\$720

DOE/ER/54196.2

DOE #DE-FG02-93ER54196

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

Covering the period December 1, 1993 to November 30, 1994

J.E. Scharer, M. Bettenhausen,
N. Lam and R. Sund

Electrical and Computer Engineering Department
University of Wisconsin-Madison
1500 Johnson Drive
Madison, Wisconsin 53706-1687

August, 1994

Prepared for

THE U.S. DEPARTMENT OF ENERGY
UNDER GRANT #DE-FG02-93ER54196

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.

NOTICE: This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, 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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

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

Covering the period December 1, 1993 to November 30, 1994

J.E. Scharer, M. Bettenhausen,
N. Lam and R. Sund

Abstract

The research performed under this grant during the past year has concentrated coupling, heating, and current drive issues for TFTR. We have developed a code and submitted for publication 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. We have also carried out TFTR ICRF full-wave field solutions and heating analyses for the second harmonic tritium supershot, and the effects of fusion alpha particle and tritium ion tail populations on the ICRF absorption. We have also published a paper on the effects of alpha particle absorption on fundamental deuterium ion cyclotron absorption incorporating self-consistent deuterium tails and fusion reactivity. Research progress, publications, and conference presentations are summarized in this report.

I. Introduction

This is the second annual report on TFTR ICRF experimental data analysis collaboration which is supported by DOE grant #DE-FG02-93ER54196 at the University of Wisconsin and covers the research carried out during the current grant period (December 1, 1993 to November 30, 1994). This is the second 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 alpha particle 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 and possible minority ion current drive alpha-particle excited TAE modes 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 year is summarized in the following sections: II. TFTR ICRF Antenna Modelling and Wave Coupling to the Plasma; and III. TFTR Wave Absorption with Alpha Particles. 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.

The computer runs that have been carried out to date include the WICS code (Wisconsin Ion Cyclotron Antenna Solver -- see report submitted to Nuclear Fusion entitled "An ICRF Antenna Coupling Model with a 3-D rectangular Cavity," M. Bettenhausen and J. Scharer, Report UW CPTC 94-4), XWAVE (see Physics of Fluids B 3, 1326 (1991)) and the SEMAL code (see O. Sauter and J. Vaclavik, Nuclear Fusion 32, 1455 (1992)). The XWAVE code has been modified to include density profiles and incorporate equivalent Maxwellians for Alphas (see "The Influence of Alpha Particles on Fundamental Deuterium Absorption," by N. Lam, J. Scharer and R. Sund, to appear in Nuclear Fusion, (1994)).

II. TFTR ICRF Antenna Modelling and Wave Coupling to the Plasma.

We have used our ICRF antenna coupling code, WICS, to study edge density profile effects using TFTR antenna and plasma parameters. The study is reported in our technical report UW CPTC 94-4, submitted to Nuclear Fusion [1]. Since our model includes a three-dimensional rectangular cavity with radial antenna feeders this study also includes investigation of the effects of changes in the poloidal structure of the antenna on the antenna performance.

Recently, Mark Carter, Greg Hanson and Dave Rasmussen of Oak Ridge National Laboratory (ORNL) have provided us with TFTR experimental data including antenna loading and density profiles for the Bay M ICRF antenna on TFTR shot 73704 at 2.899 sec and on shot 73708 at 3.409 sec. The density profiles are based on reflectometer measurements which provide accurate measurements at the plasma edge. The density profile at the edge is the factor which most strongly affects ICRF antenna coupling. The more accurate density profiles facilitate better comparison of modeling predictions with experimental results.

The density profiles used in our modeling are compared to experimental values for density in Figures 1 and 2. The antenna straps were exited in-phase (0,0 phasing) for both shots. Using the experimental parameters our WICS code predicts an antenna radiation resistance of 4.6 Ohms for shot 73704 while the experimental value is 4.4 Ohms and for shot 73708 WICS predicts a resistance of 2.5 Ohms while the experimental value is 2.0 Ohms. These results demonstrate good agreement between WICS predictions and experimental loading values. We plan to continue these studies with the assistance ORNL.

The parallel wavenumber spectrum of the ICRF power coupled to the plasma is important because it strongly affects the efficiency of current ICRF heating and non-inductive current drive. Figures 3 and 4 show the spectra predicted by WICS for the TFTR Bay M antenna with the parameters discussed above. The 0,90 phasing (90 degree phase difference between straps) and the 0,180 phasing are included in the figures to demonstrate the effects of antenna phasing on the spectrum for the same plasma profiles.

TFTR Shot 73704

Figure 1.

TFTR Shot 73708

Figure 2.

TFTR Shot 73704.2899 Density Profile

Bay M

Figure 3.

TFTR Shot 73708.3409 Density Profile

Bay M

Figure 4.

III. TFTR ICRF Heating Analysis and Computational Results for Ion Distributions and Large Gyroradius Alphas.

We have evaluated TFTR ICRF D-T supershot heating experiments where a small concentration of alpha particles ($n_\alpha = 0.4\% n_e$) are present utilizing absorption equivalent Maxwellians in the XWAVE [2] and SEMAL[3] codes. The case of second harmonic tritium and simultaneous fundamental hydrogen and helium-3 heating with second harmonic deuterium and tritium heating has been examined. The fusion process creates a small concentration of alpha particles which requires a large gyroradius formulation to describe its interaction with the ICRF. We have also examined a regime of minority alpha particle current drive for which a proof-of-principle experiment could be tried on TFTR in the coming year. This scheme could provide a core seed current for advance confinement reversed-shear steady-state operation of ITER.

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

1) We have modified our XWAVE code to include profile effects [4] to analyze the heating of beam and background tritium at the second harmonic (frequency = 43 MHz) in a deuterium plasma with or without a small concentration of He^{3++} . This code includes a magnetic field perpendicular gradient and second-order gyroradius effects as well as reacting plasma and alpha particle temperature and density profiles. With the TFTR plasma parameters set as: $n_e = 7.0 \times 10^{13} \text{ cm}^{-3}$, $n_D/n_T = 1.1$, $n_\alpha = 0.4\% n_e$ on axis with a 90 cm Gaussian width, $n_{T\text{beam}} = 5\% n_e$, $T_e = 10 \text{ keV}$, $T_D = T_T = 23 \text{ keV}$, and $T_{T\text{beam}} = 100 \text{ keV}$. The background densities are parabolic and the temperatures are parabolic squared. XWAVE predicts a 4% single pass absorption of the incident fast wave power by the tritium beam. The bulk tritium beam absorbs 7% of the power and the electrons absorb 7% of the power as well. In addition to this, XWAVE predicts 1.5% single pass absorption by deuterium and 1% alpha particle absorption near the two-ion hybrid resonances. The spatial profiles for this case are shown in Fig. 5.

2) We have considered the role of a small population of fast alpha particles in the D-T heating scenario for TFTR supershots. For this simulation, we have used both XWAVE and SEMAL, a code which has been provided to us by O. Sauter of Lausanne University of Switzerland. 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.

We are examining the possibility of a minority alpha particle current drive scenario proof-of-principle experiment which could be carried out in the coming year. The parameters used in the calculations are appropriate for a TFTR supershot and are as follows: $n_e = 7 \times 10^{13} \text{ cm}^{-3}$, $n_D/n_T = 1$, $n_\alpha = 1\% n_e$, $T_e = 10 \text{ keV}$, $T_D = T_T = 30 \text{ keV}$, $T_\alpha = 800 \text{ keV}$ and $f = 37 \text{ MHz}$ at high field operation of 6 T for TFTR. The SEMAL code absorption profile solutions for the various species is shown in Fig. 6. We consider a $k_{||} = 8 \text{ m}^{-1}$ which is indicative of the TFTR current drive antenna configuration.

The SEMAL global wave code results for TFTR high field operation are shown on Fig. 6. Note that this code has perfectly reflecting wave boundary conditions at both ends of the system and that all of the launched power is assumed to be ultimately absorbed by plasma species in the profile. As noted on Fig. 6, the alpha particles absorb 60% of the power in completion with the deuterium resonance which lies on the low field side of the

absorbed power

Figure 5

Figure 6

R (Major radius - m)

axis and deuterium absorbs 28% of the power. Note that for our corresponding ITER cases, the Shafranov shift places the deuterium resonance outside the machine and it is not competitive with the alpha particle absorption. The smaller electron absorption (11%) and tritium fundamental (1%) absorption complete the picture. We should note that corresponding XWAVE single pass runs show 20-30% of the power going to the alphas with substantial reflections from the two ion hybrid resonance zone ($n_{||}^2 = S$) and negligible mode conversion. We will continue to examine this case for a potential proof-of-principle experiment in the coming year.

3) We have examined simultaneous two frequency (43 and 64 MHz) heating for TFTR supershots. This is carried out using the SEMAL code [3] which we have obtained for small ion concentrations (5%) of He^{3++} and H ion minorities to ensure strong single pass absorption, reduce the minority ion tails for a given power input and increase the fusion reactivity. We have accomplished this by keeping the same set of species in the plasma, linearly adding the two results and renormalizing the power so that the same power is coupled from both frequency antennas. For our initial runs, we have chosen:

$n_{e0} = 9 \times 10^{19}/\text{m}^3$, $n_H = n_{\text{He}^{3++}} = 5\% n_e$, $n_\alpha = 0.25\% n_e$, $T_\alpha = 800 \text{ keV}$, $T_H = 200 \text{ keV}$, $T_{\text{He}^{3++}} = 70 \text{ keV}$, $T_D = T_T = 23 \text{ keV}$ and $T_e = 10 \text{ keV}$. Very strong absorption by the minority ions (80%) is indicated with very small (2%) alpha particle heating. The radial profiles for TFTR for all species and for the alpha particle absorption are shown in Figs. 7 and 8.

Two frequency supershot runs corresponding to the previous figures are planned for the near future on TFTR. We will refine our modelling to correspond to experimental data as results become available.

4) We have also examined single-pass absorption calculations in the $2 f_{cT}$ and the $f_{c\text{He}^3}$ heating regimes in D-T TFTR supershots similar to shots 74651 and 74652. The plasma and wave parameters are as follows: D:T ratio = 1:1; $n_H = n_{\text{He}^{3++}} = 0.02 n_e$; $T_i = 20 \text{ keV}$, $T_e = 10 \text{ keV}$; $B_T = 4.3 \text{ T}$; $f = 43 \text{ MHz}$. The central electron density n_{e0} is set at $7 \times 10^{13} \text{ cm}^{-3}$. The calculations have been carried out using XWAVE (a full-wave code based on a power conservation principle). We have chosen simple parabolic density profile and square parabolic temperature profiles. Figures 9 and 10 show the variations of the single-pass transmission, tritium absorption and electron absorption coefficients with respect to the parallel wave number $k_{||}$ (in the 2 to 8 m^{-1} range). Figures 9 and 10 correspond to second harmonic tritium and fundamental He^{3++} , respectively. The integration region in XWAVE extended between -0.8 m and 0.3 m, a region which includes all important cyclotron frequencies.

In general, the results obtained from XWAVE are quite comparable to those reported by C. K. Phillips at the Boulder meeting (4/94). The single-pass wave transmission is significant in both cases, while the absorption by D remains small ($< 2\%$).

For TFTR parameters, the inclusion of H and He^3 brings the hybrid resonance layer ($S = n_{||}^2$) inside the machine. We have used SEMAL (a finite elements code developed by O. Sauter) to study multi-pass absorption for the second harmonic tritium heating regime in TFTR. The integration region extends over the entire machine and the peak alpha concentration has been chosen as $0.4\% n_e$ (this is compatible with a simple fusion reactivity calculation), and the equivalent Maxwellian T_α is set at 600 keV. Table 1 summarizes the fractional power absorbed by each species for $k_{||} = 6 \text{ m}^{-1}$. Note that both D

Absorbed Power Density for all species

Figure 7

Figure 8

Figure 9

Figure 10

and alpha absorption can become significant ($\sim 5\%$ each), the alpha absorption profile also shows a small maximum near the $S = n_z^2$ surface. This is shown in Fig. 11 which depicts the absorbed power density profile of the alphas, as calculated by SEMAL.

Table 1	
Species	Fractional power absorption (%)
D	5.0
T	53.6
H	0.2
alphas	4.2
e	37.0

5) 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 $0.4\% n_e$, 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. A paper detailing these studies has been accepted for publication in Nuclear Fusion [4].

References

- [1] M.H. Bettenhausen and J.E. Scharer, "An ICRF Coupling Model with a 3-D Rectangular Cavity," submitted to Nuclear Fusion, (May 1994) 28 pages.
- [2] R. Sund and J. Scharer, "Full Wave Field Solutions and Power Conservation for the Ion Cyclotron Range of Frequencies (ICRF) in Nonuniform Plasmas," Physics of Fluids B 3, 1326-1337 (1991).
- [3] O. Sauter and J. Vaclavik, Nuclear Fusion 32, 1455 (1992)
- [4] N.T. Lam, J.E. Scharer and R.S. Sund, "Influence of Alpha Particle Absorption on Fundamental Deuterium Heating in a Fusion Plasma," accepted for publication in Nuclear Fusion, (1994) 18 pages.

TFTR D-T shot with alphas

Equilibrium mesh

BNOT=4.300;DN(2)=3.43E+19;TMP=1.00E+04,2.00E+04;W/WCI= 1.3119;KZ= 6.00E+00

NX=400;NPP=400;E,IK=T,T;PL=-0.960PR= 0.960A= 0.970SR= 2.800;KY= 0.00E+00

NQL1= 0, 1, 1, 1, 1, NQL2= 0, 2, 3, 2, 4,

Figure 11

IV. List of Publications and Papers During the Grant Period (Dec. 1, 1993 - Nov. 30, 1994).

A. Reviewed 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," accepted for publication in Nuclear Fusion, (1994) 18 pages.
2. M.H. Bettenhausen and J.E. Scharer, "An ICRF Coupling Model with a 3-D Rectangular Cavity," submitted to Nuclear Fusion, (May 1994) 28 pages.
3. R.J. Hawryluk, ..., J. Scharer, et al., "Preparations for D-T Experiments on the Tokamak Fusion Test Reactor," Princeton Univ. collaboration, 100 authors, Phys. Plasmas 1 (5), 1560-1567 (1994).

B. Published Conference Papers

1. D.B. Batchelor, M.D. Carter, E.F. Jaeger, D.C. Stallings, D.W. Swain, C.Y. Wang, P.T. Bonoli, M. Porkolab, P. Moroz, M. H. Bettenhausen, J.E. Scharer, Y. H. Ho. "Predictions of Fast Wave Heating and Current Drive for TPX," Submitted to the 1994 IAEA Conference, Spain, 1994.
2. J.E. Scharer, M. Bettenhausen, N.T. Lam and R.S. Sund, "ICRF Antenna Coupling and Fast Alpha Heating Models for Fusion Plasmas," 4 pages to be published in the Proceedings of the 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier, France, June, 1994.
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," 20th EPS Conf. on Controlled Fusion and Plasma Physics, Lisbon, Portugal 17C, 985-988 (1993).

C. Conference Abstracts and Posters

1. J.E. Scharer, "ICRF Coupling Heating and Current Drive modeling applied to TFTR Experiments" Seminar presented at Princeton, August, 1994.
2. J.E. Scharer, M. Bettenhausen, N.T. Lam and R.S. Sund, "ICRF Antenna Coupling and Fast Alpha Heating Models for Fusion Plasmas," 4 pages to be published in the Proceedings of the 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier, France, June, 1994.
3. M.H. Bettenhausen and J.E. Scharer, "A "3-D" ICRF Antenna Coupling Model for Heating and Current Drive Applications in Tokamaks," 35th Annual Meeting of the American Physical Society Division of Plasma Physics, 1-5 November 1993, St. Louis, MO.

4. D.B. Batchelor, D.W. Swain, E.F. Jaeger, M.D. Carter, D.C. Stallings, D.J. Hoffman, J.J. Yugo, ORNL, M. Porkolab, P.T. Bonoli, MIT, P. Moroz, J. Scharer, U. Wisconsin, T.K. Mau, UCLA, "Ion Cyclotron Heating and Current Drive on TPX," Bull. Am. Phys. Soc. 38, 2049 (1993).
5. Y. Mouzouris, J.E. Scharer, N.T. Lam, and M. Bettenhausen, "Applications of ANTENA code to TFTR, high density plasma sources, and wave propagation in a nonuniform magnetized plasma," Bull. Am. Phys. Soc. 38, 1887 (1993).
6. N.T. Lam, J.E. Scharer, R.S. Sund, UW-Madison, O. Sauter, GA-San Diego, "Heating of alphas and fast ions by ICRF in Fusion Plasmas," Bull. Am. Phys. Soc. 38, 2105 (1993).

D. Workshops

1. J.E. Scharer, M.B. Bettenhausen, N.T. Lam, R. Sund and O. Sauter, "The Influence of Alpha Particle Absorption on Heating and Current Drive," Boulder Current Drive and Advanced Confinement Workshop, April, 1994.
2. J. Scharer, M. Bettenhausen, N. Lam, R. Sund and O. Sauter, "ICRF 3-D Antenna Coupling and Fast Particle Heating in Fusion Plasmas, Princeton ICRF Physics Workshop, January, 1994.

E. Reports

1. R. S. Sund and J. E. Scharer, "Fast Wave Alpha Particle Minority Ion Current Drive for Advanced Confinement Steady State Reactors," Report in Preparation (1994).
2. M.H. Bettenhausen and J.E. Scharer, "An ICRF Antenna Coupling Model with a 3-D Rectangular Cavity," UW-CPTC 94-4, May 1994, submitted to Nuclear Fusion for publication.
3. Y.S. Zhang, J.E. Scharer and B. Chapman, "Electron Cyclotron Wave Scattering by a Probe-Launched Ion Acoustic Wave," UW-CPTC Report 93-2.
4. N. Lam, J. Scharer, R. Sund, "Influence of Alpha Particle Absorption on Fundamental Deuterium Heating in a Fusion Plasma," UW-CPTC Report 93-1.

Appendix A

Grant Modalities

During the current grant period (12/1/93-11/31/94) 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)

021
DEC 05 1993
RECEIVED