GA-A20688

DIRECT ELECTRON HEATING BY 60 MHz FAST WAVES ON DIII-D

10

NOV 1 1991

by

**C.C. PETTY, R.I. PINSKER, M.J. MAYBERRY, S.C. CHIU, M. PORKOLAB,
T.C. LUCE, R. PRATER, P.T. BONOLI, J.C.M. de HAAS,
R.A. JAMES, F.W. BAITY, R.H. GOULDING, and D.J. HOFFMAN**

OCTOBER 1991

GENERAL ATOMICS

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DIRECT ELECTRON HEATING BY 60 MHz FAST WAVES ON DIII-D

by

**C.C. PETTY, R.I. PINSKER, M.J. MAYBERRY, S.C. CHIU,
M. PORKOLAB,* T.C. LUCE, R. PRATER, P.T. BONOLI,*
J.C.M. de HAAS,† R.A. JAMES,† F.W. BAITY,‡ R.H. GOULDING,‡
and D.J. HOFFMAN‡**

**This is a preprint of a paper presented at the Ninth
Topical Conference on the Radio Frequency, August
19-21, 1991, in Charleston, South Carolina, and to
be printed in the *Proceedings*.**

**Work supported by
U.S. Department of Energy
Contract Nos. DE-AC03-89ER51114, DE-AC05-84OR21400
and DE-AC02-78ET51013**

*** Plasma Fusion Center, MIT, USA.**

† Lawrence Livermore National Laboratory, USA.

‡ Oak Ridge National Laboratory, USA.

**GENERAL ATOMICS PROJECT 3466
OCTOBER 1991**

GENERAL ATOMICS

MASTER

ab

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DIRECT ELECTRON HEATING BY 60 MHz FAST WAVES ON DIII-D*

C.C. Petty, R.I. Pinsker, M.J. Mayberry, S.C. Chiu,
T.C. Luce, R. Prater, J.C.M. de Haas,[†] R.A. James[†]
General Atomics, P.O. Box 85608, San Diego, California 92138-5608

F.W. Baity, R.H. Goulding, D.J. Hoffman
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

P.T. Bonoli, M. Porkolab
Plasma Fusion Center, MIT, Cambridge, Massachusetts 02139

ABSTRACT

Efficient direct electron heating by fast waves has been observed on the DIII-D tokamak. A four strap antenna with $(0, \pi, 0, \pi)$ phasing launched up to 1.6 MW of fast wave power with $|n_{||}| \approx 11$. This $|n_{||}|$ is suitable for strong electron interaction in ohmic target plasmas ($T_e \leq 2$ keV). Ion cyclotron absorption was minimized by keeping the hydrogen fraction low ($< 3\%$) in deuterium discharges and by operating at high ion cyclotron harmonics ($\omega = 4\Omega_H = 8\Omega_D$ at 1 T). The fast wave electron heating was weak for central electron temperatures below 1 keV, but improved substantially with increasing T_e . Although linear theory predicts a strong inverse magnetic field scaling of the first pass absorption, the measured fast-wave heating efficiency was independent of magnetic field. Multiple pass absorption of the fast waves appears to be occurring since at 2.1 T nearly 100% efficient plasma heating is observed while the calculated first pass absorption is 6% to 8%. The central electron temperature during fast wave heating also increased with magnetic field. The improved electron heating at higher magnetic fields may be due in part to a peaking of the ohmic plasma current and the ohmic electron temperature profiles. Centrally peaked power deposition profiles were measured by modulating the fast wave power at 10 Hz and observing the local electron temperature response across the plasma.

INTRODUCTION

Fast wave current drive (FWCD) is considered an attractive means of sustaining the plasma current in reactor-grade plasmas due to the potentially high current drive efficiency achievable (comparable to lower hybrid current drive) and excellent penetration of the wave power to the high temperature plasma core. In particular, using frequencies in the ICRF avoids the possibility of mode conversion between the fast and slow wave branches which characterized early FWCD experiments in the LHRF.¹ Fast wave current drive is an important part of the DIII-D long range goal of demonstrating full non-inductive current drive in a high beta plasma with good confinement. The DIII-D facility provides an excellent opportunity to test the feasibility of the low frequency FWCD approach due to its complementary high power ECRH program and high beta capability.

The direct electron absorption of fast waves for the resonance condition

$$\omega - k_{||}v_{||} = 0 \quad (1)$$

is due to electron Landau damping (ELD) and transit-time magnetic pumping (TTMP). For

Fig. 1. Antenna spectrum including plasma effects for $(0, \pi, 0, \pi)$ phasing.

* Work supported by the U.S. Department of Energy under Contract Nos. DE-AC03-89ER51114, DE-AC05-84OR21400, and DE-AC02-78ET51013.

[†] Lawrence Livermore National Laboratory, Livermore, California 94550

a Maxwellian electron distribution, the e-folding damping length at low frequencies is given by²

$$\lambda_e^{-1} = k_{\perp n_e} \frac{\sqrt{\pi}}{2} \beta_e \xi_e e^{-\xi_e^2} \left(1 + \frac{1}{\alpha^2}\right) \quad (2)$$

where $k_{\perp n_e} \approx \omega/v_A$, $v_A = c\omega_{ci}/\omega_{pi}$, $\beta_e = 2\mu_0 n_e T_e/B^2$, $\xi_e = \omega/k_{\parallel} v_{te}$, $v_{te} = (2T_e/m_e)^{1/2}$, and α is a complicated function with $\alpha^{-2} < 1$ for typical DIII-D parameters. The fast wave absorption is maximized when $\xi_e \approx 1$, which corresponds to a parallel index of refraction of

$$n_{\parallel} = \frac{ck_{\parallel}}{\omega} \approx \sqrt{\frac{256}{T_e [\text{keV}]}} \quad (3)$$

The fast wave absorption also decreases rapidly with increasing magnetic field since $\lambda_e^{-1} \propto B^{-3}$. Since it is important to maximize the direct electron absorption for FWCD, the initial 60 MHz fast wave experiments on DIII-D reported here were aimed at characterizing the direct electron heating as ξ_e and B were varied. In order to avoid the additional complications and constraints imposed by current drive, the heating of ohmic target plasmas with a symmetric antenna phasing was studied.

EXPERIMENTAL SETUP

The direct electron heating experiments were conducted using the DIII-D FWCD antenna.³ This is a four element phased antenna array which was designed to allow a highly directional spectrum to be coupled to the plasma for non-inductive current drive experiments. The current straps are 45 cm high and 11 cm wide, and are spaced 22.3 cm apart (center-to-center). The four current straps are separated by septa which are slotted to adjust the mutual coupling between antenna elements.

The FWCD antenna array is fed by a single 2 MW 30–60 MHz transmitter. The transmitter output is divided by a 90° hybrid power splitter into two 50 Ω feed lines, each of which has a tuning network consisting of a stub and phase shifter. Each 50 Ω line terminates in an unmatched tee voltage splitter which is part of a 25 Ω resonant loop section that feeds either the even or odd numbered current straps in the antenna array. Each leg of the 25 Ω resonant loop section has a length of $5\lambda/4$, therefore the two antenna elements connected to either end of the resonant loop have their currents in phase. An additional phase shifter placed between the 90° hybrid power splitter and one of the stub tuners controls the relative phase between the resonant loops, which allows either (0,0,0,0) or

Fig. 2. Time history of 60 MHz fast wave heating ($I_0 = 1$ MA, $B_T = 2.0$ T, $\bar{n} = 2 \times 10^{13} \text{ cm}^{-3}$).

Fig. 3. Electron heating effectiveness for various target electron temperatures ($I_p = 0.5$ MA, $B_T = 1.39$ T).

$(0, \pi, 0, \pi)$ phasing to be chosen. As shown in Fig. 1, for $(0, \pi, 0, \pi)$ phasing the launched parallel index of refraction is $|n_{\parallel}| \approx 11$, which is optimal for electron temperatures between 1 keV and 2 keV. Therefore this phasing is suitable for heating ohmic plasmas on DIII-D. Ray tracing calculations for this phasing show good wave penetration to the core plasma.⁴

EXPERIMENTAL RESULTS

The direct electron heating experiments on DIII-D were done in a double-null divertor (DND) configuration with the vessel walls covered with a boron/carbon coating. The hydrogen fraction in these deuterium discharges was measured by edge spectroscopy to be less than 3%. The time history of the electron and ion temperatures, plasma stored energy, and total radiated power is shown in Fig. 2 for a $B_T = 2.0$ T plasma with two pulses of 60 MHz fast wave heating. Efficient plasma heating is seen from the increase in the plasma stored energy and the central electron temperature (determined from ECE). The ion temperature determined from the D-D fusion neutron rate also shows an increase which probably results from equilibration with the hotter electrons due to a density rise (not shown) during fast wave heating. The ohmic power decreases during fast wave heating and the radiated power fraction, not including power radiated outside the separatrix, is 25%.

Since there is a second harmonic hydrogen resonance near the center of the plasma for $B_T = 2$ T, there may be some parasitic ion cyclotron absorption competing with the direct electron absorption. However, since the hydrogen fraction is kept low ($< 3\%$), full wave code calculations show that the direct electron damping is typically 4 to 5 times stronger than the second harmonic hydrogen damping.⁴ In addition, no dependence of the plasma stored energy on the second harmonic resonance location is observed during B_T scans (see below). Also the ion temperature rise measured from the D-D fusion neutron counters is slower than the electron temperature rise time measured by ECE. Finally there is no evidence of a large perpendicular fast ion content from the diamagnetic loop measurements. Although a mass-resolving charge-exchange (CX) analyzer did not observe a perpendicular hydrogen tail during these experiments, this result is somewhat inconclusive since the CX analyzer has a low sensitivity and therefore the small neutral particle signal coming from the $\approx 2\%$ hydrogen fraction tends to be masked by deuterium spillover onto the hydrogen collectors. (For strong second harmonic hydrogen heating experiments on DIII-D using a 50% hydrogen-50% deuterium mixture, a significant perpendicular hydrogen tail was observed by the CX analyzer.⁵)

A target temperature threshold for efficient central electron heating by the fast waves was observed. The ohmic electron temperature was scanned by varying the plasma

Fig. 4. Fraction of absorbed fast wave power (open circles) for a magnetic field scan for high-aspect-ratio plasmas, and calculated first pass absorption (filled circles) for these same discharges ($I_p = 0.3$ MA, $\bar{n} = 2.5 \times 10^{13} \text{ cm}^{-3}$).

Fig. 5. Fraction of absorbed fast wave power for a magnetic field scan for standard size plasmas ($I_p = 0.5$ MA, $\bar{n} = 1.5 \times 10^{13} \text{ cm}^{-3}$).

density from $1.1 \times 10^{13} \text{ cm}^{-3}$ to $1.9 \times 10^{13} \text{ cm}^{-3}$. The toroidal magnetic field was 1.4 T for this experiment, which placed the third hydrogen harmonic resonance near the plasma center. As shown in Fig. 3, the electron heating effectiveness, defined as

$$\eta_e = \frac{\Delta T_e n_e V}{P_{FW}} \quad (4)$$

where V is the plasma volume, increased substantially as the target electron temperature increased above 1 keV. This threshold corresponds to a ratio of the (toroidally downshifted) wave parallel phase velocity to the electron thermal velocity of $\xi_e \approx 1$.

The magnetic field scaling of Eq. (2) was tested by scanning the toroidal magnetic field at constant plasma current and density from 0.9 T to 2.1 T. The fraction of absorbed fast wave power is calculated from

$$\eta = \frac{(W_{tot}/P_{tot})}{\tau_E} \quad (5)$$

The energy confinement time is assumed to be given by the ITER-89 linear offset scaling relation developed for the ITER design:⁶

$$\tau_E = 0.064 I^{0.8} R^{1.6} a^{0.6} n^{0.6} B^{0.35} (A\kappa)^{0.2} / P + 0.04 I^{0.5} R^{0.3} a^{0.8} A^{0.5} \kappa^{0.6} \quad (6)$$

where τ_E is the confinement time in sec, I is the plasma current in MA, R and a are the major and minor radii in m, n is the electron density in 10^{20} m^{-3} , B is the toroidal magnetic field in T, A is the atomic mass number, κ is the elongation, and P is the total power in MW. The ITER scaling relations agree with ECRH⁷ as well as NBI L-mode shots on DIII-D. In addition, fundamental hydrogen minority heating shots on DIII-D at 32 MHz have energy confinement times which are also in reasonable agreement with the ITER scaling relations.⁵

The fraction of absorbed fast wave power for a magnetic field scan is shown in Fig. 4 for high-aspect-ratio plasmas. These plasmas have a major radius of 1.89 m, compared to a more typical distance of 1.78 m, so that central Thomson scattering data could be collected (Thomson scattering views along a vertical chord at $R = 1.34 \text{ m}$). The first pass absorption calculated from a slab model⁸ for these same discharges is also shown in Fig. 4 for comparison. Although the first pass absorption decreases from about 25% to 5% as the toroidal magnetic field is varied from 0.9 T to 2.1 T, the absorbed power fraction is independent of B_T and has a value of $\eta = 0.84 \pm 0.13$. Therefore the direct electron heating by fast waves is efficient even for discharges where the first pass absorption is weak. The absorbed power fraction was also measured for standard size DND plasmas on DIII-D. As shown in Fig. 5, a toroidal magnetic field scan from 1.0 T to 2.0 T found that the fast wave heating efficiency was $\approx 100\%$ for all B_T . These results indicate that multiple pass absorption of the fast waves may be occurring.

The direct electron heating by the fast waves is very centrally peaked. As shown in Fig. 6 for a high-aspect-ratio plasma with

Fig. 6. Electron temperature profile from Thomson scattering for 0.9 MW of fast wave heating ($I_p = 0.3 \text{ MA}$, $B_T = 2.0 \text{ T}$, $\bar{n} = 2.5 \times 10^{13} \text{ cm}^{-3}$).

Fig. 7. Electron heating effectiveness for a magnetic field scan for high-aspect-ratio plasmas ($I_p = 0.3 \text{ MA}$, $\bar{n} = 2.5 \times 10^{13} \text{ cm}^{-3}$).

$B_T = 2.1$ T, the central electron temperature measured by Thomson scattering increased from 1.1 keV to 2.5 keV with the addition of 0.9 MW of fast wave heating. Efficient central electron heating was not observed under all conditions, however. The electron heating effectiveness (defined in Eq. (4) for the high-aspect-ratio plasmas increased with increasing magnetic field, as shown in Fig. 7. Although the total plasma stored energy has no B_T dependence (outside the weak ITER B_T scaling), the central electron temperature increased strongly with B_T . The improved central heating at higher magnetic fields may be due in part to a peaking of the ohmic plasma current and the ohmic electron temperature profiles since the B_T scan was performed at a fixed plasma current. As shown in Fig. 8, the normalized plasma internal inductance and the central electron temperature for the ohmic target plasma increased with the magnetic field. As seen earlier in Fig. 3, the electron heating effectiveness substantially increased for T_e above 1 keV. This value was achieved in the high-aspect-ratio ohmic plasmas only at the highest toroidal magnetic fields. In addition, the decreased sawtooth mixing radius and the improvement in τ_E with increasing B_T also probably contributed to the increased electron heating effectiveness at the higher magnetic fields.

The fast wave absorption profile was measured directly by modulating the rf power at 10 Hz. Similar experiments have previously been done on JFT-2M, where the fast wave absorption characteristics and the electron thermal diffusivity were studied [9]. The time history for a 100% amplitude modulation shot on DIII-D is shown in Fig. 9. By observing the local electron temperature response (using ECE) across the plasma while the fast wave power was modulated,¹⁰ centrally peaked power deposition profiles were measured, as shown in Fig. 10. The power deposition profiles measured using 50% and 100% amplitude modulation are nearly identical. The measured absorption profile shape is consistent with the deposition profile calculated from a full wave code.⁴ There was no phase shift of the modulated ECE signals across the plasma, indicating that the power was being absorbed simultaneously across the deposition profile. Also shown in Fig. 10 is the power absorption profile for (0,0,0,0) phasing. As expected, this low $|n_{||}|$ phasing is found to heat very poorly compared to (0, π ,0, π) phasing since for this phasing $\xi_e \gg 1$.

CONCLUSIONS

Highly efficient direct electron heating with 60 MHz fast waves has been observed on the DIII-D tokamak. A centrally peaked absorption profile was measured by modulating the fast wave power and observing the local electron temperature response across the plasma with ECE. The electron heating effectiveness of the fast waves increased with increasing target electron temperature, and a threshold for good central electron heating of $\omega/k_{||} \approx v_{te}$ was observed during density and B_T scans. Nearly 100% absorption was measured for all magnetic fields, indicating that multiple pass absorption may be occurring. (However, for FWCD the first pass

Fig. 8. (a) Normalized plasma internal inductance and (b) central electron temperature of the ohmic plasma for a magnetic field scan ($I_p = 0.3$ MA, $\bar{n} = 2.5 \times 10^{13} \text{ cm}^{-3}$).

absorption should still be maximized since the wave directionality and $n_{||}$ spectrum may change substantially over many passes.)

The efficient direct electron heating observed on DIII-D points to an alternative method of plasma heating by fast waves. The amount of power coupled to the electrons by this method is not restricted by the fast ion energetics as it is for ICRH,¹¹ and it has a favorable temperature and density scaling. In addition, since the absorption is nonresonant, direct electron heating may work better than ICRH in stellarators because the absorption is always peaked in the plasma center (that is, at highest temperature), whereas for ICRH the resonant layer moves in and out of the plasma center as the wave propagates around the torus.

REFERENCES

- ¹ R.I. Pinsky, "Fast Wave Current Drive Experiments on the Princeton Large Torus," Ph.D. dissertation, Princeton University, 1988.
- ² M. Porkolab, these proceedings.
- ³ R.H. Goulding, these proceedings.
- ⁴ P.T. Bonoli and M. Porkolab, these proceedings.
- ⁵ C.C. Petty, *et al.*, "Fundamental and Second Harmonic Hydrogen Heating on DIII-D," these proceedings.
- ⁶ ITER Team, "ITER Conceptual Design — Interim Report," IAEA, Vienna (1989).
- ⁷ T.C. Luce, *et al.*, in the Proceedings of the Thirteenth Conference on Plasma Physics and Controlled Nuclear Fusion, Washington, DC, October 1–6, 1990, (IAEA, Vienna), Vol. 2.
- ⁸ S.C. Chiu, V.S. Chan, R.W. Harvey, M. Porkolab, Nucl. Fusion **29**, 2175 (1989).
- ⁹ Y. Uesugi, *et al.*, Nucl. Fusion **30**, 831 (1990).
- ¹⁰ J.C.M. de Haas, T.C. Luce, C.C. Petty, W.M. Meyer, "ECH Modulation Experiments at DIII-D," submitted to Phys. Fluids B.
- ¹¹ J.G. Cordey, *et al.*, in Proceedings of the Eighteenth European Conference on Controlled Fusion and Plasma Heating, (Berlin, 1991), Vol. 15C, Part III, p. 385.

Fig. 9. Time history for a 100% amplitude modulation shot ($I_p = 1$ MA, $B_T = 2.0$ T, $\bar{n} = 2 \times 10^{13}$ cm⁻³).

Fig. 10. Fast wave absorption profiles determined from modulation experiments for $(0, \pi, 0, \pi)$ and $(0, 0, 0, 0)$ phasings ($I_p = 1$ MA, $B_T = 2.0$ T, $\bar{n} = 2 \times 10^{13}$ cm⁻³).

END

**DATE
FILMED**

12/11/91