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Doubling the Efficiency of Off-axis Current Drive Using Reactor-relevant 'Top Launch ECCD'on the DIII-D Tokamak

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For the first time, experiments on the DIII-D tokamak have demonstrated electron cyclotron current drive (ECCD) with more than double the efficiency of the conventional outside launch by using a novel top launch geometry (figure 1), as predicted by linear ray tracing and quasi-linear Fokker-Planck simulations. Studies have shown that off-axis current drive is a requirement for a steady-state reactor in the Advanced Tokamak (AT) regime[1,2]; however, driving current off-axis efficiently remains a challenge. Launching electron cyclotron 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 (illustrated in figure 2) is found to greatly increase the ECCD efficiency at mid-radii compared to conventional outside launch. The higher ECCD efficiency is due to 1) selective EC wave damping on higher $v_{||}$ electrons, and 2) longer absorption path lengths to compensate for inherently weaker absorption at higher $v_{||}$. DIII-D experiments using a prototype top launch system with a fixed mirror have established these two tenets through scanning $v_{||}$ of the wave-particle interaction by varying the magnetic field B_T. Power deposition measurements show that the absorbed EC power decreases for higher $v_{||}$ interaction (lower B_T), giving rise to a "sweet spot"(optimal B_T) for maximum ECCD efficiency at ρ~0.5 (figure 3) where the higher current drive efficiency for higher $v_{||}$ is balanced by sufficient absorption. Simulations of 'top launch'ECCD for FNSF, DEMO and CFETR support it as an improved efficiency off-axis current drive technique for future fusion reactors[3−5].

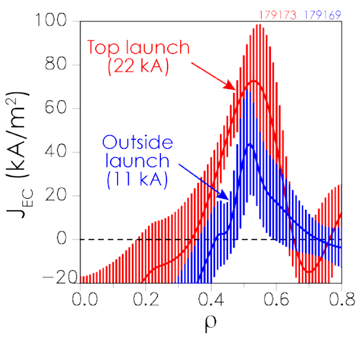

Figure 1: Measured ECCD current density profiles via top and outside launch with 0.5MW absorbed power from a single 110GHz gyrotron

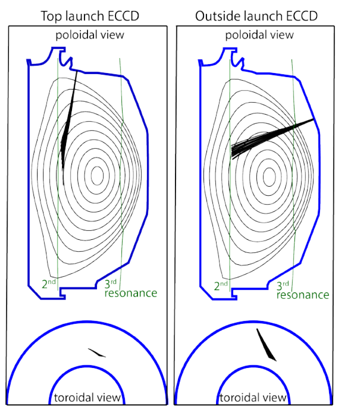

Figure 2: EC trajectories via top launch ECCD compared to outside launch in DIII-D

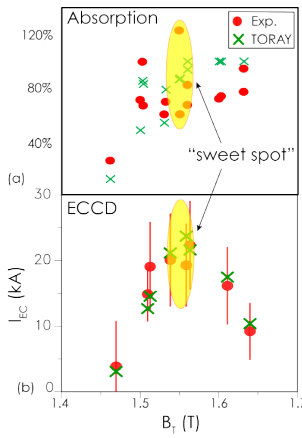

Figure 3: (a) Absorption and (b) ECCD via top launch at different B_T for H-mode plasmas

Figure 1: Figs 1-3

Top launch ECCD with a long wave-electron interaction zone and a large Doppler shift ensures strong damping on tail electrons leading to higher ECCD. Top launch ECH experiments have been done previously on TCV using radial launch and 3^{rd} harmonic X-mode to heat high density plasmas; the top launch experiments on DIII-D have the different goal of efficient off-axis current drive, and the launch scheme has been uniquely optimized for this purpose. As illustrated in figure 2, EC wave from this top launch 1) propagates nearly parallel to the resonance plane and only gradually approaches the resonance, resulting in a longer absorption path; 2) suffers less trapping effects by being on HFS of the axis; and 3) allows a larger Doppler shift, thus interacting with higher energy (less collisional) electrons. To experimentally validate and characterize this approach, a prototype top launch system is installed on DIII-D with a fixed mirror angle utilizing 2^{nd} harmonic damping of either a single 110GHz or 117.5GHz gyrotron with injected power between 0.5-0.6MW.

The longer absorption path of top launch predicted by the TORAY ray-tracing code is measured by modulating the ECCD power and observing the electron temperature oscillations with an ECE radiometer. The measured power deposition location generally agrees with TORAY. The vertical path is verified via comparison of X-mode and O-mode deposition, where the predicted location shift between X and O (reflecting the different vertical paths due to the different absorptions) is confirmed. A much longer (i.e., three times) absorption zone for top launch ECCD compared to outside launch is also measured, consistent with TORAY. The longer interaction zone usually results in a broader deposition profile when mapped onto ρ space but not always. The more parallel the EC ray is to the flux surface, the narrower the deposition profile.

Selective damping on electrons with different $v_{||}$ via top launch ECCD geometry is evidenced by the reduced absorption measured with lower B_T in DIII-D experiments, as predicted by TORAY. The cold resonance moves to higher $v_{||}$ at lower Bt and the wave-electron interaction follows. Damping on tail electrons that are less collisional and drive current more efficiently is crucial for high ECCD efficiency; however, because the electron population decreases with increasing energy, the total absorption can drop far below 100%. Reduced total absorption at extreme low B_T (i.e., high $v_{||}$) is observed in both L-mode and H-mode (figure 3(a)) plasmas in DIII-D.

The highest top launch ECCD efficiency is predicted and achieved when balancing higher $v_{||}$ interaction and sufficient total absorption. The ECCD profile is determined from the change in the magnetic field pitch angles measured by motional Stark effect (MSE) polarimetry. As illustrated in figure 3(b), at high Bt (low $v_{||}$) the ECCD efficiency is low despite full absorption. The measured ECCD efficiency increases with decreasing B_T (increasing $v_{||}$) until the curve rolls over when too little wave energy is absorbed by too few high v|| electrons. In H-mode plasmas, the 'sweet spot'for highest top launch ECCD is predicted and measured at Bt~1.55T, where the driven ECCD at ρ~0.5 is double for top launch compared to outside launch (figure 1), consistent with the predictions from TORAY and quasi-linear Fokker-Planck code CQL3D.

Studies are underway to evaluate whether the high-beta, steady-state goals of the AT program on DIII-D can be achieved using four top-launch gyrotrons and four outside-launch gyrotrons. Initial FASTRAN simulations with self-consistent transport/pedestal/current profile modeling shows that 3MW top launch can drive as much ECCD at ρ~0.65 as 6+ MW outside launch in the "high qmin" AT regime owing to the near doubling in ECCD efficiency, allowing access to the highest stable β_N (~4.5) with a non-inductive current fraction of 1. These results suggest that the combination of 3 MW top launch and 3 MW outside launch is a reasonable optimum to achieve the high-beta, steady-state goal of the DIII-D AT program.

Top launch ECCD is a promising off-axis current drive technique for future fusion reactors. Top launch ECCD shares the same reactor-relevant features of conventional outside launch ECCD, such as easy coupling to the plasma, no near-plasma antenna, and small port requirements, along with long experience in gyrotron development. Modeling for FNSF-AT shows >50% higher off-axis current drive efficiency for top launch ECCD compared to outside launch[3], similar to the predictions for DEMO[4]. Greater than 35% improvement in ECCD at ρ~0.5 has already been found in modeling the CFETR baseline[5], reaching a current drive figure of merit of γ~0.16x10^{20} A/m^2W for 14.5keV; or a dimensionless current drive efficiency of ξ~0.37. The experimental demonstration of doubling off-axis ECCD on DIII-D and the great enhancement found in simulations of FNSF-AT, DEMO and CFETR strongly support top launch ECCD as an exciting reactor-relevant and efficient off-axis current drive technique.
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[1]*F. Najmabadi, et al, FED38(1997) 3;* [2]*F. Najmabadi, et al, FED80(2006) 3;* [3]*R. Prater, et al, APS-DPP (2012);* [4]*E. Poli, et al, NF53(2013) 013011;* [5]*Xi Chen, et al., EPJ Web of Conferences,203** (2019) 01004

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