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Synergy in Two-Frequency Fast Wave Cyclotron Harmonic Absorption in DIII-D

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Abstract. Fast waves (FWs) at 60 MHz and at 90 MHz are coupled to DIII-D discharges for central heating and current drive at net FW power up to 3.5 MW. The primary absorption mechanism is intended to be direct electron damping in the plasma core. In discharges at B = 2 T with fast deuteron populations from neutral beam injection, 4th and 6th deuterium cyclotron harmonic absorption on the fast ions competes with direct electron damping. Previous experiments have shown that the $6\Omega_D$ absorption of the 90 MHz FWs is weaker than the $4\Omega_D$ absorption of 60 MHz FWs, in agreement with a model that includes unspecified edge losses. Recent experiments have shown that if the fast deuterons are accelerated by absorption of 60 MHz ($4\Omega_D$) FWs, adding 90 MHz power ($6\Omega_D$) can increase the fusion neutron rate by a larger increment than is obtained with 90 MHz power alone. Details of this synergy between $4\Omega_D$ and $6\Omega_D$ absorption are presented.

Keywords: Ion cyclotron heating, high harmonics
PACS: 52.50.Qt, 52.35.Hr, 52.40.Db

INTRODUCTION

Applications of fast Alfvén waves (FWs) in the ion cyclotron range of frequencies (ICRF) for heating and current drive in burning plasma devices will require a quantitative understanding of absorption of the waves on fast ions, either from injection of energetic ions from neutral beams or from fusion products (alphas). Previous experimental work on this topic on DIII-D [1–3] has focused on damping of the FWs on injected deuterium beams at the 4th–8th harmonics, with FW power at 60, 83, 90, and 116 MHz. Strong damping of 60 MHz FWs at $\omega = 4\Omega_D$ and in separate cases at $\omega = 5\Omega_D$ has been observed by substantial increases in D-D beam-target fusion rates and more directly with the fast-ion D_α diagnostic [4]. Only relatively weak beam-ion absorption of FWs at higher frequency and higher harmonic numbers has been observed to date; although the expected single-pass absorption is lower at higher harmonics (at a fixed static magnetic field), it is not obvious why the global absorption efficiency should be a strong function of the single-pass absorption. Previous DIII-D results on FW heating and current drive by direct electron absorption in L-mode [5,6] and H-mode [7] indicated the importance of an edge loss on the order of a few percent per bounce to explain the dependence of the core heating and current drive efficiencies on the single-pass core absorption. A similar edge loss must be present in these cases, where core damping mechanisms include cyclotron harmonic damping on energetic ions in addition to the direct electron damping studied in the previous work. Since the single-pass absorption in the core due to ion cyclotron harmonic damping decreases with increasing harmonic number, an edge loss that is independent of frequency will result in a decreasing fraction of core absorption as the harmonic number increases at fixed field.

For the parameters of the DIII-D experiments, the moderate-to-high ion cyclotron harmonic damping is strongest on the highest energy part of the fast-ion distribution function [3]; therefore one expects strong quasilinear effects on the damping if the FW power is comparable to the injected beam power. To the extent that the fast ion population at energies above the injection energy is enhanced by the absorption of the FW, the damping at high harmonics should increase. Therefore the possibility of a "synergy" between 4th and 6th harmonic damping exists, in which the 4th harmonic absorption pulls out a tail in the fast ion distribution which then allows a much stronger damping at the 6th harmonic than would be obtained if the 4th and 6th harmonic FWs were applied separately.

EXPERIMENT

The previously described [8] three sets of four-element phased-array antennas, transmission lines and transmitters were used for this experiment. The 285/300 antenna (labeled by the toroidal angle in the DIII-D vacuum vessel where it is located) was used to couple 60 MHz ($\omega = 4\Omega_D$) FWs at ~1 MW power levels to the L-mode discharges studied here; the 0 deg and 180 deg antennas were used at 90 MHz ($\omega = 6\Omega_D$) at similar power levels per antenna. The injected deuterium neutral beam power was 2.7 MW at an energy of 81 keV, except for periodic short pulses of an additional beam to improve the quality of the equilibrium reconstruction constrained by motional Stark effect data. Comparison of separate pulses of 1.1 MW of 60 MHz FW power with 1.5 MW of 90 MHz was performed in a 1.1 MA L-mode discharge at a line-averaged target density of $2.2\times10^{19}\ \mathrm{m}^{-3}$, with the results shown in the left panel of Fig. 1. Fourth harmonic heating (60 MHz, 2 T) of the injected beam ions results in a clear enhancement of the beam-target neutron rate, and the observed neutron rate is compared with the predictions from TRANSP not including any fast-ion acceleration in the model (but including all of the measured time-dependent radial profiles of all of the factors that enter into the neutron rate) in the lower plot. The 90 MHz ($6\Omega_D$) power level (40% higher power than the 60 MHz pulse) produces only a small neutron enhancement over the "classical" rate — about one-third as large as the 4th harmonic power does. This is presumably due to the weaker absorption of the FW power at the 6th harmonic relative to the edge losses. When, as shown in the right panel of Fig. 1, the 90 MHz power is added to the 60 MHz power, after allowing 0.4 s for the fast ion distribution under 4th harmonic heating to reach a stationary state, the increment in neutron rate is about twice as large as the sum of the individual increments when the two pulses are separated in time.

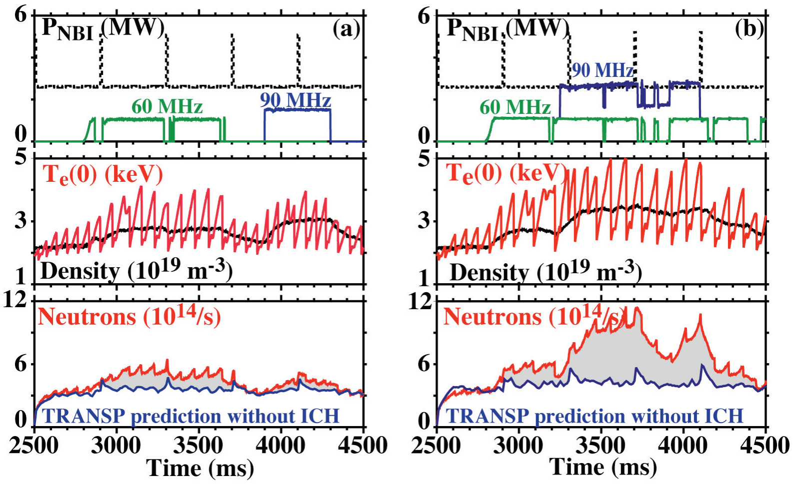

FIGURE 1. A strong "synergy" is observed in the combination of 4th and 6th harmonic heating at 2 T toroidal field. The discharge shown in (a) has separate pulses of 60 MHz and 90 MHz, while the case in (b) has a period of combined 60 MHz + 90 MHz power after preheating with 60 MHz alone.

A synergy is also observed in the global confinement, as is illustrated in Fig. 2. The measured plasma stored energy from the equilibrium reconstructions (solid curves in the upper panels) is compared with two predictions. The dashed curves show the predicted stored energy assuming square-root degradation of confinement time with total power, as in the ITER-89P scaling law, while the dotted lines show what the predicted stored energy would be in the absence of degradation of confinement with FW power. In the case with separate pulses, it is apparent that the global confinement of the 60 MHz power is somewhat better than the scaling law predicts, while the 90 MHz confinement is in good agreement with the scaling law. This is thought to arise from the better energy confinement in plasmas with large fast ion fractions and the denser high-energy ion tail produced by the stronger 4th harmonic absorption compared with the 6th harmonic absorption. In the combined case, the improvement in global energy confinement with respect to the scaling law prediction is larger than in the 4th harmonic alone case, again presumably due to the additional enhancement of the high-energy ion tail from the combined two-frequency heating compared with that due to 4th harmonic alone.

In another experiment, the neutral beams were modulated (10 ms on/10 ms off) and the neutron rate decay rates (during the beam-off intervals) were measured before, during the 60 MHz FW alone, and during the combined 60 MHz and 90 MHz FW heating. The decay rates were compared with those calculated by TRANSP not including any fast-ion acceleration, but including measured time-dependent radial profiles of electron and ion temperatures, density, carbon impurity, and toroidal rotation. The TRANSP prediction of the decay time constant is about 0.017 s, not changing much during the FW period. The 60 MHz FW increases the decay time constant to about 0.023 s, while the addition of 90 MHz FW causes the measured time constant to rise slowly to about 0.033 s over a 0.3-s period of combined 4th and 6th harmonic heating. The long time scale over which the neutron synergy develops is consistent with a small fraction of the injected 81 keV ions being accelerated to energies over 100 keV (towards the peak in the D-D fusion cross-section).

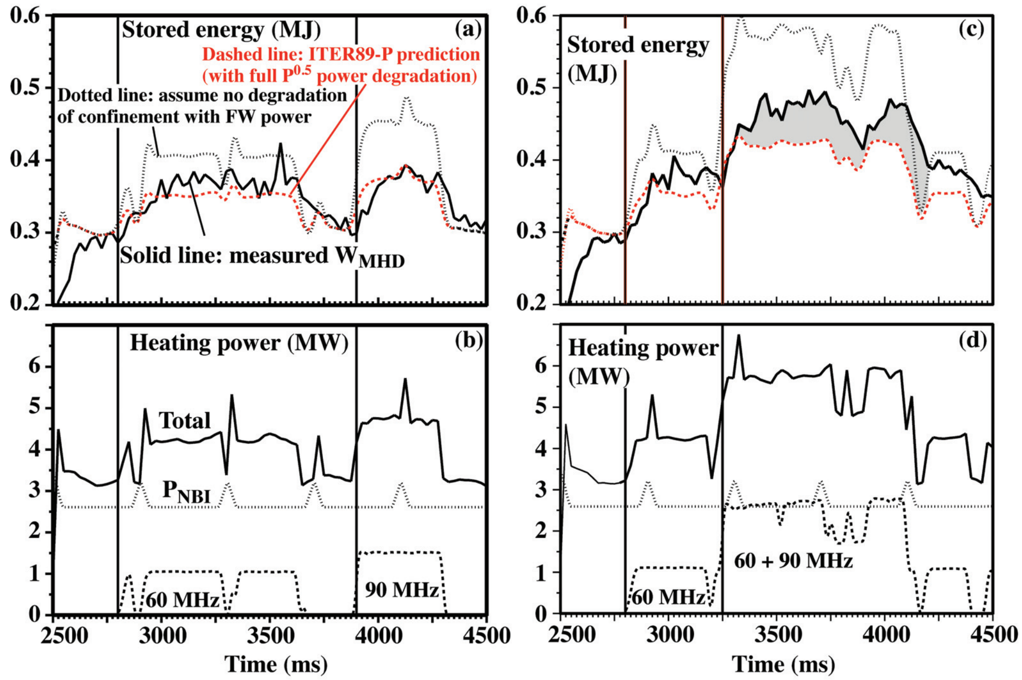

FIGURE 2. Synergy is observed in the global heating efficiency in the same pair of discharges as shown in Fig. 1. In the upper panels, the solid lines show the measured stored energy and the dashed lines show the stored energy predicted from the ITER-89P scaling law with the full square-root-power degradation. The dotted curves show what the stored energy would be if it were assumed that the FW power did not degrade the confinement time at all.

CONCLUSION

Clear evidence of a synergy between 4th and 6th harmonic absorption of FWs on injected 81 keV deuterium neutral beams is observed in DIII-D experiments. Extension of these experiments to a wider range of plasma parameters is ongoing.

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REFERENCES

1. C.C. Petty, *et al.,* in *Radio Frequency Power in Plasmas (Proc. 12th Top. Conf., Savannah, GA, 1997)* (AIP, New York, 1997) p. 225.
2. W.W. Heidbrink, *et al.,* Nucl. Fusion **39**, 1369 (1999).
3. R.I. Pinsker, *et al.,* Nucl. Fusion **46**, S416 (2006).
4. W.W. Heidbrink, *et al.,* Nucl. Fusion **49**, 1457 (2007).
5. R.I. Pinsker, *et al.,* in *Plasma Physics and Controlled Nuclear Fusion Research 1992 (Proc. 14th Int. Conf., Wuerzberg, 1992)* (IAEA, Vienna, 1993) Vol. I, p. 683.
6. C.C. Petty, *et al.,* Phys. Rev. Lett. **69**, 289 (1992).
7. C.C. Petty, *et al.,* Nucl. Fusion **39**, 1421 (1999).
8. R.I. Pinsker, Fusion Sci. and Technol. **48**, 1238 (2005).