OPERATION SPACE OF OFF-AXIS ELECTRON CYCLOTRON CURRENT DRIVE AT HIGH DENSITY ON THE DIII-D TOKAMAK

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Electron Cyclotron Heating (ECH) and Electron Cyclotron Current Drive (ECCD) is a widely used approach to heating plasmas and driving current in toroidal magnetic confinement devices for fusion energy applications. The ECH system on the DIII-D tokamak is being upgraded. Not only the torque free heating on DIII-D will be increased, the operation space of ECH application on DIII-D will be broadened and pushed closer to reactor conditions due to the higher frequency, higher power gyrotrons. This study presents how these different frequency gyrotrons could allow heating and drive current in higher density plasmas when aimed off-axis via top launch and/or O-mode injection.

Addition of higher frequency gyrotrons will extend ECH application to higher density plasmas on DIII-D. The ECH density cutoff is an important limitation because of increasing interest in pushing DIII-D experiments towards high-density plasmas (*e.g.*, super H-mode, radiative divertor). All the gyrotrons presently on DIII-D are at 110 GHz. For 110 GHz electron cyclotron (EC) waves, the cutoff of the X-mode polarization for outside launch starts to become an issue for densities above 5×10^{19} m^{-3}. The planned new 1MW gyrotrons with triple frequency of 104/137/170 GHz will increase the density limit (except operating at 104GHz). At the toroidal magnetic field strengthen of B_T>=2.1T that super H-mode plasmas operate, 137 GHz 2nd harmonic X-mode (X2) injection could provide heating with >50% higher density limit than 110 GHz X2 injection. Figure 1 presents the extension in density space of off-axis ECCD application in steady-state advanced tokamak (AT) plasmas on DIII-D brought by the planned new higher frequency gyrotrons. For example, when gyrotrons are used for off-axis (ρ~0.6) ECCD in those plasmas at B_T=2.1T, 137 GHz X2 injection has ~40% higher density limit than 110 GHz X2 injection. Since the cutoff density for O-mode polarization is twice as high as for X-mode, this polarization can be used for direct electron heating of high-density plasmas. As illustrated in Figure 1, with O2 injection, plasmas with high Greenwald density fraction ($n_{ped}/n_{GW} \geq 1$) can be accessed by ECH at higher frequency. X3 has even higher density limit. 170 GHz X3 injection could provide central heating at B_T=2-2.2T (Figure 2) which will be very useful especially when central heating is required for impurity control on DIII-D.

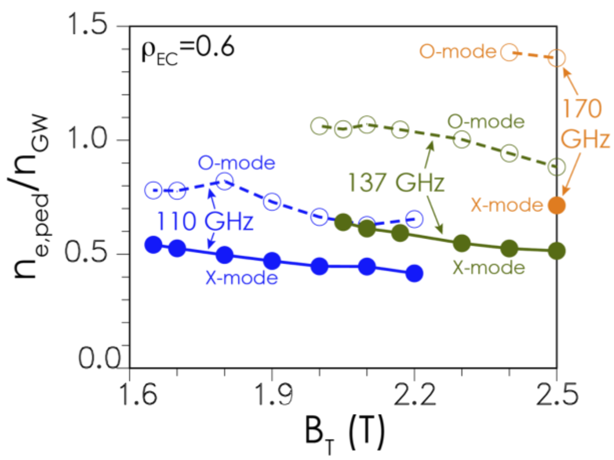

Figure 1: Density limit for conventional outside launch ECCD when aimed at ρ~0.5 in an AT plasma on DIII-D

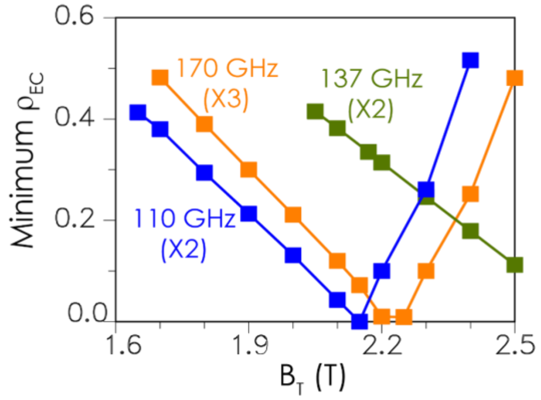

Figure 2: Central most deposition location of new high frequency (137 GHz & 170 GHz) gyrotrons compared to existing 110 GHz gyrotron on DIII-D

Controllable and efficient off-axis current drive is crucial for economic, steady-state tokamak fusion power plants. Although ECH has the advantage of remotely locating the RF sources and readily transmitting the RF power through the vacuum-vessel interface and could drive current in a highly localized, robustly controllable way, the efficiency of conventional ECCD decreases as the deposition location is moved away from the magnetic axis [1]. Top launch ECCD --- launching EC waves from the high field side of the plasma, but the low field side of the resonance, with large toroidal steering in a plane nearly parallel to the resonance layer is found to greatly increase the ECCD efficiency at mid-radii compared to conventional outside launch [2]. Although the density limit of O-mode is significantly higher than X-mode, the absorption is weaker than for X-mode (which especially affects the current drive). Owning to the longer wave-electron interaction path, at the same density, top launch ECCD is predicted to generally have higher ECCD efficiency ζ_{ec} in both X2 and O2 than conventional outside launch as shown in Figure 3 where ζ_{ec} is the dimensionless current drive efficiency as defined in Ref [3]. Top launch O2 injection has 25% to 50% of ECCD efficiency as conventional outside launch X2 injection in DIII-D AT plasmas. 137 GHz X2 top launch injection is predicted to provide significant higher current drive efficiency than the existing 110 GHz gyrotron in B_T range between 1.75T and 2T (not shown). A new top launch scheme is installed on DIII-D which has the potential to expand the capability of switching between top launch and outside launch for any/all gyrotrons on DIII-D.

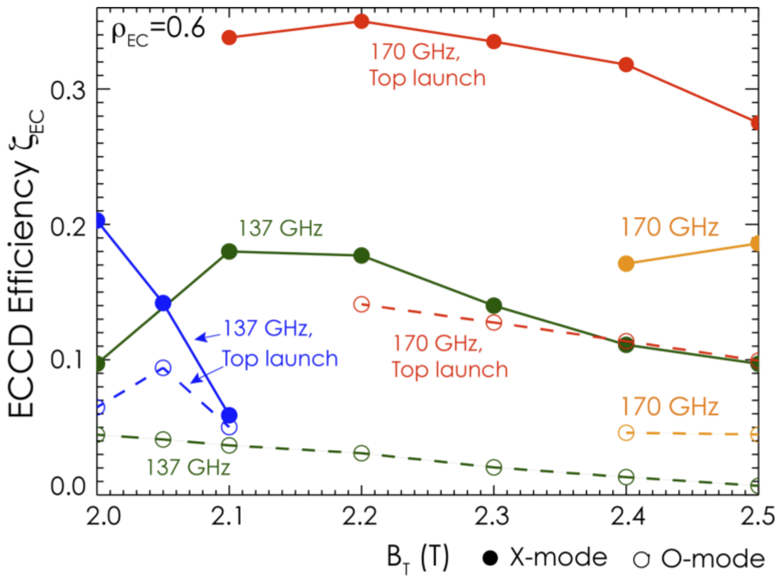

Figure 3:Off-axis current drive efficiency via conventional outside launch and via top launch in both X2 and O2 injection

The aimings (deposition location and injection angle) of different frequency gyrotrons can be optimized to achieve central heating, off-axis current drive and NTM control in the same plasma and with much higher ECH power, DIII-D will be able to make plasmas much closer to reactor conditions with even more ECH flexibility in high density plasmas.

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