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GENERAL ATOMICS

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Abstract. Fast Waves (FWs) at 60 MHz and 90 MHz are used in DIII-D for central electron heating and current drive. Coupling of FWs to high-performance discharges is limited by low antenna loading in these regimes. To extend the application of high-power FWs to such regimes, methods of increasing the antenna loading in these regimes are needed. A systematic study of loading enhancement techniques has been carried out in DIII-D, including reduction of the antenna/plasma distance, gas puffing into the far scrape-off layer (SOL), and control of other parameters that affect the particle balance in the far SOL. Quantitative understanding of the physics of the loading resistance and its dependence on edge density profiles is demonstrated. The core FW heating efficiency appeared to be ~100% in the Advanced Inductive regime, consistent with the high first-pass direct electron absorption of ~75% that is predicted by the ray-tracing code GENRAY in this high electron beta regime.

INTRODUCTION

Compressional Alfven waves, referred to here as Fast Waves (FWs), at 60 MHz and 90 MHz are used in DIII-D for central electron heating and current drive. The FW system is used to complement the Electron Cyclotron (EC) system [1] to study high-performance tokamak regimes with dominant electron heating, which is relevant to any D-T burning plasma such as ITER or DEMO. Coupling of FWs to high-performance discharges is limited by low antenna loading in these regimes. The goal of the work reported here is to determine the mechanisms responsible for limiting the FW power level that can be coupled to DIII-D plasmas in the relevant regimes with the existing system, and thereby to ascertain what upgrades would be possible to increase the coupled power level.

APPLICATION OF FAST WAVES TO
ADVANCED INDUCTIVE DISCHARGES

To develop the application of FWs to advanced operating regimes, the Advanced Inductive (AI) regime [2] ($\beta_N \geq 2.4$, $H(98y,2) \geq 1$) was chosen as the first target. In order to separate the effects of incremental electron heating on confinement from possible inefficiency of coupling power to the core plasma, the added FW power was compared with an equal increment of electron cyclotron heating (ECH) power in the same discharge, as illustrated in Fig. 1. The neutral beam power is feedback controlled to maintain a constant normalized $\beta_N = 2.7$, which results in a nearly constant P_{NB} of 7.6 MW. A constant 1.6 MW level of 110 GHz ECH power is applied throughout, except for the period between 4.8-5.3 s, where the EC power is increased to 3.2 MW for comparison with the earlier period with 1.5 MW of FW power. For the 1.9 T toroidal field of this discharge, the EC power is deposited inboard of the magnetic axis, at a normalized minor radius of $\rho = 0.25 \pm 0.04$, while the deposition of FW power via direct electron damping is expected to be more central. In the absence of any effect on confinement from the addition of 1.5 MW of electron heating to a background of 9.4 MW of neutral beam and EC power, that increment in heating power would be expected to increase the stored energy by ~6% or less, which is comparable to the noise level in the total stored energy measurement in this edge localized moding (ELMing) discharge. The changes in electron and ion thermal stored energy in the plasma core can be observed in the central profiles of electron and ion temperature and electron density, and it is found that both forms of electron heating increase $T_e(0)$ and decrease $T_i(0)$, the latter presumably through an effect on local diffusivity that depends on the ratio T_e/T_i. Absorption of a fraction of the FW power on the fast deuterons at $(4-6)\Omega_D$ [3] causes a small but distinct increase in the D-D neutron rate, while none of the EC power is deposited on ions. The amount of central electron heating is somewhat larger for the 1.5 MW FW than for the 1.6 MW EC power, due to more central deposition; the similar effects of the FW power and the EC power, which is certainly 100% absorbed on first pass, plus the additional absorption of the FW on the beam ions, indicate that there cannot be a large fraction of the FW power lost at the plasma edge. The efficient core absorption of the FW power in this regime demonstrates the usefulness of the FW system for providing core electron heating to high-β ELMing H-mode discharges. This in turn motivates an investigation of the factors that determine the amount of power that can be coupled to these discharges with the existing DIII-D FW system, which consists of three 4-element antenna arrays and three 2-MW transmitters.

Ray-tracing studies with the GENRAY code using the measured profiles from the discharge shown in Fig. 1 have shown that the predicted first-pass absorption by direct electron damping of 90 MHz FWs is approximately 75%, which appears at first to be difficult to reconcile with the peak launched $n_\parallel \sim 4$ and the central electron temperature of ~ 8 keV. Detailed study of the ray-tracing results shows that the $n_\parallel$ upshift is much larger than would be expected solely from the $n_\parallel R$=constant effect, with the $n_\parallel$ reaching values of 9 as the ray makes its closest approach to the magnetic axis. This beneficial effect arises from the whistler-like propagation of the 90 MHz FWs [3], with the angle between the group velocity vector and the static magnetic field limited to <19.5 degrees. The resulting strong first-pass core absorption means that typical edge losses of a few percent per bounce will not be able to compete with core absorption, and the overall absorption in the core (multi-pass) will be nearly 100%.
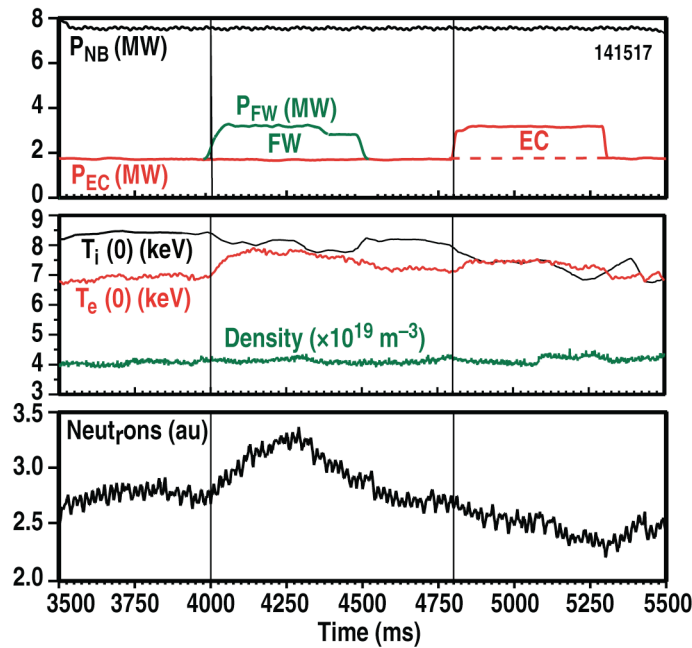

FIGURE 1. Comparison of 1.5 MW of FW power with an equal level of incremental 110 GHz EC power in an AI discharge. I_p= 1.25 MA, B_T=1.9 T.

LOADING ENHANCEMENT METHODS

Having established that FW direct electron heating is roughly as efficient as an equal amount of EC power in the AI regime at the 1.5 MW level, we would like to couple a greater fraction of the available source power (~ 4.5 MW or more at DIII-D) to these discharges. The coupled power P_c scales as $P_c \sim I_{max}^2 R_L \sim \left(V_{max}/Z_0\right)^2 R_L$, where I_{max} is the peak antenna current, V_{max} is the maximum voltage in the antenna feedline that can be sustained without unacceptably high probability of high-voltage breakdown in the

antenna and feed system, Z_0 is the characteristic impedance of the feedline, and R_L is the series resonant load resistance. For a given antenna and feeding system, the factor V_{max}/Z_0 is fixed, so the only way to increase P_c without improving the antennas or the conditioning procedures is to increase the antenna loading R_L. This key parameter is determined by the plasma parameters in the antenna near-field region, most importantly by the edge density profile [4,5]. Unfortunately for potential R_L control techniques that would modify the edge density profile to increase R_L, global confinement is also strongly affected by the edge density profile. A hypothetical method of increasing the antenna loading by, for example, 50% that causes a 25% drop in the energy confinement time would not lead to an overall increase in stored energy if the FW power was 15-30% of the total heating power. Therefore, the goal becomes finding techniques to enhance antenna loading with acceptable effects on confinement.

The most straightforward method of increasing RL is to reduce the radial distance over which the FW is evanescent by moving the edge plasma closer to the antenna surface, i.e. reducing the 'outer gap'. Attempts to do this in advanced tokamak regimes in 2003-2004 showed that in these neutral-beam-dominated regimes, an outer gap of less than 6 cm led to unacceptable overheating of first-wall components in less than 1 s , in particular the three discrete graphite backup poloidal limiters. In 2009, the graphite tiles of which these limiters are constructed were replaced with carbon-fiber-composite tiles that have higher thermal conductivity to the cooled vacuum vessel surface and can tolerate higher temperatures. These improved limiter tiles had the desired effect: discharges can now be run at neutral beam power levels of 8 MW or more at outer gaps of 4 cm or less without overheating plasma-facing components.

However, systematic studies of AI discharges in which the outer gap was reduced, either dynamically within a single discharge or shot-to-shot, in an effort to increase R_L, showed that in this regime the global confinement time was independent of the outer gap until the gap was less than 4 cm, and at smaller outer gaps, the confinement was somewhat degraded, as shown in Fig. 2. The co-current toroidal rotation speed (all co-injected neutral beams were used) dropped more significantly at small outer gaps, indicating that the degradation at small outer gaps may be due to a change in transport in the ion channel, as the density and electron temperature were not strongly affected by the reduction in gap. In order to avoid this confinement degradation, the minimum outer gap used in subsequent experiments was 4 cm.
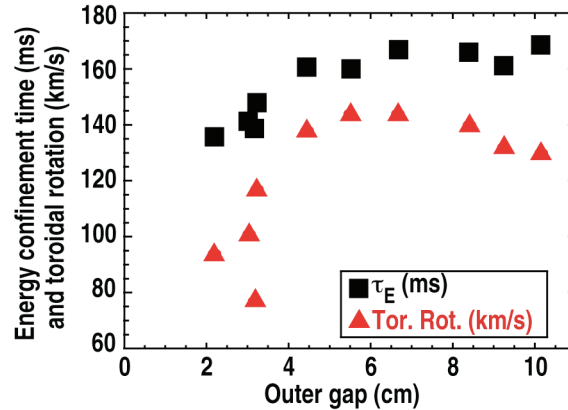
FIGURE 2. Degradation of energy confinement time (squares, in ms) and toroidal rotation speed (triangles, in km/s) in AI discharges as the outer gap is reduced below 4 cm. I_p=1.2 MA, B_T=1.3 T, P_{NBI}~5 MW, β_N=2.4.

Given this minimum useable outer gap of 4 cm, other means to modify the far scrape-off layer (SOL) density profile to increase R_L were investigated. One such technique which has been studied on JET, AUG, Tore Supra and other devices is puffing of deuterium gas from an orifice located near the active FW antenna [6,7]. Either a small fraction of the rf power goes into ionization of the gas in the antenna near-fields or the cross-field power exhaust from the plasma ionizes the gas; in either scenario the hoped-for effect is to decrease the wave evanescence by moving the right-hand cutoff layer closer to the antenna surface. A puffing orifice was installed adjacent to one corner of one of the three 4-element antenna arrays in DIII-D, such that the static magnetic field line that passes in front of the orifice inclined at an angle of 10-12 degrees from horizontal passes in front of the array. As described in detail in Ref. [7], injection of deuterium at a rate of 1×10^{22} electrons/s in an AI plasma (P_{NBI}~6 MW, β_N=2.4) yielded a strong increase in the minimum R_L between ELMs, from about 0.17 Ω up to ~1 Ω during the puffing. However, the confinement time was degraded relative to the H98(y,2) scaling by about 20% during the puffing, so that the overall effect in this strongly neutral-beam-dominated case is a net negative one.

A key question for the puffing technique is the extent to which the effect is local to the antenna nearest to the puffing location. Indications so far from the DIII-D work are that the effect appears to be primarily a global one, with the loading on the antenna remote from the puffing location also increasing by a comparable amount as on the antenna near the orifice. One counter-example has been observed, however, in which the antenna adjacent to the puffing location was excited at very low power, ~0.1 kW and two discharges compared: one with a low level of puffing and the other without any puffing. Both discharges had a dynamic scan of the outer gap in the ELMing H-mode. As illustrated in Fig. 3, the antenna near the puffing location ('285/300') shows a significant

increase in loading during the puff compared with the no-puff discharge, while the loading on the distant antenna ('0 deg') is unaffected by the puffing. In other discharges in this series, it was found that whether or not the local puffing has a strong effect on the nearby antenna's loading was a sensitive function of the separatrix geometry with respect to the cryopumps at the top and bottom of the DIII-D vessel. The geometry of the top and bottom cryopumps differ, so that it is reasonable that the pumping speed and hence balance between particle sources and exhaust depend on the details of the flux surface geometry in the neighborhood of the separatrix. Whether the local effect in this case is connected with near-field sheath dissipation becoming important at extremely low power levels [8,9] has not yet been tested by repeating this comparison at higher power.
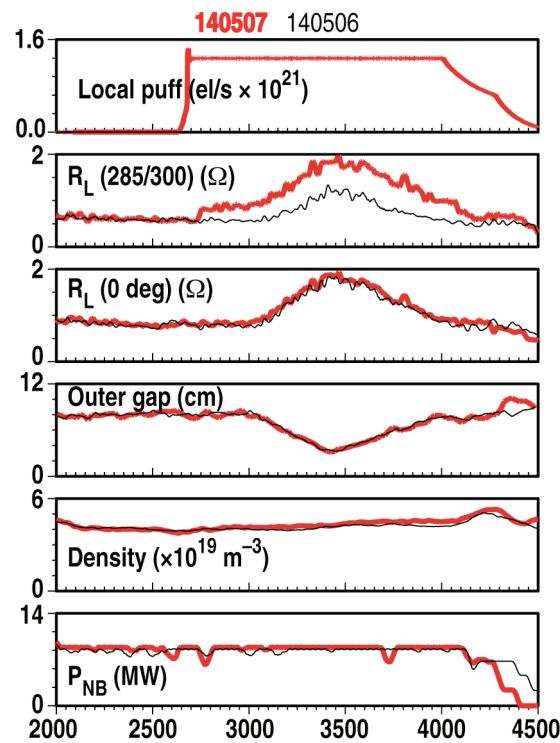

FIGURE 3. Puffing adjacent to 285/300 antenna can have a local effect, at least at extremely low FW power (~0.1 kW applied to 285/300 antenna, 50 kW applied to 0 deg antenna).

In high-power ELMing H-mode discharges, control of the pumping speed by small changes to the magnetic geometry near the separatrix can have a strong effect on the far-SOL density and therefore on RL even in the absence of puffing (either local or global). This sensitivity has been exploited to increase the minimum loading between ELMs in AI discharges without puffing. Even without puffing, there is a tendency for high far-SOL density to be correlated with some degradation in global confinement, so it is necessary to find the optimal trade-off between confinement and RL. In the best cases found so far

with acceptable global confinement (confinement factor H98(y,2)>1), the loading obtained should permit coupling of ~2.5 MW of FW power to AI discharges at values of Vmax lower than have been sustained in vacuum conditioning of the antennas ($V_{max} < 25$ kV). Ray-tracing studies in this case have shown that good first-pass absorption (65-70% on electrons) can still be expected even without EC pre-heating, as a result of the $n_{\parallel}$ upshift mentioned above.

To help reach the near-term goal of coupling more than 3 MW of FW to AI discharges, the major radius of the face of all three antenna arrays has recently been reduced by ~1 cm, while still remaining in the shadow of the protective side and top limiter tiles surrounding the arrays. The consequent reduction of the antenna/plasma gap without changing the outer gapshould yield a ~20% increase in R_L at fixed plasma parameters and shape and hence a similar increase in the coupled power at a given system voltage limit V_{max}, without affecting global confinement. Incremental improvements to the arc/ELM discrimination system may also result in a further increase in the coupled power in this challenging regime.

QUANTITATIVE MODELING OF LOADING

As part of the evaluation of the application of FW heating and current drive to advanced operating regimes in DIII-D, we are evaluating possible antenna upgrades that would permit an increase in the "antenna engineering" factors in parentheses in $P_c \sim \left(V_{max}/Z_0\right)^2 R_L$. Because of the quadratic dependence of the coupled power on these factors, even a modest improvement in that factor can increase P_c significantly. To reduce the cost and time necessary for antenna development, modern 3-D electromagnetic modeling tools are used to evaluate and refine proposed designs [10,11]. As a first step in applying these tools to DIII-D, the TOPICA code [12] is being validated by detailed comparison of its predictions for one of the existing antenna arrays to a wide range of loading measurements from DIII-D experiments.

A detailed model of the geometry of the 285/300 antenna array was constructed based on the original design drawings and verified with as-built physical measurements, and the electrical properties of the antenna in vacuum (no plasma) were predicted using CST Microwave Studio [10]. These results are being compared with network analyzer measurements of the antenna. The results to date show that in order to obtain quantitative agreement between the code predictions and the measurements it is necessary to model details of the septa between the elements in the array at high resolution. The model was then imported to TOPICA, which also was used to predict the parameters of the unloaded antenna, and those results were also compared in detail with the measurements. Very

good agreement between the electrical properties of the current straps and the measured values was achieved.

Next, the plasma profiles measured on the DIII-D discharges were imported to TOPICA. The edge density profile from the far SOL to well beyond the separatrix is crucial for accurate modeling of the loading, so special attention was paid to obtaining high-quality edge density profiles in the experiment. Two profile reflectometer systems were used: one with an antenna about 1.6 m away toroidally from the 285/300 antenna and the other about 0.1 m from one edge of the antenna. Data were obtained on a wide range of plasma regimes, including L-mode outer gap scans, ELM-free H-modes, Quiescent H-modes with a large outer gap, and ELMing H-modes with and without local puffing from the orifice located just below the reflectometer antenna. Space limitations preclude discussion of many of these results here. One example of the detailed comparison between TOPICA modeling and the experimentally measured values of loading just prior to and just after an L-H transition is shown in Fig. 4, where absolute quantitative agreement between the predicted and measured values of R_L is observed, without any adjustable parameters in the model. The agreement is especially good in the H-mode phase; to date, the trend has been that the predictions agree most closely with the experimental results at lower values of loading. The detailed comparison of the scattering parameters in vacuum (no plasma) with the model has very recently revealed an inaccuracy in the geometry of the antenna model, and ongoing work is incorporating the necessary refinement to the model to the TOPICA input. This may result in a further improvement in the agreement between model and experiment under high loading conditions, as the details of the currents in the antenna structure affect the short wavelength components of the near fields. These components affect the loading significantly only if the plasma is very near the antenna, i.e. under high loading conditions.
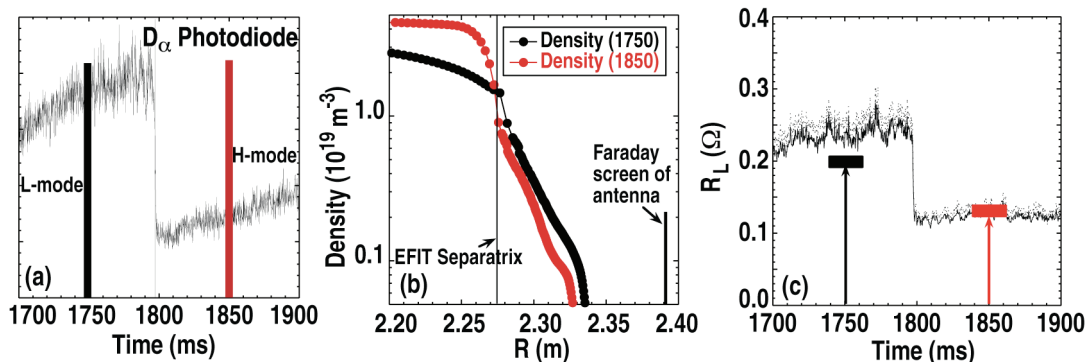

FIGURE 4. (a) D_α trace showing timeslices before and after L-H transition where antenna parameters are predicted by TOPICA. (b) Density profiles (log scale) measured with a profile reflectometer. (c) Comparison of predictions (rectangles) and measured values (time history) of R_L.

The fact that absolute agreement between the predicted and measured loading is found, without any adjustable parameters in the model, when the antenna geometry is modeled in detail and measured profiles are used indicates that the physics of the FW coupling process is well understood. This yields confidence in the application of these modeling tools to evaluate proposed antenna modifications aimed at increasing the FW power that can be coupled to DIII-D plasmas, and to quantitatively evaluate antenna designs for future devices such as ITER [13].

SUMMARY AND CONCLUSION

The DIII-D Fast Wave system has been used to apply 1.5 MW of electron heating power to the core of Advanced Inductive discharges with high β_N and good confinement. Comparison with identical levels of EC power shows that the global absorption efficiency of the FW power is excellent. To increase the level of FW power in these discharges to $\geq$3 MW, it is necessary to obtain higher levels of antenna loading R_L, and/or to improve the antenna systems. Several techniques of increasing the loading have been evaluated, taking into account the effect of those techniques on the global confinement properties of the discharge as well as their effectiveness in increasing R_L. Marginally adequate loading has been found in the best cases to permit achievement of the 3 MW goal. To further increase the power, antenna modifications are being considered, and those modifications evaluated with modern 3-D modeling tools. These tools have been validated by applying them to prediction of the existing antenna's parameters; absolute agreement without adjustable parameters gives credence to the use of the models to evaluate proposed antenna designs.

Acknowledgments

References

[1]   C.C. Petty, et al., these proceedings.

[2]   T.C. Luce, et al., Plasma Physics and Controlled Nuclear Fusion Research (Proc. 23rd Int. Conf., Daejeon, Korea, 2010), paper ITR/1-5.

[3]   R.I. Pinsker, et al., Nucl. Fusion 46, S416 (2006).

[4]   M.J. Mayberry, et al., Nucl. Fusion 30, 579 (1990).

[5]   R. Bilato, et al., Nucl. Fusion 45, L5 (2005).

[6]   M.-L. Mayoral, et al., Plasma Physics and Controlled Nuclear Fusion Research (Proc. 23rd Int. Conf., Daejeon, Korea, 2010), paper ITR/P1-11.

[7]   R.I. Pinsker, et al., paper O4.124 in 37th EPS Conference on Plasma Phys. Dublin, Ireland, 21-25 June 2010, available at http://ocs.ciemat.es/EPS2010PAP/pdf/O4.124.pdf.

[8]   D.W. Swain, R. I. Pinsker, et al., Nucl. Fusion 37, 211 (1997).

[9]   D.A. D'Ippolito and J. R. Myra, Phys. Plasmas 3, 420 (1996).

[10] P.M. Ryan, et al., in Radio Frequency Power in Plasmas (Proc. 18th Top. Conf., Gent, Belgium, 2009) (AIP, NY, 2009) 305.

[11] D. Milanesio and R. Maggiora, in Radio Frequency Power in Plasmas (Proc. 18th Top. Conf., Gent, Belgium, 2009) (AIP, NY, 2009) 233.

[12] V. Lancellotti, D. Milanesio, et al., Nucl. Fusion 46, S476 (2006).

[13] D. Milanesio and R. Maggiora, Nucl. Fusion 50, 025007 (2010).