Hot Electron Confinement in a Microwave Heated Spindle Cusp

Final Report

For Period September 1, 1987 - August 31, 1990

Mark A. Prelas

University of Missouri
Columbia, Missouri 65211

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

August 1991

Prepared for

THE U.S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-FG02-87ER53255

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Final Report DOE Grant # DE-FG02-87ER53255

9/87 to 8/90

The Plasma Research Laboratory at the University of Missouri — Columbia was established with awards from the McDonnell Douglas Foundation, ARMCO, Union Electric, Black and Vetch, Kansas City Power and Light, the National Science Foundation, and DOE. The Plasma Research Lab's major effort is the Missouri Magnetic Mirror (MMM or M³) Project. The technical goals of MMM have been 1) Diagnostic Development, 2) Plasma Physics in the Cusp geometry, 3) plasma—wall interactions, 4) impurity effects in a steady—state plasma, and 5) Development of Diagnostics for use in harsh plasma processing environments. The other major goal of MMM has remained providing a facility for hands—on training in experimental plasma physics. The major experimental facility of MMM is the MMM Modified Experiment (M4X).

Other research efforts in the Plasma Research Laboratory include small efforts in cold fusion, toroidal magnetic confinement, and inertial confinement and a potentially major effort in direct conversion of nuclear energy.

Recent trends in Fusion

It has been a time of major change for all areas of fusion: hot and cold, magnetic and inertial. The Plasma Research Laboratory has been active or is positioned to be active in these areas.

Fusion

Although cold fusion got most of the press, the biggest changes in years were occurring in hot fusion. DoE's Director of Energy Research from 1988 to 1989, R.O. Hunter, who unlike his predecessors comes from an inertial fusion background, had significantly shaken—up the magnetic fusion community. Hunter had frozen the request for funds from Congress for construction of the Compact Ignition Tokamak (CIT), the next large Magnetic Confinement Fusion experiment. He indicated that this would continue until the magnetic fusion community understands "anomalous transport" in magnetic confinement devices. To address this issue, in December 1988, Hunter established a Transport Initiative. As part of this Initiative, a Transport Task Force (TTF) was established and \$5 million was rebudgeted for studying transport. This transport initiative is still a major issue in the fusion community.

Transport Initiative

MFAC Panel 22 Report

As can be seen in the supporting materials, two areas that are of intense interest in the new transport climate are edge probes and edge impurity radiation. This is because turbulent fluctuations are thought to drive anomalous transport and because thermal gradients, due to variations in impurity driven radiation at the edge, are considered a leading contender for driving those fluctuations. A recent workshop on Transport in Tokamaks was held in San Diego, CA, 8/21 to 8/24/89. Two members of the MMM project attended the workshop and presented papers (E. Leal—Quiros on Novel Probes for Edge Plasma Diagnostics and F. P. Boody on Transport in Detached Tokamak Plasmas). The contributions of these papers are documented in the Workshop report. With regard to the diagnostics, the report on a new class of diagnostics, the hyperbolic energy analyzer, was received with some excitement due to its ability to operate at plasma densities above $1 \times 10^{12} \text{ cm}^{-3}$.

Opportunities for the PRL

The Plasma Research Laboratory is well positioned to contribute to the Transport Initiative because of our strength in probe development and edge impurity radiation phenomena. One member of our staff, Edbertho Leal—Quiros did his Ph. D. Thesis on Novel Probes and Energy Analyzers and was instrumental in developing an international reputation for the MMM project in this area. Another staff member, Fred Boody, was the Princeton Plasma Physics Laboratory's specialist in MARFEs and Detached Plasmas, edge phenomena known to be driven by the same peak in impurity radiation thought to possibly drive edge turbulence, before he left PPPL when Gramm—Rudmann caused cuts in the budget resulted in this area of research being de—emphasized in order to conserve funds for "parameter pushing"

Diagnostic Development

Probes

The Plasma Research Laboratory has developed the skills necessary to build and utilize all of the common probes (e.g., single and double Langmuir probes, energy analyzers, emissive probes, etc.). In addition the technology to miniaturize energy analyzers has been perfected.

Four new probes have been designed, built, and tested in the Plasma Research Laboratory. The principles of plasma diagnostics have been well established. It is rare to identify new principles of plasma diagnostics, but common to make improvements upon the use of established principles. Of the four new probes developed by PRL researchers, 3 have improved upon established principles of plasma diagnostics (the variable energy analyzer, the magnetic moment analyzer, and the double energy analyzer). However, one of the probes uses a new principle in plasma diagnostics based upon an electrostatic lens (the hyperbolic energy analyzer—HEA). The HEA can be used in the high density, high temperature plasmas characteristic of the edge plasma in a tokamak. This analyzer has all of the features of conventional energy analyzers thus giving tokamak researchers a significant diagnostic tool for edge plasmas.

Collaboration with other Labs

PRL researchers have collaborated with a number of laboratories and are in the process of establishing new collaborative efforts. Among the laboratories that have ongoing collaborative interests are General Atomics, the University of Illinois, the University of Missouri at Rolla, the Plasma Processing Center at the University of Missouri—Columbia, Princeton Plasma Physics Laboratory, UCLA, Idaho National Engineering Laboratory, and Mississippi State University. Professor Hirotsugu Yasuda, Director of the Plasma Processing Laboratory at the University of Missouri and one of the leading scientists in the area of plasma processing, have established a collaborative effort to test probes developed by PRL researchers on processing plasmas.

PRL Participation in TTF Workshops

Leal—Quiros and Boody presented talks (20 min. and 30 min., respectively) at the First Transport Task Force Meeting in San Diego in August that concentrated on Basic Experiments, Diagnostics, and Edge Turbulence. Leal—Quiros' talk was entitled "Novel Probes for Edge Plasma Diagnostics" and was presented in the Diagnostics Workshop. Boody's talk, which was entitled "MARFES, Detached Plasmas, and Applications to Edge Turbulence Studies," was presented in the Edge Turbulence Workshop. Prelas and Leal—Quiros presented talks at the DoE US/Japan Workshop on RF Induced Radial Transport, September 25—28 in Madison WI. This Workshop included representatives from all of the major mirror programs in the world. The acknowledged contributions of the PRL to transport studies included the development of the HEA and a transport experiment that utilizes the MVI system to study impurity transport. A carbon pellet is injected into the center of the plasma and the carbon impurities are imaged as they are transported from the

center of the plasma.

PRL Publications and participation in other meetings

Publications 1987-1990

1. M. A. Prelas, F. P. Boody, J. F. Kunze, and G. H. Miley, "Nuclear—Driven Flashlamps", Lasers and Particle Beams, 6(1), 25, (1988).
2. G. Gu, M. A. Prelas, and J. F. Kunze, "Neutronic Considerations of Nuclear—Pumped Laser/Reactor Concepts", Space Nuclear Power Systems, M. S. El—Genk and M. Hoover, editors, Orbit Book Company 1988.
3. M. A. Prelas, D. E. Wessol, B. J. Merrill, "Feasibility Study of a Nuclear Driven $O_2(^1\Delta)$ Generator to Drive a 18 MW Average Power Iodine Laser for Inertial Confinement Fusion", Laser Interactions and Related Plasma Phenomena, Vol. 8, H. Hora and G. Miley, editors, (1988)
4. C. Wallace, and M. Prelas, "Numerical Study of Gyrophase and Time Dependent Non—adiabatic Electron Losses in Axially—Symmetric Magnetic Mirror Fields", Fusion Technology, 14(2), 284 (1988).
5. E. Leal—Quiros, and M. A. Prelas, "Wien Energy Analyzers For High Temperature Plasma Diagnostics", Review of Scientific Instruments, 59, 1738 (1988).
6. E. Leal—Quiros, and M. A. Prelas, "A New Tilted Poles Wien Filter With Enhanced Performance", Review of Scientific Instruments, 60(3), 350 (1989).
7. Gu G., Kunze J. F., Boody F. P., and Prelas M. A., "A UF_6 Fueled Visible Nuclear—Pumped Flashlamp", Space Nuclear Power Systems, M. S. El—Genk and M. Hoover, editors, Orbit Book Company 153-160 (1989).
8. E. Leal—Quiros, and M. A. Prelas, "An Enhancement of Ion Energy Spectra Resolution and Sensitivity In a Multigrid Energy Analyzer With A Retarding Grid Potential: The Variable Energy Analyzer (VEA)", IEEE Transactions on Plasma Science, 16(6), 661 (1988).
9. M. A. Prelas, E. J. Charlson, "SYNERGISM Inertial Confinement Fusion: A Total Direct Energy Conversion Package", Lasers and Particle Beams, 7, 449 (Aug 1989).
10. M.A. Prelas, E. Leal—Quiros, J.F. Kunze, T.J. Dolan, F.P. Boody, W. Miller, W. Wei, G. Gu, J. Javedani, T. Pennington, R. Hane, M. Mosquera, and J. Burnett, "Magnetic Cusp. Contours and Measured ECRH Surfaces", Fusion Technology, 15(2), 1119 (1989).
11. M. A. Prelas, F. P. Boody, W. Gallaher, E. Leal—Quiros, D. Mencin, and S. Taylor, "Cold Fusion Experiments Using Maxwellian Plasmas and Sub—Atmospheric Deuterium Gas", J. Fusion Energy, 9(3), 309-313 (1990).
12. E. Leal—Quiros, and M. A. Prelas, "Lithium—Proton Beam Using an Astigmatic Wien Filter", Rev. Sci. Inst., 61(1), 636—638 (1990).
13. F. P. Boody, and M. A. Prelas "Very High Average Power Solid—State Lasers Pumped by Remotely—Located Nuclear—Driven Fluorescers", Advanced Solid—State Lasers, G. Dube and H. P. Jenssen, eds. 192-199 (Optical Society of America, Washington, 1991).

14. E. Leal—Quiros, and M. A. Prelas, "A Hyperbolic Energy Analyzer", To be Published in Review of Scientific Instruments, 61(6), 1708-1712 (1990).
15. M. A. Prelas, E. J. Charlson, F. P. Boody, and G. H. Miley, "Advanced Nuclear Energy Conversion Using a Two Step Photon Intermediate Technique", Progress in Nuclear Energy, 23(3), 223-240 (1991).
16. M. A. Prelas, "Nuclear—Driven Solid—State Lasers", Proceeding of the International Conference on Lasers '89, D.G. Harris and T. M. Shay, eds., 263—269 (STS Press, McLean, VA 1990).
17. M. A. Prelas, and F. P. Boody, "Nuclear—Driven Solid—State Lasers For inertial Confinement Fusion", Laser Interaction and Related Plasma Phenomena. Vol. 9, H. Hora and G. H. Miley, eds., 197-210 (Plenum Press, 1991).
18. E. Leal—Quiros, M. A. Prelas, and Eduardo Garcia-Otero, "Measurements of Distribution Functions, Densities, and Temperatures of Electrons and Ions Using a Novel Plasma Diagnostic Device : The Hyperbolic Energy Analyzer (HEA)," Rev. Sci. Inst., 61(10), 3304-3305 (1990).
19. F. P. Boody, and M. A. Prelas, "The Multiline Visible Imaging System", Accepted for Publication in Rev. Sci. Inst., 61(10), 3064-3066 (1990).
20. A. K. K. Chung, M. S. Peck, and M. A. Prelas, "Effects of Helium Buffer Gas on the Atomic Carbon Laser", Accepted for Publication in Lasers and Particle Beams, (1990).
21. E. Leal—Quiros and M. A. Prelas, "The Identification of Hot Electron Rings in a Spindle Cusp Using a Magnetic Dipole Analyzer", Invited Paper accepted for Fusion Technology, (1991)
22. T. Dolan, H. K. Tseng, C. Eschelman, M. A. Prelas "X—Ray Tomography of Hot Electron Rings in Simple Mirrors and Spindle Cusps", accepted for publication in Rev. Sci. Inst., (Oct. 1990)

Meetings (72 presentations)

APS Plasma Science (regular contributors), IEEE Conf. on Plasma Sciences (regular contributors), Laser Interactions and Related Plasma Phenomena (regular contributors and invited papers Oct., 1987 and Nov. 1989), International Conf. on Laser Science (invited paper, Aug. 1989), Lasers' 89 (invited paper, Dec. 1989), 16th European Conf. on Plasma Physics and Fusion in Venice, Italy, March 1989, School on Plasma Physics in Varenna, Italy, June 1989, Conf. On Fusion Technology (regular contributors), and Topical Conference on High-Temperature Plasma Diagnostics (regular contributors).

Summary of Research Projects

Diagnostics Probes

Development and miniaturization of a hyperbolic energy analyzer for use as an alternative to Langmuir probes is being developed. (HEA arrays can also be designed for advanced applications).

Transport Diagnostics

A Multiline Visible Imaging (MVI) system has been designed to investigate anomalous transport and impurity ion transport in tokamaks. The multiple line capability will allow the MVI to measure electron parameters that will provide direct observations of the electron density and temperature fluctuations which accompany anomalous transport. In addition, a pellet injector to launch a carbon pellet and the imaging system will be filtered for a specific carbon line to study the transport of the carbon in Tokamaks.

Cusp Geometry Physics

The caviton that was discovered in the cusp mode is being investigated by doctoral candidate J. Javedani. Ring formation in cusps and simple mirrors using the x—ray imaging system will be investigated by M.S. student D. Mencin. A new diagnostic called the Multiline Visible Imaging System (MVI) has been developed for anomalous transport studies and impurity ion transport studies and an 8 channel device will be tested on the M4X.

Facilities Progress

M4X

The Missouri Magnetic Mirror Modified Experiment (M4X) has developed into an excellent machine for testing probes. Even though it is basically a low field, low density, low temperature machine it has excellent access, a wide range of operating conditions, and, because of its ability to produce hot electron rings, the ability to produce high electron temperatures. This ability is unique in that, because the density is low, the high temperatures are produced at power loadings that will not destroy prototype probes that have not been specially designed to withstand high power loadings. Much more can be expected to come out of this machine now that a usable set of diagnostics, highlighted by the variety of probes and a rebuilt X—ray imaging system, and the computer based data acquisition and analysis system are in place and space limitations,

which previously prevented addition of additional capabilities such as additional microwave and RF heating, have been mostly solved.

Specifications

Space

The greatest impediment that the MMM project has had to face throughout its history has been lack of adequate space. This lack of space has pervaded all aspects of the project and greatly slowed the achievement of its goals. The facilities that we have had in the past were excessively dispersed and, until this summer, very cramped. The dispersion has not been solved and is not likely to be solved in the near term. The crowding has at least temporarily been solved by a doubling of the space allotted to MMM, both on campus and at the Dalton Research Center (April 1988), and by building elevated utility and storage space at Dalton (Summer 1989). The doubling of space on campus is only temporary and results from Nuclear Engineering being relocated into new space in the Electrical Engineering Building, to allow for construction of an addition to and renovation of the space in the Engineering Complex in which Nuclear Engineering was previously housed, but still having the use of the old space due to delays in the work on the Engineering Complex. While this extra space will be lost shortly, its availability during the past year made it possible for us to make the major modifications, described below, at Dalton while simultaneously continuing probe, data acquisition, and other development efforts.

Dalton Research Center

Usable space for the MMM Project at the Dalton Research Center has been increased by approximately a factor of four. This is due to an increase of approximately 100% in the space allotted to the Fusion Research Laboratory (April, 1988—now 900 sq. ft. or about 50% of the floor space in the Dalton high bay) and infrastructure improvements that take advantage of the very high ceiling (Summer 1989). These improvements, which are described in more detail below, include a 12'x12'x10' fully shielded data acquisition room, an 8'x12'x10' enclosed "clean" work area, and a 200 sq. ft. storage and utilities "loft".

Shielded Data Acquisition Room

The new shielded data acquisition room is a commercial model (Universal Shielding) that was assembled by the MMM Project staff. It is air conditioned to protect the computers and magnetic disks that acquire and archive the data from the M4 Experiment. It is large enough to hold five equipment racks and table space for three monitor positions for controlling the computers and analyzing the acquired data. Three 4" dia. steel pipes extend the shielding envelope of the room to a shielded terminal box located near the M4X vacuum vessel. The room also contains sufficient shelf space for storing the extensive software and reference manuals for the data acquisition computers.

Clean Work Room

Prior to construction of the clean work room, due to the high bay nature of the PRL space at DRC with its 36 feet high ceilings and 18 feet high doors, any work that required a reasonably clean environment had to be performed in another building over a mile away or a table had to be temporarily dragged into the data acquisition room, making it unusable for its intended purpose. The new clean work room has 16' of bench space and extensive shelf space floor storing reference materials, instruments not currently being used, work—in—progress, etc.

Storage and Utilities Loft

The storage and utilities loft is a 20'x10'x12' wooden platform on which are located storage cabinets and utilities such as compressors and cooling systems. The floor space freed—up by its construction will allow installation of the 10 kW ICRH system purchased previously.

Development Labs

Diagnostics

This lab, located on the Electrical Engineering Building ground floor was

previously storage space and was setup during the summer of 1988. Its 1000 sq. ft. provides room for 64' of lab bench space, small offices for the non—faculty senior personnel (Boody and Leal—Quiros), and one node of the PRL's AppleTalk network. The lab space is used mostly for probe and energy analysis construction, optical diagnostic development, and nuclear—driven fluorescer apparatus assembly.

Data Acquisition and Control

This lab, located on the ground floor of the Engineering Complex and previously known as the Magnet Lab, contains bench space for construction and testing of electronics and instruments for diagnostics and data acquisition and control. Its use will be lost in the near future due to construction.

Hardware

M4X

Data Acquisition and Analysis

A computer based Data Acquisition and Analysis Network (DAAN) has been developed for MMM during the past two years. The M4X DAAN combines the networking ability (*software* and hardware) of VAX workstations; the DMA performance of MacII (NuBus) and AT—compatible I/O buses; Ethernet and GPIB; VAX data archiving and analysis software from PPPL (e.g., UGRAPH); commercial data acquisition software (e.g., Labview); and Tek compatible graphics terminals (Macintosh w/VersaTerm) to form a high performance network, comparable to those previously available only for large experiments (e.g., TFTR), on the much lower budget of experiments such as M4X.

The M4X Data Acquisition and Analysis Network

As shown in the Figure, data from individual diagnostics are acquired by A/D modules located in CAMAC crates with GPIB crate controllers or by individual instruments with GPIB interfaces, which are connected to GPIB cards located in Macintosh II or IBM compatible computers, or by NuBus or AT bus cards located directly in the Macintosh II or IBM compatible computers. The Mac IIs run Labview software while the IBM compatibles run Asyst. The raw data for analysis and archival as well as analyzed data from the data acquisition PCs are transferred to a network of VAX computers for archiving, further analysis, and access by remote terminals. A VAXstation 2000 serves as the network server, a VAXstation 3100 performs high speed image reconstruction, and a remote VAX 8650, part of UMC's VAX cluster, hosts our large dedicated archiving and analysis disk and provides back—up and remote terminal support. Data analysis can be performed on the VAXes from remote Tek 4014 compatible graphics terminals, in our case Macintoshes running VersaTerm terminal emulation software, either from on campus locations such as staff offices (9600 bps) or from dial—up locations, such as individual homes or other campuses such as Rolla (1200 bps). Currently available analysis software includes Labview for the Macs, Asyst for the PC compatibles, and Ugraf and Locus (from PPPL) for the VAXes.

Grounding and Shielding

The M4X DAAN is designed to be a fully shielded, single point ground system. The shield envelope includes the aluminum vacuum vessel, the shielded Data Acquisition Room, and the piping, cabling and connectors in between. Three 4" steel pipes with permanently installed coaxial and multiconductor cables run from the Data Acquisition Room to the Data Acquisition Panel located close to the vacuum vessel. The Data Acquisition Room ends of the cables are connected to bulkhead connectors installed in an insulating panel. The Data Acquisition Panel is the front of a conducting steel box, which is part of the shielding envelope. This panel is also filled with bulkhead connectors but these are insulated from the panel itself, to prevent ground loops. The vessel and the shielded room are connected to a single grounding point by very low resistance cables. Being a steady-state system without any pulsed high voltages, high voltage isolation was not required.

Diagnostics

Major recent diagnostic additions include a number of probes and energy analyzers built and tested by Edbertho Leal—Quiros as part of his Ph. D. research and a rebuild and recalibration of the X-ray imaging system. A large quantity of hardware for use in additional new diagnostics is currently on hand, both purchased and obtained through DoE (either temporarily on loan or permanently as donations or surplus). These diagnostics are being assembled and tested as manpower allows, frequently as master's projects. Examples of these include a bolometer, new probes, a new microwave interferometer, and visible and UV spectroscopy.

Heating

M4X is currently heated by 2.5 kW of 2.45 GHz ECRH. A 10 kW 10.4 GHz ECRH power source, a 10 kW 2—5 MHz ICRH power source, and a 5 kW 5 MHz ICRH power source are operational and available for heating the M4X plasma.

Personnel, Student Participation and Degrees Granted

Ph. D. Students (4)

One Ph D. was granted in 1987 to Dr. Albert Gu, One Ph. D. was granted in 1989 to Edbertho Leal—Quiros, and one Ph.D. was granted in 1991 to Frederick P. Boody. One other student will receive his Ph.D in 1991, Jalal Javedani.

M.S. Students (10)

David Brinegar (MSNE 1985), Jalal Javedani (MSNE 1985), Richard Hane (MS Physics 1988, MSNE 1989), Ms. Wei Wei (1989), Tad Pennington (MSNE, 1989), Scott Taylor (EE1990), Eduardo Garcia (MSNE 1991), David Mencin (NE), Sayhan Akkouyan (NE).

Undergraduates (17)

Over the past five years, 17 undergraduates have been supported by this project. Five of these undergraduate students are currently employed by PRL. Three of these are basically hourly student technicians while the other two have made substantial commitments of time and it is hoped will continue for graduate degrees with MMM. Undergraduate students have come from Electrical, Mechanical, and Chemical Engineering and from Physics.

Allied Research

An interest outside the mainstream of fusion research is that of direct conversion of Nuclear Energy. Dr. Prelas has been active in this area since the middle seventies. During that time he has evolved a concept of utilizing fluorescence produced by nuclear reaction products to produce a number of desired end products, such as electricity, chemicals, and coherent light. Prelas first suggested producing electricity by the use of fusion driven excimer radiation for powering high bandgap photovoltaics at the 1981 APS Division of Plasma Physics Meeting in New York. In the Spring of 1988, in conjunction with three faculty members from electrical engineering, Prelas submitted a proposal to DoE's Division of Advanced Energy Projects to develop and test high bandgap photovoltaics. This proposal was awarded a grant December, 1990. The substrate growth and the testing of the completed photovoltaic cell portions of this effort would, in particular, takes advantage of the PRL's abilities in plasma and fluorescence production and diagnostics.

Appendix A. Related Materials

- 1.0 Wein Energy Analyzer (Paper)
- 2.0 Hyperbolic Energy Analyzer (Papers)
- 3.0 Variable Energy Analyzer (Paper)
- 4.0 MVI (Preprint of Paper)

(reprints removed and cycled separately)

END

**DATE
FILMED**

12 / 16 / 91