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Annual Progress Report on TFTR Ion Cyclotron Range of Frequencies (ICRF)
Experimental Data Analysis Collaboration

Covering the period December 1, 1992 to November 30, 1993

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Annual Report on TFTR Ion Cyclotron Range of Frequencies (ICRF) Experimental Data Analysis Collaboration

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J.E. Scharer

Abstract

The research performed under this grant during the past year has been concentrated on two TFTR tokamak ICRF (Ion Cyclotron Range of Frequencies) coupling, and heating issues. This includes a "3-D" coupling analysis of the TFTR ICRF cavity-backed coil antennas to plasma edge profiles including the Faraday shield blade angle and fast wave coupling for heating and current drive; TFTR ICRF full-wave field solutions, heating analyses for the D-T supershot; and the effects of fusion alpha particle and ion tail populations on the ICRF absorption. Research progress, publications, and conference presentations are summarized in this report.

I. Introduction

This first annual report on TFTR ICRF experimental data analysis collaboration is supported by DOE #DE-FG02-93ER54196 at the University of Wisconsin and covers the research carried out during the current grant period (December 1, 1992 to November 30, 1993). This is the first year of a three year grant.

The research progress described in this report emphasizes TFTR ICRF (Ion Cyclotron Range of Frequencies) antenna coupling, plasma heating and current drive and is relevant to tokamak plasma confinement issues. These areas of research are also relevant to theoretical interpretations of JET experimental observations, Toroidal Plasma Experiment (TPX/Steady State Advanced Tokamak) physics analysis and advanced tokamak design concepts, and future radiofrequency roles in tokamaks including ITER. Drs. C. Phillips, R. Majeski and R. Wilson of PPPL have served as our contacts for TFTR and have been invaluable in orienting our research towards planned and important past experiments and access to the TFTR database.

Our research program is emphasizing the efficient TFTR ICRF antenna power coupling to L-mode and supershot plasmas. 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 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 TFTR ICRF absorption by alpha particles on the fusion breakeven, alpha-particle excited TAE mode influence on confinement are important issues. Our research program, within the limitation of budget constraints, is focused on these TFTR physics issues.

The research progress during the past six months is summarized in the following sections: II. TFTR Wave Absorption with Alpha Particles; and III. TFTR ICRF Antenna Modelling and Wave Coupling to the Plasma. The progress report concludes with lists of the publications, conferences, reports and workshops in section IV and the personnel and their degree of involvement in Appendix A.

II. TFTR ICRF Heating Analysis and Computational Results for Large Gyroradius Alphas and Minority Ion Tail Distributions

We are currently evaluating TFTR ICRF D-T supershot heating scenarios where a small concentration of alpha particles and tail ion species are present utilizing absorption equivalent Maxwellians in the XWAVE and SEMAL codes. We have used SNAP and TRANSP results from previous supershot runs and Budny's predictions [1] for alpha particle production in our current studies. This problem is particularly important for simultaneous fundamental hydrogen and helium-3 heating with second harmonic deuterium and third harmonic tritium heating. The fusion process creates a small concentration of alpha particles which requires a large gyroradius formulation to describe its interaction with the ICRF. We are also developing a formalism that includes the effects of parallel and perpendicular magnetic field gradients to more rigorously analyze the fast particle - ICRF interaction.

The works of Koch and Van Eester [2] and Sauter and Vaclavik [3] have argued that the alpha particle slowing down distribution absorption of ICRF over the transverse spatial Doppler width can be equivalently modeled by Maxwellians in the range of 600-900 keV. Our recent research has quantified this for fundamental ion cyclotron resonance heating. We are currently evaluating the effects of TFTR alpha particle absorption competing with the fundamental hydrogen and helium

resonance absorption. We are comparing our finite gyroradius absorption model results [4] and SEMAL code large $k_{\perp}\rho$ results [2]. We are also working on an extension of Smithe's work [5] to include a compact representation of the wave fields in order to evaluate the interaction with large gyroradius particles including parallel and perpendicular magnetic field gradients.

During this grant period, we have carried out calculations and theoretical analyses on the following topics:

1) We have used XWAVE to analyze the heating of a beam of tritium at the second harmonic (frequency = 46 MHz) in a deuterium plasma. This scenario is being considered to test the fusion diagnostics on TFTR while keeping the tritium inventory low. XWAVE is a code that we have developed. Full details on the code are given in [3]. This code includes a magnetic field perpendicular gradient and second-order gyroradius effects. With the TFTR plasma parameters set as: $n_e = 6.0 \times 10^{13} \text{ cm}^{-3}$, $n_T = 2\% n_e$, $T_e = 10 \text{ keV}$, $T_D = 25 \text{ keV}$, $T_T = 100 \text{ keV}$, XWAVE predicts a 2% absorption of the incident fast wave power by the tritium beam. This fraction rises to 5% as the temperature of the tritium beam is increased to 200 keV. Note that in XWAVE, the beam distribution is assumed to be a Maxwellian. Further work concerning the inclusion of a more realistic beam distribution is in progress.

We have also considered the role of a small population of fast particles (alphas in particular) in the D-T heating scenario for TFTR supershots. For this simulation, we use SEMAL, a code which has been provided to us by O. Sauter. SEMAL is based on a finite element solution of the plasma wave equation. It can handle an arbitrary number of harmonics and is not limited by a small gyroradius compared to transverse wavelength assumption. The parameters used in the calculations are appropriate for an expected TFTR supershot and are as follows: $n_e = 9 \times 10^{13} \text{ cm}^{-3}$, $n_D/n_T = 1$, $n_{\alpha} = 0.25\% n_e$, $n_H = 5\% n_e$, $T_e = 10 \text{ keV}$, $T_D = T_T = 20 \text{ keV}$, $T_{\alpha} = 800 \text{ keV}$ and $f = 64 \text{ MHz}$ (near the second harmonic of deuterium). For $T_H = 200 \text{ keV}$ (this temperature is estimated from a Stix-type calculation for 5 MW of coupled power), the absorption profile of the various species is shown in Figure 1. In this case, we also find that a significant portion of the total absorbed power (up to 8%) can go to the alphas. However, by increasing the temperature of the hydrogen minority to 400 keV, we find that the percentage of power absorbed by the alphas decreases to 5%. Further work concerning the effect on RF absorption by the simultaneous addition of fundamental absorption of He^{3++} at 43 MHz is in progress.

TFTR Supershot plasma
 Equilibrium mesh
 BN0T=4.500, ON(2)=4.25E+19, THP=1.00E+04, 2.00E+04, W/VCI= 1.8657, KZ= 6.00E+00
 NX=400, NPB=400, E, IK=T, T, PL=-0.380PR= 0.950A= 0.970SR= 2.700, KY= 0.00E+00
 NQL1= 0. 2. 1. 1. 1. 1. NQL2= 0. 2. 3. 2. 4.

Fig. 1. ICRF absorption for TFTR D-T supershot.

The analysis of ICRF heating dynamics for many of the up-coming TFTR shots requires that we go beyond the limitations of differential equation based wave codes. These rely on the assumption that particle gyroradii are small compared to wavelengths. There are three primary cases for which another approach is necessary: when there are significant numbers of fusion produced alphas, when a minority species heated at its fundamental resonance reaches sufficiently high energies (several hundred keV), and when ion-Bernstein waves are excited. In the first two instances the particle gyroradii are large and in the third the wavelength is short.

We have used the SEMAL code written by Olivier Sauter to look at a few cases of interest. SEMAL solves a set of coupled integro-differential equations for a 1-D slab configuration and allows arbitrary gyroradii. In the following we provide some caveats concerning SEMAL's applicability and correctness. We then describe our work thus far in correcting this formulation.

The code has the usual limitations inherent in any 1-D model that obtains solutions across the entire tokamak cross section. It incorporates perfectly reflecting boundaries, and there is no option to select radiation boundary conditions in order to examine single pass absorption. Consequently, in all runs 100% of the launched power must ultimately be absorbed by the plasma. Another difficulty stemming from the full cross section solution is the very large number of mesh points needed to resolve the ion-Bernstein wave in cases where there is significant mode conversion. Additionally, the code is presently restricted to isotropic Maxwellian distribution functions. Lastly, although the gradients of density and temperature are treated correctly the effects of perpendicular magnetic field gradients are not explicitly incorporated in Sauter's work.

We have developed the correct equation for the electrostatic case and for the same set of assumptions. The electromagnetic case would follow very similar steps. We begin by explicitly including the transverse $1/x$ dependence of the magnetic field in Vlasov's equation before Fourier transforming. The result is a first order partial differential equation in the gyroangle, ϕ , and the transform variable, k . This equation is reduced to an ordinary differential equation via the method of characteristics. The final result shows that the magnetic field depends on x' everywhere it appears in the dielectric tensor K . Additionally, K includes a new term consisting of the error function complement times d/dx' . We expect that the

new kernel if implemented in the code would show differences that would be most significant for low values of $k_{\parallel}$, high temperatures and for high field side incidence. Once this analysis is completed, we will implement it in a code to compare with the TFTR ICRF supershots to examine the interaction of ICRF with alpha and beam particles which can affect the fusion Q and confinement.

2) We have also examined the influence of a small population of fast alphas on the fundamental deuterium heating scenario in an ITER-like tokamak. We found that the presence of an ion hybrid (D-T) resonance inside the tokamak can give rise to significant RF absorption by a small concentration of fast alpha particles. For example, for ITER-like parameters with $n_e = 9 \times 10^{23} \text{ cm}^{-3}$, $B_0 = 4.85 \text{ T}$, $R_0 = 6 \text{ m}$, $n_D/n_T = 0.5$, and a fast alpha concentration of 0.3% n_e , the alphas can absorb 25% of the fast wave incident power, mainly at the two-ion hybrid resonance position which is located 70 cm away from the center, towards the high field side. In these calculations, the equivalent Maxwellian temperature is $T_{\alpha} = 600 \text{ keV}$. For these parameters, the small gyroradius condition $(k_{\perp} \rho_{\alpha t})^2 \ll 1$ is well satisfied. This allows us to use XWAVE. We have submitted a paper on these calculations to Nuclear Fusion [6].

III. TFTR ICRF "3-D" Antenna Modelling

Studies of TFTR ICRF antenna coupling are being conducted using a new model which is an extension to the earlier models developed by Brambilla [7] and Chiu et al. [8]. The computer code WICS has been developed which incorporates features of the new model and calculates antenna coupling properties such as radiation resistance and wavenumber spectrum of coupled power. Included in the model is a finite length antenna in a three-dimensional recessed cavity and parallel electric field and warm plasma effects. WICS also includes the effect of misalignment between the Faraday shield blades and the tokamak magnetic field.

A rectangular coordinate system is assumed with x , y and z corresponding to the radial, poloidal and toroidal directions, respectively. Figure 2 shows the geometry used and defines various parameters. The current distribution on the antenna straps is assumed to be sinusoidal in the poloidal direction with a phase velocity of ω / k^* on the straps which face the plasma. The current distribution on the radial feeders is taken to be uniform.

Table 1 presents values of radiation resistance calculated with WICS for the dimensions of the TFTR Bay M antenna and TFTR supershot plasma conditions (shot no. 67911). The currents on the two antenna straps are phased 180 degrees apart for these cases. The results demonstrate that as the cavity height is increased the radiation resistance increases. This is likely due to smaller return currents on the cavity walls. Similarly, as the length of the antenna is increased the radiation resistance per meter antenna length increases provided the ends of the antenna are far enough from the cavity walls. This result is due to the decreased importance of end effects due to the radial feeders and the finite antenna length.

R_A	b_h	h	R_A/m
Ω	(cm)	(cm)	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.

Figure 3 shows the parallel wavenumber spectrum of the coupled power spectrum for the TFTR Bay M antenna for a 90 degree phase difference between currents on the straps. 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 4 shows a similar result for in-phase excitation of the antenna straps. The differences in the spectra 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 . This is consistent with the reduction in radiation resistance due to the cavity as discussed above. These studies are being carried out to determine the coupled wave spectra for plasma heating and phase optimization for current drive experiment.

Fig. 2. Antenna model geometry.

Fig. 3. TFTR Wavenumber spectrum for coupled power with $(0, \pi/2)$ phasing.

Fig. 4. TFTR Wavenumber spectrum for coupled power with $(0, 0)$ phasing.

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

A. Published Conference Papers

1. M.H. Bettenhausen and J.E. Scharer, "A '3-D' ICRF Antenna Coupling Model for Heating and Current Drive Applications in Tokamaks," to be published in the Proceedings of the 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," 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.
4. N.T. Lam, J.E. Scharer, R.S. Sund, "Heating of alphas and fast ions by ICRF in Fusion Plasmas," Bull. Am. Phys. Soc. **38**, 2105 (1993).
5. Mike Bettenhausen and J.E. Scharer, "Three-Dimensional Recessed Cavity Effects on ICRF Antenna Coupling in Tokamaks," Bull. Am. Phys. Soc. **38**, 2105 (1993).

B. 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.

C. 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.

Appendix A

Grant Modalities

During the current grant period (12/1/92 - 11/30/93) 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 6 months)
- E. Y. Mouzouris (16% for 6 months)

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