The development and qualification of physics and technologies that deliver off-axis current drive (CD) with the desired profile and high efficiency under reactor-like conditions to achieve high stability and high overall energy gain will greatly enhance steady-state fusion power plants. General Atomics (GA) proposes a program to validate the physics and technology of an unexplored technique – top launch electron cyclotron current drive (ECCD). Modeling suggests that the approach can increase the ECCD efficiency by 50% or more. The enhanced CD off-axis efficiency is obtained by launching the electron cyclotron (EC) wave from top of the vessel to force a large Doppler shift, thereby selectively damping the wave energy on more energetic (less collisional) electrons. An example of a top launch ECCD application on the DIII-D tokamak is displayed in Fig. 1.

Studies of many tokamak reactors have shown that off-axis current drive ($\rho \sim 0.5-0.7$) is a requirement for a steady-state device in the Advanced Tokamak (AT) regime. For example, the Fusion Development Facility study found that the current drive at $\rho \sim 0.6$ with an efficiency of $\sim 40 \text{kA/MW}$ is needed to achieve a large region of negative central shear and high fusion gain.

Neutral beam current drive can be an efficient non-inductive current drive scheme. However, neutral beams are large objects that are challenging to make mechanically consistent with other systems on the tokamak (the vacuum vessel, the blanket and neutron shielding, etc.) in the reactor environment. The large tangency and port size needed to achieve off-axis current drive increases the challenges. Radio frequency (RF) wave injection is another common non-inductive current drive technique. Among these techniques, lower hybrid current drive usually has the highest efficiency. However, in fusion plasma conditions, the absorption of lower hybrid waves is so strong that it usually drives current only in the pedestal region ($\rho > 0.85$). ECCD launched from the low field side (LFS) is another common RF current drive technique that drive current at $\rho \sim 0.5-0.7$ in reactor-like plasmas but it has low efficiency in this region due to electron trapping in the
magnetic well. Increasing the applied wave frequency can improve the CD efficiency by moving the primary resonance layer to the high field side (HFS) where the impact of trapped particles is less, but parasitic second (or third) harmonic absorption can become problematic. As reference, a previous study of FNSF-like conditions shows that the projected global current drive efficiency of ECCD based on present-day LFS launch is too small to achieve a fusion gain well above 1.

A top launch ECCD system can satisfy the need for off-axis current drive at high efficiency in steady-state tokamaks. Some features of the top launch ECCD scheme that differ from the conventional ECCD scheme are shown in Fig. 2, where the wave trajectories of these two schemes are compared in the poloidal and toroidal planes. In both examples, the ECCD deposition location is at $\rho \approx 0.55$ and the primary resonance is fundamental O-mode. In Fig. 1, the primary resonance is second harmonic X-mode. In the top launch concept, the EC wave is launched from the top or bottom of the tokamak on the HFS of the magnetic field axis before reaching the primary resonance layer, whereas in the conventional ECCD concept the wave is injected from the LFS, on or off the outer midplane. Another unique feature of the top launch concept is that the EC wave is steered with a large toroidal angle in the plane, nearly parallel to the primary resonance layer.

The combination of the unique launch location and steering geometry of top launch ECCD concept greatly improves the current drive efficiency. The physics features that lead to this increase are as follows:

- The wave-plasma interactions take place on the HFS of the flux surface where the trapping effect is greatly reduced.
- Strong toroidal steering forces a larger Doppler shift, which benefits the driving current because the wave absorption occurs when the difference between the applied wave frequency and the local cyclotron frequency is nulled by the Doppler shift. If the frequency difference

---

**Fig. 2. Typical ray trajectory comparison between top launch ECCD and conventional ECCD in poloidal and toroidal views.**

---

**Fig. 3. Power absorption fraction ($P_0$ is initial power) and the difference frequency ($\omega$) between applied EC wave frequency ($\omega$) and local electron cyclotron frequency ($\Omega_e$) for top launch (solid) and LFS launch (dashed) ECCD**
remains large because the wave trajectory does not reach the vacuum resonance, then the wave energy is damped on faster, less collisional electrons that give a higher CD efficiency. Fig. 3 compares the power absorption and the frequency difference along the ray trajectory for the two cases shown in Fig. 2. It shows that the frequency difference in the conventional LFS ECCD is small for the deposition region, but it is much larger and nearly constant along the whole ray trajectory for top launch ECCD.

- The wave trajectory is nearly parallel to the resonance layer, approaching the resonance much more slowly than the near perpendicular injection of the conventional LFS launch, which results in a long absorption path. As is illustrated in Fig. 3, the absorption path for top launch is ~20 times that of LFS launch. Although the density of high-energy electrons selected by the large Doppler shift is small, the long path enables sufficient wave interaction with these more energetic electrons to damp all of the EC wave power.

As previously noted, conventional ECCD for off-axis current can be limited by the parasitic absorption at the second (or third) harmonic, which depletes the wave energy available for fundamental (or second harmonic) current drive. For example, in the case shown in Fig. 1, outside launch EC first passes through the third harmonic before reaching the second harmonic. The third harmonic absorption is far from off-axis and does not drive current, decreasing the ECCD by ~40%. The launching geometry of the top launch ECCD can avoid the problem.

Significant enhancement of off-axis ECCD efficiency for top launch has been found in several modeling studies. Modeling for FNSF-AT has shown that the improvement of the off-axis current drive efficiency of top launch over the conventional LFS ECCD can be more than 50% [1]. Initial assessment of top launch ECCD in the baseline scenario for China Fusion Engineering Test Reactor (CFETR) has already found 35-40% higher CD efficiency at $\rho \sim 0.5$ compared to the LFS side launch, and this concept is adopted in the following CFETR design development.

GA has been examining the possibility of validating this concept on DIII-D within the next two years. A physics feasibility study found 50% to 100% higher off-axis ECCD efficiency in some DIII-D high-$q_{\text{min}}$ steady-state plasmas. These improvements, found using TORAY ray tracing code, have also been confirmed by CQL3D Fokker-Planck code. Figure 4 gives an example where the CD efficiency doubles using top launch over the LFS launch. CQL3D results show additional quasilinear increases in ECCD efficiency in the top launch ECCD scheme. With a new launcher at the top of the DIII-D vessel as illustrated in Fig. 1, the concept can be tested on DIII-D using the existing 110 GHz gyrotrons or the new 117.5 GHz gyrotrons.
ECCD is a well-developed technique for driving current in present-day high performance tokamak plasmas, and is the most technically mature CD system envisaged for ITER. However, studies of future machines, such as FNSF and CFETR, show that high power gyrotrons with frequencies higher than currently available are needed for top launch, e.g., 190 GHz for FNSF and 230 GHz for the CFETR conceptual design. Thus, the development of new high power gyrotrons may be required for the utilization of top launch ECCD. In addition, this concept is sensitive to changes of the operating region, especially the magnetic field, which can move the location of the resonance layer. For reactors, the operating region is generally fixed, so this sensitivity is not a problem, and the launcher can be very simple (e.g., with fixed angles) and very well aligned with the overall objectives of the engineering design (e.g., minimal space on first wall, no moving parts, excellent neutron shielding, minimal mechanical support). However, the specifics of the EC launcher and the compatibility and integration of the EC launcher with the structures in the top of the vacuum vessel (i.e., structures near the divertor) are not assessed yet. These issues need to be studied using a DIII-D ECCD installation to bring the top launch ECCD technique to TRL6.

Regarding international interests, as previously described, the top launch ECCD concept has been adopted in the on-going CFETR design. Additionally, Korea Superconducting Tokamak Advanced Research has proposed installing top launch ECCD.

REFERENCES