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*Compx, Del Mar, California.

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Application of Electron Cyclotron Current Drive on ITER

R. Prater[1], M. Choi[1], R.W. Harvey[2], and R. J. La Haye[1]

[1]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*
[2]*CompX, Del Mar, California, USA*

Plans for the ITER tokamak include electron cyclotron waves for heating and driving current in the plasma [1]. Key objectives for the electron cyclotron system include heating to temperatures where alpha heating becomes dominant, stabilizing magnetohydrodynamic (MHD) modes like neoclassical tearing modes and sawteeth, and contributing to maintenance of the current profile required for higher ("advanced") performance in the high bootstrap fraction regime. These functions rely on the strong localization of the power deposition characteristic of electron cyclotron (EC) waves. Modeling can be employed to evaluate the power needed to carry out these objectives, since the validity of the computational models used to predict the heating and current drive effects have been largely confirmed by recent experimental results worldwide [2]. In this study, the linear ray tracing code TORAY-GA is used to model the current drive in ITER.

The fulfillment of the objectives of ECCD in ITER is greatly complicated by the range of the engineering parameters over which ITER is expected to operate. The primary objective of the ITER program is to achieve Q=10 in the Scenario 2 equilibrium with 15 MA of plasma current and toroidal field of 5.3 T. However, the EC system should also work with different equilibria. Cases with different profiles of safety factor q and different internal inductances have been treated by Zohm [3]. In this study, ECCD for a range of toroidal fields is evaluated.

The toroidal field, in combination with the EC source frequency and the Doppler shift, determines the major radius at which the absorption takes place. For the fixed design frequency of 170 GHz, the range of normalized minor radius ρ which intersects the resonance magnetic field is shown in Fig. 1 as a function of the toroidal field. This figure suggests that there may be a range of field for which this frequency is ineffective in driving current, although the Doppler shift (which can be substantial) is neglected.

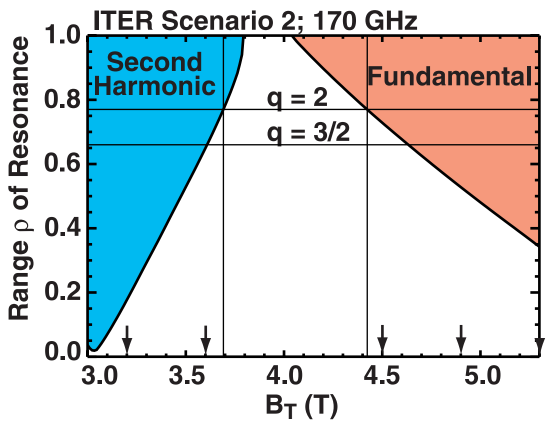

Fig. 1. Range of normalized minor radius ρ which intersects the electron cyclotron resonance for ITER Scenario 2 equilibrium (colored regions), as a function of toroidal field. The ρ of the q=3/2 and q=2 surfaces are shown. The markers on the horizontal axis show the B_T values for equilibria used in this study.

In order to test the effectiveness of the EC system, new equilibria were generated at the toroidal field values of 4.9, 4.5, 3.6, and 3.2 T as indicated on the horizontal axis of Fig. 1. The CORSICA/TEQ code [4] was used to scale the equilibrium using a constant q-profile and scaling the pressure profile to keep β constant. At the same time, the density profile was scaled to keep the Greenwald number fixed. Then the EC systems were assessed computationally using the upper launcher (R = 6.485 m, Z = 4.11 m) and the three midplane launchers at (R = 9.076, Z = 1.211), (R = 9.163, Z = 0.611), and (R = 9.118, Z = 0.011). In each case, the EC Gaussian beam divergence was set to 1.08 deg to approximate the Gaussian beam size at the distance corresponding to the q=3/2 and q=2 surfaces, and the effective launch point was moved away from the final launch mirror by 50 cm to simulate finite beam diameter at the final mirror.

The upper launcher is usable only for the part of Fig. 1 labeled fundamental, above about 4.5 T. For lower fields the second harmonic may be available, but use of this resonance would require that the upper launcher direct the EC beam toward the outer midplane, drastically outside the anticipated steering range of this launcher. However, for $B_T \geq 4.5$ T the effectiveness of ECCD—that is, the ability to drive a current density comparable to the bootstrap current density — is not strongly dependent on the toroidal field, as illustrated in Fig. 2. For the q=2 surface, for example, the peak current density is 0.84 A/cm^2/MW for B_T = 5.3 T [Fig. 2(a)], while for 4.5 T it is 1.00 A/cm^2/MW [Fig. 2(b)]. This favorable independence from the toroidal field accrues from the geometry of this launcher location.

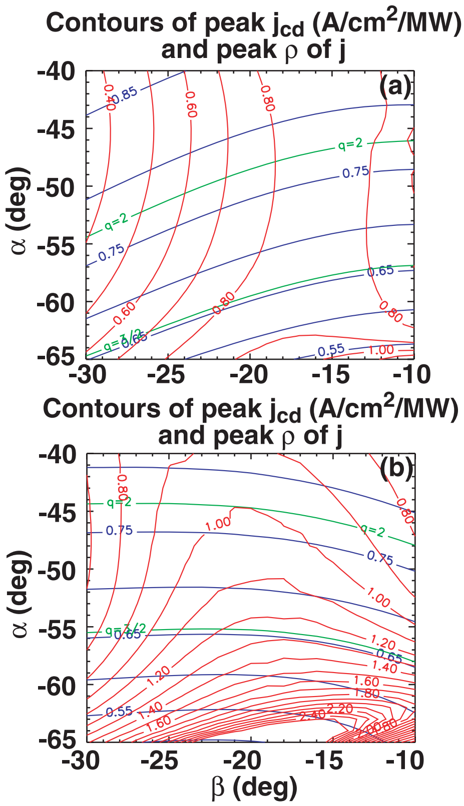

Fig. 2. Contours for the upper launcher of the peak ECCD (A/cm^2/MW) (red) and the normalized minor radius of the peak of the driven current (blue), as a function of the vertical steering angle alpha and the toroidal steering angle beta. Also shown are the minor radius of the q=3/2 and q=2 surfaces (green). (a) B_T = 5.3 T, (b) B_T = 4.5 T.

The midplane EC launchers drive current over a range of ρ depending on the toroidal field and the toroidal steering component, as shown in Fig. 3. These data were obtained by running TORAY-GA for toroidal steering angle 0 deg to 30 deg in 1 deg steps. For each toroidal field, the range in ρ is limited; for example, for 5.3 T the current drive is limited to ρ = 0.1 to 0.4 as shown in Fig. 3(b). For 4.5 T the ECCD can be extended to the radial region of interest for control of neoclassical tearing modes, but the efficiency is less than half that of the upper launcher due to the effects of trapping in the magnetic well of the electrons on which the

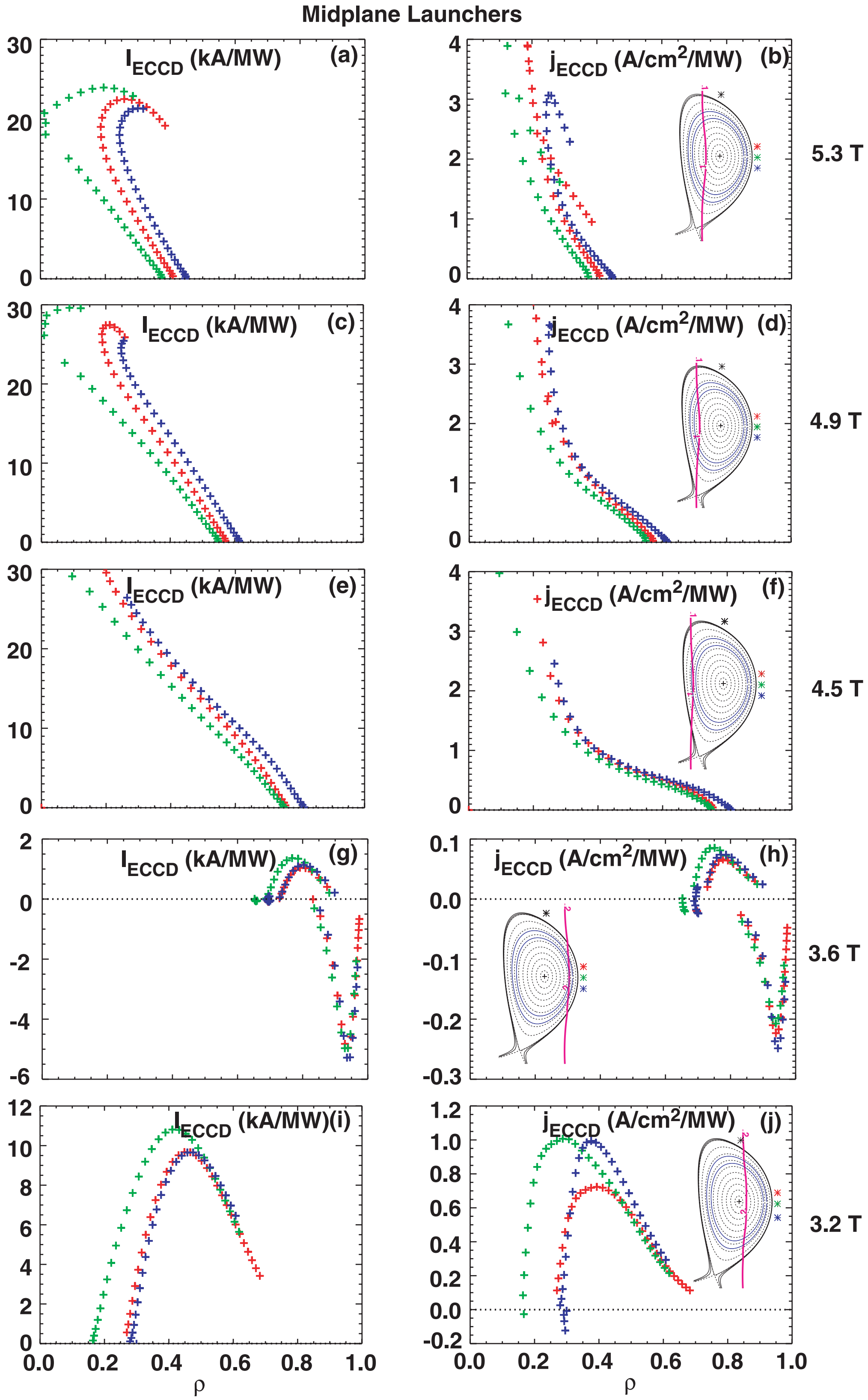

Fig. 3. Total current and peak current density for the midplane launchers: top (red), middle (green), and bottom (blue), for equivalent equilibria with toroidal fields of 5.3 T (a,b), 4.9 T (c,d), 4.5 T (e,f), 3.6 T (g,h), and 3.2 T (i,j). For each launcher, the toroidal steering angle beta is varied in 1 deg steps from 0 deg to 30 deg, while the vertical steering component is such that the ray bundle travels in a horizontal plane at the elevation of the launcher (α=0).

EC wave damps [2]. So for $B_T > 4.5$ T the upper launcher would be preferentially used. For the 3.6 T case, shown in Figs. 3(g,h), the current drive is necessarily limited to $\rho > 0.75$ by the location of the resonance, and in this case the trapping effects are very severe and little current can be driven. Moderate current drive efficiency returns for the lowest field, 3.2 T, but in this case the resonance is too far inboard so that the ECCD takes place for $\rho < 0.5$. It appears that there may be a window of sufficiently efficient ECCD for the midplane launchers for toroidal field around 3.4 T, but further calculations will be needed to determine the peak ECCD and the region over which it can be controlled.

In summary, for toroidal fields greater than or equal to 4.5 T, the upper launcher is quite effective in driving large peak current densities which may be useful in stabilizing the m/n=3/2 and 2/1 neoclassical tearing modes, but for fields lower than 4.5 T this launcher cannot be used. At the larger end of this field range, the upper launcher can also drive current effectively at smaller minor radius, to about $\rho \geq 0.5$, for possible use in controlling sawteeth. As the toroidal field is reduced, this minimum ρ and the width of the driven current profile, $\delta\rho$, become larger, reducing the effectiveness of ECCD in controlling sawteeth. In the same range of toroidal fields, $5.3 \geq B_T \geq 4.5$ T, the three midplane launchers are useful for central heating and current drive, with current drive in the range of 25 kA/MW for ρ less than 0.4. In terms of the conventional current drive efficiency, this corresponds to $\eta_{ECCD} = n_e I_{EC} R / P_{EC} = 0.2\times10^{20}$ A/W/m^2, which is in the same range as that found previously [1]. For $B_T \approx 3.6$ T, the midplane launchers are effective only at heating near the edge of the plasma, $\rho > 0.7$, but current drive is very poor due to the effects of trapping. As the toroidal field is reduced to around 3.4 T the peak current drive increases, possibly to a level of interest, but by 3.2 T the current drive is limited to $\rho < 0.6$, which would be ineffective for NTM control but possibly useful for sawtooth control.

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