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Lower Hybrid Counter Current Drive for Edge Current Density Modification in DIII-D*

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ABSTRACT

Each of the Advanced Tokamak operating modes in DIII-D is thought to have a distinctive current density profile. So far these modes have only been achieved transiently through experiments which ramp the plasma current and shape. Extension of these modes to steady state requires non-inductive current profile control, *e.g.* with lower hybrid current drive (LHCD). Calculations of LHCD have been done for DIII-D using the ACCOME¹ and CQL3D² codes, showing that counter driven current at the plasma edge can cancel some of the undesirable edge bootstrap current and potentially extend the VH-mode. Results will be presented for scenarios using 2.45 GHz LH waves launched from both the midplane and off-axis ports. The sensitivity of the results to injected power, n_e and T_e , and launched wave spectrum will also be shown.

INTRODUCTION

Recent experiments in DIII-D have focussed on four modes of plasma operation which have produced either enhanced confinement and/or high beta stability under transient conditions. Known as the VH-mode, the high I_i H-mode, the second stable core mode, and the high $\epsilon\beta_p$ mode, each is thought to have a distinct current density profile. In particular, large bootstrap current density at the plasma edge builds up during the VH-mode and may need to be cancelled by a non-inductive counter current drive system to extend this mode to steady state.

The existing current drive program on DIII-D, including Neutral Beam (NB) injection, Electron Cyclotron (EC) harmonic waves, and Ion Cyclotron (ICRF) Fast Waves (FW), allows the current density profile in the plasma core (near the plasma axis and out to about 2/3 of the plasma radius) to be modified. However, none of these systems has shown a high enough current drive efficiency to affect the current density profile near the plasma edge where the temperature is comparatively low.

LHCD has comparatively high efficiency in this region, the waves can be strongly damped there with proper choice of launched spectrum, and there exist simulation codes that have been benchmarked to previous experimental results. Also, the power sources and other components of the necessary LHCD system for this DIII-D application are readily available and have been proven on previous experiments at ASDEX and PLT. This paper presents ray-tracing, power absorption and counter current drive calculations for LHCD in DIII-D VH-mode-like plasmas.

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VH-MODE MODEL PLASMA

The plasma conditions assumed for the LH ray-tracing and CD calculations are those of DIII-D shot 75121 at 2540 ms. This was a double null (vertically symmetric) plasma with $B_T = 2.13$ T, $I_p = 1.63$ MA, $R_o = 1.67$ m, $a = 0.62$ m, $\kappa_x = 2.1$, $\delta_x = 0.89$, and $Z_{eff} = 2.0$. The shot progressed from L-mode to the H-mode and finally into the VH-mode at approximately 2400 ms. Analysis of the VH-mode phase has shown that the edge bootstrap current density continually increased throughout the period until it terminated at approximately 2600 ms. Plasma profiles for the fully developed VH-mode at 2540 ms are shown in Fig. 1. Also given is the profile of the bootstrap current density, showing a maximum of 0.42 A/cm² at $\rho = 0.9$. The integrated bootstrap current in the region $0.75 < \rho < 1.0$ was estimated to be 130 kA. It is not clear how much of this edge bootstrap current must be cancelled to extend the VH-mode. The objective of the LHCD calculations was to determine whether counter current could be driven in this region and to calculate the CD efficiency there.

CQL3D RESULTS

In addition to the efficiency and radial location of current drive for a given input power spectrum, an important question is whether the LH driven electron tail leads to appreciable Ohmic conductivity enhancement ("hot conductivity") which for the counter-LHCD case reduces the overall efficiency of the edge current control. The CQL3D Fokker-Planck code² is a comprehensive 2D-in-velocity-space, 1D-in-radius computational model which addresses these problems. It incorporates a LH ray tracing code, includes self-consistent damping of the energy flowing along the rays, the effects of trapping, and the toroidal electric field. Here it is used with the noncircular equilibria of the shot described above.

Fig. 2 shows current profiles obtained with CQL3D, using the experimental 0.1 V loop-voltage and 2 MW of LH power incident from the plasma periphery on the outer equatorial plane, with $N_{||}$ from 4.0 to 6.0. The net current density was substantially flattened out near the plasma edge by the LHCD. Damping in these cases is essentially single pass.

Varying $N_{||}$ from 3.5 to 7.0 (central value) gave driven rf currents from 160. to 70. kA, respectively, peaked in the range of radial ρ values from 0.75 to 0.975. The optimal situation for cancelling the bootstrap current near the plasma edge was with the $N_{||}$ spectrum from 4.0 to 6.0, which gave 100 kA rf current peaked at $\rho = 0.85$. For the values of loop voltage obtained in the experiment ($V_\phi = 0.1 - 0.2$ volts) there was no appreciable synergy between the LHCD and the toroidal electric field. That is, the Ohmic and rf currents simply added.

Again using CQL3D, a series of code runs were performed to evaluate possibilities for increasing the LHCD efficiency using combinations of two injected spectra. The higher $N_{||}$ spectrum can set the radial position of peak damping near the plasma edge, and the lower spectrum will increase the tail at that location.³ Combining one-third power in $N_{||}=3-4$ with two-thirds power in $N_{||}=4-6$ for a total of 2MW input power, gave 120 kA peaked at $\rho = 0.85$, to be compared with 100 kA for the pure $N_{||}=4-6$ spectra. Thus efficiency is increased by 20 percent. Using a half-and-half split of the power in the above two spectra, the total current was 130 kA, still peaked at $\rho = 0.85$, but the radial width of the current generation became greater than the extent of the bootstrap

hump. If the spectra do not touch each other in $N_{\parallel}$, the damping locations decouple. Thus a compound spectra (two independent antenna) capability adds flexibility to the experiment, although the useful efficiency increase is only of order 20-30 percent.

ACCOME RESULTS

The ACCOME/SELENE code package¹ calculates a self-consistent 2D free boundary plasma equilibrium and non-inductively driven currents from NB, ICRF and LH injection and bootstrap currents. The LH ray-tracing and current drive package⁴ uses a 1-D Fokker-Planck equation with an effective perpendicular temperature. Quasi-linear damping is calculated and the driven current is obtained from the adjoint formulation of Karney and Fisch.⁵

The plasma profiles are input to ACCOME in terms of normalized poloidal flux, ψ as $X(\psi) = (X_o - X_a)(1 - \psi^{\beta_x})^{\alpha_x} + X_a$ where $X = (n_e, T_e, \text{ or } T_i)$, X_o and X_a are the central and separatrix values. The VH-mode data from shot 75121 were fit with these functions using X_o, X_a, β_x , and α_x as fitting variables. The weighting function emphasized the outer data more strongly than the core so that the edge bootstrap current density calculated by ACCOME would accurately reflect the experiment.

Rays were launched from the plasma separatrix adjacent to the off axis DIII-D port above the midplane. This was done in an attempt to achieve the maximum toroidal upshift of the launched $N_{\parallel}$ spectrum as the LH wave cone propagated into the plasma. This has the desirable effect of reducing the required $N_{\parallel}$ of the spectrum launched at the antenna which simplifies the antenna design.

For the baseline calculations, the absorbed power in the plasma was $P_{lh} = 3.0$ MW, two Gaussian peaks were used in the spectrum with central refractive indices, $N_{\parallel o} = 4.5$ and 6.0 , and $1/e$ width, $\Delta N_{\parallel} = 0.33$. The counter LH current, $I_{LH} = -86$ kA, was driven in the outer region, $0.75 < \psi < 0.95$. The efficiency was, $\eta_{lh} = -0.028$ A/W.

Given the $N_{\parallel}$ upshift due to the off-midplane injection, the comparable case with CQL3D has $N_{\parallel} = 5 - 7$ and an efficiency, $\eta_{lh} = 0.038$, about 35% higher than the result above. This enhancement is likely due to both the broad $N_{\parallel}$ spectrum used (reaching higher T_e) and to 2-D velocity space effects not adequately modeled in ACCOME with the assumption of $T_{e\perp} = 2.5T_{e,th}$. Benchmarking of the codes continues.

Results of an ACCOME scan of absorbed power using the baseline spectrum values are given in Fig. 3, showing a constant current drive efficiency. Also, in anticipation of density control with the DIII-D divertor cryopump, cases for higher plasma temperature and lower density (constant pressure) were done for baseline profile shape parameters, $P_{lh} = 3$ MW, and $N_{\parallel}$ adjusted to keep the counter LH current at approximately the baseline radial location. Results are also shown in Fig. 3. The current density profiles, for the case with $T_e = 9.2$ keV, are shown in Fig. 4.

SUMMARY

It has been shown that LH waves, with a spectrum launched in the counter current direction can modify the edge current density profile in DIII-D VH-mode plasmas. LH counter current drive efficiency in the region of undesirable bootstrap current, $0.8 < \rho < 1.0$, was in the range $0.028 < \eta < 0.065$ for the calculations done with

the present VH-mode plasma. The higher values were obtained with the full Fokker-Planck treatment and a compound wave spectrum launched from the midplane port. Scans at constant plasma pressure showed a factor of 2.2 efficiency increase when the temperature (density) increased (decreased) by 50%.

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Fig. 1. Profiles of n_e , T_e , T_i , and pressure (points) and fits used in ACCOME (lines).

Fig. 2. Current density profiles from CQL3D for $N_{\parallel} = 4 - 6$, $T_{eo} = 6.1 \text{ keV}$, and $P_{lh} = 2 \text{ MW}$.

Fig. 3. Lower hybrid counter current vs. P_{lh} and $T_e(1/n_e)$ from ACCOME sensitivity scans.

Fig. 4. Current density profiles from ACCOME for $N_{\parallel} = 3.7, 5.4$, $T_{eo} = 9.2 \text{ keV}$, and $P_{lh} = 3 \text{ MW}$.

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