Helicon Current Drive for the DIII-D Tokamak

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Tokamak fusion reactor studies [1,2] have shown that current needs to be externally driven off-axis in order to sustain steady-state operation. This current, which complements the bootstrap current, must be driven efficiently in order for the reactor to have suitably high overall electrical efficiency. Helicons, also known as "whistler waves" or very high harmonic fast waves in the lower hybrid range of frequencies, have been shown computationally to have higher efficiency in the mid-radius region than other current drive techniques under reactor-like conditions [2–4]. However, off-axis current drive by helicons has not been validated experimentally due to the difficulty in most present-day tokamaks obtaining conditions of suitably high electron density and temperature. These conditions can be obtained in the DIII-D tokamak, making it a good facility for testing this wave physics. An experiment at the 1 MW power level using a frequency of 0.5 GHz is planned for DIII-D in 2016 to test this physics.

1. Wave Propagation and Absorption

Use of helicons for off-axis current drive places requirements on the wave attributes and the plasma characteristics. First, we look for wave parameters that have the wave trajectories lie off axis. This is done by using a frequency that is a very high harmonic of the ion cyclotron frequency, so that the frequency is below but approaches the lower hybrid frequency. This gives the wave the whistler-like quality of tending to propagate along the magnetic field lines, but with also a small radial velocity. The second requirement is strong enough damping that the power can be deposited off-axis. And the third requirement is that the radial propagation not be too fast, so that the wave is fully damped before it approaches the magnetic axis. Strong damping and small radial velocity place requirements on the wave and plasma conditions. These conditions can be evaluated using expressions developed by Chiu *et al.* [5]. In particular, the radial damping wavenumber is $k_{\perp i} = \left(\sqrt{\pi}/4\right) k_\perp \beta_e \xi_e e^{-\xi_e^2} G$, where $k_\perp$ is the radial wavenumber, $\beta_e = 2\mu_0 n_e k T_e / B^2$ is the electron beta, ξ_e is the ratio of the wave parallel speed to the electron thermal speed, and G is a known function of the density, temperature, field, and parallel index of refraction $n_{||}$. Figure 1(a) shows the factor G as a function of frequency for two values of density, with the other parameters fixed to the characteristic values of DIII-D discharge 122976 used in the modeling study. The cyclotron resonance for deuterium ions in the toroidal field of 1.6 T is 0.012 GHz, where G has an asymptotic value of unity. At an applied frequency of 0.5 GHz, the 42nd harmonic, G has increased to about 20, improving the damping over the low harmonic case by this factor.

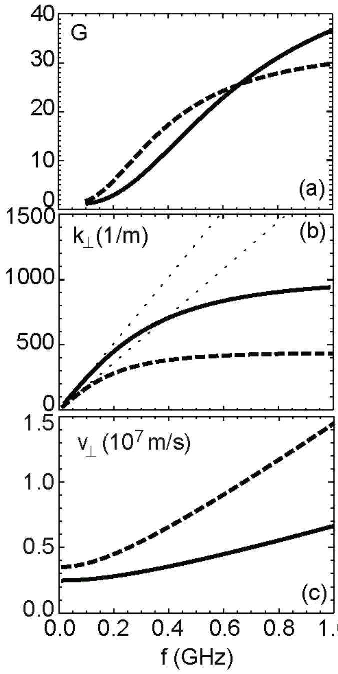

Fig. 1. (a) The damping factor G, (b) the radial wavenumber, and (c) the radial velocity as functions of the applied frequency. In each figure, the solid line is for electron density of $1.0\times10^{20}\,\mathrm{m}^{-3}$ and the dashed line for $0.5\times10^{20}\,\mathrm{m}^{-3}$. Fixed parameters are magnetic field 1.6 T, $\xi_e = 2.0$, which implies local $n_{||} = 4.6$ at electron temperature 3 keV.

Another factor in the radial damping wavenumber is $k_\perp$, the frequency dependence of which is shown in Fig. 1(b). At low frequency, $k_\perp$ is proportional to frequency (i.e., Alfvén-like). At higher frequency, above the 5-10$^{\mathrm{th}}$ harmonic, $k_\perp$ increases more slowly with frequency and saturates, and at 0.5 GHz this increases the damping wavenumber by a factor 5-10. The other two factors in the absorption are the Landau damping factor $\xi_e e^{-\xi_e^2}$ and β_e. Extensive modeling [4] shows that the absorption $(1/P)dP/ds$, where P is the power remaining in a ray and s is the distance along a ray, peaks where $\xi_e \approx 2$.

While increasing the frequency beneficially increases the damping, it has the negative effect of weakly increasing the radial propagation speed. Figure 1(c) shows that the radial velocity $v_\perp = \omega / k_\perp$ increases with frequency, doubling between zero frequency and 0.5 GHz at the lower density illustrated but increasing only 30% for the higher density case.

2. Modeling

Modeling has been performed using the GENRAY ray tracing code [6] and the AORSA full wave code [7]. Figure 2 shows the ray trajectory calculated by GENRAY for a sample DIII-D deuterium discharge with plasma current 1.5 MA, toroidal field 1.51 T, electron density in the mid-radius region of $0.5\times10^{20} m^{-3}$ and electron temperature of 3 keV, and launched $n_{||}$ of 3.0. As expected, the rays travel along the field lines while slowly moving inward until the $n_{||}$ has upshifted enough (with $n_{||}R$ roughly conserved) and the electron temperature has increased enough that the condition $\xi_e \approx 2$ is satisfied. It is because of the strong damping conditions that the absorption takes place where $\xi_e \approx 2$ rather than at $\xi_e = 0.73$ where the peak value of $\xi_e e^{-\xi_e^2}$ is 12 times larger.

Corroborating results were obtained for the same configuration using the AORSA code. Figure 3(a) shows the magnitude of the wave electric field (left hand polarized component), and the power trajectory is quite similar to that from GENRAY. Figure 3(b) shows the wave absorption by the electrons. This absorption is somewhat more centrally localized than for the ray tracing. The AORSA calculations showed negligible absorption on the background thermal ions and beam ions (about 5% of thermal density.

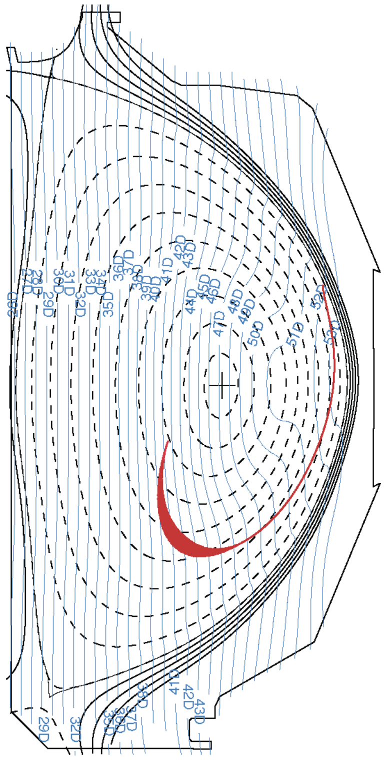

Fig. 2. Poloidal cross-section of DIII-D discharge 122976 at 3.021 s. The vertical blue lines are the deuterium cyclotron harmonics, with the 47th crossing the magnetic axis. The red line is the central ray calculated by GENRAY for 0.5 GHz with launched $n_{||}$ of 3.0. The thickness of the ray is proportional to the strength of the local damping, and the ray is fully extinguished at the end.

The profiles of driven current are shown for GENRAY and AORSA in Fig. 4. The AORSA profile is substantially more central than the GENRAY profile, and the integral is 75 kA/MW versus 60 kA/MW for GENRAY. Also shown is the profile from the CQL3D Fokker-Planck code [8], which integrates to 70 kA/MW.

Extensive GENRAY modelling [4] has shown that the driven current for DIII-D is characterized accurately as having a constant value of the dimensionless current drive efficiency $\zeta = e^3 n_e I_{CD} R / \varepsilon_0^2 P_{CD} k T_e \approx 0.64$. It is notable that this expression has no dependence on $n_{||}(a)$, the launched value of the parallel index of refraction. In fact, the modelling both with GENRAY and with AORSA show that the driven current profile is independent of $n_{||}$.

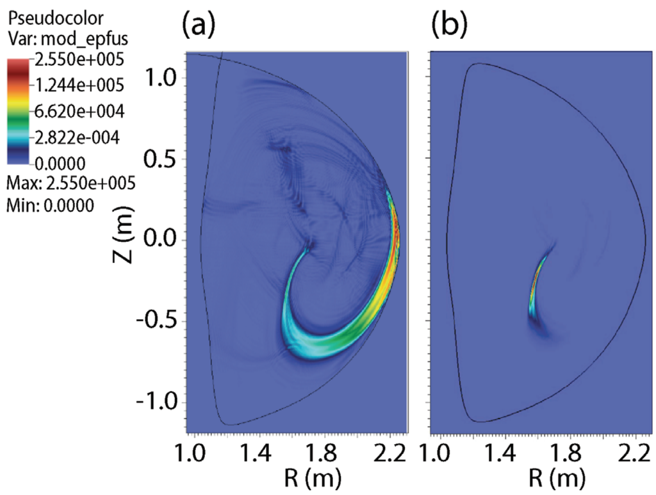

Fig. 3. (a) Contours of the magnitude of the wave electric field over the cross-section of DIII-D for the same conditions as for Fig. 2, and (b) contours of the magnitude of electron absorption, as calculated by the AORSA full wave code.

3. Launching the Helicon

Launching the helicon can be done using a Traveling Wave Antenna (TWA) [9]. Previous experiments launching the fast wave in this frequency range on JFT-2M tokamak were successful [10]. The TWA has many advantages, including its insensitivity to the density profile at the plasma edge. This is accomplished by making the antenna long, so that uncoupled power near the launch point is transmitted along the antenna where further coupling can occur. For DIII-D, it is expected that an antenna 2 meters in length with 40 elements can couple 90% of the incident power to the plasma through a gap of 5 cm between the antenna surface and the plasma surface where the density is high enough for propagation.

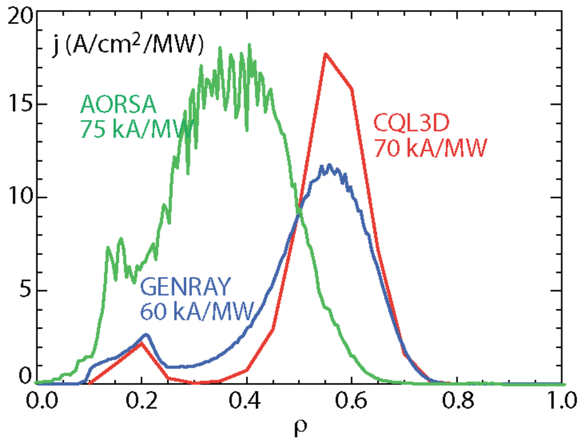

Fig. 4. Current density profiles for the case of Fig. 2, as calculated by GENRAY (blue), CQL3D (red), and AORSA (green).

4. Conclusions

Helicons are a promising technology for off-axis current drive in tokamaks with high β_e. Use of high frequencies approaching the lower hybrid frequency helps to ensure that the driven current will be off-axis. The driven current under DIII-D conditions is consistent with constant dimensionless efficiency of 0.64, which is substantially better than that obtained from the other current drive techniques available. Effective wave launching can be done by use of a combline travelling wave antenna.

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