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ANNUAL REPORT ON FUSION PLASMA THEORY GRANT

TASK III: Auxiliary Radiofrequency Heating of Tokamaks
Covering the period November 16, 1992 to November 15, 1993

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TASK III: Auxiliary Radiofrequency Heating of Tokamaks
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J.E. Scharer, Principal Investigator; N.T. Lam, Scientist;
M. Bettenhausen and R. Sund, Graduate Students

Abstract

The research performed under this grant during the past year has been concentrated on the following several key tokamak ICRF (Ion Cyclotron Range of Frequencies) coupling, heating and current drive issues. We have made progress in developing a "3-D" cavity backed antenna array code to examine ICRF coupling to general plasma edge profiles. The effects of the finite antenna length and feeders as well as Faraday shield blade angle are being examined. We are also developing an analysis to examine large $k_{\perp} \rho$ gyroradius interaction between alpha or beam particles and ICRF waves. This topic has important applications in the areas of ICRF heating for deuterium-tritium fusion plasmas, TAE modes, ash removal and minority ion current drive. Research progress, publications, and conference and workshop presentations are summarized in this report.

I. Introduction

This annual report on Task III-Auxiliary Radiofrequency Heating in Tokamaks of the Fusion Plasma Theory DOE Grant Number DE-FG02-86ER53218 at the University of Wisconsin covers the research carried out during the current grant period (November 16, 1992 to November 15, 1993). This is the second year of a third 3 year grant which was issued under the same grant number. These grants evolved out of the previous DOE Contract Number DE-AC02-80ER53104 that supported

research in this area at the University of Wisconsin-Madison from July, 15, 1980 through December 31, 1985.

The Task III research progress described in this report emphasizes ICRF (Ion Cyclotron Range of Frequencies) antenna coupling, plasma heating and current drive. These areas of research are relevant to theoretical interpretations of JET and TFTR experimental observations, the Toroidal Plasma Experiment (TPX/Steady State Advanced Tokamak) physics analysis and advanced tokamak design concepts (funded by Princeton University), and future radiofrequency roles in tokamaks including ITER and to tokamak plasma confinement issues. Our group has maintained a continuous collaboration with Dr. Jacquinot and the JET ICRF group since the summer of '83 and annual visits in both directions and regular phone and FAX contacts have served to stimulate ICRF research activity and the exchange of ideas.

Our research program emphasizes the physics of ICRF antenna coupling to general edge plasma profiles. It also addresses an improved understanding of interactions between plasma edge conditions and ICRF wave coupling which are important to future fusion experiments such as TPX and ITER. The role of ICRF in producing near steady-state operation of future tokamaks via lower hybrid/fast wave current drive synergistic effects with high efficiencies is an important issue for future tokamaks. The role of minority ion current drive which can be accomplished by ICRF at high densities is an important confinement issue which can provide high performance tokamak reactors in the future. Finally, the influence of ICRF absorption by alpha particles on the fusion breakeven, alpha-particle excited TAE mode influence on confinement, ash removal and ignition heating scenarios are important issues. Our research program, within the limitation of budget constraints, is focused on these physics issues which will provide an attractive fusion power source during the next century.

One member of our group (Mike Bettenhausen) also made substantial contributions to acquisition, installation and configuration of three new high-end Unix workstations which will be used by about 30 fusion theory researchers here at the University of Wisconsin - Madison. This effort included evaluation of hardware and software from four different workstation vendors.

The research progress during the past year is summarized in the following sections: II. ICRF Heating of Fast Ions and Alpha Particles in Tokamaks; III. ICRF Antenna Modelling and Wave Coupling to Tokamak Plasmas; and IV. Analysis of Plasma Waves Experimental Research. The progress report concludes with lists of the publications, conferences, reports and workshops in section V and the personnel and their degree of involvement in Appendix A.

II. ICRF Heating of Fast Ions and Alpha Particles in Tokamaks

During the past year, we have pursued our examination of the role of fast ions in various RF heating and current drives in tokamaks. Most of these investigations have been carried out with XWAVE, a full-wave code based on an energy conservation principle. We have modified XWAVE to include density profiles of the various ion species in the region of dominant plasma-wave interaction. We have also developed a formalism to describe a nonlocal ICRF interaction with ions which have an arbitrarily large gyroradius. This includes transverse and parallel magnetic field gradients and extends and corrects previous work done by Sauter and Vaclavik. ICRF coupling to alpha particles can have an important impact on such topics as TAE mode stability, alpha particle transport, minority ion current drive and helium ash removal. A summary of the results to date follows:

1) The role of the ion-hybrid resonance in the minority scenario in tokamaks.

We have considered the role of the ion-ion hybrid resonance for the minority fundamental heating scenarios in tokamaks. In certain cases, notably ITER, an ion-ion hybrid resonance (between the D and T fundamental resonances) exists on the high field side of the machine. At such a resonance position, the component of the electric field which rotates in the same direction as the gyromotion of the ions has a local maximum. For high alpha temperatures, the Doppler width of the alphas may be sufficiently wide to allow them to interact with the wave near the ion-ion hybrid resonance. Three parameters are important: the tail temperature of the minority species, the fast alpha concentration, and the equivalent Maxwellian temperature of the alphas. We have shown that the slowing down distribution of the alphas can be adequately approximated at the ion hybrid resonance position by a Maxwellian with $T_\alpha \sim 600$ keV. This equivalent temperature is still in the range where the small gyroradius approximation can be applied. For realistic RF absorbed power densities for the fast wave $P = 0.5$ W/cm³ we have estimated the tail temperature of the deuterium using Stix's formula. The fast alpha densities $n_\alpha = 0.2 - 0.4\%$ n_e has been estimated from slowing down theory.

We have carried out alpha particle wave absorption studies using XWAVE, a full-wave code we have developed. For fundamental deuterium heating with ITER parameters, we find that alpha particle absorption is small (<5%) for low deuterium concentrations ($\leq 10\%$) at high deuterium temperatures (≥ 25 keV). However, as the deuterium concentration is raised to 33% and corresponding deuterium temperatures decrease to ≤ 15 keV, the single pass alpha particle absorption near the two-ion D-T resonance can increase to 25%. As even higher deuterium concentrations of 50% are reached, the alpha particle absorption is reduced since the two-ion resonance location moves further out on the alpha particle Doppler width.

Recently we have compared XWAVE results directly with those given by SEMAL, a full-wave, finite element code developed by the Lausanne group.¹ The

results are quite comparable, thus reinforcing our confidence in XWAVE. A paper discussing these results has been submitted to Nuclear Fusion.²

2) ICRF-Beam Heating in Tokamaks

We have examined the interaction of ICRF with beam heated plasmas in tokamaks at large ion gyroradii and for higher harmonics. For example, for a current drive scenario in TPX with the third harmonic deuterium at the center, we point out the fact that the small gyroradius approximation may be violated for a deuterium beam heating case. Since the SEMAL code is not limited by the small gyroradius approximation, we have used it to determine the partitioning of the ICRF absorption profile for each species (deuterium, hydrogen, electrons) in this current drive scenario. A preliminary conclusion is that it is difficult to find a frequency window in which electron absorption is dominant ($\geq 70\%$ of the incident wave power).

The problem of two-frequency heating in TFTR has also been analyzed. Physically, using two minorities (hydrogen and ^3He) and heating at the fundamental cyclotron resonance frequencies of both species tend to increase the fractional power going to the bulk ions. The results of our simulation also show that this scenario decreases the fractional power that goes to the alpha particles and electrons.

III. ICRF Antenna Modelling and Wave Coupling to Tokamak Plasmas

The focus of this work is to improve upon previous studies of ICRF antenna coupling to better analyze coupling for reactor relevant parameters and operating scenarios. Specifically, this includes the study of antenna performance for non-inductive current drive applications and investigation of the effects of higher plasma temperatures, particularly near the antenna at the plasma edge and higher densities in the plasma core which increase the importance of plasma edge density gradients.

Initial development of an ICRF coil antenna coupling model which will be used to address these reactor relevant issues has been completed.^{3,4} This model is used to calculate antenna coupling properties such as radiation resistance and parallel wavenumber spectrum of the coupled power. Features of this model which distinguish it from most previous models include

1. The finite length of the antenna and the radial current feeders are included in the model.
2. A three dimensional rectangular model of the antenna's recessed cavity is included.
3. The component of the electric field which is parallel to the tokamak magnetic field is included.
4. Warm plasma effects are included for calculation of the plasma surface impedance.
5. A Faraday shield model is included which facilitates the study the effect of misalignment between the Faraday shield blades and the tokamak magnetic field.

R_A (Ω)	b_h (cm)	h (cm)	R_A/m (Ω/m)
4.1	81	38	5.4
8.7	550	38	11.4
11.8	550	50	11.8
20.7	550	100	10.4

Table 1: Variation of radiation resistance with antenna and cavity height.

The first two features are important for studying non-inductive current drive due to their effect on the coupled power spectrum. Features 3-5 are important for studying the effects of the increased temperatures and density gradients near the edge in a reactor-grade plasma. The higher edge temperatures increase the potential for parasitic coupling to wave modes with electric fields which are dominantly parallel to the tokamak magnetic field. Such parasitic coupling is undesirable because the energy coupled to these modes would be damped primarily near the edge of the plasma.

The computer code WICS (Wisconsin Ion cyclotron Coupling Solver) has been developed to study ICRF antenna coupling based on the model discussed above. Initial modeling results have been obtained using ICRF parameters from TFTR⁴ and the proposed TPX system. These results have been used to investigate the effect of the three dimensional cavity on the parallel wavenumber spectrum of the power coupled to plasma and on antenna radiation resistance.

Table 1 presents values of radiation resistance, R_A , calculated with WICS for the TFTR Bay M antenna with supershot plasma conditions and a 180 degree phase difference between the currents on the two antenna straps. The results demonstrate that as the cavity height, b_h is increased the radiation resistance increases due to smaller return currents on the cavity walls. Similarly, as the length of the antenna, h , is increased the radiation resistance per meter antenna length, R_A/m , increases provided the ends of the antenna are far enough from cavity walls. This result is due to the decreased importance of end effects due to the radial feeders and the finite antenna length.

Figure 1 shows the parallel wavenumber spectrum of the coupled power spectrum for the same TFTR conditions except that the phase difference between currents on the straps is 90 degrees. The spectrum has been normalized to give a maximum of 1.0 for each case. The presence of the cavity increases the percentage of the coupled power in the secondary lobe of the spectrum at negative k_z . Figure 2 shows a similar result for in-phase excitation of the antenna straps. The differences in the spectrum shown in these figures are primarily due to a reduction in the power coupled to low k_z rather than an increase in the power coupled to higher k_z .

Immediate plans for additional modeling efforts include a careful study of the return currents on the tokamak and cavity walls.⁵ This is necessary to better

understand the physical mechanisms responsible for differences in the coupled power spectrum as calculated by WICS versus results obtained when neglecting the recessed cavity or with a two-dimensional model.

The boundary conditions used in the plasma edge region will be reexamined to better model effects of large density gradients at the plasma edge which can influence wave propagation. An adaptation of the integral equation methods developed by Sauter [6] is currently planned. Improvements to our model will be made in conjunction with this effort and initial results should be available in January 1994.

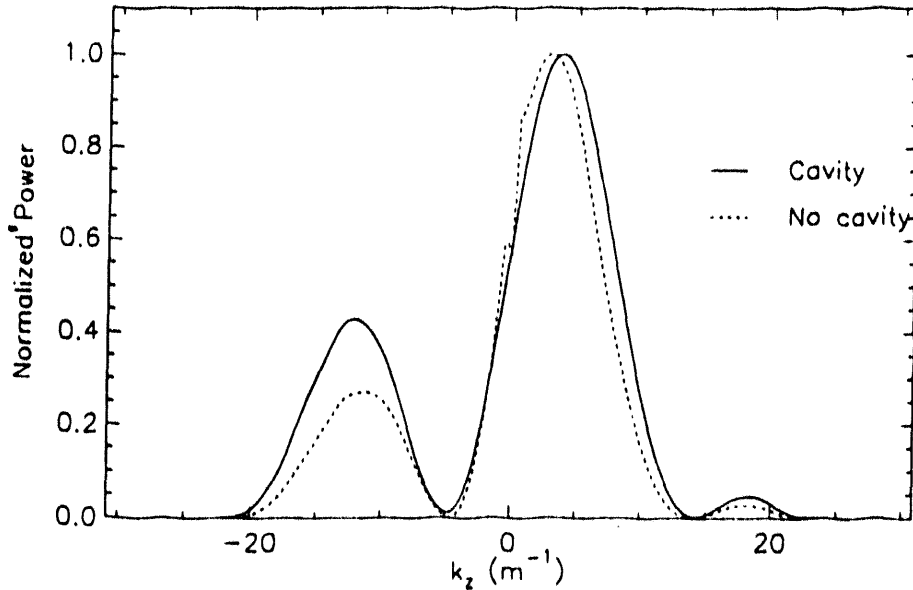


Figure 1: Wavenumber spectrum for coupled power with $(0, \pi/2)$ phasing.

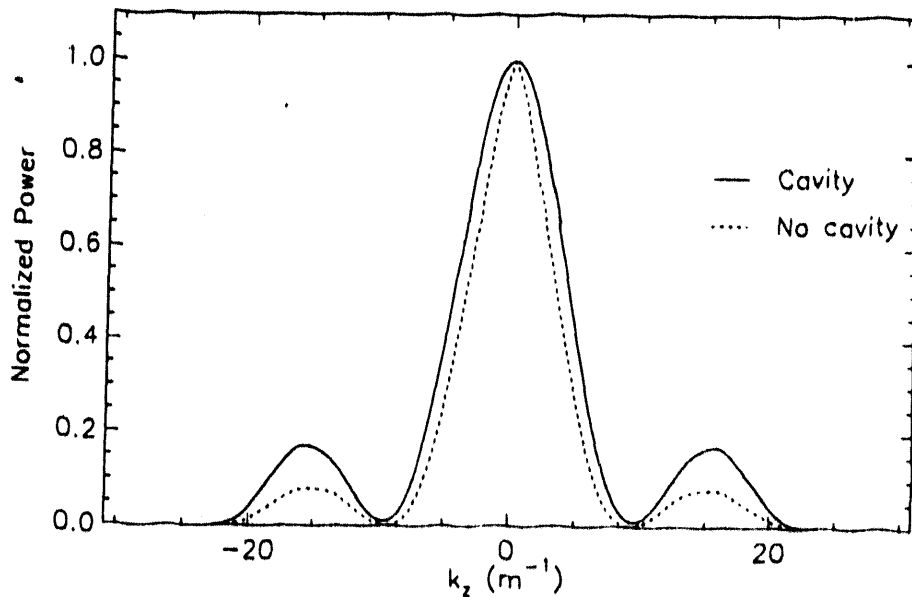


Figure 2: Wavenumber spectrum for coupled power with $(0,0)$ phasing.

IV. Analysis of Plasma Waves Experimental Research

We have carried out ray tracing and hot plasma descriptions of electron cyclotron wave damping in an inhomogeneous plasma to support experimental work by our research group in this area. The plasma is described in two dimensions with experimentally determined density and magnetic field gradient profiles. We examined ray trajectories in a hollow plasma column launched in a magnetic beach at different angles to the dominant axial magnetic field. We found that an axial wave guiding effect for rays launched at small angles to the magnetic field allows a quasi-axial power flow in a bounded plasma, in agreement with experimental results. We also examined the breakdown of ray theory when rays are launched at large angles to the magnetic field and wavelengths become comparable to the density gradient scale length.

We also carried out a WKB weak-damping analysis of experimentally measured wavelengths and collisionless cyclotron damping lengths to compare with the measured strong damping process. It was found that the theoretically predicted wave phase shifts were in reasonable agreement with the measured values in the region but the damping decrement was lower than the measured one in the strong gradient field, in agreement with the strong damping theory predicted by Fructmann et al.⁷ Our research was accepted for publication⁸ and will appear in the near future.

We have also examined the theoretical problem of electromagnetic wave scattering in a plasma half-space from a propagating ion acoustic wave density perturbation. An analytical solution was obtained for the scattered wave field. The results show that of the two types of scattered waves, one propagates only in the region of the perturbed plasma density and satisfies the energy and momentum conservation process for a three-wave process. The other wave propagates as an unperturbed electron cyclotron mode with an up-shifted or down-shifted frequency. We found that the scattered wave that propagates with a wavenumber close to that of the ion acoustic wave is in good agreement with the experimental results. The other mode that propagates at an upshifted wavenumber does not agree as well with the experimental results and is attributed to additional wave mixing processes. The research has been submitted to the Physics of Fluids, has been accepted for publication⁹, and will appear in the near future.

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1. O. Sauter and J. Vaclavik, Nucl. Fusion 32, 1455 (1992).
2. N.T. Lam, J.E. Scharer and R.S. Sund, "Influence of Alpha Particle Absorption on Fundamental Deuterium Heating in a Fusion Plasma," submitted to Nuclear Fusion, 1993.

3. M.H. Bettenhausen and J.E. Scharer, "A '3-D' ICRF Antenna Coupling Model for Heating and Current Drive Applications in Tokamaks," Tenth Topical Conference on Radio-frequency Power in Plasmas, Boston, 1993.
4. M.H. Bettenhausen and J.E. Scharer, "A "3-D" ICRF Antenna Coupling Model for Heating and Current Drive Applications in Tokamaks," in Proceedings of the 10th Topical Conference of Radio-Frequency Power in Plasmas, 1--3 April 1993, Boston, MA, edited by M. Porkolab, (American Institute of Physics, New York, 1993).
5. M.H. Bettenhausen and J.E. Scharer, "Three-Dimensional Recessed Cavity Effects on ICRF Antenna Coupling in Tokamaks," to be submitted to Nuclear Fusion.
6. O. Sauter, "Nonlocal Analyses of Electrostatic and Electromagnetic Waves in Hot Magnetized Nonuniform Bounded Plasmas," PhD Thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne, 1992.
7. A. Fruchtman, K. Reidel, H. Weitzer, and P.B. Batchelor, Phys. Fluids 30, 115 (1987).
8. M.H. Bettenhausen and J.E. Scharer, "A "3-D" ICRF Coupling Model for Heating and Current Drive Applications in Tokamaks," in Proceedings of the 10th Topical Conference of Radio-Frequency Power in Plasmas, 1 - 3 April 1993, MA, edited by M. Porkolab, (American Institute of Physics, New York, 1993).
9. Y.S. Zhang, J.E. Scharer and B. Chapman, "Electron Cyclotron Wave Scattering by a Probe-Launched Ion Acoustic Wave", accepted for publication in the Physics of Fluids, 22 pages, (1993).

IV. List of Publications and Papers During the Present Grant Year (1992-93).

A. Reports and Journal Papers

1. N.T. Lam, J.E. Scharer and R.S. Sund, "Influence of Alpha Particle Absorption on Fundamental Deuterium Heating in a Fusion Plasma," submitted to Nuclear Fusion, 1993.
2. M.H. Bettenhausen and J.E. Scharer, "Three-Dimensional Recessed Cavity Effects on ICRF Antenna Coupling in Tokamaks," to be submitted to Nuclear Fusion, (1993).
3. J.E. Scharer, O.C. Eldridge, S.F. Chang, Y.S. Zhang, M. Bettenhausen and N.T. Lam, "Electron Cyclotron Wave Propagation, Absorption and Backscatter Measurements in a Laboratory Plasma", IEEE Plasma Sciences **21**, 10 journal pages, June (1993).
4. Y.S. Zhang, J.E. Scharer and B. Chapman, "Electron Cyclotron Wave Scattering by a Probe-Launched Ion Acoustic Wave", accepted for publication in the Physics of Fluids, 22 pages, (1993).

B. Published Conference Papers

1. M.H. Bettenhausen and J.E. Scharer, "A "3-D" ICRF Coupling Model for Heating and Current Drive Applications in Tokamaks," in Proceedings of the 10th Topical Conference of Radio-Frequency Power in Plasmas, 1 - 3 April 1993, MA, edited by M. Porkolab, (American Institute of Physics, New York, 1993).
2. J.E. Scharer, N.T. Lam, R.S. Sund and O. Sauter, "Ion Cyclotron Range of Frequencies (ICRF) Heating of Fast Ions in Fusion Plasmas," to be published in the Proceedings of the Tenth Topical Conference on Radio-frequency Power in Plasmas, Boston, 1993.
3. J.E. Scharer, M. Bettenhausen, N.T. Lam, R.S. Sund, and O. Sauter, "ICRF '3-D' Antenna Coupling and Fast Ion Heating Models for Fusion Plasmas," to be published in EPS Conference on Plasma Physics and Controlled Fusion, Lisbon, 1993.

C. Conference Abstracts and Posters

1. M.H. Bettenhausen and J.E. Scharer, "A '3-D' ICRF Antenna Coupling Model for Heating and Current Drive Applications in Tokamaks," Tenth Topical Conference on Radio-frequency Power in Plasmas, Boston, 1993.
2. J.E. Scharer, N.T. Lam, R.S. Sund and O. Sauter, "Ion Cyclotron Range of Frequencies (ICRF) Heating of Fast Ions in Fusion Plasmas," Tenth Topical Conference on Radio-frequency Power in Plasmas, Boston, 1993.
3. J.E. Scharer, M. Bettenhausen, N.T. Lam, R.S. Sund, and O. Sauter, "ICRF '3-D' Antenna Coupling and Fast Ion Heating Models for Fusion Plasmas," Lisbon EPS Conference on Plasma Physics and Controlled Fusion, 1993.
4. M.H. Bettenhausen, J.E. Scharer and N.T. Lam, "A "3-D" ICRF Antenna Coupling Model for Heating and Current Drive Applications in Tokamaks," Bulletin of the American Physical Society, vol. 37 #6, p. 1602, (1992).
5. J.E. Scharer, N.T. Lam and R. Sund "ICRF Coupling to Alpha Particles," Bulletin of the American Physical Society, Vol. 37, #6 p.1602 (1992).

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Appendix A

Grant Modalities

During the current grant period (11/16/92 - 11/15/93) the participating personnel and their approximate degree of involvement has been as follows:

- A. John Scharer, Principal Investigator (20% for 12 months)
- B. Dr. N. Lam, Scientist (20% for 12 months)
- C. M. Bettenhausen, graduate student (33% for 12 months) Including SUN and DEC workstation operations management for General Fusion Theory and Computational Research.
- D. R. Sund, graduate student (16% for 12 months)

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10/27/93

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