THE EFFECT OF ICRF ANTENNA PHASING ON METAL IMPURITIES IN TFTR

J. E. Stevens, C. Bush, P. L. Colestock, G. J. Greene, K. W. Hill,
J. C. Hosea, C. K. Phillips, B. Stratton, S. von Goeler, and J. R. Wilson

Princeton Plasma Physics Laboratory

and

W. Gardner and D. Hoffman
Oak Ridge National Laboratory

and

A. Lysojvan
Kharkov Institute of Physics and Technology

PPPL--2640

DE89 014009

ABSTRACT

ICRF power levels of up to 2.8 MW were achieved during the 1988 experimental run on TFTR. Metal impurity concentrations (Ti, Cr, Fe, Ni) and Z_{eff} were monitored during ICRF heating by X-ray pulse height analysis and UV spectroscopy. Antenna phasing was the key variable affecting ICRF performance. No increase in metallic impurities was observed for $P_{\text{rf}} \lesssim 2.8$ MW with the antenna straps phased 0- π , while a measurable increase in titanium (Faraday screen material) was observed for $P_{\text{rf}} \gtrsim 1.0$ MW with 0-0 phasing.

1. INTRODUCTION

A density rise and an influx of metal impurities are often observed during ICRF experiments (EQUIPE TFR, 1982; HOSEA et al., 1984). Impurities can be controlled to some extent when the tokamak is well conditioned and operated at sufficiently high plasma current (HOSEA et al., 1979). Slanted Faraday shields (BURES et al., 1988a) and wall carbonization (MESSIAEN et al., 1986) also reduce the metal impurity influx. Nevertheless the impurity question is of increasing concern as RF powers and pulse lengths approach reactorlike values. Reviews of ICRF-related impurity studies are given in several references (WILSON, 1984; MANNING et al., 1986; LEHRMAN, 1988). The effect of the antenna spectrum on impurity production is now

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

beginning to be explored experimentally (MORI et al., 1985; MAZZUCATO et al., 1985; WATARI et al., 1987; KIMURA et al., 1987; BURES et al., 1988b), while theories have generally not addressed the question of antenna phasing.

2. EXPERIMENTAL SETUP

The ICRF experiments reported on here were begun on TFTR in 1988 with an antenna consisting of two current straps excited at their ends and separated toroidally by 28 cm (HOFFMAN et al., 1988). The antenna loops can be driven toroidally either in-phase (0-0) or out-of-phase (0- π). The Faraday screens are TiC-coated Inconel rods, and the antenna has deep slots cut in the sidewall casing. Power levels of 2.8 MW (≈ 0.7 kW/cm²) have been achieved, limited to date by the RF generator. ICRF pulse widths of 0.5 sec were used for most of the experiments reported here.

The poloidal location of the antenna relative to the plasma is shown in Fig.1. Large size plasmas were used during ICRF experiments on TFTR so that the antenna-plasma separation was small enough for good loading. These plasmas had $R=2.62$ m and $a=0.96$ m versus a previously standard size of $R=2.45$ m and $a=0.82$ m. Loading was approximately twice as high for in-phase operation compared to out-of-phase operation and loading increased with decreasing antenna-plasma separation.

Two heating modes were used for the ICRF experiments on TFTR. The H-minority mode operated at a central toroidal field of ≈ 3.3 T, and the ³He-minority mode operated at ≈ 5.0 T. The primary gas was either deuterium or helium. Helium was used for all experiments with ICRF alone in order to avoid loading the limiter with deuterium, thereby maintaining desired operating conditions for non-ICRF experiments. Experiments with ICRF in combination with neutral beams had a low density deuterium prefill and used beam fueling to supply most of the deuterium density. The metal impurity concentration observed in TFTR depends mainly on the type of plasma discharge. Figure 2 shows that high density He plasmas have low

Z_{metals} and low density, neutral-beam-heated deuterium plasmas produce $Z_{\text{metals}} \approx 1$. This behavior with density also applies to Z_{eff} and is typical of TFTR plasmas (HILL et al, 1987).

The overall Z_{eff} of the plasma is dominated by carbon and did not change significantly for the power levels used in these experiments ($P_{\text{rf}} < 2.8$ MW). However, the titanium in the antenna Faraday screen provided a sensitive monitor of metal impurities generated directly from the antenna since it is the only significant source of titanium in TFTR. The concentration of titanium and other metals in the central part of the plasma is measured by monitoring the $K\alpha$ lines ($E \approx 4-8$ keV) with an X-ray pulse height analysis system which views along a horizontal midplane chord. Absolute impurity concentrations derived from X-ray PHA measurements are accurate to within a factor of two with the main inaccuracy due to systematic uncertainties in line radiation rates. However, the relative impurity levels are statistically accurate to within $\approx 15\%$, which is sufficient to show the important trends as rf parameters vary. UV spectroscopy gave relative titanium levels similar to X-ray pulse height analysis.

3. RESULTS

Titanium is generally not an important impurity in standard size TFTR discharges as shown in Fig.3(a) for an extreme case having 30 MW of neutral beam injection. The X-ray spectrum in Fig.3(a) was taken during the time the beams were on and has a negligible titanium line. Higher titanium concentrations are expected for large size plasmas where the plasma boundary is much closer to the antenna Faraday screen. In Fig.3(b), a measurable titanium line is seen for a large size plasma with 1.8 MW of in-phase ICRF power in the H-minority regime. However, the titanium line is not present in Fig.3(c) where 2.8 MW of out-of-phase power was applied to a similar discharge.

Metal concentrations during the ICRF pulse are derived from X-ray spectra such as those shown in Fig.3. Negligible titanium is observed during the ohmic phase of these discharges. Z_{eff} due to titanium (Z_{Ti}) is plotted versus rf power in Fig.4(a) for the in-phase and

out-of-phase conditions in He plasmas. No change in the level of titanium or other metals versus rf power is observed for out-of-phase antenna operation with up to 2.8 MW of power, while in-phase operation shows a significant increase in Z_{Ti} above ≈ 1 MW. The increase in Z_{metal} for in-phase operation, shown in Fig.4(b), appears to be due largely to titanium. A visible glow on the Faraday shields at the top and bottom of the antenna was also observed during in-phase operation at power levels above 1 MW.

A number of possible mechanisms have been suggested for ICRF-induced metal impurity production which may be aggravated during in-phase operation. In-phase excitation (low $k_{||}$) may produce higher local electric fields leading to higher rf sheath potentials (PERKINS, 1988) or to local acceleration of ions such as 3rd harmonic C^{+5} or 5th harmonic C^{+3} and He^{+1} (HOSEA, 1985; PURI, 1988). The high impurity level with the in-phase spectrum may also be related to weaker first pass absorption of the in-phase spectrum. The observation of large toroidal eigenmodes in TFTR for in-phase operation is consistent with the picture of weak damping. Also, the toroidal field scan shown in Fig.5, although somewhat limited, indicates a minimum in Z_{eff} due to metals and titanium around $B_0=3.25$ T which is the field where central absorption is the best.

ICRF incremental confinement, plotted in Fig.6, varied with antenna phasing. Absorption efficiency ($\epsilon=\dot{W}/P_{rf}|_{t_{rf}}$) also varied in the same manner with antenna phasing. Absorption efficiency was $\approx 90\%$ for out-of-phase operation versus $\approx 50\%$ for in-phase operation. Thus, impurity generation, weak damping, and poor heating efficiency are correlated with antenna spectra having small $k_{||}$ (in-phase), while best results occur for the out-of-phase condition with a spectrum centered at $k_{||}=7m^{-1}$. The 3He -minority mode had heating results only slightly better than the H-minority in-phase mode and also showed a titanium signal slightly above background. However, further optimization of the 3He concentration is needed in our experiments before a firm conclusion can be drawn for the 3He -minority mode.

Neutral beam heating and combined beams plus ICRF both produce

measurable Ti levels in the large size TFTR plasmas as shown in Fig.7. This suggests that high power levels into the plasma, rather than ICRF power per se, can cause some of the impurity influx from the antenna. A factor complicating the interpretation of Fig.7 is that various combinations of co and counter beam fractions were used. Nevertheless, comparing equal power shots with and without ICRF shows that 2 MW of ICRF do not produce any strikingly detrimental effects compared with the beams, especially when beam fueling with higher beam powers is taken into account. The Z_{eff} due to all metals was $\approx 0.75 \pm 0.25$ for out-of-phase rf and $\approx 1.1 \pm 0.25$ for in-phase rf for the shots plotted in Fig.7. The Z_{eff} due to titanium was $\lesssim 15\%$ of Z_{metals} for $P_{beam} + P_{rf} + P_{OH} \lesssim 12$ MW.

In contrast to neutral beams, the ICRF does not provide central fueling to dilute an initially high Z_{eff} plasma. Even so, the radiated power fraction, plotted in Fig.8, decreased from $\approx 50\%$ to $\approx 30\%$ during ICRF heating for rf power levels approaching 2.8 MW. This decrease of the radiated power fraction is similar to the decrease typically observed with neutral beam heating. Total radiated power scales approximately linearly with stored energy during ICRF.

4. CONCLUSION

Driving the antennas out-of-phase reduces the metal impurity generation caused directly by the launched rf wave and also improves the ICRF heating efficiency. However, metal structures near the hot plasma do contribute metal impurities approximately in proportion to total power in the plasma. Thus, the antennas should be far enough from the plasma to avoid impurity generation from the hot scrape-off layer while at the same time the antennas should be close enough to the plasma to provide sufficient RF loading for an out-of-phase (high $k_{||}$) spectrum. These conditions have been satisfied so far on TFTR for plasmas with up to 12 MW of input power (2 MW of which is ICRF) for ≈ 0.5 sec pulses.

Higher power experiments are planned for both of the antennas on TFTR. The second antenna has a water-cooled Inconel Faraday screen

which has a bonded graphite tile surface. These experiments should shed more light on the issue of impurity suppression for out-of-phase antenna operation and provide a comparison between TiC and carbon Faraday screen materials.

ACKNOWLEDGMENTS

We thank R. Hawryluk, D. Meade, P. Rutherford, and H. Furth for their support of this project. This work was supported by US DOE Contract No. DE-AC02-76-CHO-3073.

REFERENCES

- BURES M. et al. (1988a) Proc. 15th European Conf. on Controlled Fusion and Plasma Physics, Dubrovnik, Vol. 2, p.713.
- BURES M. et al. (1988b) Plasma Physics and Controlled Fusion, 30, 149.
- EQUIPE TFR (1982) Plasma Physics, 24, 615.
- HILL K. W. et al. (1987) Plasma Phys. Contr. Fusion, IAEA Vienna, Vol. 1, p. 207.
- HOFFMAN D.J. et al. (1988) Proc. 15th European Conf. on Controlled Fusion and Plasma Physics, Dubrovnik, Vol. 2, p. 770.
- HOSEA J. C. et al. (1979) Proc. of Course on Physics of Plasmas Close to Thermonuclear Conditions, Varenna, Vol. 2, p. 571.
- HOSEA J. C. et al. (1984) Proc. of the Fourth Int. Symp. on Heating in Toroidal Plasmas, Rome, Vol. 1, p. 261.
- HOSEA J. C. (1985) Course on Applications of RF Waves to Tokamak Plasmas, Vol. II, p. 666.
- KIMURA H. et al. (1987) Proc. 14th European Conf. on Controlled Fusion and Plasma Physics, Madrid, Vol. 3, p. 857.
- LEHRMAN I. S. (1988) Ph.D. dissertation, U.Wisconsin.
- MANNING H. L. et al. (1986) Nucl. Fusion, 26, 1665.
- MAZZUCATO E. et al. (1984) Plasma Phys. Contr. Fusion, IAEA Vienna, Vol. 1, p. 433.
- MESSIAEN A. M. et al. (1986) Plasma Physics and Controlled Fusion, 28, 71.
- MORI M. et al. (1984) Plasma Phys. Contr. Fusion, IAEA Vienna, Vol. 1, p. 445.
- PERKINS F. W. (1988) Nucl. Fusion, 29, 583.
- PURI S. (1988) Phys. Rev. Lett., 51, 959.
- WATARI T. et al. (1987) Plasma Phys. Contr. Fusion, IAEA Vienna, Vol. 1, p. 495.
- WILSON J.R. (1985) Course on Applications of RF Waves to Tokamak Plasmas, Vol. I, p. 146.

FIGURES

- Fig.1 TFTR plasma cross-section.
- Fig.2 Z_{metals} versus density for shots with ICRF power applied.
- Fig.3 (a) PHA spectrum for 11 shots with 28-30 MW of neutral beam power in a standard TFTR plasma. (b) PHA spectrum for a large TFTR plasma with $P_{rf} \approx 1.8$ MW and antenna driven in-phase. (c) PHA spectrum with $P_{rf} = 2.8$ MW and antenna driven out-of-phase.
- Fig.4 (a) Z_{titanium} versus P_{rf} for helium plasmas. (b) Z_{metals} versus P_{rf} for helium plasmas.
- Fig.5 Z_{metals} and Z_{titanium} versus toroidal field for $P_{rf} \approx 1.6$ MW.
- Fig.6 Incremental stored energy versus P_{rf} .
- Fig.7 Z_{titanium} versus $P_{rf} + P_{\text{beams}}$.
- Fig.8 Radiated power fraction versus P_{rf} .

Fig. 1

Fig. 2

#89X0377

#89X0379

Fig. 3(c)

#89X0380

Fig. 4(a)

Fig. 4(b)

Fig. 5

#89X0378

Fig. 6

Fig. 7

Fig. 8

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Plasma Research Lab., Australian Nat. Univ., AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. M. Heindler, Institut für Theoretische Physik, AUSTRIA
 M. Goossens, Astronomisch Instituut, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Commission-European, Dg-XII Fusion Prog, BELGIUM
 Prof. R. Boucique, Rijksuniversiteit Gent, BELGIUM
 Dr. P.H. Sekanaka, Instituto Fisica, BRAZIL
 Instituto De Pesquisas Espaciais-INPE, BRAZIL
 Documents Office, Atomic Energy of Canada Limited, CANADA
 Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
 Dr. M.M. Skarsgard, University of Saskatchewan, CANADA
 Dr. H. Bernard, University of British Columbia, CANADA
 Prof. J. Teichmann, Univ. of Montreal, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Bolton, Centre canadien de fusion magnetique, CANADA
 Dr. C.R. James, Univ. of Alberta, CANADA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 The Librarian, Rutherford Appleton Laboratory, ENGLAND
 Mrs. S.A. Hutchinson, JET Library, ENGLAND
 C. Mouttet, Lab. de Physique des Milieux Ionises, FRANCE
 J. Radet, CEN/CADARACHE - Bat 506, FRANCE
 Ms. C. Rinni, Librarian, Univ. of Ioannina, GREECE
 Dr. Tom Muat, Academy Bibliographic Ser., HONG KONG
 Preprint Library, Hungarian Academy of Sciences, HUNGARY
 Dr. B. Das Gupta, Saha Inst of Nucl. Phys., INDIA
 Dr. P. Kaw, Institute for Plasma Research, INDIA
 Dr. Philip Rosensau, Israel Inst. of Tech, ISRAEL
 Librarian, Int'l Ctr Theo Phys, ITALY
 Prof. G. Rostagni, Istituto Gas Ionizzati Del CNR, ITALY
 Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
 Dr. G. Grosso, Istituto di Fisica del Plasma, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. I. Kawakami, Atomic Energy Res. Institute, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Director, Dept. Large Tokamak Res. JAERI, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. S. Tanaka, Kyoto University, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
 S. Mori, JAERI, JAPAN
 H. Jeong, Librarian, Korea Advanced Energy Res Inst, KOREA
 Prof. O.I. Choi, The Korea Adv. Inst of Sci & Tech, KOREA
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Institute of Plasma Physics, PEOPLE'S REPUBLIC OF CHINA
 Librarian, Institute of Phys., PEOPLE'S REPUBLIC OF CHINA
 Library, Tsing Hua University, PEOPLE'S REPUBLIC OF CHINA
 Z. Li, Southwest Inst. Physics, PEOPLE'S REPUBLIC OF CHINA
 Prof. J.A.C. Cabral, Inst Superior Technico, PORTUGAL
 Dr. Octavian Petrus, AL I CUZA University, ROMANIA
 Dr. Jam de Villiers, Fusion Studies, AEC, SO AFRICA
 Prof. M.A. Heilberg, University of Natal, SO AFRICA
 C.I.E.M.A.T., Fusion Div. Library, SPAIN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Institute of Tech, SWEDEN
 Prof. Hans Wilhelmson, Chalmers Univ of Tech, SWEDEN
 Centre Phys des Plasmas, Ecole Polytech Fed, SWITZERLAND
 Bibliotheek, Fon-Inst Voor Plasma-fysica, THE NETHERLANDS
 Metin Durgut, Middle East Technical University, TURKEY
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Elishev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electrophysical Apparatus, USSR
 Prof. O.S. Padichenko, Inst. of Phys. & Tech, USSR
 Dr. L.M. Kovrizhnykh, Institute of Gen. Physics, USSR
 Nuclear Res. Establishment, Julich Ltd., W. GERMANY
 Bibliothek, Inst. Für Plasmaforschung, W. GERMANY
 Dr. K. Schindler, Ruhr-Universität Bochum, W. GERMANY
 ASDEX Reading Rm, c/o Wagner, IPP/Max-Planck, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Prof. R.K. Janav, Inst of Phys, YUGOSLAVIA