Potential of Helicons at 0.5 GHz and Lower Hybrid Waves at 4.6 GHz for Off-Axis Current Drive in DIII-D

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Efficient non-inductive current drive methods have been found to be essential for an economical steady-state tokamak fusion reactor. In particular, reactor design studies have highlighted the importance of current drive in the mid-radius region, with normalized minor radius ρ~0.4-0.8 [1]. The DIII-D tokamak program is evaluating several concepts for efficient off-axis current drive, including top-launch electron cyclotron current drive, inside-launch lower hybrid (slow wave) current drive, and helicon wave (fast waves in the lower hybrid range of frequencies) current drive. As part of this study, the ray-tracing code GENRAY in conjunction with the Fokker-Planck solver CQL3D has been used to compare wave penetration and damping of 0.48 GHz helicon waves and 4.6 GHz lower hybrid waves in a variety of experimentally-realized DIII-D high-beta equilibria, with good current drive efficiency predicted for both techniques in the mid-radius region.

A key constraint on lower hybrid current drive in reactor-grade plasmas is wave accessibility to the desired deposition region in the plasma [1]. The index of refraction of the wave along the static magnetic field, $n_{\|}$, must be *high* enough to reach the core plasma, where it is absorbed by electron Landau damping and thereby drive current, without being subject to mode conversion to an outgoing fast wave. Simultaneously, $n_{\|}$ must be sufficiently *low* to avoid strong electron Landau damping in the lower temperature plasma periphery. The higher the local magnetic field (i.e., the lower the electron dielectric constant $\sim 1+\omega_{pe}^2/\Omega_e^2$), the less constraining wave accessibility becomes, which suggests launching the lower hybrid waves from the inboard region. Here the toroidal field is higher than at the usual outboard midplane launch location by a multiple of $\sim(R_0+a)/(R_0-a)$, a factor of two for DIII-D's aspect ratio of ~3. For this reason, high-field-side launch lower hybrid current drive is practical at reasonably high electron density in a relatively low-field device like DIII-D (maximum central toroidal field = 2.15 T). In addition, positioning the wave launcher in a region of good magnetic curvature has other potential advantages [2] over the outside mid-plane position, further arguing for the importance of an experimental evaluation of this technique. On the other hand, the practical difficulties of this launcher positioning, particularly for a device not designed from the beginning with this in mind, explain why such a test has not yet been carried out.

By contrast, the helicon wave [typically with $f < f_{LH}(\rho=0)$] has significantly weaker electron Landau damping than the slow wave at the appropriate frequency [$f > f_{LH}(0)$] and $n_{||}$, allowing helicon waves at higher $n_{||}$ values to penetrate large, hot plasmas without damping at the edge of the plasma. Furthermore, unlike the slow wave, the helicon wave is not subject to the fundamental density limit of the lower hybrid wave resonance, so that significantly lower frequencies may be used than for the slow wave. Depending on the specific model of the observed lower hybrid wave density limit, which occurs even in discharges in which there is no lower hybrid resonance layer [2], the helicon may not suffer from this density limit either, affording the possibility of much improved wave accessibility to the high-electron-beta plasma core region.

To compare the two proposed schemes in the lower hybrid range of frequencies for DIII-D, the effects of helicon and of lower hybrid wave injection were modeled in experimentally-realized ELMy H-mode discharges in different Advanced Tokamak regimes, including discharges in which off-axis neutral beams were used to sustain broad profiles, a 'hybrid' discharge with central current drive, and a discharge with a peaked current profile ('high li'). A slab model of accessibility [3] is inadequate and 3-D ray tracing is required to evaluate accessibility due to the crucial effects of poloidal wavenumber evolution along the ray trajectory at finite aspect ratio [4]. Furthermore, the importance of quasilinear effects on the electron distribution function for the lower hybrid wave case necessitates iteration between ray tracing and a Fokker-Planck solver for quantitative evaluation of that case, while the weaker electron Landau damping and thus of quasilinear effects for the helicon wave means that a linear calculation of the ray trajectories is sufficient [5], i.e. using only GENRAY and not invoking CQL3D.

The qualitative character of the ray trajectories is similar for both the helicon and lower hybrid waves: to lowest order the rays follow the magnetic field lines and to next order slowly penetrate radially. The lower hybrid ray trajectories form a small angle with the field line, which is the resonance cone angle in the electrostatic limit. The size of that angle is independent of $n_{||}$ in that limit and decreases as the local density increases. The helicon rays similarly make a small angle with the magnetic field lines, also decreasing as the density increases, and in the ‘whistler’ approximation, the maximum angle is 19.5 degrees. That angle also depends on $n_{||}$, and at lower values of $n_{||}$, the angle is smaller than this limiting value; at the accessibility limit, the angle goes to zero.

The relatively low toroidal field of DIII-D requires the launched $n_{||}$ for the 4.6 GHz slow wave to be ~2.7 or greater for core penetration at all but the lowest examined line-average densities. The helicon, at an order-of-magnitude lower frequency, has good accessibility to the core at low toroidal fields with outside launch, while the weaker electron damping leads to the absorption being closer to the magnetic axis than for the slow wave. Figures 1 and 2 compare the lower hybrid and helicon cases in a DIII-D equilibrium in which off-axis neutral beams were used to create a broad current profile. The lower hybrid wave drives 0.15 MA/MW at ρ=0.6 [6], with some of the rays being inaccessible to the core, while the helicon rays easily access the core and drive 0.076 MA/MW at about ρ=0.35. A higher density, lower field (higher beta) case shown in Figs. 3 and 4 (discussed extensively for the helicon in Ref. [5]) shows that the lower hybrid waves cannot access the core while the helicon waves penetrate and drive current around ρ=0.55.

For both waves, efficient coupling at relatively high values of $n_{||}$ is a crucial issue. Though the cutoff density for the slow wave at 4.6 GHz [$n_e(f_{pe}$=4.6 GHz) = 2.6×10^{17} m^{-3}] is much lower than for the fast wave at 0.48 GHz at $n_{||}$=3 [n_e(cutoff) $\approx 1.3\times10^{18} B_T$ m^{-3}, where B_T is the local magnetic field in T], more rapid evanescence of the wave in the vacuum region at higher frequency at a fixed $n_{||}$ yields poor coupling for both cases if conventional wave launchers are used. We are evaluating the practicality of innovative traveling-wave launchers for both waves and have tested such a helicon wave launcher at very low power in DIII-D, with good coupling obtained in a discharge with single-pass absorption of the helicon waves at mid-radius [7].

We conclude that provided the coupling issues for both the lower hybrid wave and helicon can be successfully resolved, both methods of off-axis current drive would be useful to advance the DIII-D program. The lower hybrid wave launched from the inboard side would be most efficient in the higher field, lower density part of the advanced tokamak operating space on DIII-D, while the helicon is better suited to lower toroidal field and higher density, i.e. high beta, conditions.

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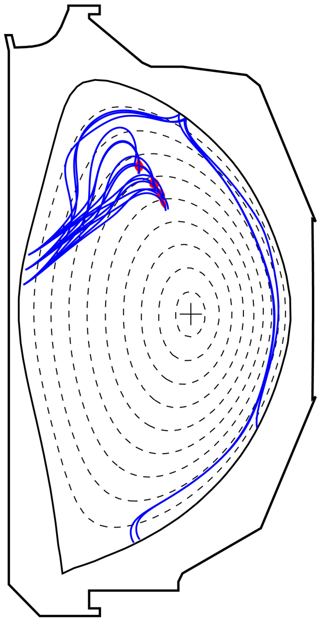

Fig. 1. Ray trajectories for $n_{\parallel}$=2.7, 4.6 GHz slow waves launched just above the midplane in a DIII-D equilibrium with broad current profiles (shot 147634, B_T=1.66 T, I_p=1 MA); red indicates absorption region.

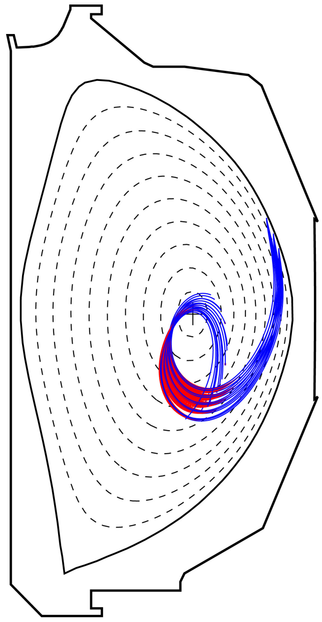

Fig. 2. Ray trajectories for $n_{\parallel}$=3, 0.48 GHz helicons launched above the outboard midplane in the same equilibrium as in Fig. 1.

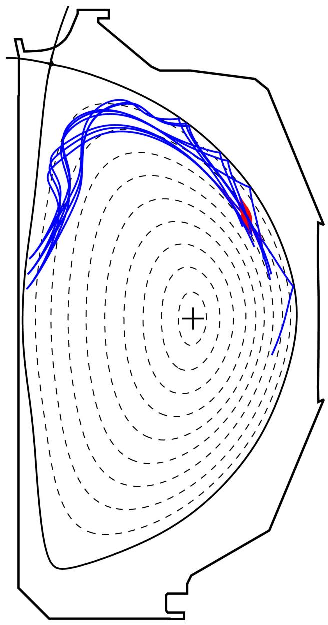

Fig. 3. $n_{\parallel}$=2.7, 4.6 GHz slow waves in a high beta DIII-D equilibrium (shot 122976, B_T=1.5 T, I_p=1.55 MA).

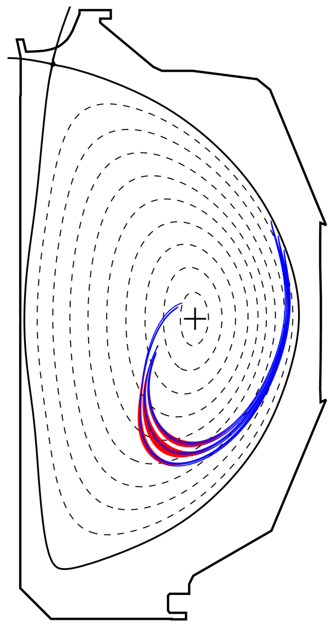

Fig. 4. $n_{\parallel}$=3, 0.48 GHz helicons in the same high beta DIII-D equilibrium as in Fig. 3, described in detail in [5].