of density (and hence coupling of T_e and T_i) can be used to vary the ratio $\frac{T_i}{T_e}$.

We have recently designed and built a Langmuir/Mach probe array which should give new insights into the importance of curvature drives. The Langmuir/Mach probe array will measure the amplitude of ion saturation (density) fluctuations propagating in both directions along a magnetic field line in addition to the fluctuation parameters measured by the Langmuir probe arrays that we have used in the past. With this new probe, we will be able to study how the turbulence propagates along the magnetic field line and perhaps identify the drive

Because of current interest in divertor design and modeling of the SOL, this will be a critical experiment. It is in the mainstream of present research as indicated by discussion of the instability at recent TTF workshops.²¹ The measurement detail indicated above is a minimum necessary in trying to understand the instability. This type of detail is available only on TEXT-U.

Milestones

- Survey discharges in the three configurations using a minimum diagnostic set consisting of D_α fluctuation measurements for the poloidal dependence of density fluctuations and a single Langmuir probe at one location to benchmark the D_α fluctuation measurements.
- Use a Langmuir/Mach probe to study the propagation of turbulence along the magnetic field and relate results to curvature drive.
- Characterize the turbulence parameters (that is, $k_\theta, \tilde{n}, \tilde{\phi}$, and the phase angle between $\tilde{n}$ and $\tilde{\phi}$) with variation of curvature.

- Use ECRH and density variation to vary $\frac{T_i}{T_e}$. Look for changes in turbulence.

Conducting Wall Drive

The conducting wall drive arises on open field lines.^{3 2} Fundamentally, it is due to a cross field gradient in the difference in electrostatic potential between the plasma and a conducting end wall in conjunction with end loss and polarization drift. It can arise in the presence of the electron temperature gradients that occur naturally in the SOL as a result of cross field and parallel transport and perhaps as a result of radiation. Once the gradient is present, a radial electric field follows because an ambipolar potential is needed to regulate the electron endloss to maintain quasineutrality. As the ambipolar potential is proportional to the electron temperature the radial electric field is proportional to the temperature gradient. This geometry is sketched in Figure IIIB.2.

Figure IIIB.2. Slab representation of a tokamak plasma SOL. The temperature gradient generates an electric field.

The instability can also be viewed in other ways, for example, as due to plasma flow with conducting wall-sheath boundary conditions. However it is viewed, this instability appears as a distinct possibility for one of the contributors to turbulence in the SOL.

The obvious way to study this instability is to construct a divertor that can be made insulating or conducting. This is straightforward in a medium sized device such as TEXT-U because the thermal load is well within the capabilities of standard insulators. That alternative is discussed below. Still, it is preferable to try something simpler first. As a first attempt to gain insight into this problem, we will compare the turbulence measurements made with field lines terminating on an insulating probe body to measurements with the field lines terminating on a conducting probe body. In other words, does the boundary condition on the probe body make any difference to the signal measured by a Langmuir/Mach probe mounted in the probe body? There are problems here too. First, is the signal measured by the probe mounted in the probe body characteristic of the turbulence downstream from the probe body? Second, the probe body size (17mm in the poloidal direction) may be too small for the waves to grow as the plasma flows by the probe with a large flow velocity in the poloidal direction. Keeping these in mind, we have made first attempts at establishing the importance of sheath impedance drives on SOL turbulence.

We built a Langmuir/Mach probe in a probe body that was insulating on one side, and conductive on the other side. The probe was mounted above the plasma so that we could align either the insulating side or the conducting side against the magnetic field. That is, the magnetic field lines could terminate either on a conducting surface or on an insulating surface facing either upstream or downstream along the magnetic field. There were four probes mounted on each side of the probe body. Two probes on each side were biased to collect ion saturation current and two probes measured floating potential. In the plasma edge, with the magnetic field line terminated on an insulator, we observed a feature at about 100 kHz in the power spectrum of both the floating potential and ion saturation current signal. The characteristics of the feature are:

- only appears when the flux tube is terminated by an insulator
- not observed when the field lines terminate on the conducting side of the probe,
- weaker when the field lines are terminated on the insulator near the edge of the probe body, and

- observed when the insulating probe body is looking towards the high field side of the tokamak.

Clearly, we see a difference. This experiment is worth repeating under a variety of conditions with improved supporting data.

If this experiment fails to produce a definitive result, we will continue with a more complex experiment. This instability will then be studied in diverted discharges and in toroidally limited discharges to avoid the toroidal asymmetries. The end walls (divertor tiles or belt limiter) in TEXT are conducting. We are led by the theory³² of this turbulence drive to expect a particular relationship for the magnitudes of $\frac{e\tilde{\Phi}}{T_e}$, $\frac{\tilde{T}_e}{T_e}$, $\frac{\tilde{n}_e}{n_e}$ based on the gradient scale lengths. In TEXT in poloidally limited discharges, we have observed²²

$$\frac{\tilde{n}_e}{n_e} > \frac{\tilde{T}_e}{T_e} \quad \text{and} \quad \frac{\tilde{n}_e}{n_e} < \frac{e\tilde{\Phi}}{T_e}$$

In these experiments, we are probably seeing a variety of turbulence processes, but one of these can be eliminated in future experiments by making measurements on the high field side in a double null discharge where we believe that the curvature drive is removed.

To significantly change or even eliminate the conducting wall modes, the walls must be made insulating. To facilitate comparisons between the two, we need to be able to switch between the two with some facility. In fact this can be done. The principle of the experiment is illustrated in Figure IIIB.3. The idea is to insert insulating segments between the conducting segments. The conducting segments are then isolated from each other. The conducting segments can be connected together to form a wall that appears from the point of view of the instability to be fully conducting. Further, it would be interesting to have this facility available on the high field side of the plasma to minimize the effects of curvature drive.

In light of difficulties with insulation and installation of tiles on larger devices, this might seem to be an experiment that would be a severe financial and technical burden. In fact, TEXT-U has the advantage of small size and a cool SOL which make these sorts of experiments relatively straightforward. The three configurations of interest are the double null, the equatorial single null, and the toroidally limited plasma. The "end walls"

analogous to those in the figure are the stacks of tiles on the high field side of the vacuum vessel (see Divertor in section II for a description of these tile stacks). The stacks will be composed of tiles that are alternately conducting and insulating. The insulating segments could be boron nitride. The conducting tiles would likely be graphite. The principal configuration will be the toroidally limited discharge. Using the same set of insulating tiles, the effect of an x-point can be studied using the equatorial single null discharge. Again using the same set of tiles, the effect of curvature can be studied using the double null configuration.

Figure IIIB.3. A schematic view of an arrangement for alternating between insulating and conducting walls.

Milestones

- Redo experiments with larger two headed probe array body (insulating on one side, conducting on other) to confirm effect.
- Remeasure $\frac{e\tilde{\Phi}}{T_e}$, $\frac{\tilde{n}_e}{n_e}$, $\frac{\tilde{T}_e}{T_e}$ in toroidally limited discharges and in double null discharges to confirm the relative magnitudes of the fluctuations.
- If no resolution is available from the experiments above, then (and only then) install insulating/conducting tile stacks as described above and

repeat measurements in the three configurations to determine whether there is a change in relative magnitudes of fluctuations or transport due to a change from insulating to conducting tiles.

Turbulence Control

Electrostatic turbulence appears to drive transport in the plasma periphery.^{1,2} Can this transport be controlled without a detailed knowledge of the sources of the turbulence? By "control" we mean "deliberately make the turbulence larger or smaller." In the next section, control will be via feedback on the fluctuations. Here, we have a different approach. We are trying to use our physics knowledge of the drives to identify a ubiquitous feature of all the expected drives or to find a very powerful physical statement about turbulence to use for control of the turbulence. We have both.

The ratio $\frac{T_i}{T_e}$ is a control parameter. Certainly, for the curvature and conducting wall drives considered above, a large value tends to reduce the turbulence.³⁰ Checking of this was already mentioned as a planned experiment.

Sheared poloidal rotation can quench turbulence.³³ This is the powerful physical statement that we were looking for because it is independent of drive. It is the one that we wish to test. Physically, sheared poloidal rotation tears apart the turbulent eddies. The condition for turbulence suppression is

$$\frac{\Delta r_t}{L_v} > \frac{\Delta \omega_t}{\omega_\theta}$$

where L_v is the shear length in the poloidal flow, Δr_t is the radial correlation length for the turbulence, $\Delta \omega_t$ is the inverse of the corresponding correlation time, ω_θ is the poloidal rotation frequency. The poloidal shear will be varied by changing the radial electric field, which can be done with a biased divertor.

A conceptual design for a biased divertor experiment is depicted in Figure IIIB.4. The divertor target plate is segmented. The shaded segments will be biased with the same polarity, and the remaining segments will be floating in the absence of plasma. The separatrix is then biased relative to

the vacuum vessel wall or relative to one of the movable limiters (shown). In the single null configuration, two types of bias could be used. In addition to this uniform bias configuration, a differential bias is also possible but probably not necessary for this experiment.

Figure IIIB.4. A conceptual design for a biased divertor.

The concept is quite simple, but detailed measurement in the SOL is required. Langmuir probes and the heavy ion beam probe will be used to measure the turbulence parameters and the mean quantities. The poloidal rotation measurements will be made using impurity Doppler shifts and Mach probes.

Milestones

- As a background experiment, conduct a survey of $\frac{T_i}{T_e}$ in all available discharges and look for correlations with turbulence parameters.
- Attempt to modify $\frac{T_i}{T_e}$ in the SOL with ECRH and compare effects on turbulence.

- Install a biased divertor arrangement as in Figure IIIB.4. Vary the electric field. Verify the existence of a velocity shear using impurity Doppler shift measurements. Observe the effects on turbulence.

Feedback Control of Fluctuations

Electrostatic fluctuations play a dominant role in edge transport, determining the scale lengths of density, temperature, particle flux and power flux in TEXT as well as most other tokamaks, and stellarators.³⁴ Electrostatic fluctuations may also play a large role in the interior transport through the dissipative trapped electron mode³⁵ A natural conclusion is that, if a way could be found to modify the electrostatic turbulence in the plasma, radially distinct regions of improved and deteriorated confinement could be artificially created.

Why should we try to modify the plasma transport? Aside from the obvious motive of slowing the escape of hot working gas ions and energy from the plasma interior, controlled confinement could selectively increase the transport of ash and other impurities. Control of transport in the edge and scrape-off region could prove particularly important. Increased perpendicular transport would spread the heat load in the region of a divertor strike point, making materials requirements less demanding and helping with impurity control. Work on the tokamak H-mode³⁶ has shown a correlation between decreased fluctuation levels and improved confinement transport at the L to H transition. Active control of the edge turbulence could be used to probe the mechanics of the H-mode, and could lead to improved reliability of the H-mode at lower power.

A series of experiments has been initiated on TEXT to modify the spectrum of the naturally occurring turbulence in the plasma scrape-off layer by inserting a double Langmuir probe into the plasma.³⁷⁻⁴⁰ In the "feedback" configuration, the floating potential in the plasma edge region is sampled, the fluctuations are amplified, and the amplified signal is used to drive the active Langmuir probe in the plasma edge with either a positive or negative phase. A 50 V bias (see below) is added to the signal so that the feedback will operate in the linear region of the I-V characteristic. A schematic of this configuration, showing the location of the active probe, and the far sensor probe array in the tokamak is shown in Figure IIIB.5.

Figure IIIB.5. Experimental setup of the active probe experiment in the feedback configuration showing the location of the driver and far sensor probes, the amplifier(A), phase shifter (ϕ), the bias, the magnetic pickup coils (M), and the top (T) and radial (R) limiter diagnostics. Also shown is the field line starting at the driver and traveling parallel (P) or anti-parallel (AP) to the plasma current.

Two sensor probe tips, also on the driver probe head, were used for the feedback experiments. A "far sensor probe" diagnostic array, consisting of seven probes spaced 1.3 cm apart arranged on a poloidal arc of radius 26 cm, is located 180° toroidally and poloidally from the active probe. This probe array was used to give a poloidal profile of floating potential fluctuations either driven by the active probe, or the naturally occurring edge fluctuations. Other diagnostics for studying a driven probe in the plasma edge include a magnetic pickup coil inside the vacuum vessel, and three Rogowski coils to monitor the current flowing to the top, outside radial, and bottom rail limiters.

Feedback

Though wave stabilization was applied in linear systems,⁴¹ this is the first application of the techniques to turbulent spectra in tokamaks. Preliminary results are very encouraging. With the combined effects of the feedback and bias (see below), we were able to either decrease the potential fluctuation level by up to a factor of 2 or increase the fluctuations by a factor of 10 over a broad frequency band along a flux tube at least 12 m in length. Figure IIIB.6 shows typical results, in which both suppression and enhancement of turbulence are observed, depending on the phase of the driver relative to the sensor signal. We observe these effects either when the feedback source is near the drivers (using sensor probes mounted on the driver probe head) or at the far sensors, 12 m away.

This work represents a collaboration between the TEXT group and T. Uckan and B. Carreras of ORNL. In addition, Prof. A. Sen of Columbia University is collaborating on the data analysis.

Figure IIIB.6. The spectra of potential fluctuations measured away from the active probe (at P3B), without any feedback, with suppression and with destabilization.

Proposed feedback research

Global transport changes - We need to demonstrate an effect on the global transport and particle diffusion in order to make sure that the feedback is more than an interesting curiosity. In conjunction with the

above scans, we need to look for the configurations that have the greatest impact on global particle transport and perpendicular particle diffusivity. Such changes would manifest themselves in H_{α} changes at the limiter or wall, changes in the central profiles or peak central density, and, possibly, MHD, sawteeth, or internal fluctuations (FIR scattering or HIBP). We propose the following experiments to increase the global effects:

a. Improved phase shift control for improved coupling to the plasma and greater influence on turbulence - The existing feedback network has a large frequency dependent phase shift, approximately 2π radians across the band from 10 to 100 kHz. As a result, we could not control the phase such as to be either suppressing or de-stabilizing over the whole band. It is, in fact, not possible to correct this shift to give a flat phase response over the whole band using analog circuitry. Therefore, future work will employ several narrow band filters with adjustable phase shift to create regions of the frequency spectrum with suppressed or increased fluctuation levels.

Enhanced control of the phase shift could also provide other advantages. Although we have performed several experiments in which two poloidally separated probes have been driven with a relative phase shift between them, we have not fully exploited this capability to specifically couple into waves which are expected to be present in the plasma edge such as drift waves. That is, we want to drive waves with wave numbers which match the background turbulence. By adjusting the phase between driver probes, or by using multi-pin arrays, it should be possible to couple into the target turbulence.

b. Different Feedback Sources. To date, we have concentrated on generating the signal on which we feed back from potential fluctuations, measured either near the driver probe or far from it, along a field line. We will investigate what happens when we use a sensor signal from a probe ion saturation current, a pair of probes, and an H_{α} signal. We will investigate the possibility of increasing the poloidal extent of the turbulence suppression or de-stabilizing effect by feeding back on an off-field-line probe. We will attempt to increase the coupling into the core turbulence by feeding back on heavy ion beam probe signals. We will attempt to affect the MHD activity by using a signal derived from the MHD loops.

c. Multi-probe driver array The addition of a second, separate driver probe head allows for more flexibility than in the current experiments. With a second probe, two configurations are possible:

1. With the probes separated poloidally, we expect to couple into lower m-number modes. For example, the possibility exists for modifying convective cells in the plasma edge and studying their effect on enhanced confinement modes. Returning to the "poloidal coverage" question, we will look at whether the poloidal extent of the turbulence-modifying effects of two probes is greater than for individual probes.
2. A second configuration will be studied, in which the probes will be separated in a direction along a field line for a "typical" discharge. In this case, we expect that the interaction of the probes with the plasma will be such as to draw an electron current filament in the toroidal direction between the probes. Thus the coupling would be more of an electromagnetic nature. These filaments might couple better into MHD modes than our usual electrostatic case, and, coupled with feedback from the MHD coils, could provide an independent method of controlling the growth of MHD modes. The possibility of creating small magnetic islands within the plasma and, with mode overlap, an "SFX" (see Perturbations in section II) will be studied. If this works, it offers the possibility of using powered poloidally segmented limiters or divertor target plates to modify the edge magnetic structure.

d. Other related experimental research. Active control of the plasma, not requiring that an additional probe be introduced into the plasma edge, may be possible by using an insulated limiter or divertor tile as a driver. Alternately, probe heads similar to those already tested can be mounted directly into either limiter or divertor target. Both ideas will be tested.

The possibility of an active divertor plate is particularly attractive. Because the two halves of a split divertor plate map into different radial locations of the non-diverted portion of the scrape-off region, we gain the possibility of better coupling into modes based on different values of k_r rather than k_θ .

Figure IIIB.7 a) Coherence of a signal on the far sensor probe with a single probe drive signal as a function of plasma current and/or field line position. b) Cross power of the signal on the far sensor probe with a drive signal for two-probe drive for in-phase and out-of-phase drivers.

Probe Coupling Physics.

In the course of the active probe feedback experiments, we obtained results that challenge current understanding of the physics of diagnostic probes and plasma sheaths. Thus, our work to understand the probe coupling with the plasma in the feedback experiments has taken on a life of its own. It appears that the results of this research will have immediate consequences in the design of divertors and in divertor modeling and in the application of probes in the vicinity of divertors and near limiters.

The size and structure of perturbations generated by the driven probe is different from that predicted with standard probe theory.^{42,43} In a typical driven probe experiment, we drive a single frequency signal, for example at 30 kHz, with a current of 5-10 A into one or two of the driver probe tips. At distances of 12 or 28 meters down the flux tube, the detected potential and density perturbations were well correlated with the driver signal, as is shown

in Figure IIIB.7. The upper figure is the linear correlation coefficient or coherence of the detected floating potential fluctuations 12 m downstream from the driven probe. The lower figure shows the cross power of the floating potential signal downstream with the two driver probes driven in and out of phase. Both the coherence and cross power are plotted versus plasma current or equivalently poloidal probe separation using a multiple pin probe array. The plasma current was scanned as a substitute for a poloidal scan of the detector probe. As can be seen in the figure, we measure a region with high correlation with the driver probe with a poloidal dimension of 2 cm, indicating that the shadow of the driven probe [mm dimension] has increased to two cm downstream. Measurements 28 meters downstream indicate a similar increase in the driver shadow or broadening of the flux tube. The radial dimension of the shadow is about 1-2 cm, roughly comparable to the 1 cm dimension of the driving probe. For comparison, the correlation length of the background turbulence in the poloidal direction is about 2 cm.

We have detected currents associated with the driven signals far down the field lines. A set of Rogowski coils measuring limiter current has measured significant currents at the probe driving frequency. We have also observed magnetic fluctuations at the drive frequency on a magnetic pickup coil located inside the vacuum vessel for several different plasma currents. The signal strength was consistent with the driven current flowing down the field lines which intersect the magnetic probe; it varied with the distance of that field line to the pickup coil.

Phase delay experiments between the driver and downstream probe with different frequency drivers suggest that the disturbance driven by the active probe propagates along the flux tube at about the Alfvén velocity over the frequency range 10-100 kHz, much faster than ion sound speed, and somewhat faster than thermal electron velocity. It should be pointed out that the edge plasma is quite collisional with a typical mean free path of order a meter, much less than the probe separations.

Consider first the fluid probe theory proposed by Stangeby⁴³ to describe a probe in a magnetized plasma. This theory involves free motion of ions along field lines to a probe at the sound speed and anomalous diffusion perpendicular to the field lines to fill in the flux tube. By balancing these flows, the downstream disturbance (or collection) length of a

probe in a magnetized plasma is approximately $d^2 c_s / D_{\perp}$, where d is a typical probe dimension, c_s is the ion sound speed, and $D_{\perp}$ is the perpendicular diffusion coefficient. In our experiments, this is about 0.2 m. Later theory by Hutchinson⁴⁴ added viscous effects to the fluid theory, but did not fundamentally change the disturbance length. Matthews and Stangeby⁴⁵ observed that a probe may disturb the plasma potential for a larger distance (the non ambipolar collection length) due to effects such as finite connection lengths, but should not disturb plasma densities over a greater distance.

A more recent non ambipolar fluid theory which includes the effects of the probe current and the bias has been proposed by Gunther.⁴⁶ This theory may be of limited use to us because it was developed for flush mounted probes in a divertor and depends on quantities such as plasma viscosity and neutral friction in the scrape off layer. However, it does qualitatively predict the parallel and perpendicular extent of the perturbation caused by a biased probe. It does not predict the structure of the observed local density perturbation.

Our experimental results are not predicted by current theory so we have sought collaborations to develop models of the probe coupling with the plasma. Experimental results suggest either a parallel electric field exists in the flux tube connecting the two probes or there is a perpendicular electric field around the flux tube connecting the two probes. We are working with S. M. Mahajan of the Institute of Fusion Studies and Y.-Z. Zheng at ICTP, Trieste, Italy to develop a theoretical model for our experimental results. After we develop a model, we will carry out further experiments to test the model.

These recent results appear to attack our fundamental understanding of a sheath formation at a plasma material interface. This has immediate consequences in the design of divertors and in divertor modeling. In the application of probes in the vicinity of divertors and near limiters, the extended disturbance lengths are particularly troubling. Is the probe I-V characteristic described by a single probe model, or is it a double probe characteristic where the current collected with a positively biased probe is limited by the ion saturation current from another surface connected to the probe through a flux tube? Current theory fails us, and the problem is

important for both the diagnostics in the scrape off layer and in the understanding of a divertor.

Non-linear Coupling of Driven Waves

We have observed a poloidal wave number of order $k_\theta(30 \text{ kHz}) \ll 1 \text{ cm}^{-1}$ for driven waves in both the near and far field⁴⁰, while k_θ for the background turbulence $\sim 1 \text{ cm}^{-1}$ at 30 kHz, indicating that, if a wave model is appropriate, the waves driven by the probe are dramatically different from the edge turbulence found in all tokamaks. We propose to investigate the non-linear coupling of the driven waves with the plasma turbulence using bicoherence,⁴⁷ a higher order statistical technique. Figure IIIB.8 shows the auto-bicoherence

$$\gamma^2 = \frac{|\langle \varphi_1 \varphi_2 \varphi_3^* \rangle|^2}{\langle |\varphi_1 \varphi_2| \rangle^2 \langle |\varphi_3| \rangle^2},$$

where the frequency matching condition, $f_3 = f_1 \pm f_2$, holds for potential fluctuations, φ_1 , for an experiment in which a 30 kHz wave is driven by the probe in the plasma edge. Coupling of the wave into the background turbulence is clearly seen. These experiments will provide insight into the nature of the edge turbulence, the energy sources and sinks and nonlinear wave coupling.

The fact that the current follows a field line suggests a possible diagnostic application of the active probe. The currents driven by a probe (e.g., in a divertor tile) can tag a given field line and magnetic coils can then be used to follow the magnetic field to another location in a non-perturbing fashion. This could find application in tracing a field line through an ergodic region or through a divertor x-point.

We have demonstrated that we can drive a potential fluctuation, or a current, in a magnetic flux tube over distances up to 28 m; the propagation velocity along the field line is fast - about the Alfvén velocity; the disturbances driven by the probe are not the same as the background turbulence, but do couple with the background turbulence; and that the interpretation of Langmuir probe I-V characteristics in a tokamak scrape off layer or divertor is not understood.

Figure IIIB.8. Measured auto-bicoherence of the floating potential fluctuations with a driven 30 kHz wave. The increased auto-bicoherence at $f_1 = 30$ kHz and $f_2 = 30$ kHz are indicative of coupling of the driven wave with the background turbulence.

Proposed work

- Develop a theoretical understanding of the coupling of a probe with a plasma. This work will be done in collaboration with S. M. Mahajan, IFS, and Y. Z. Zheng, ICTP, Trieste.
- Further experimental tests of the model developed.
- Investigate wave-wave coupling in the plasma using bicoherence and other higher order statistical tools.
- Use driven currents to follow a field line through x-point and ergodic regions in the plasma edge.
- Measure and understand probe I-V characteristics in the SOL and/or divertor region to develop divertor diagnostics on large tokamaks.

Impurity and Ion Flow

Motivation

To measure the velocity shear in turbulence control experiments, we require impurity and ion flow diagnostics. Besides simply measuring them, we will also try to understand the physics basis for these quantities. If flow can suppress turbulence as was argued in a previous section, then there may be something in the physics of these quantities that we can use to enforce particular structures in velocity shear. Even if that is not the case, we still need these diagnostics for the shear flow experiments described earlier.

Comparison of theory and experiment for impurity rotation is a means for testing basic plasma theory. Through these comparisons, understanding of basic plasma physics is improved with collateral improvement in the ability to interpret rotation measurements and to use rotation as a diagnostic. Poloidal and toroidal viscosity play important roles in L-H transition theories, and should be accessible to measurement through the use of perturbative techniques. TEXT is an excellent device for rotation studies because it combines a complete diagnostic set, including a unique direct measure of E_r , and a number of perturbative techniques to drive rapid changes in E_r .

The theory that predicts impurity rotation in Ohmically heated tokamak plasmas is relatively straightforward so that experiment/theory disagreements are surprising. Even so, disagreements occur. Possibly the best example of surprises that may be in store is a TEXT experiment in which it was found that rotation velocity measurements were consistent with then-current theory only for plasma regions with low neutral concentration.⁴⁸ In the experiment, it appeared that ion-neutral charge exchange was damping the rotation but not quenching it as is sometimes asserted. Appropriate theory was developed⁴⁹ and successfully compared with experiment.

Ion flow velocity measurements are also required to further improve our understanding of the edge plasma. For example, the DC potential in the SOL has an up-down asymmetry that depends on toroidal position, and this may be explicable in the SOL as an artifact of plasma flow along the

magnetic field. Also, the flow of ions along magnetic field lines to the limiter or divertor is a primary loss mechanism for particles and energy. As in the case of impurity rotation, the ion rotation measurements can be compared with neoclassical transport and may explain the observations of asymmetries in plasma potential, shear layers, and plasma rotation.

Experiments

- Simultaneous measurement of rotation and turbulence. The Langmuir/Mach probe described earlier will be used for these measurements along with Doppler shift measurements of impurity spectral lines. With the Langmuir/Mach probe, the fluctuating quantities of density, temperature and floating potential, along with derived quantities of wave number, radial particle flux, poloidal velocity, and the parallel flow velocity can be made as a function of position on every shot. This is the primary flow velocity experiment. Those following are subordinate.
- Test the common hypothesis that impurity toroidal rotation and ion toroidal rotation are the same. This simple hypothesis is a critical element to our understanding of plasma rotation. It appears to be well supported by consideration of ion-impurity collisionality, and it is commonly used to predict plasma rotation from the neoclassical theory,⁵⁰ which considers only ions and electrons but omit impurities. Yet it is contradicted by a neoclassical theory which attempts to account for multiple ion species. An experimental result here would certainly help to resolve this theoretical discrepancy.
- Are there in-out asymmetries in the toroidal rotation? We have made qualitative observations of in-out asymmetries in the impurity toroidal rotation velocity in TEXT. This type of asymmetry is predicted.⁵¹ It will be relatively easy to conduct experiments to quantify this asymmetry in TEXT and to compare it with theory. This experiment will be used to continue our comparisons of experiment and theory and perhaps extend our ability to predict plasma rotation.

- Use the available perturbative techniques to investigate toroidal acceleration in the presence of strong ion-neutral charge exchange. By suddenly changing the radial electric field in the plasma, and then observing the plasma spin-up/spin-down, it may be possible to learn something about the toroidal viscosity. This experiment will be carried out in the plasma periphery where we can perhaps look at the effect of ion-neutral charge exchange on toroidal viscosity. The primary means for changing the radial electric field is by applying a bias to an electrode immersed in the plasma. A second technique which avoids the contamination problems associated with the electrode is to use an SFX to change the radial electric field. This experiment will extend our understanding of momentum transport in the presence of strong charge exchange and may ultimately contribute to better appreciation for the physics of gaseous divertors.

Milestones

- Correlate turbulence and flow velocity in experiments on shear flow control of turbulence.
- Measure the in-out asymmetries in the impurity rotation.
- Compare impurity toroidal rotation velocity with working gas ion rotation.
- Measure the toroidal spin-up due to a change in E_r in the presence of strong charge exchange.

ELM EXPERIMENTS ON TEXT-U

Motivation

ELMs may be beneficial or deleterious. Thus far they have been used to allow 'steady state' H-mode operation by expelling impurities and thereby preventing radiative collapse⁵². On the other hand, the cost of this impurity reduction is a degradation in confinement along with the possibility of large heat pulses on the divertor target⁵³. Only after they are more fully understood will it be possible to decide whether some types of ELMs are useful and should be used for control of H-mode or whether all ELM types must be eliminated from operating scenarios.

The nature and number of ELM types differ from machine to machine. For example, 'Type I' or 'giant' ELMs on DIII-D may be ballooning modes⁵⁴. However, their smaller 'Type III' resemble the ELMs on ASDEX which are consistent with peeling mode theory⁵⁵. The large ELMs on PBX-M appear to be pressure-driven kink modes⁵⁶, and the appearance of ELMs on the W 7-AS stellarator may also indicate the importance of pressure gradients⁵⁷. This diversity may simply mean that ELMs have different origins on different types of devices, but then it is surprising that the experimental phenomena are so similar. ELM studies on TEXT will contribute results from a device of different size and a tokamak with a different heating mechanism. This will certainly enlarge the database of ELM phenomena and perhaps contribute to better understanding.

Temporal and Spatial Structure of ELMs

Poloidally: If ELMs begin at a particular poloidal location and propagate at the ion sound speed, as on DIII-D⁵⁴, we might expect a time delay of about $qR/c_s \approx 60 \mu s$ between the H_α rise at the inboard and outboard sides. The 4-5 μs sampling rate of our high frequency H_α detectors should allow us to resolve this delay if we observe both the inboard and outboard sides tangentially.

Radially: Perhaps viewing tangentially with the multichannel PDA (see discussion of SOL diagnostics below) will show some radial propagation of the H_α burst during ELMs. Also, ELM precursors observed

by soft x-ray measurements, or by electron cyclotron emission might show some time dependent radial variation, as on PBX-M⁵⁶ and TFTR⁵⁸.

ELM precursors

One key to identifying the relevant MHD instability is the observation of a high frequency (50-250 kHz) magnetic precursor to the ELM's $H\alpha$ rise, which several groups have reported^{58,59,55}. This mode is seen on JET in reflectometer signals, and on ASDEX in the $H\alpha$ light itself. The diagnostics needed to observe such precursors will be available on TEXT-U, including internal magnetic probes.

The effect of pressure gradients on ELMs

In addition, the SFX might be used to trigger ELMs, as was done on JFT-2M⁵², allowing us to discriminate between pressure and current gradient driven instabilities.

ELMs and impurity and particle transport

Besides comparing the usual operating parameters of ELMing H-modes with ELM free H-modes, we can also determine how ELMs affect τ_p , and perhaps impurity transport.

Milestones

- Obtain ELMs
- Characterize the spatial and temporal structure of ELMs in limiter and diverted H-modes
- Compare with those observed on other devices and speculate as to cause

Diagnostics and Standard Analysis Tools

The quantities measured in the SOL and the plasma periphery are T_e , n_e , ϕ , $\tilde{\phi}$, $\tilde{n}_e$, T_i , $\tilde{T}_e$, ion and impurity flow velocity, current onto the divertor or limiter tiles, heat flux onto the tile surface, impurity emission distributions, fueling neutral emission distributions, neutral pressure, gas flow measurements, and radiated power. Particle, thermal, and impurity transport can be inferred as well. Thus, we can study turbulence, infer turbulence induced transport fluxes, and extract transport fluxes from the mean quantities. This will provide a complete picture of turbulence and its implications in the SOL.

Figure IIIB.9. The relative poloidal locations for the edge diagnostics.

Two SOL simulation codes are available for analysis. For neutral transport, we use EIRENE⁶⁰. Because of the completeness of the measurements, it is not required for analysis of circular discharges, but it is a definite asset for diverted discharges. For plasma simulation, we are exploring the addition of B2⁶¹ and to support our work in the interaction of

neutrals with the plasma, we are considering a coupled B2-EIRENE code. Both are being tested at present with data from TEXT discharges. At present though, the relatively uncomplicated nature of the TEXT-U SOL does not seem to require the use of the plasma simulation codes such as B2.

The diagnostics are located at various toroidal locations. The experiments that we plan tend toward the use of plasmas that are toroidally symmetric. In Figure IIIB.9, the SOL diagnostics are projected onto a single poloidal cross section. That figure will be used in the following discussion.

Langmuir Probes

Langmuir probes are used to measure $n_e(r)$, $\bar{n}_e(r)$, $T_e(r)$, $\bar{T}_e(r)$, $\phi_p(r)$, $\bar{\phi}_p(r)$, k_{pol} , and $V_{phase}(r)$. As an example of the measurement and analysis capabilities, Figure IIIB.10 displays examples of these measurements from a single shot. The probes have four or five pins to allow simultaneous measurements of the above quantities on a single shot. This array allows direct estimates of particle and energy transport, $\Gamma(r)$ and $Q(r)$, from the electrostatic turbulence. These probes are mounted in a pneumatic reciprocator which scans the probe array through the plasma SOL and edge for a distance of 7.5 cm with a speed of about 1-2 m/s. The Langmuir probes are used routinely to measure plasma conditions in the SOL and into the plasma edge about 1 cm. Probe ranges are shown in Figure IIIB.9.

We have just begun operation of a 16 pin Langmuir/Mach probe array which will measure the parallel flow velocity of the bulk plasma in addition to the quantities mentioned above. Twelve pins in a circle shielded by the probe body collect ion current flowing from twelve directions to measure the plasma flow velocity. To reduce perturbations from the probes, the probe body was built with a boron nitride shield and the probe tips are made of carbon. This new probe has been successfully tested once and should soon be a routine edge diagnostic. In addition, we are constructing a visco-Mach probe in collaboration with Dr. Kyu-Sun Chung, a visitor from Han Yang University, Korea. This probe should measure viscosity of the edge plasma. This probe array should be tested and available for measurements prior to the beginning of the next grant period.

Figure IIB.10 Edge measurements on a single shot with a four pin Langmuir probe array mounted on a reciprocating drive.

We have developed a new probe technique for simultaneous measurements of plasma temperature, potential, and density in the plasma edge -- the time domain triple probe method.⁶² The time-domain triple probe method uses high speed switching of Langmuir probe potential rather than spatially separated probes to gather triple probe information, thereby avoiding problems of local differences in the plasma measured at each probe. Initial results from this new technique were promising and during the next year, this technique will be used extensively for definitive local measurements of plasma parameters in the edge and SOL. The time-domain triple probe technique may be the best technique available to measure temperature fluctuations in the edge.

Infrared Camera

The IR camera provides a measure of heat flux. An Inframetrics 600 IR camera is used to image the emission from the divertor tiles or the toroidal limiter. Data is collected with a full 8 bit accuracy. The image contains 182 by 240 pixels. Typically, the resolution used has been 2mm by 4mm per pixel but that can be significantly improved with recent hardware upgrades. Output images or frames are generated at a rate of 30/s. As many as 48 consecutive frames can be digitized into solid state memory in real time. The device which facilitates this is a definite improvement over commercially available devices and was developed at the FRC. To facilitate the calculation of the heat flux, the tiles viewed by the camera will soon contain thermocouples and black body cavities to remove the effects of long-term changes in window transmission and tile emissivity.

Tile Probes

An array of tile probes is used for measurement of particle flux and T_e and n_e directly in front of the divertor tiles (see Figure IIIB.9). The probes protrude above the surface of the tile by 2 mm. The tip of the carbon probe is a 1mm hemisphere. Heat flux is not an issue in TEXT so the probes can protrude above the surface of the tile. This avoids the interpretation problems that plague flush mounted probes.⁶³ The tile probes have seen the changes in density and temperature associated with divertor ramp-up in

equatorial single null discharges. They are located to allow direct view by the IR camera.

TEXT Divertor Thomson Scattering System

Design and construction of a Thomson scattering system for the divertor X-point region on TEXT-U is underway. The high field side divertor in TEXT-U severely limits diagnostic access. An additional mirror will be added to the existing Thomson scattering system to allow the laser beam to enter the vacuum vessel on the high field region through a small 2" port. Horizontal movement of the laser beam is not possible due to physical obstructions, so the divertor location must be adjusted to intercept the laser beam.

Initial measurements with the existing Thomson scattering system have measured the drop in temperature at the last closed flux surface. With a low temperature measurement limit of just below 100 eV, accurate measurements were not possible. However, we could determine that the drop off occurred in just a few centimeters and that the temperatures in this region were around 100 eV. This implies we will need a system with much lower limit of measurement. Our previous edge temperature diagnostic on TEXT utilized a 1 m spectrometer and a set of 10 photomultiplier tubes. This system could measure temperatures down to a few eV at density as low as $1 \times 10^{12} \text{ cm}^{-3}$. With this spectrometer, temperatures from 1 to 200 eV are possible and this should be adequate for the region of interest.

Spectroscopy

The spectroscopy provides distributions for the emission of the fueling species (usually deuterium), impurity emission distributions, impurity flow velocity, and impurity temperature measurements which are interpreted as ion temperature measurements. TV cameras are used primarily for tangential views of deuterium emission. In addition, there is a toroidal array of detectors that sample the toroidal distribution of deuterium emission. Typical sampling chords are shown in Figure IIIB.9. Rotating mirrors at two toroidal locations can be used to scan the view of a spectrometer across the plasma. The fan of observation chords is shown for each view in Figure IIIB.9 as the Z Fan and the R Fan. Thus are distributions of deuterium and

impurity emission acquired. Further, Doppler shift and Doppler broadening measurements can be used for velocity and T_i measurements respectively.

Radiated Power

An X-UV photodiode array is used for measurement of radiated power. The array has 16 channels and covers about 10 cm along the minor radius in a single shot. A few shots are required to scan the plasma. The low-field-side SOL or a complete x-point region can be covered in a single shot. There is a recurring concern with the X-UV type of device that its wavelength sensitivity is not adequate for use as radiated power monitor. We have a true bolometer array against which we can and do benchmark the X-UV results. The X-UV detector is preferred over the bolometer because of greater sensitivity and faster response.

D_α Fluctuation Diagnostic (or Photodiode Array (PDA))

Optical imaging has been used to study turbulent fluctuations in the SOL of TEXT-U¹⁵. This technique permits the study of turbulence in otherwise inaccessible regions of the plasma, making it an attractive choice for the proposed curvature drive experiments. For example, we have made some preliminary comparisons of fluctuation levels near the LCFS on the high-field and low-field side of diverted and circular discharges. However, because the measured light intensities are chord integrals, the analysis of the data involves a careful consideration of finite sample volume (FSV) effects.

The spectroscopic turbulence diagnostic employs a simple lens to image D_α light (6563 Å) from one edge of the plasma onto a linear photodiode array (PDA) with unity magnification. The collisional-radiative model of Johnson and Hinnov⁶⁴ predicts that, for typical TEXT-U SOL parameters, local D_α emissivity fluctuations reflect primarily n_e fluctuations and have only a weak dependence on T_e . We have found no evidence that the neutral population itself has an effect on the measured relative fluctuation levels.

Figure IIIB.11 shows a typical application of the PDA diagnostic on TEXT-U. Localization of the measurement in the poloidal direction is provided by the imaging optics, consisting of a simple lens and an interference filter to image line emission from the plasma onto a 32-element

linear photodiode array. Each diode's amplifier provides a constant transimpedance gain in the range of 10^5 - 10^6 up to 100 kHz. We have measured the crosstalk between adjacent diodes to be less than 1%. The poloidal separation of sample volumes in the plasma is equal to the 1 mm separation of diode centers on the array. The transverse width of each diode's viewing chord is about 2 mm in the front focal plane. The radial distribution of $D\alpha$ emission, peaked strongly near the LCFS, provides natural radial discrimination in a tokamak. The PDA signal is a chord average over both the near and far edges, but because the transverse dimension of the viewing chords on the far side is much larger than the turbulence scale lengths, spatial averaging greatly attenuates the far side contribution.

Figure IIIB.11: PDA imaging optics. This cross sectional view also shows the focused viewing chord of one diode in the array.

We have made a detailed comparison of PDA and Langmuir probe measurements of density fluctuations. The comparison has helped to validate the spectroscopic diagnostic and has resulted in an improved

understanding of the FSV effects associated with this measurement. The most severe of these is the PDA's extended radial viewing volume which overlaps the naturally occurring velocity shear layer near the LCFS. The result is that the spectral density function $S(k, \omega)$ measured by the PDA reflects the presence of both positive and negative k features in the chord integrated signals. This is demonstrated in Figure IIIB.12 which shows the $S(k, \omega)$ function derived from a Fourier transform of the data from 10 diodes. Traditional estimates for $S(k, \omega)$ using data from just two sample volumes cannot adequately describe such a distribution, but we have developed a three sample volume estimate for the spectral density function which can in fact detect the presence of two modes in wave number space. We can therefore estimate the contribution from each side of the velocity shear layer without needing to routinely record the signals from a large number of diodes.

Figure IIIB.12. Spectral density function computed using a spatial and temporal Fourier transform of the signals from 10 diodes. Positive wave numbers correspond to the electron-drift direction.

Because the fluctuation power decays strongly with increasing frequency, the electronic amplifier noise in the higher frequency components

of the PDA's signal is significant. This problem is mitigated in part by using the close spacing of the array diodes. The separation between adjacent diode sample volumes is much less than the fluctuation scale lengths. As a result, the plasma contribution to the cross power between adjacent diodes will represent the local fluctuation power spectrum while the incoherent noise component can be substantially reduced by using a large number of data realizations. Typically, the data from two or three identical discharges is enough to provide an estimate of the local power spectrum at frequencies up to 100 kHz.

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PROJECT DESCRIPTION

III. PROPOSED RESEARCH

IIIC. TURBULENCE ANALYSIS

IIIC. Turbulence Analysis

This section describes the fluctuation measurements that can be done on TEXT-U to provide additional physical insight into (1) nonlinear phenomena, such as nonlinear mode coupling, and nonlinear wave interactions and associated energy cascading; and (2) transient or nonstationary phenomena, associated with, for example, L to H transitions and other types of transient events, whether naturally occurring or externally excited. It is generally agreed that turbulence plays a major role in tokamak transport. On TEXT-U, turbulence measurements are readily available. The techniques described here when developed for and applied to these measurements will lead to deeper insight into turbulence in tokamaks that could well change our basic understanding. There will be immediate application of these techniques to turbulence measurements on all other tokamaks. Further clues to the sources of turbulence in tokamak may be uncovered.

This work will be performed by Professor E. J. Powers of the University of Texas along with his colleagues and students. Dr. Powers, together with his students and postdocs (e.g. Dr. Ch. P. Ritz), developed the two-point correlation technique that is now generally used in the fusion community to analyze turbulence data and did the first measurements of energy cascading in the scrape-off layer. In a 1974 Nuclear Fusion article, Dr. Powers spelled out the basic ideas underlying experimental measurements of fluctuation-induced transport, a technique widely used on TEXT-U and other tokamaks.

The basic tools involved in investigating nonlinear phenomena reside in recent advances in higher-order statistical signal processing and its applications (HOSSPA), whereas the basic tools to investigate transient and nonstationary phenomena involve relatively new concepts such as the wavelet transform, as well as older concepts such as short-time Fourier transforms, Wigner-Ville distributions, complex demodulation, and evolutionary spectra. The following is divided into two major parts, the first dealing with quantification of nonlinear phenomena, the second dealing with transient and nonstationary events.

Nonlinear Phenomena

The work proposed herein is based on several observations. First, and foremost is the fact that a heavy ion beam probe (HIBP) is installed on TEXT-U, and it is capable of making two-point measurements of density and potential fluctuations at a number of spatial locations. One of the immediate objectives from a fluctuation point-of-view is to make reliable measurements of wave number k . The basic theme of the work proposed below is based on the fact that by properly processing the data originally collected to measure wavenumber k , we can provide new insight into the nonlinear characteristics of the fluctuations in the core, thereby significantly enhancing the scientific productivity of the heavy ion beam probe (HIBP) at a relatively small incremental cost (compared to the capital and operating costs of the HIBP). Although focusing on the HIBP in this proposal for the sake of specificity, it should be understood that the advanced signal processing techniques described in subsequent paragraphs are applicable to other fluctuation diagnostics as well.

The basic objective would be to investigate the nonlinear nature of the fluctuations (density, or potential, or both) by quantifying nonlinear wave interaction phenomena and the associated energy cascading. Our approach rests upon innovative applications of higher-order statistical signal processing¹ to detect and model nonlinear phenomena and is based on work we have done over the past several years relating to nonlinear system modeling,^{2,3,4} quantification of nonlinear phenomena underlying the transition to turbulence in neutral fluids,⁵⁻⁹ and nonlinear wave interaction phenomena in plasmas.¹⁰⁻¹³

Our approach is based on the fact that the HIBP generates time series data collected at two closely spaced points. We then take this data and model the linear and nonlinear wave physics occurring between these two points with the aid of a frequency-domain Volterra model.^{2,3} This model consists of a hierarchy of frequency domain transfer functions, which model the linear, quadratic, cubic, ... wave physics. In reference 14 we demonstrated, for example, that knowledge of the linear transfer function enables one to determine both growth rates and the dispersion relation of various modes present in the fluctuation spectrum. More importantly is the fact that, in the same reference, we point out that knowledge of the

quadratic transfer function enables one to estimate the three-wave coupling coefficient. Experimental knowledge of the three-wave coupling coefficient is important in that the nonlinear-wave physics is imbedded in it and thus, in principle, can be compared with theory. Furthermore, knowledge of the three-wave coupling coefficient is essential if one is to experimentally quantify energy-cascading-associated nonlinear wave interactions.

There are three advances that we have made over the past five or six years that represent a significant advancement in our capabilities to detect and quantify nonlinear wave phenomena. In principle, one or all of these could be applied to the HIBP data currently being collected to determine wave number k . The three advances are described below:

Wavenumber Mismatch: For resonant three-wave interactions, both ω and k should satisfy $\omega_3 = \omega_1 + \omega_2$, and $k_3 = k_1 + k_2$. Most experimental investigations of three-wave interactions, including our own, only investigate coupling between three waves whose frequencies satisfy $\omega_3 = \omega_1 + \omega_2$; however, wavenumber effects are overlooked. (This is not obvious if you look at our past work¹⁴) This is because one generally has copious amounts of time series data from a limited number of spatial locations. Thus, a bispectrum in ω -space, rather than k -space, is utilized and such a bispectrum is only concerned with those frequency triplets satisfying $\omega_3 = \omega_1 + \omega_2$.

Ideally one would like to generate a bispectrum in ω - and k -space, $B(\omega_1, \omega_2, k_1, k_2)$, but this has proven to be exceedingly difficult, if not impossible, using two-point data. In recent years we have, however, developed an approach^{15,16} that does the next best thing. Specifically, for each triplet satisfying $\omega_3 = \omega_1 + \omega_2$, we calculate the wave number mismatch (Δk), where $(.)$ denotes a statistical average, and $\Delta k = k_3 - k_1 - k_2$. Because of the stochastic nature of turbulent plasma fluctuations in which the dispersive properties are described by a statistical, rather than a deterministic, dispersion relation, one cannot measure the wave number mismatch directly from measurements of k_1, k_2, k_3 . Rather one must use a statistical approach. Our new approach to measuring wavenumber mismatch utilizes a new higher-order spectrum, namely the cross-correlation of the auto-bispectra measured at the two spatial points. The

degree of confidence in the measurement of Δk is provided by a new coherence spectrum, the bispectrum coupling coherency. The closer this coherency is to unity, the better our ability to measure Δk accurately. Finally we note that our ability to measure wave number mismatch in turbulent plasmas may have important physics implications, because of the dependence of energy cascading on Δk .

Cubic or Four-Wave Interactions: Immediate past attempts to quantify nonlinear wave coupling and associated energy cascading have involved second-order or quadratic-type nonlinearities which lead to three-wave interactions. At the time we did our original work on this topic,¹⁴ we were asked, "What about third-order or cubic-type interactions?" Partially in response to these questions, and partially because of the need to go to third order in our work in offshore technology and communication systems, we have developed the capability to model third-order or cubic nonlinearities.^{2,3,4} As a result, we are in a position, using the same two-point data as before, to model the cubic wave physics occurring between the two spatial points at which the fluctuations are measured. This is an important first step to experimentally measuring four-wave interactions and associated energy cascading.

Density and Potential Coupling: There was another comment pertaining to our past work and related to the fact that we only investigated three-wave coupling between density fluctuations at one point and density fluctuations at the second point. We were often asked about coupling between potential fluctuations at the two points, and coupling between density fluctuations at the first point and potential fluctuations at the second, and vice-versa. To carry out such measurements requires a dual-input dual-output Volterra model, which we developed in the late 1980's.¹⁷ We used this to investigate coupling between various combinations of density and potential fluctuations in the edge of TEXT. The results were disappointing, mainly because the coupling was very low; thus, they were never published. The situation in the core, however, may be quite different. In any event, since the HIBP measures both density and potential fluctuations, we may be in a unique position to shed new insight into the density-potential nonlinear coupling issue.

Transient and Nonstationary Fluctuation Analysis

An important challenge in plasma fluctuation diagnostics involves the analysis and interpretation of nonstationary fluctuation data and/or transient events. The transient events may be naturally occurring (e.g., "bursty" phenomena) or externally excited (e.g., L to H transitions). Nonstationary phenomena are associated with those situations where the underlying statistics of the fluctuations change over time, and, in some sense, include transient phenomena, but are not limited to such phenomena. To analyze and interpret transient or nonstationary fluctuation data, one would ideally like to describe such signals in both the time and frequency domains. In such a situation one cannot obtain arbitrary precision in both the time and frequency domains because of limitations imposed by the uncertainty principle.

There are five basic approaches that have been exploited to extract the time-frequency features of a signal:

- (1) Short time Fourier transform¹⁸
- (2) Wigner-Ville distributions¹⁹
- (3) Evolutionary spectra²⁰
- (4) Complex demodulation²¹
- (5) Wavelet transforms²²

There is a fair amount of literature dealing with each of these techniques individually. We are not aware of an overall assessment of the pros and cons of each technique. This latter point is important because each technique has its strengths and limitations, thus implying that there is probably no universal best way to analyze nonstationary and transient fluctuation data.

In addition, the vast majority of the work on nonstationary and transient signal analysis deals with second-order statistics, i.e., generalization of such concepts as power spectra to a time-frequency power spectrum $P(\tau, \omega)$. With regard to the analysis of stationary fluctuation data the utilization of higher-order statistics has proven to be an extremely powerful tool with which to detect and quantify nonlinear phenomena and

the nonlinear energy transfer associated with frequency and/or wavenumber "mixing". Initial attempts to extend higher-order statistics to Wigner-Ville distributions and wavelet transforms have been reported in the literature.^{23,24} The work of Van Milligen et al.²⁴ on the wavelet bicoherence looks especially interesting but there are a number of fundamental questions that need to be addressed before their technique is widely accepted.

Thus the objectives of transient and nonstationary fluctuation data analysis on TEXT would be two fold. First and foremost would be the goal to provide new insight into: (1) the physics underlying transient and nonstationary phenomena and (2) the consequences of such phenomena on transport, and other processes of interest. Transient events appropriate for study will be identified with the help of the TEXT group. Second would be an assessment of the various approaches described previously in an attempt to determine which are most powerful in analyzing various classes of plasma fluctuation signals. Although all approaches will be evaluated, we would definitely focus on wavelets, and build upon our past experience in utilizing wavelets to detect and classify transient events in electric power systems.^{25,26} Finally, we would utilize our extensive past experience in higher-order statistical signal processing to advance the state-of-the-art in the application of higher-order statistics to nonstationary and transient plasma fluctuation data. Since all this work would be done using actual fluctuation data from the TEXT-U tokamak, we can guarantee that it will be relevant to the plasma fusion community in general.

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PROJECT DESCRIPTION

III. PROPOSED RESEARCH

IIID. IMPROVED CONFINEMENT

IIID. Improved Confinement

At present, we are studying three regimes of improved confinement. One appeared serendipitously following boronization in a poloidally limited configuration with electron-cyclotron resonance heating (ECRH). It appears to be a limiter H-mode though more experimentation will be required to verify that. The second regime of interest is the divertor H-mode. That regime remains elusive though the plasmas appear to meet the common H-mode requirements: x-point in the direction of the ion gradient B drift, low impurity content, and sufficient auxiliary power. The third regime is a form of improved Ohmic confinement. It occurs spontaneously near the density limit and may be associated with the formation of a MARFE.

All three of these regimes will be studied. Until the ECRH limiter H-mode is understood, it will receive the highest priority. This limiter H-mode plasma might well serve as a starting point for the development of a *diverted*, auxiliary-heated H-mode. We will continue to investigate all critical aspects (listed in a subsequent section) of our ECRH diverted plasmas, compare them with H-modes on other devices, and, hopefully, determine the reason for the absence of H-mode. Because the diverted plasmas do seem to meet the criteria for H-mode, this research should be critical to the community at large. Other improved confinement regimes such as the Ohmic regime already mentioned will be studied to identify the transition mechanism, but these will have lower priority than the search for the ECRH, diverted H-mode.

In the remainder of this section, there are discussions of results and plans for each of the three regimes:

- Transitions to Enhanced Confinement in Limiter Discharges Caused by ECRH
- Experiments to Develop a Diverted H-mode
- An Improved Ohmic Confinement Regime

Transitions to Enhanced-Confinement in Limiter Discharges Caused by ECRH

Introduction

In March of 1995, we observed the first transitions to a state of improved tokamak particle and energy confinement that were caused by the introduction of ECRH. From the small database collected thus far, these transitions have similar phenomenology to L-H transitions, and have only been observed with high current and recycled fueling (corresponding to low target density $\bar{n}_e \approx 1.5 \times 10^{19} \text{m}^{-3}$) in a limiter configuration. There is presently insufficient data to determine whether edge pedestals develop in the density and electron temperature. Also, as a scaling with density there appears to be little or no improvement in the energy confinement τ_e over L-mode confinement in TEXT, so we have not at this time been able to clearly classify the transition state as H-mode. The operational prescription for achieving this transition has been elusive. Efforts to regain and control the transition has, as a general conclusion, not been facilitated by guidelines (magnetic geometry, threshold power levels, etc.) suggested from results of similar investigations on other devices. This experience is not unlike that of other research groups and emphasizes that these tokamak state-transitions are complex and are still some distance from being sufficiently understood.

Transition Phenomenology

The temporal phenomenology of a transition occurring during the ECRH-pulse is shown in Fig. IIID.1. The ohmic phases are labeled by 'OH1' and 'OH2', and the L-mode phase by 'L'. The transition phase is labeled by 'H' (during ECRH) and 'HOH' (continuing after ECRH). The start of the transition is always marked by a sharp drop in the edge D_α emissions (proportional to the particle source) and a simultaneous rise in the line-averaged electron density $\bar{n}_e$. Both observations are consistent with improved particle confinement, assuming no additional impurity fueling. Likewise, the central electron cyclotron emission (ECE)

phenomenology of transitions occurring during ECH

shot 218117 - with transition
shot 218116 - without transition

Figure IIID.1. Phenomenology of transitions occurring during ECRH

(proportional to electron temperature) and diamagnetic energy (proportional to total plasma energy) start to rise, indicating improved energy confinement. The transition is most typically initiated following a sawtooth crash. Dithering between L-mode and the state of enhanced confinement is common, with the dithering again coordinated with the sawtooth crashes. The radiated power signal from the core typically rise slowly, indicating a more gradual accumulation of impurities. ELMs have not been routinely observed in the D_α emission, although sharp spikes in the radiated power from the edge have been occasionally observed. Perhaps a stronger transition is required for the clear development of ELMs. The soft-x-ray signals also show a longer time-scale impurity accumulation, which is revealed when removing contributions from the more rapidly increasing density and temperature.

Neither the electron nor the ion temperature profile has been measured thus far. FIR interferometry shows a rather uniform increase, yielding a peaking of the density profile. No edge pedestal is evident from these data. Although the edge pedestal is a universal H-mode characteristic in both separatrix and limiter configurations, it can appear weaker for limiter H-modes with strong density peaking as shown in TFTR¹. In JET, it has been suggested that the interaction with the limiter in the case of H-mode-like Improved Limiter Confinement (ILC) discharges prevents the development of large edge pedestals². The limiter interaction in TEXT-U may have a similar effect. Also like the ILC mode, no large change in the loop voltage or inductance accompanies the transition, although there may be small increases.

At the L-H transition, it has been widely postulated that a reduction in the local fluctuation-driven transport coefficients in the edge - probably as a result of increased EXB velocity shear - is responsible for the global confinement enhancement. In the case of the ILC, it is possible that the edge-limiter interaction pushes the shear layer deeper into the confinement region. Hugill, however, recently emphasized in a review of the experiments that there exists no unambiguous support for such hypothesis, and that further measurements with better space and time resolution are required³. The diagnostics for such measurements exist on TEXT-U.

Figure IIID.2. Interior density fluctuation profiles measured by the HIBP.

In TEXT-U, the transition is accompanied by an increase of the plasma potential with respect to L-mode throughout the interior on the high-field side as measured by a Heavy-Ion Beam Probe (HIBP). In contrast, the interior potential profile on the low-field side does not change observably. The broadband interior density fluctuations measured by the HIBP are also typically observed to increase or remain the same after the transition. This novel but preliminary result is shown in Fig. IIID.2. Both the density fluctuation and potential profile measurements were performed by sweeping the HIBP beam along a central chord as shown in Fig. IIID.2. The diagnostic has not yet been calibrated to yield values of absolute potential, so the potential data is not shown. Insufficient data in the far edge was obtained in both cases. We plan to collect more HIBP data to confirm these results, and to map the fluctuations along additional chords throughout the interior and edge.

In contrast, a Langmuir probe observing the scrape-off layer (SOL) fluctuations at the top sees a significant decrease of turbulent electron temperature T_e and floating potential Φ_{fl} fluctuations during the transition state. The average quantities also decrease, so that the relative level of

Figure IID.3a. Temperature and temperature fluctuations measured in the SOL by a Langmuir probe.

Figure IID.3b. Potential and potential fluctuations measured in the SOL by a Langmuir probe.

temperature fluctuations $\tilde{T}_e/T_e$ is not much changed. Less of a change is observed in the measured average density and density fluctuation levels. These observations are shown in Figs. IID.3a-c.

Figure IID.3c. Density and density fluctuations measured in the SOL by a Langmuir probe.

Given the strong poloidal asymmetries that have been recently observed over the density turbulence structure in other TEXT-U discharges, more comprehensive measurements are clearly needed before the results from the HIBP, probes, and other TEXT-U diagnostics can be incorporated into a global model of the transition. We note that the change in the fluctuations measured in other devices during the L-H transition have also yielded mixed results: decreasing in some cases, increasing in others. Our program will be to measure the fluctuations, along with their phases and coherences, everywhere in order to show

where reductions/enhancements in the local transport coefficients occur with the transition.

Changes in Energy Confinement at the Transition

In JET, the proposition that the ILC mode is a modified but weaker version of H-mode is also reflected by the smaller increase in the global energy confinement τ_e . In JET, the τ_e increase during ILC confinement can be of order 50% over L-mode, compared to an increase of order 100% for H-mode confinement over L-mode. Changes in τ_e for shots exhibiting the transition in TEXT-U are shown in Fig. IIID.4b. The increase in τ_e is more modest in TEXT-U, typically being only of the order 10-20%.

Figure IIID.4. Comparison of energy confinement scaling with density for shots with and without a transition

As shown in Figs. IIID.4a and IIID.4b, τ_e does scale strongly with plasma density in the Ohmic, L-mode, and transition phases in TEXT-U. For reference, these phases during a discharge are labeled as in Fig. IIID.1. Fig. IIID.4b alone shows that as a function of density, τ_e in the transition state does not appear to scale more favorably than it does prior to the transition. By comparing Figs. IIID.4a and IIID.4b, one can see that this is true for cases where the plasma is in the transition state both during and after the application of ECRH. In other devices, H-mode confinement with auxiliary heating usually scales somewhere between L-mode and Ohmic confinement. Our objective will be to develop a model which explains such behavior of the energy confinement in terms of the measured equilibrium and fluctuation profiles.

Transition Conditions

Despite our limited database, several operational conditions appear to be critical for achieving the transition. First, a high plasma current $I_p > 250 \text{ kA}$ is required. Such currents help to drive large sawteeth which, upon crashing, carry a large transient heat flux towards the plasma edge. Sawtooth perturbations to the edge D_α signals are observable only for the case of these high currents. The correlation between a sawtooth crash and the start of the transition is shown in Fig. IIID.5. The D_α drop occurs first at the low-field-side midplane edge, then at the top and bottom (no data are yet available on the high-field-side midplane). The initiation of the L-H transition by a sawtooth crash has been noted previously in other tokamaks. We further note that $I_p = 250 \text{ kA}$ is just below the $q_a = 3$ disruption limit, where the discharges become susceptible to MHD and locked modes. The proximity of a rational magnetic surface (i.e. a helical divertor) near the edge may be important for achieving the transition.

Second, a minimum of 300 kW of central ECRH (60 GHz O-mode heating at the fundamental $B_T = 21.5 \text{ kG}$) is needed. Such ECRH also drives the sawteeth and raises the overall plasma temperature. We have yet to observe the value of an electron or ion temperature critical gradient that might be necessary for the transition. Also, a relatively large superthermal population

$$n_{e \text{ sup}}/n_{e \text{ ther}} \approx 10^{-4} - 10^{-3}, E_{\text{sup}} > 10 \text{ keV}$$

is generated and measured under our low-density target conditions. Here the subscript "sup" represents superthermal and "ther" represents thermal. It is unknown whether these electrons play a role in the transition process.

Figure IIID.5. The transition is initiated near the midplane by a sawtooth crash

Fueling of the discharge through deuterium recycling rather than through external gas puffing is used. For recycled fueling alone, the detailed condition of the limiters and vessel walls is likely to be especially crucial. In devices where the L-H transition is observed, a different wall conditioning method had to be developed (often by trial and error) in nearly every case. The physics of such wall/limiter conditioning is another poorly understood area in plasma research, although it can have dramatic impacts on many aspects of tokamak operation. Fueling of both the working gas and of impurities is affected. A superior wall-coating or

conditioning method has yet to be identified or widely accepted. In TEXT-U, we made substantial progress by coating the limiters and a large fraction of the vessel interior with boron (see Wall Conditioning in Sect. II). Helium glow cleaning between applications removes adsorbed deuterium. Transitions of the kind shown in Fig. IIID.1 were first observed one month after starting this boronization program. Dramatic reductions in both the plasma impurities and deuterium recycling were observed during this period.

The transition has been observed with nearly equal probability in plasmas riding on either the top or bottom limiters. The transition is increasingly difficult to obtain during successive shots, unless the plasma is shifted to the opposing limiter, or to another surface on the same limiter that was unused during the preceding several shots. The position of the low-field-side radial limiter does not appear to be crucial as it was for the limiter H-modes reported in JFT-2M⁴ and JIPP T-IIU⁵, although this limiter in TEXT has always been within 3cm of the last closed flux surface. In JFT-2M, JIPP T-IIU, and TFTR, limiter H-modes were obtained with the plasma running on the toroidal belt limiter. In JET, the ILC mode is obtained when riding on the low-field-side radial limiter. In TEXT, we have not obtained the transition when limited on either the inboard or outboard limiters. This apparent disparity of results might not be significant in the case that limiter conditioning is more important than limiter positioning.

Future Plans

Analysis of the growing data set obtained on these discharges is still in progress. We first need to establish that the transition is an L-H transition, rather than an impurity effect associated with heating of the boronized limiter during ECH. As part of this effort, we will better determine the sensitivity of the transition to the limiter placement, and whether an increasingly aggressive, but measured, boronization program allows us to access the transition more readily. The array of TEXT equilibrium and fluctuation diagnostics will continue to be applied. All fluctuations will be measured through the transition and throughout the plasma volume. We will determine the spatial and temporal relationship

between changes in the radial electric field, the fluctuations, the deuterium and impurity fueling, the rotational velocity shear, and the transport at the transition.

Experiments to Develop a Diverted H-mode

Though enhanced confinement was achieved in an auxiliary heated, limited configuration, a reproducible, auxiliary heated, diverted H-mode has eluded us. Still, H-mode-like features have been observed in isolated instances. Since our efforts have been imitative of the techniques applied on other devices, the absence of an H-mode is physically intriguing. Because we feel that our diagnostics are eminently suited for the study of H-mode and therefore could contribute substantially to its understanding, its absence is also frustrating. The current strategy in our research is to investigate all relevant aspects of the ECRH, diverted plasmas and to compare them with H-modes on other devices in order to determine the reason for the absence of H-mode in TEXT. It is particularly useful that the H-mode-like discharge is available in an auxiliary heated, limited configuration as that may be a starting point for development of the diverted H-mode.

Initially, H-mode development was focused on a discharge in which the ion gradient-B drift was in the direction of the x-point, ECRH power levels (less radiated power) were apparently adequate, and impurity levels were controlled using boronization. The ECRH power was launched from the low field side and absorbed at the first harmonic. The duration of the ECRH pulse was longer than two energy confinement times for the Ohmic discharge that preceded the injection of ECRH. When H-mode did not appear, an analysis of the discharges and a comparison with experiences on other devices suggested the following issues for additional study.

Separatrix-to-wall distance

In some (but not all) of our experiments, the plasmas were such that the separatrix-to-wall distance was not always larger than the scale lengths (density or temperature) in the SOL. This type of discharge was excluded from the database that was used to generate the well-known H-mode scaling laws⁶ because in both ASDEX and JET, it was shown that the threshold increased by as much as a factor of two when the separatrix-to-wall distance was less than a characteristic length for the SOL gradient. In determining whether TEXT plasmas are above or below the power

threshold for H-mode, the standard H-mode scaling law is used along with measured power thresholds from other tokamaks. Though there is little detailed data from other machines, it may be that the power threshold was not exceeded in TEXT plasmas in those instances where the separatrix-to-wall distance criterion was violated. Increasing the auxiliary power is an option for the future. Before that, H-mode experiments will be confined to plasmas that obey the criterion.

The TEXT discharges that violated the criterion on separatrix-to-wall distance were used for H-mode attempts because at the time of the experiments, these discharges had the best electron cyclotron (EC) absorption characteristics. These were relatively high current diverted discharges in biased double null (BDN) configuration (Fig. II.2), and they were of sufficiently large size compared to the vacuum vessel dimensions so that the distance between separatrix and wall was near the critical length. At lower currents, the separatrix-to-wall criterion can be met and was met. Those discharges did not achieve H-mode, but those experiments were conducted before extensive use of boronization. We plan to return to those discharges with improved wall conditioning.

Shape

With the x-point in the direction of the ion gradient-B drift, the TEXT shapes are still dissimilar in shape from typical H-mode discharges. (see Fig. II.2) In TEXT, the x-point is not near the average major radius, but well to the high field side. This is troubling as Compass did not achieve H-mode with an inner x-point.⁷ In at least one device, TCV, that has produced H-mode,⁸ shapes close to that of Figure II.2 can be reproduced. It would be interesting to know whether this device can produce H-mode in a TEXT-like configuration. A collaboration would be of general interest and is being pursued.

The single null discharges in TEXT-U were often disconnected double nulls.⁹ In single null H-mode discharges with the x-point above (below) the plasma, there is always a second x-point located below (above) the plasma and outside of the separatrix that is associated with the upper (lower) x-point. At the outside equator of TEXT discharges, the two separatrices were quite close. One physically relevant measure of this

distance is the radial correlation length of the turbulence because turbulence controls cross field transport in the SOL. The distance between the two separatrices was on the order of a radial correlation length so it is expected that the single null had some properties of a double null. In typical H-mode discharges, the double null has a higher power threshold than the single null.¹⁰

Heating

H-mode can be produced in a diverted tokamak with ECRH heating.^{7,11,12} There are several issues involved in selecting the way that ECRH is applied in TEXT-U. The H-mode scaling law⁶ suggests that the power threshold increases with both toroidal field and with electron density. Recently, experiments in Wendelstein 7-AS demonstrated that high ion temperature can improve the likelihood of H-mode.¹³ These are somewhat contradictory because ECRH heats electrons, and higher density leads to improved ion heating due to improved electron-ion coupling.

In TEXT experiments in a boronized machine, ECRH was launched from the low field side for first harmonic absorption. Second harmonic experiments were conducted only in an unboronized vacuum vessel. We plan to return for additional experiments with second harmonic heating. This will provide an advantageous toroidal field scaling. With improved wall conditioning, higher densities can now be achieved in these discharges and electron-ion coupling will be improved. With respect to current experiments, we expect to use second harmonic heating to lower the threshold via toroidal field scaling so that we have more flexibility in the choice of electron density.

With inside launch, heating at the first harmonic can be achieved at higher density than with outside launch. This would lead to better ion heating, but would be subject to disadvantageous density scaling. Unlike the second harmonic experiment just described, there is no improvement due to toroidal field scaling. These experiments are still interesting because they may allow us to explore the trade-off between density and ion temperature. The necessary hardware has been acquired to implement launch from the high field side. (see section IIIE).

Finally, the new 110GHz system will add 500 kW to the power already available so that the power threshold for H-mode will be greatly exceeded. The 110 GHz gyrotron is now available for installation. (see section III E).

Figure IIID.6. There is an apparent correlation between the H-mode power threshold and the measured neutral pressure during the discharge.

Neutral density

Recent studies of the effects of neutrals on H-mode indicate that high neutral content or high recycling is deleterious to H-mode.¹⁴ There is an experimental correlation between low neutral pressure and H-mode.¹⁵ The correlation is statistical in the sense that some discharges with low neutral pressure and with sufficient auxiliary power will not necessarily make the transition to H-mode. It appears then that neutral pressure or neutral density is an important, but secondary factor in the transition of H-mode. Some additional data is shown in Fig. IIID.6.

Boronization and avoidance of H or D during wall conditioning have lowered wall recycling, but there are additional options if this is not sufficient improvement. Gas fueling ports will be installed at several locations on the inner wall so that the plasma can be fueled through the x-point. This will reduce the locally high neutral density that now exists near the single fueling port. There are other plans for reducing the neutral pressure by fueling inside the separatrix. One is to install a gas fueling port in one of the reciprocating probe drives. The fueling source would then be plunged briefly past the separatrix. The dwell time for the probe is controlled by the heat flux, but there should be sufficient time in the plasma to produce the required fueling. Recently, Dr. Paul Bellan of Cal Tech installed a compact torus injector on TEXT-U. This system is configured for internal fueling of the tokamak plasma and should be effective at the lower toroidal fields used for second harmonic heating.

Wall Conditioning

The boronization of the walls has reduced the impurity content and the wall recycling. Further reductions may well be possible, and wall conditioning experiments are now being conducted. (see Wall Conditioning in section II) The glow discharge used for boronization is being studied using spectroscopy and Langmuir probes in an effort to understand the deposition of the layer and devise means for improving it. Wall condition is monitored daily to determine its recycling and impurity production characteristics. This work will be expanded to include deposition monitors and automatic glow systems to improve the consistency of the boronization process.

Lessons from the H-mode-like limiter discharge

The lesson that we may be learning from the limiter H-mode plasmas is that high current is required for entry into H-mode on TEXT. Obviously, we do not yet know why. Perhaps the power threshold in TEXT is still quite high and the additional Ohmic heating is needed. Large sawteeth are typically observed in such discharges so the deposited ECRH power is efficiently delivered to the plasma edge. Perhaps, this enhanced

transport to the edge is important. The high current discharges are accessible with the x-point in the direction of the ion gradient B drift, but so far our experiments have shown that H-mode is not produced. One feature of these discharges is that the separatrix-to-wall distance is on the order of the SOL gradient scale lengths. Tests of the high current mode in equatorial single null discharges (see Figure II.1) are planned. These discharges are expected to have more favorable separatrix-to-wall distances.

Work Plan

- Continue comparisons of TEXT discharges with typical H-mode discharges. The principal points of comparison are separatrix-to-wall distance versus SOL scale lengths, shape (in particular location of x-point), edge ion temperature, and edge neutral and impurity concentration.
- Attempt to imitate the success of the H-mode-like limiter discharge with an equatorial single null discharge.
- Attempt H-mode with second harmonic heating in a boronized vacuum vessel.
- Install inside launch systems at 56/60 GHz and attempt H-mode. Investigate trade-off between density and ion temperature.
- Install x-point fueling. Assess the effects on discharge asymmetries and H-mode.
- Investigate SOL transport in disconnected double null configurations.
- Install the 110 GHz system and attempt H-mode. Investigate trade-off between density and ion temperature.
- Investigate the effects of fueling inside the separatrix using a probe mounted gas fueling port and using a compact torus injector.

An Improved Ohmic Confinement Regime

Improved Ohmic confinement studies are continuing on TEXT-U 16. In previous experiments the spontaneous transition to an improved confinement mode has been investigated. The transition occurred in shots with a high level of impurities. A sharp decrease in H_{α} and drop of the SOL electron temperature were detected simultaneously during the transition indicating a possible temperature or neutral flux dependent trigger for the mode. The density was increasing at the edge at the time of transition, thus the drop in H_{α} may indicate a decrease in the peripheral neutral influx. A factor of two to three reduction in the fluctuation-driven particle flux and a 30% reduction in the density fluctuation level observed by Langmuir probes indicates a reduction in edge turbulence leading to improved confinement.

The goals of recent experiments were to achieve a controlled transition to this mode and then make detailed, reproducible measurements of the plasma parameters for comparison with fluctuation analysis results. Plasma conditions were very different than in previous experiments. Boronization efforts to clean the vacuum chamber led to very low levels of residual impurities and a low Z_{eff} . Initially attempts were made to reproduce the controlled transition via neon injection. Density profiles were measured by FIR scattering while profiles of radiation loss were measured by both photodiode detectors and conventional bolometers. It was found that in clean plasma conditions, a moderate injection of neon caused the formation of a MARFE at the high-field side of the tokamak which moved to the top limiter causing a disruption. Diamagnetic measurements showed no increase in the internal stored energy. A strong increase in density fluctuations was measured by the HIBP at the edge of the high-field side of the tokamak during MARFE formation. Thus, this behavior was unrelated to previously measured transitions to improved confinement.¹⁶

It was found in the new series of experiments that the transition to higher confinement occurs in operating regimes with a high toroidal field ($B_t = 25 - 26$ kG) low current ($I_p = 130 - 150$ kA), and high density (n_e close to the density limit of $\sim 5 \times 10^{13} \text{ cm}^{-3}$) achieved by slow constant gas

puffing. Detailed measurements of the density profile (see Fig. IIID.7) shows the formation of a MARFE on the high-field side of the tokamak. However, in this case, the MARFE is suppressed after formation and strong peaking of the density is observed. In general, the behavior of plasma parameters is similar to that seen in the previous transition¹⁶ to improved confinement.

Figure IIID.7. Chord averaged density showing the transition near 200 ms. The units for the vertical axis are arbitrary.

Fluctuations were studied in similar regimes¹⁷ and variations of the amplitude of the fluctuations seen by FIR, BES and probes were used to explain the changes in the diffusion coefficient during this transition. It was shown by a computation using the ASTRA code¹⁸ and a model¹⁹ that the strong density peaking measured could be described by a reduction of the particle diffusion coefficient (Fig. IIID.8, solid line is diffusion coefficient before transition, dashed line is the coefficient after transition) and that the

reduction is proportional to the measured reduction in the fluctuation power.

Fig. IIID.8. Result of numerical calculation via the ASTRA code¹⁸ and the model¹⁹. Diffusion coefficient before (upper solid line) and after (lower dashed line) transition to improved confinement mode. Also shown are particle diffusion coefficients inferred from fluctuations measured with FIR, BES, and Langmuir probes (normalized to the solid curve).

Future Plans

Further experiments are planned to obtain detailed measurements of the radial distribution of fluctuations. The full array of TEXT equilibrium and fluctuation diagnostics will continue to be applied to this discharge. In particular, we will determine the spatial and temporal relationship between changes in the radial electric field, the fluctuations, the rotational velocity shear, and the transport at the transition.

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PROJECT DESCRIPTION

III. PROPOSED RESEARCH

III.E. ECH PHYSICS

III.E. Electron Cyclotron Heating Physics

Waves that are resonant at the electron-cyclotron (EC) frequency can modify the electron velocity distribution. Practically, this means that EC waves, like lower-hybrid or ion-cyclotron waves, can be used for both bulk plasma heating (ECH) and current drive (ECCD) in tokamaks. A valuable property of EC waves is that they can also deposit their energy with precise spatial localization. Many recent applications of ECH have exploited this property for tokamak diagnosis and control, but further work is still needed. For example, observations of the propagation and thermalization of EC heat pulses continue to provide insights into the fundamental processes of tokamak transport. Improvements in tokamak stability and confinement are also being achieved through ECH control of the current profile and of specific instabilities. This is likely one of the most important uses of ECH in proposed future devices such as ITER and TPX, where stable and long-pulse operation will be a basic requirement. The capacity of ECH to assist the performance of these next-generation devices will, however, also remain contingent upon the continued development of high-power, long-pulse microwave sources.

The TEXT-U ECH/ECCD system presently consists of three 200 kW Varian gyrotrons operating at 56 GHz (one tube) and 60 GHz (two tubes) for heating via the ordinary mode (O-mode) at the fundamental cyclotron frequency $f=f_{ce}$. The spatial profile of the power deposition is partially controlled using a set of focused and steerable launching antennae which are located on the tokamak low-field-side. Heating is possible up to the electron plasma frequency $f=f_{pe}$ cutoff density of $n_e=4.4\times 10^{13} \text{ cm}^{-3}$. Inside launch antennae will be installed to provide accessibility of the extraordinary mode (X-mode) from the high-field side, extending heating up to $n_e=8.8\times 10^{13} \text{ cm}^{-3}$. A 500 kW, 110 GHz Varian gyrotron and supporting transmission components (from General Atomics) have also been purchased, and are being prepared for installation later this year. 110 GHz waves in the extraordinary mode will be applied to heat at the second-harmonic $f=2f_{ce}$ up to $n_e=1\times 10^{14} \text{ cm}^{-3}$. The ECH hardware is further described in the section on TEXT-U resources.

A primary application of ECH on TEXT-U is to sustain the tokamak plasmas for detailed study by a variety of diagnostics in the L- and H-mode confinement regimes. In addition, several applications using ECH itself as a diagnostic will continue to be developed, with particular emphasis on those that will improve understanding of transport and turbulence. As was already noted above, ECH can be used to generate electron heat pulses, which are then observed to yield a measurement of the heat transport. The extent to which the ECH itself modifies the MHD, turbulence, and transport is being concurrently investigated. Other recent work on TEXT-U has shown that the dynamics of the hot particles created under ECH and observed by electron cyclotron emission (ECE) can provide even more detailed insight into the diffusive transport caused by electrostatic and magnetic fluctuations. We are also using one ECH beam as a source for scattering measurements of the density turbulence structure.

The continuing and newly proposed experiments are described in the following paragraphs. We separate these experiments into two non-distinct groups: control and diagnostic uses of ECH. Our progress with using ECH to access higher confinement modes of tokamak operation is included in the section on improved confinement.

ECH uses for Tokamak Plasma Control

Turbulence Modification

The effects of ECH on the level and distribution of microturbulence have been examined previously in TEXT [1]. In these experiments, it was observed that off-axis heating led to a larger increase in core plasma density fluctuations measured by a Heavy Ion Beam Probe (HIBP) compared to on-axis heating.

Relative Changes in Density Fluctuations and Central Electron Temperature vs. Toroidal Field. $B_t = 2.16$ T corresponds to central heating, $B_t = 1.5$ T is at the limiter.

The results shown in the above figure clearly demonstrated that the fluctuations are not driven by changes in the core electron temperature (T_e) or its gradient, since changes in the T_e profile are much less for the

off-axis case than the on-axis case (which results in a very peaked T_e profile).

The changes in the core density fluctuations scale closely with changes in the edge plasma parameters, both in the amplitude and also the timing of the changes relative to the application of the ECH pulses (see figure below).

*Relative Changes in Edge Electron Temperature and
Floating Potential Fluctuations vs Toroidal field.*

This surprising result has led to a re-examination of the HIBP diagnostic to make certain that measurements of the core fluctuations are not being contaminated by fluctuations in the plasma edge. Modeling of the beam modulation effects indicates that such effects should not be important at the plasma parameters of the TEXT ECH experiment [2].

These results will first be verified using the 2MeV HIBP. Then it will be important to determine whether the modification is local or perhaps non-local, and study the mechanisms involved. This will be done by measuring radial profiles of plasma equilibrium and fluctuation parameters as the ECH resonance position is scanned radially. Focused beam launchers will preserve the poloidal heating localization during these scans.

Milestones

- Determine whether the turbulence modification is local or non-local.

- Investigate the mechanisms for the turbulence modification.

MHD Suppression

Past experiments in TEXT demonstrated that application of continuous ECH (~200 kW) could improve stability near the $q=2$ surface [3].

MHD Suppression by ECH in TEXT. Solid Lines:

Off axis ECH. Dotted Lines: On-Axis ECH.

Some of the recent results on JFT-2M are very similar to the earlier TEXT results, except that the ECH stabilization of the $m=2$ MHD activity was able to suppress disruptions at low q values, while in the TEXT result, the MHD had been induced by impurity gas puffing. Other experiments suggest synchronization of the ECH pulse with the $m=2$ island rotation may lead to more efficient stabilization [4,5]. The availability of q -diagnostics

such as the UCLA FIR Polarimetry and the charge-exchange system will aid in the interpretation of the experimental results. We plan to continue our MHD suppression studies, with an emphasis on disruption control in order to increase the operating regimes of the tokamak. In particular, we intend to synchronize the heating with the island rotation using timing feedback provided by internal magnetic coils (see fig. III E.4 below). MHD oscillations are detected by internal magnetic pickup coils. The signal from these coils is used to generate a synchronous modulation of the ECH power to heat the island.

Fig. III E.4 MHD suppression by feedback island heating

Milestone

- Attempt $m=2$ stabilization using focused ECH with feedback.

Current-Density Profile Modification

Advanced tokamak designs call for the use of strongly localized current drive to tailor the q-profile and thus achieve high confinement modes. In particular, off-axis ECCD has been proposed to maintain a hollow current density in the ITER device and thus achieve second stability in the core of the plasma [6]. Efficient ECCD requires very strong absorption of the launched EC waves; thus the fundamental and second-harmonic X-modes are used in such experiments.

TEXT-U will have the capability of performing fundamental X-mode ECCD experiments using the 56/60 GHz gyrotrons by the end of 1995, and second-harmonic experiments using the 110 GHz system by early 1996. Existing current-density profile diagnostics on TEXT-U will facilitate meaningful q-profile modification experiments.

Milestone

- Attempt off-axis ECCD using X-mode 60 and 110 GHz ECH and measure changes in current-density profile.

Startup Assistance

In future tokamaks employing thick-walled vacuum vessels, the Ohmic electric-field penetration will be smaller and slower than in present devices. ECH provides a reliable means for ionizing the gas, and should be useful for shaping the current profile during tokamak startup (note: ECCD is not expected to be active during the startup). This has important consequences for advanced tokamaks like ITER, which require efficient and stable startup.

ECH startup assistance has been demonstrated over a wide range of breakdown and target plasma conditions in a number of tokamaks [7-10]. ECH breakdown has also been recently used to assist startup of helium plasmas in TEXT-U. We propose to investigate in greater detail the development of the startup current profile as functions of the EC wave polarization (ordinary vs extraordinary), toroidal angle of incidence ($k_{||}$), and resonance radius. The current profile will be measured in collaboration with the UCLA group using FIR polarimetry. The availability of both the 56 and 60 GHz microwave sources (resonances separated by 8 cm) allows the size of the ECH breakdown area to be increased. The effects of doing so on the plasma current and loop voltage evolution can therefore be investigated.

Milestones

- Measure the evolution of startup current profile with FIR polarimetry
- Optimize startup for deposition and launch of a single frequency
- Investigate the possible advantages of using two frequencies

ECH Used as a Diagnostic

Heat-Pulse Propagation

In most devices where it has been measured, the thermal diffusivity χ_e determined from observation of the ECH- or sawtooth-induced heat-pulse has been found to be a factor of 1-5 larger than the χ_e suggested by power-balance analysis [11-13]. Recent measurements also show a large discrepancy in TEXT-U [14]. As is described in further detail in the section on transport modeling, there is an ongoing effort in TEXT-U to improve the understanding of such differences in terms of coupled transport, non-local transport, and non-thermal effects.

Milestone

- Compare the transport coefficients determined from incremental and power-balance analysis with those from developing models of tokamak transport.

Fast-Electron Generation and Transport

At low plasma densities, ECH - in synergy with the tokamak inductive electric field - can generate an observably large and long-lived population of suprathermal electrons. The contribution by electrostatic and magnetic fluctuations to the diffusive transport of these electrons away from the resonant flux surfaces is a strong function of their parallel energy. For electrostatic fluctuations diffusivity, $D_e \propto (1/v_{\parallel}) \langle \tilde{E}_{\perp}/B \rangle^2$, while for magnetic fluctuations $D_e \propto v_{\parallel} \langle \tilde{b}_{\perp}/B \rangle^2$. For fluctuation levels previously measured in tokamaks, these transport processes exceed the neoclassical transport that is due to collisions [15]. ECH, the electric field, and fluctuation-induced transport are thus main factors determining the strength and distribution of the local fast-electron population.

Experimentally, the fast-electron distribution can be distinguished from the thermal background within the spectrum of vertically-viewed electron-cyclotron emissions [16]. Such measurements have been performed in the core of TEXT-U for one discharge condition where ECH suprathermal generation was optimized. Comparison of the spectra with that predicted by comprehensive simulations confirms diffusion of the type caused by magnetic fluctuations, and suggests an interior magnetic turbulence level of $\tilde{b}_{\perp}/B = 2.5\text{--}5 \times 10^{-5}$ [17]. This novel work is being performed in collaboration with Gerardo Giruzzi of TORE SUPRA.

Measurements of the core magnetic turbulence characteristics are rare, and much additional work is needed to fully exploit our method. For the same discharge condition we intend to measure the distribution out to larger minor radii. By developing other discharges we will evaluate the scaling of the fast-electron diffusion coefficient D_e and the scaling of $\tilde{b}_{\perp}/B$ with plasma current and β . The turbulence will be studied in runaway, reduced (L-mode), and enhanced (e.g. H-mode) confinement discharges. For selected discharge conditions the array of TEXT-U equilibrium diagnostics will be employed to provide the radial profile of the electron thermal diffusivity χ_e . This will allow a comparison of the total χ_e with that driven by the magnetic turbulence. For further selected discharge conditions the array of TEXT-U fluctuation diagnostics will be employed

to provide radial profiles of the electrostatic turbulence. This will allow comparison between magnetic $\tilde{b}_{\perp}/B$, density $\tilde{n}/n$, temperature $\tilde{T}_e/T_e$, and potential $\tilde{\Phi}/\Phi$ fluctuations, and comparison with the expectations of certain drift wave models ($\tilde{b}_{\perp}/B = q \beta (\tilde{n}/n)$, where q is the safety factor and β the ratio of plasma pressure to total magnetic pressure) [18]. For still further selected discharge conditions the array of TEXT-U sawteeth diagnostics will be employed, allowing a determination of the variation of $\tilde{b}_{\perp}/B$ within a sawtooth cycle.

Milestones

- Determine radial profiles of $\tilde{b}_{\perp}/B$. Evaluate $\tilde{b}_{\perp}/B$ near rational surfaces.
- Compare the total electron thermal diffusivity with that driven by magnetic turbulence (i.e. a statement on the importance of magnetic fluctuations to the total electron energy transport).
- Compare the behavior of $\tilde{b}_{\perp}/B$ within and between runaway, L-mode, and improved confinement regimes.
- Compare $\tilde{b}_{\perp}/B$ with electrostatic turbulence characteristics and with the predictions of certain drift-wave models.
- Determine how $\tilde{b}_{\perp}/B$ varies within a sawtooth cycle.

Microwave Scattering

An antenna array installed on the high-field-side wall of TEXT-U measures absorption, refraction, diffraction, and scattering of the ECH microwave beam by collecting the transmitted power [19]. Investigations with this array have so far demonstrated that our focused ECH beam can be applied for localized heating over a wide range of densities [20]. Absorption was found to be in good agreement with gross fundamental estimates. Beam defocusing remained close to the expected limits of refractive broadening, and was not substantially enhanced through scattering by density fluctuations. Nevertheless, the broadband edge turbulence could induce large power fluctuations within the beam by the time it accessed the plasma center [21]. To further understand these scattering observations, we extended the application of a full-wave modeling algorithm known as the Beam Propagation Method (BPM) [22] to simulate the beam scattering. We found that we could diagnose edge turbulence characteristics to yield results that were consistent overall with previous measurements by the HIBP[23] and Langmuir Probes[24,25]. In particular, we found $\bar{\omega} \approx \sigma_{\omega} \approx 100$ kHz and $k_{\theta} \approx \sigma_{k_{\theta}} \approx 0.5$ -1 cm⁻¹ when using $k_r \approx 1$ cm⁻¹ and $\sigma_{k_r} \approx 1$ -2 cm⁻¹ to constrain the analysis. This scattering diagnosis further suggests the strong localization of these fluctuations to the low-field-side edge [26]. We expect that such continued scattering diagnosis will provide new insights into the phenomenology of the L-H transition and other edge fluctuation physics.

Milestone

- Diagnose changes in edge density fluctuations during L-mode and improved confinement regimes.

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PROJECT DESCRIPTION

III. PROPOSED RESEARCH

IIIF. ALFVEN WAVE CURRENT DRIVE

IIIF. Alfven Wave Current Drive

A tokamak reactor will probably require a non-inductive current drive scheme. Among the RF techniques that can be used for current drive, the low frequency techniques have the advantage that power generation is simple and relatively inexpensive. In a reactor or in a machine designed to study reactor concepts, an electron current drive scheme would have the advantage that the drive would not damp on fast alpha particles. Alfven wave current drive has these properties¹. In recent experiments on Phaedrus-T,² Alfven wave current drive was demonstrated for the first time in a tokamak, where current drive efficiencies of 0.2 A/W were demonstrated. The results of these experiments are no longer of simple academic interest. Alfven waves are serious candidates for current drive in tokamak reactors and in alternative concepts such as the small aspect ratio devices. In fact, the recent interest in small aspect ratio machines lends these methods even greater importance, because Alfven wave current drive is expected to work well at the low magnetic fields, high densities, and high beta in these machines. The small inner core size of such machines makes auxiliary heating and current drive a necessity.

The pioneering Alfven wave current drive experiments have a critical place in the evolution of current drive techniques. However, they do not include direct observation of the mode structure of the driving waves, the resultant current profile modification, the evolution of the current profile, or the effects on plasma stability. Since theoretical studies of the rich Alfven mode structure indicate that both current drive and heating efficiencies are rather sensitive to the frequency and mode selection, a detailed study of the modes is essential for the optimum use of RF power and for confident extrapolation of the results to reactor scenarios.

At TEXT-U, we can build on this excellent start. We bring to this work

- a team with long experience in the study of the experimental and theoretical aspects of Alfven waves,
- an existing diagnostic capability which allows direct observation with unequalled resolution of the mode profiles excited in the plasma,

- two existing diagnostics capable of measuring the current profile with good resolution,
- a tokamak which allows us to create an experimental design to make this study possible.

Thus, we can

- study the physics of Alfvén wave current drive,
- provide a theory-experiment comparison at high aspect ratio which can be used to benchmark later theoretical development at arbitrary aspect ratio,
- study a current drive mechanism that might be of use in small aspect ratio tokamaks,
- provide means to vary the magnetic shear for turbulence and MHD suppression experiments that are directly related to our work in core turbulence and transport.

Important and pioneering theoretical and experimental work on various Alfvén modes was done during the eighties at the Fusion Research Center (FRC) and Institute for Fusion Studies (IFS)³⁻¹¹. Since most of the people involved in this effort are still at The University of Texas (along with much of the experimental equipment), we are in an advantageous position to explore this rather promising field at a fairly low cost. Until recently though, we were not in a position to take advantage of this research base. We lacked the precision profile diagnostics in this particular area to do physics experiments, but these are now available. In the meantime, the difficulties associated with excitation of surface modes and impurity influx from antennas that damped the initial enthusiasm for these methods in the eighties have been addressed through improved antenna designs and impurity control techniques such as boronization. The time is ripe for a dedicated pursuit of this current drive mechanism on TEXT-U.

TEXT-U is an ideal machine for these experiments. Our extensive diagnostic set can yield detailed physics information and aid in removing the many uncertainties still present in this area. This is essential for the optimum use of RF power at low frequencies. Only after the physics of these low frequency modes is identified and understood can the advantages of RF current drive and heating be optimized on present and near term devices. It will then be possible to make reliable predictions about their role in reactor dynamics.

Alfven Modes of Interest

Alfven wave heating was first proposed in the 70's¹² and was followed by detailed theoretical and experimental investigations of antenna-wave coupling, wave propagation, mode structure, and absorption processes^{3-11,13-15}. The two basic Alfvenic modes in the ideal MHD limit are the shear wave with the dispersion relation $\omega^2 = K_{\parallel}^2 v_A^2$, with $\tilde{B}_{\parallel} = 0$, and the compressional wave with $\omega^2 = K^2 v_A^2 = (K_{\parallel}^2 + K_{\perp}^2) v_A^2$, with $\tilde{B}_{\parallel} \neq 0$, where $k_{\parallel}$ is the wavenumber parallel to the local unperturbed magnetic field, and the Alfven speed is given by $v_A^2 = B_0^2 / \mu_0 m_i n(r)$ with $n(r)$ being the local density in an inhomogeneous plasma. In a large aspect ratio confined plasma with magnetic shear these low frequency oscillations are characterized by local wavevectors that depend on minor radius through $k_{\parallel} = (-l + m/q(r))/R$ and $k_{\perp} = (l + mR^2 q(r)/r^2) B_p / R$, where l and m are the toroidal and poloidal mode numbers, $q(r) \approx (rB_T)/(RB_p)$ depends on the plasma current profile, and R is the major radius. For these MHD modes, which become kinetic Alfven waves (KAW) when kinetic effects are included, the absorption from an externally driven antenna at frequency ω is closely associated with the "Alfven resonance layer" in the plasma where $\omega^2 = k_{\parallel}^2 v_A^2$. The MHD singularity at this layer disappears when kinetic effects such as electron inertia, Landau damping, finite ion gyroradius, finite ion cyclotron frequency etc., are included. The basic dispersion relation is modified. In a hot plasma with $\beta m_i / m_e > 1$, where $\beta = p / B_0^2$ at the resonant surface,¹⁶ the wave converts to a "kinetic shear Alfven wave"³ which propagates to the plasma interior and is absorbed. Otherwise, in a cold plasma, the energy from the antenna is reflected at the resonance layer, and can create a resonant surface Alfven eigenmode (SAE)¹⁰ under appropriate conditions.

Even in ideal MHD the plasma is capable of sustaining non-singular eigenmodes. At a frequency slightly below the minimum of the range of $|k_{\parallel} v_A|$ in the plasma, i.e., slightly below the "Alfven continuum", the equilibrium current density gradient and finite ω/ω_{ci} effects can lead to global cavity modes (or global alfven eigenmodes (GAE))¹⁷⁻¹⁸ extending over the entire plasma cross section. In addition, the inclusion of toroidicity removes the poloidal symmetry, coupling poloidal (m)

harmonics of a cylindrical plasma and leading to new modes called toroidal Alfvén eigenmodes (TAE)¹⁹⁻²². However, at small aspect ratio, the breaking of poloidal symmetry is too strong to allow the use of perturbation techniques around the cylindrical case. The spherical tokamaks are truly two dimensional for which the theory of Alfvén modes has not yet been fully worked out.

The shear Alfvén waves discussed above imply no compression of plasma or magnetic field. The plasma also supports cavity modes with non-zero compression. These are called compressional Alfvén eigenmodes (CAE)⁹.

Out of the rich Alfvén spectrum in a plasma, the lightly damped modes with extended wavefunctions can be driven to high amplitudes from properly shaped and phased external antennas⁴. Different modes are optimal for different applications. They couple best to different parts of the distribution function depending on their phase speeds, and deposit their energy and momentum in different parts of the plasma. Here we give a brief glossary of the various modes and their possible applications.

- Compressional Alfvén Eigenmodes (CAE) are suited for current drive^{1,9}. This is because their parallel phase speed can be high even for small mode numbers, since it is decoupled from the Alfvén speed which is generally less than the electron thermal speed. The current drive efficiency is predicted to be 0.3 A/W, and the mode structure allows some control of the current profile.
- Surface Alfvén Eigenmodes (SAE)¹⁰ could be used to heat the edge and study the effects on fluctuations and transport. In the proposed experiments, their study is mandatory because they can inhibit both central heating and current drive. They need to be studied to find frequencies and antenna phasing so that they can be altogether avoided or their effects minimized.
- Global Alfvén Eigenmodes (GAE)⁵⁻⁶, when relatively less damped, can be used for global heating. These were observed in previous experiments⁷⁻⁸. In the early stages of present experiments, GAE will be observed first and then used as a reference to locate other modes.
- Kinetic Alfvén Waves (KAW) can be used for local heating and for precise q-profile measurements²³⁻²⁵.

- Toroidal Alfvén Eigenmodes (TAE)¹⁹⁻²² are intrinsically two-dimensional, and are likely to be destabilized by fast fusion alpha particles in a reactor causing deterioration in alpha confinement. A direct study of their mode structure is crucial in confidently assessing their role in reactors.

Areas of interest in Alfvén wave studies

- Structure of the Alfvén modes. Although the theory of Alfvén modes is well developed, the predicted multitude of modes has not yet been fully explored experimentally in well controlled and diagnosed experiments like TEXT-U. These waves have a very rich spectrum in a confined, current carrying system, and their optimum use requires more precise experimental understanding. The structure of these modes is the primary goal of these experiments.
- Current drive with compressional Alfvén waves. In studying the structure of Alfvén modes, the principal goal for these experiments is to develop a physics basis for the use of CAE for current drive. This then is the ultimate purpose of these experiments, but because of the state of understanding of Alfvén waves, it is not the primary goal. With an expected current drive efficiency of 0.3 A/W, at low power (<10 kW) we can measure the current profile modifications only if they are local.
- Selective plasma heating in the center, in the edge, or over bulk of the plasma. This will be studied as a spin-off from the primary mode structure experiments.
- Kinetic Alfvén waves for precise q-profile measurement. This was proposed in the past. Again, this may develop as a spin-off of the main effort.

Antenna array for Alfvén spectroscopy

We can explore all these modes with one properly designed antenna structure⁴. The antenna must have good selectivity in low toroidal (l) and poloidal (m) mode numbers. In addition, the same antenna array can be used to study fast waves above the ion-cyclotron frequency.

Based on experience, a phased array of small antennas is better than a single large antenna. Each antenna can be quite small (10 cm by 3 cm

flat plate), because it is the spacing between antennas and not the size of each antenna that determines mode selectivity. A minimum of 4 small antennas is needed for adequate mode resolution. An array of 16 small antennas is preferred (4 in each toroidal location) so that we have one antenna each at $(\phi, \theta) = (l, m)\pi/2$, $l, m = 0, 1, 2, 3$, where ϕ and θ are toroidal and poloidal angles. This allows selection of one (l, m) mode modulo 4 (For example the (2,4) mode). The next mode is off by 4 in l and m and thus is expected to be far removed in frequency. When the antenna is driven at the natural frequency of a given mode, it resonantly excites a density fluctuation (along with $\tilde{B}$ and $\tilde{E}$) of the form $f(r; l, m) \exp[i(l\phi - m\theta)]$, where the radial structure of $f(r; l, m) = \tilde{n}(r)/n(r)$ depends on (l, m) . The quantity $\tilde{n}/n$ scales with $(\text{RF power})^{0.5}$ and is approximately 5×10^{-5} at 1 kW power levels at the antenna. The diagnostic task is to detect the density fluctuation produced by the mode and eventually to detect current drive via changes in the q profile.

The arrangement of the antennas in the poloidal plane is shown in figure IIIF.1. Note that the outer two antennas are moveable. These will be used in 4-antenna (toroidal spacing) experiments. The antennas are movable so that plasmas of various radii can be studied. Some possible plasma radii are illustrated by the circles in the figure. The two internal antennas are fixed. Using these, the 16-antenna experiments can be performed on a plasma of minor radius 27 cm, which is the standard size for a TEXT-U plasma.

Relevant diagnostic techniques

- Antenna loading measurements can be used at all power levels to detect the spectra of discrete modes.
- Magnetic probes in the plasma edge can also be used at all power levels to study the edge structure of the modes. This can be quite effective for marking the onset of SAE and most GAE. For the SAE, using a reciprocating magnetic probe may provide the full radial mode structure.
- At power levels in the range from 1 to 10 kW, a microwave or an FIR interferometer²⁶ can be used for the detection of GAE provided lock-in techniques are employed. This was demonstrated in previous

experiments at higher power levels with a less sensitive CO₂ interferometer⁸. The greater sensitivity of the FIR will allow us to study the onset of any non-linear power scaling effects.

- Phase contrast imaging²⁷ will provide more precise measurements of the fluctuations. The existing system design will permit measurements to the level of $\tilde{n}/n \approx 10^{-5}$. This corresponds to powers above 1 kW. Wavenumbers can be detected in the range between 12 cm⁻¹ and low k determined by the beam width 0.62 cm⁻¹ for 10 cm beam. The TEXT system is discussed in section IIIG.
- q profile measurements using methods above to locate KAW location.

Figure IIIF.1. Conceptual design for installation of Alfvén antennas on TEXT-U. Four antennas in one poloidal plane are shown. Each antenna extends 15 cm in the toroidal and 4 cm in the poloidal directions.

Experimental plan

We propose to follow an incremental approach in which we first make maximum use of existing equipment to establish the techniques we believe we know, and only then proceed to the next stage.

- Start with just 2 antennas located at opposing toroidal locations. This can be done mostly with existing equipment. Our goal in this phase is to establish the techniques by finding GAE by measuring antenna loading at RF power in the range of 1 to 10 kW. This will employ transmitters that we already have.
- We next look for SAE. If we find them, we can map their structure using edge magnetic probes.
- Next we add 2 more antennas and look for ways to bypass the surface modes and excite GAE, CAE, and TAE. If we find them, we can try to put higher power into them to observe their radial structure using phase-locked interferometry or phase contrast imaging (PCI) for detection. For the latter part of this experiment, additional transmitters will be required.
- We then try to drive local currents by coupling to CAE, and attempt to measure the current profile modifications directly with our $q(r)$ diagnostics.
- Finally, we install the full 16 antenna structure, and use the high mode resolution to study mode structure, plasma heating and current drive in detail.

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PROJECT DESCRIPTION

III. PROPOSED RESEARCH

IIIG. THE ROLE OF TEXT-U IN DIAGNOSTIC DEVELOPMENT

III G. The Role of TEXT-U in Diagnostic Development

Here we outline the proposed role of TEXT-U as a facility for the development of diagnostics and related equipment. Such an activity has been identified as a major need for both TPX and ITER, and present large devices no longer have the physical access, schedule opportunities or resources to provide it. TEXT-U is ideally suited for this purpose; the device has easy diagnostic access, an extensive operating envelope including limited and diverted discharges, both L and H mode confinement, and a complete base diagnostic set.

This section covers specific diagnostics, remote handling, and some other diagnostic related development that would be invaluable to the fusion community. The specific diagnostics described here include

- Electron cyclotron emission (ECE) imaging
- Thomson scattering fluctuation diagnostic
- Densitometry
- Long pulse magnetic diagnostics
- Surface probes
- Phase contrast imaging

Specific Diagnostics

ECE Imaging

As recently documented [1], high resolution ECE is the ideal diagnostic to detect small MHD perturbations of the magnetic surfaces in a tokamak. This is particularly true in larger more performance oriented devices where the high level of X-ray and neutron radiation blinds the more traditional X-ray diagnostics. Up to now ECE multichannel systems have been based only on frequency spectrometers. This technique limits the spatial resolution of the temperature measurements to chords along the

Figure IIIG.1. Implementation of the ECE imaging array on TEXT-U.

Figure IIIG.2. The radiative power profiles with position, both with and without a dichroic plate.

equatorial plane. For TEXT-U we have proposed and built in collaboration with the Department of Applied Science, University of California at Davis a new radiometer which will allow for high resolution both along a surface of constant cyclotron resonance frequency and across it. More specifically, as shown in Figure IIIG.1, wide bandwidth, low cost, 20 channel monolithic and hybrid Schottky diode mixer arrays have been built for extraordinary mode ECE detection on TEXT-U. These arrays, designed to measure 2nd harmonic ECE emission between 90 and 140 GHz, will be used to form two-dimensional temperature profiles and one-dimensional profiles of high frequency turbulence fluctuations. Conversion loss of 9 ± 1 dB has been achieved at 94 GHz, which will allow adequate frequency bandwidth to explore MHD plasma oscillations.

Figure IIIG.2 shows that better than 2 cm resolution can be obtained in the constant cyclotron frequency (vertical) plane. The resolution in the equatorial plane, which is obtained by frequency selection, has been already measured in TEXT-U to be 1 cm or better [2].

Thomson Scattering Fluctuation Diagnostic

Advances in high sensitivity optical imaging techniques allow one to obtain high resolution Thomson Scattering profiles of electron temperature and density [3]. The achievable spatial resolution (1 mm) is comparable, or better, than that for Langmuir probes, which have proven to provide sufficient resolution to diagnose the turbulence which is responsible for transport in the Tokamak edge. We propose to apply these high resolution techniques to the TEXT-U Thomson scattering diagnostic. The high resolution time history of fluctuations is not as critical as spatial resolution in transport studies, but it is important to allow for the identification of the unstable plasma oscillations responsible for transport, through their dispersion relationship. Conventional Thomson Scattering has very good time resolution (~ 10 ns) but in conjunction with a very slow repetition rate. We propose to overcome this drawback in TEXT-U with a two laser system capable of firing pulses at arbitrary delay one from the other. This flexibility would allow us to construct a time correlation function of the temperature and density fluctuations on a shot to shot basis. High repetition rate and low unitary cost of the plasma shots are a crucial requirement for this technique,

which requires a large number of experimental points to reconstruct temperature and density fluctuation power and cross spectra. TEXT-U, with its fast repetition rate and reproducible discharge conditions, is particularly suited in this respect and would allow for in depth studies of a number of specific and reproducible plasma conditions.

Densitometry

Dr. W. A. Peebles of UCLA has proposed to develop a tangential Faraday rotation densitometer [4] on TEXT-U for application to TPX. Dr. Peebles and his co-worker, Dr. D. L. Brower, have considerable experience with designing, building and operating similar devices on TEXT. Much of the equipment will be time shareable and this will reduce both the time and the costs required to test the concept. This proposal is supported by Dr. H. Neilson, TPX physics manager. This diagnostic has been identified as the prime candidate for routine measurement of density profiles for both TPX and ITER and an experimental test of feasibility is crucial.

Long Pulse Magnetic Diagnostics

The measurement of magnetic fields on future long pulse machines has instigated research into very stable integrators, as well as non inductive techniques [5]. We propose to test both integrators and non standard techniques in the real experimental environment of TEXT-U. Most proposed techniques (Faraday rotation, Hall probes, etc.) can be tested on a short pulse machine. Some concepts, such as very stable integrator systems, require long pulse testing. This can be accomplished by integrating over multiple pulses, providing a severe test of stability and dynamic range because of the on/off cycles of the toroidal and poloidal field systems.

Surface Probes

Single probes mounted in limiter or divertor target surfaces are used to monitor plasma fluxes, near surface plasma equilibrium and fluctuating temperatures and densities, and will be used on future machines. However, the interpretation of probes in magnetic fields, especially single surface mounted probes, is problematic. We propose to extend our basic research into single free probes to include single surface probes. In particular, we

will compare the plasma fluxes, temperatures and densities inferred by such probes with those determined both by regular Langmuir probes and spectroscopically.

Phase Contrast Imaging

Although broadband turbulent fluctuations have been extensively studied in TEXT and other tokamaks, our understanding remains incomplete. Measurements have shown that the particle flux driven by electrostatic turbulence can account for most of the particle flux at the plasma edge. Measurements in the plasma interior are much more difficult, and basic information such as the turbulence dispersion characteristics are not well established. Phase contrast imaging (PCI) of plasmas is a relatively new technique which we expect will yield a great deal of new information. Our group has the potential to definitively characterize interior turbulence in collaboration with the other powerful turbulence diagnostics on TEXT-U (RPI heavy ion beam probe [6], UCLA FIR scattering [7], and UWM beam emission spectroscopy [8]) and the FRC/IFS modeling expertise.

In addition to the study of plasma turbulence, PCI is well suited to the study of coherent waves. This includes both externally driven waves and natural plasma oscillations such as MHD. PCI will be an important component of the Alfvén wave experiments proposed for TEXT-U. The structure of these modes is very rich and complicated, with many fusion relevant experiments possible on TEXT-U. These include current drive, heating, q-profile measurements, and TAE studies. PCI can clearly resolve the mode structure driven by external antennas, even at low power. We should also be able to settle the issue of surface modes, which can block RF access to the central plasma region, and find pathways to avoid them. The combination of the TEXT-U machine, PCI and other high performance diagnostics, and the excellent local Alfvén theory group make these experiments extremely important to the fusion program.

The most important feature of PCI is that it is an imaging diagnostic. PCI provides a direct spatial representation of plasma density oscillations. It is a multichannel instrument, allowing full spatial Fourier transforms, and is not limited to two point correlation analysis. The spatial resolution perpendicular to the probing beam is set by the system optics, and can range

from submillimeter to centimeters, as appropriate for the measurements of interest.

PCI has a large wavenumber range, which is set by the detector spacing and the requirement for Raman-Nath scattering [9]. A typical TEXT-U configuration gives a measurement range of $0.5 \text{ cm}^{-1} < k < 12 \text{ cm}^{-1}$. An important aspect of this is the ability of PCI to measure long wavelength fluctuations. Some turbulence studies have indicated that more than one-half of the turbulence power is concentrated at long wavelengths ($k_0 < 3 \text{ cm}^{-1}$). Another motivation for the TEXT-U PCI system is the need to resolve the differences observed by the HIBP and FIR scattering. As discussed in section IIIA, in the interior of TEXT the FIR scattering observes a wavenumber spectrum that peaks at $k_0 \approx 3 \text{ cm}^{-1}$. The 500 keV HIBP on TEXT (pre-upgrade) identified a peak at $k_0 < 1 \text{ cm}^{-1}$. The discrepancy may be due to multiple modes, instrument resolution or errors, or the fact that both diagnostics make limited measurements of a very complex phenomena.

The most serious limitation of PCI is that the measurement is line integrated along the beam path; spatial resolution is only provided perpendicular to the probing beam. Although this is an important limitation, it is not unique. For example FIR scattering is chord integrated for $k < 5 \text{ cm}^{-1}$, and the HIBP has beam integral effects. TEXT-U has the advantage of these and other diagnostics to help sort this out. It is the combination of these powerful diagnostics, each with their own type of measurement and errors, that is expected allow TEXT-U to dramatically increase our understanding of interior tokamak turbulence. Our approach to overcoming this limitation will be to construct plausible models of the spatial distribution and spectral form of the turbulence. We will then synthesize the expected PCI chord-integral signals, and compare them with the experimental data.

Diagnostic

Density fluctuations of a plasma cause refractive index perturbations, which diffract a probing electromagnetic wave. PCI operates in the Raman-Nath regime (as opposed to the Bragg regime of conventional scattering) where the scattering angle is extremely small ($\approx 0.01^\circ$) and the plasma acts as a thin phase object. PCI can be thought of as an internal reference interferometer, with probe beam phase shifts given by the line integral of the plasma density.

The excellent port access provided by TEXT-U will allow PCI measurements over almost the complete radial extent of the plasma. TEXT-U access allows all components to be mounted on isolated optical breadboards, minimizing vibration problems. The PCI diagnostic will share the optical tower and vacuum vessel ports of the existing TEXT FIR interferometer. A vacuum flange with both polyethylene windows (for the FIR interferometer) and antireflection coated ZnSe windows (for the PCI system, which uses a $10.6\text{ }\mu\text{m}$ probing wavelength) will allow simultaneous operation of the FIR and PCI systems.

In operation, the output of a 25 W Synrad CO_2 laser is expanded by a set of mirrors to form a Gaussian beam waist in the equatorial plane of the plasma. The width of this beam is adjustable from 3.5 cm to 15 cm, by changing the position of mirrors which are located on optical rails. A similar arrangement images this waist on to the groove of a quarter wave phase plate. The phase plate is a key component of a PCI system. It changes the relative phase between the scattered and unscattered (internal reference) beam components by 90 degrees. This phase change converts the phase modulation of the beam to an intensity variation that can be detected with a square law power detector.

A variable beam width is an important and novel aspect of the TEXT-U PCI system. It allows the system to be optimally configured for a desired measurement. A small (3.5 cm) beam size is used for high spatial resolution and a large maximum k . The larger (15 cm) beam sizes are used to allow measurements at very low k . An optical system has been designed that provides very low aberrations over the entire range of operation.

A 64 element liquid nitrogen cooled linear staggered photoconductive array will be used for low frequency turbulence measurements. The detector elements are $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ with a $100\text{ }\mu\text{m}$ pitch. The detectors have a video noise level of $4 \times 10^{-13}\text{ W}/\sqrt{\text{Hz}}$ and a bandwidth of 1 MHz. The detector outputs are amplified by about 60 dB by low noise amplifiers and then directly digitized. Initially, 16 elements will be used, limited by the number of amplifiers and digitizers we have available.

For Alfvén wave studies involving direct detection of the density fluctuations the detector will be replaced with a photovoltaic array, which has the necessary bandwidth. A typical detector which is available has approximately 12 channels and 100 MHz bandwidth. The data acquisition

system will also be changed, with the addition of wide bandwidth amplifiers and mixers for heterodyne detection.

The existing PCI system may be modified such that the probing beam has two parts that are collinear, but have a heterodyne frequency difference close to that of the Alfvén frequency used. The resulting interference of the diffracted and undiffracted parts of the two beams will produce a signal at the difference frequency of the Alfvén waves and the heterodyne frequency. This downshifting of the Alfvén density fluctuation information may allow using the existing detectors and electronics. Also, the heterodyne technique will allow the operation of the diagnostic without the extensive shielding required in the direct detection mode.

Figure III-G.3. PCI signal power (W) profile predicted for an $m = 1$ mode.

We have operated the TEXT-U PCI system in a sidelab for testing and calibration [9]. Using acoustic waves, we have verified its sensitivity in the wavelength range of 0.5-12 cm. Using a calibrated microphone, we have verified the sensitivity to be 10^{-6} radians at a wavelength of 3 cm. This is equivalent to a density fluctuation of $4.8 \times 10^{10} \text{ cm}^{-3}$. This sensitivity was

limited by noise in the RF oscillator in the laser, and is expected to improve when this problem is corrected.

Figure III G.4. PCI signal power (W) profile predicted for an $m = 2$ mode.

Simulation work to verify whether PCI will be able to detect several fluctuation modes in the plasma has also been done. Gaussian models of the spectra $S(k, \omega)$ that match the experimentally observed modes in TEXT are used as input to the simulation. Initial results have been obtained with a spatially homogeneous model of the turbulence. The expected PCI signals were obtained by performing an FFT of the input spectra and using appropriately spaced autocorrelation lags in space as the time series from the detector. These expected spectra are seen to closely match the input spectra. It was found that the spatial resolution afforded by a large number of detectors is necessary to detect a drift wave feature and a wide beam is necessary to resolve a long wavelength mode. Future work on the simulations will include an inhomogeneous plasma model and the addition of noise to the signals.

A simulation was performed to determine whether PCI will resolve coherent mode structures. To simulate a kinetic Alfvén wave, we used

eigenmodes localized to a region of 5 cm around $\rho = 0.5$ with a peak density fluctuation of 10^{10} cm^{-3} . The results in Figure IIIG.3 and Figure IIIG.4 show the average power level variation over the minor radius for the $m=1$ and 2 modes respectively. The structure of the mode is clearly resolved and the power levels are above the NEP of the detectors.

Remote Handling Operations

Concepts for remote handling of equipment on D-T machines require testing in a real tokamak environment. It is highly desirable that these remote handling concepts be initially tested in a non radioactive device so that components and procedures can be developed without penalty for failures. We propose that groups involved in this research and development activity utilize the TEXT-U machine to test their concepts. In particular we would identify components such as end effectors and multi-channel fiber optic feedthroughs as suitable for testing in this tokamak environment.

Other Diagnostic Related Development

One area of concern is coating of optical components, particularly windows, during long pulse operation. Some estimates of coating rate predict significant loss of transparency occurring during a single 1000 s pulse. A study on methods of in-situ real time window cleaning is in progress for TPX. We propose to collaborate with the TPX and ITER study groups in testing concepts in real plasma environments, using the TEXT-U experiment.

With the continuing development of the TPX and other future machine diagnostic programs, other areas of diagnostic data needs and experimental tests will arise. The TEXT program plans to participate in these activities. In addition to its unique capabilities as a test facility for this facet of the program, considerable economies could be accrued because many of these tests could be piggy-backed together with the main TEXT-U research program.

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PROJECT DESCRIPTION

IV. ANNOTATED BIBLIOGRAPHY OF SOME OF THE MAJOR PHYSICS RESULTS FROM TEXT AND TEXT-U

IV. An Annotated Bibliography of Some of the Major Physics Results from TEXT and TEXT-U

May 1995

- 1 We completed a survey of interior and edge turbulence characteristics, and compared our results with those from other devices, including stellarators and torsatrons [A. Wootton, H. Tsui and S. Prager, *Plasma Physics and Controlled Fusion*, **34**, 2023 (1992) and references therein; A. Wootton, B. A. Carreras, H. Matsumoto, K. McGuire, et al., *Physics of Fluids B2*, 2879 (1990) and references therein].
- 2 We demonstrated experimentally for the first time the suppression of turbulence by radial electric fields [Ch. Ritz, H. Lin, T. L. Rhodes and A. J. Wootton, *Phys. Rev. Letts.* **65**, 2543 (1990)], and developed a model for the naturally occurring shear layer [H. Tsui, *Phys. Fluids. B4*, 4057 (1993)].
- 3 We identified experimentally a long-time micro turbulence precursor to disruptions [D. Brower, C.X. Yu, R. V. Bravenec, H. Lin, et al., *Phys. Rev. Letts.* **67**, 200 (1991)].
- 4 We demonstrated experimentally for the first time the applicability of quasilinear test particle theory to fast electron transport [R. Bengtson, M. R. Freeman and A. J. Wootton, *Rev. Sci. Instrum.* **63** 4595 (1992); P. Catto, J. R. Myra, P. W. Wang, A. J. Wootton, et al., *Phys. Fluids B8* 2038 (1991)]. We verified analytic quasilinear test particle theory using Monte-Carlo calculations in various collisionality regimes; this was the first verification of "Rechester-Rosenbluth diffusivity". We demonstrated for the first time the applicability of quasi linear theory ("Rechester-Rosenbluth diffusivity") to thermal plasma transport in an externally applied stochastic magnetic field [A. Wootton, S. McCool and S. B. Zhang, *Nucl. Tech.* **19** 473 (1991)].

- 5 We showed that quasilinear drift wave theory was capable of explaining interior transport at low collisionalities only if the FIR inferred values of wave vector were assumed applicable. This led us to be the first to propose that there are two distinct turbulence features, one long wavelength and one short wavelength (drift wave-like) [R. Bravenec, K. W. Gentle, B. Richards, D. W. Ross, et al., Phys. Fluids **B4** 2127 (1992); D. Ross, R. V. Bravenec, Ch. P. Ritz, M. L. Sloan, et al., Phys. Fluids **B3** 2251(1991)].
- 6 We were the first to experimentally verify the effects of charge exchange on rotation in tokamaks [W. Rowan, A. G. Meigs, R. L. Hickok, P.M. Schoch, et al., Phys. Fluids **B4** 917 (1992); P. M. Valanju, M. D. Calvin, R. D. Hazeltine, and E. R. Solano, Phys. Fluids **B** 4(8), (1992)].
- 7 We made the first measurements of the magnetic field associated with a tearing mode inside a hot plasma [V. Simcic, K. A. Connor, T. P. Crowley, R. L. Hickok, et al., Rev. Sci. Instrum. **61** 3061 (1990), and V. J. Simcic, T. P. Crowley, P. M. Schoch, et al., Phys. Fluids **B** 5 (1993) 1576].
- 8 We showed theoretically that transport of ripple trapped ions was reduced by ExB rotation [K. Gentle and R. D. Hazeltine, Phys. Fluids **B3**, 3198 (1991)].
- 9 We showed by analysis of gas puff experiments that quasilinear theory of electrostatic drift waves cannot explain particle transport [K. Gentle, B. Richards, M. E. Austin, R. V. Bravenec, et al., Phys. Rev. Letts. **68** 2444(1992), and B. Richards, M. E. Austin, R. Bravenec et al., Nucl. Fusion **32** 567 (1992)].
- 10 We showed by comparing experiment and theory that atomic physics drives might explain some of the measured edge turbulence properties [J. LeBoeuf, D. K. Lee, B. A. Carreras, N. Dominguez, et al., Phys. Fluids **B3** 2291 (1991)], but also called into question some of the theoretical work [D. W. Ross, Phys. Plasmas **1**, 2630 (1994).

- 11 We quantified the effects of resonant magnetic fields on edge parameters, especially particle and impurity transport [S. McCool, A. J. Wootton, M. Kotschenteuther, A. Y. Aydemir, et al., Nucl Fusion **30** 167 (1990); S. McCool, J. Y. Chen, A. J. Wootton, M. E. Austin, et al. J. Nucl. Mater. **176** 716 (1990); S. Lippmann, M. Finkenthal, H. W. Moos, S. C. McCool, et al., Nucl. Fusion **31** 2131 (1991)].
- 12 We showed experimentally that edge transport and turbulence are enhanced by sawteeth [T. Rhodes, C. P. Ritz, and H. Lin, Phys. Rev. Letts. **65** 583 (1990)].
- 13 We found, using sawtooth propagation experiments, evidence for coupling of particle and heat fluxes [D. Brower, S. K. Kim, K. W. Wenzel, M. E. Austin, et al., Phys. Rev. Letts. **65** 337 (1990)].
- 14 We identified a quasi coherent mode in the plasma edge [H. Tsui, P.M. Schoch, and A. J. Wootton, Phys. Fluids **B5** 1274 (1993)] and determined its coupling to the background turbulence [H. Tsui, K. Rypdal, Ch. P. Ritz and A. J. Wootton, Phys. Rev. Letts. **70** 2565 (1993)].
- 15 We verified experimentally a model predicting the radial electric field in stochastic regimes [Y. Yang, B. Z. Zhang, A. J. Wootton, P. M. Schoch, et al., Phys. Fluids **B12** 3448 (1991)].
- 16 We demonstrated for the first time the "Rutherford regime" growth rate of tearing modes [Y. Zhang, R. Denton, S. M. Mahajan, C. Jiaju, et al., Phys. Rev. Letts **65** 2877 (1990)], and at the same time identified the effects of tearing modes on micro turbulence [C. Yu, D. L. Brower, S. J. Zhao, W. A. Peebles, et al., Phys. Fluids **B 4** 381(1992); C. Yu, D. L. Brower, S. J. Zhao, R. V. Bravenec, et al., Nucl. Fus. **32** 1545 (1992)].
- 17 We showed that external sensor coils could be used for plasma position control [A. Wootton and L. Wang, IEEE transactions **18** 6 (1990); E. Solano, G. H. Neilson and L. L. Lao, Nucl. Fus. **30** 1107 (1990); E. Solano, PP and CNFR **32** 759(1990)].

- 18 We discovered possible non local turbulence effects by correlating ECH and turbulence measurements [D. Sing, V. Krivenski, M. Austin, J. A. Boedo, et al., Nucl. Fus. 1757 (1991)].
- 19 We provided the first definitive identification of electrostatic turbulence as a major drive mechanism for particle transport in the edge ["Global particle confinement in the Texas experimental tokamak, "W. L. Rowan, C. C. Klepper, Ch. P. Ritz, Roger D. Bengtson, K. W. Gentle, P. E. Phillips, T. L. Rhodes, B. Richards, and A. J. Wootton, Nuclear Fusion 27], but noted that steady state convection could also be important at low densities [G. X. Li, R. D. Bengtson, H. Lin et al., Nucl. Fusion 34 659 (1994)]. We then extended this work to show that edge energy fluxes could be explained by the measured turbulence [Ch. Ritz, R. Bravenec, R. Bengtson, et al., Physical Review Letts., 62 (1989) 1844].
- 20 We provided the first evidence that biasing in tokamaks improves confinement because of reduced fluctuation levels [P. E. Phillips, A. J. Wootton, W. L. Rowan, Ch. P. Ritz, and others, J. Nucl. Mater. 145-147 807 (1987)].
- 21 We have confirmed the presence of non local transport effects, using a cold pulse [K.W. Gentle, et al., Phys. Rev. Lett. 74, 3620 (1995)].
- 22 We have developed a technique using ECRH to drive fast electrons, and then infer magnetic fluctuation levels and their importance in determining thermal plasma transport [D. R. Roberts, R. F. Steimle, and G. Giruzzi, Rev. Sci. Instruments, 66 (1995) 427].
- 23 We have used fast and runaway electrons to infer that magnetic fluctuations do not explain thermal transport either in TEXT, or most other machines [A. Wootton, in Transport, Chaos and Plasma Physics, Ed S. Benkadda, F. Doveil and Y. Elsken, World Scientific, (1994), P. J. Catto et al, Phys Fluids B5 125 (1993), P. J. Catto et al, Phys. Plasma 1 684 (1994)].
- 24 We have provided detailed scaling studies of edge turbulence properties [T. L. Rhodes and others, Nucl. Fusion 33 1147 (1993)].

- 25 We have demonstrated for the first time that a turbulent medium can be partially controlled using feedback [B. Richards et al., Phys. Plasma 1 1606 (1994)].
- 26 We have made the first measurements of temperature fluctuations in a hot tokamak, and concluded that low k electrostatic modes do not explain thermal transport [G. Cima, R. V. Bravenec, A. J. Wootton et al., Phys. Plasmas 2 720 (1995), T. Rempel and others, Rev. Sci. Instrum. 65 2044 (1994)].
- 27 We have identified and quantified the effects of finite sample volumes on various fluctuation diagnostic measurements [R. Bravenec and A. J. Wootton, Rev. Sci. Instrum. 66 802 (1994)].
- 28 We have developed various new diagnostics and analysis techniques [a safety factor diagnostic, a time domain Langmuir probe, an ultra fast bolometer, a correlation radiometer, a neutral spectral analysis technique, a wave launching technique for edge plasma probing, an Infra Red interface for automatic heat flux measurements, an optical technique for measuring density fluctuations on otherwise inaccessible regions].
- 29 We have provided TEXT as a facility for spectroscopic studies [Sugar and others, J. Op. Soc. Am. 799 (1993), and J. Op. Soc. Am. B10 1321 (1993)].
- 30 We have demonstrated that the plasma edge turbulence is well approximated by Gaussian statistics [A. V. Filippas, R. D. Bengtson, G. X. Li et al, Phys. Plasmas 2 839 (1995)], i.e. that if any coherent structures exist they must themselves have a Gaussian distribution.
- 31 First observation of an ion feature in the turbulence spectrum were made, having many of the features expected for ion temperature gradient modes [D. L. Brower, W. A. Peebles, S. K. Kim, N. C. Luhmann, Jr., W. M. Tang, and P. E. Phillips, Phys. Rev. Lett. 59, 48 (1987)].

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