Doubling the Efficiency of Off-Axis Current Drive Using Reactor-relevant ‘Top Launch ECCD’ on the DIII-D Tokamak

by
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Steady-State Advanced Tokamak (AT) Operation Requires Efficient Off-Axis Current Drive

- Off-axis current drive is needed to achieve the broad “AT” current profile favorable for stability and transport
  - High CD efficiency ($\xi_{CD}$) is needed for high fusion gain \( \Rightarrow Q = \frac{P_{fus}}{P_{aux}} \sim \xi_{CD} \)

- Efficient methods of off-axis current drive need to be demonstrated in ongoing fusion experiments
  - Top launch ECCD is one of the reactor-relevant techniques being developed on DIII-D to efficiently drive current at the right location
Doubling of Off-axis ECCD Achieved on DIII-D via Reactor-relevant ‘Top Launch ECCD’ Approach

- New top launch ECCD system is installed on DIII-D to allow experimental validation
- Experiments tested main tenets of top launch ECCD
  - Geometry allows selective wave interaction with high $V_{\parallel}$ electrons having high CD efficiency
  - Long absorption path compensates for inherently weak damping at high $V_{\parallel}$
Outline

• What’s top launch ECCD?

• Longer absorption zone with top launch ECCD

• Strong damping on high $v_{||}$ electrons

• Significantly higher off-axis ECCD measured on DIII-D

• Top launch ECCD for reactors
Top Launch ECCD injects EC wave$^1$: 

1. nearly parallel to the resonance plane
   - longer absorption path arises from EC trajectory that gradually approaches the resonance

2. with strong toroidal steering
   - increased Doppler shift ensures EC wave power is absorbed by higher energy (less collisional) electrons throughout long interaction zone

3. on HFS of the plasma
   - reduce trapping effects (reduce the cancellation of Ohkawa counter current)

4. either O1 or X2-mode
   - Strongly absorbed for Te>1 keV

1 R. Prater, et al., APS (2012); E. Poli, et al., NF 53 (2013) 013011
2 Xi Chen, et al., EPJ Web of Conferences, 203, 01004 (2019)
Important high density heating experiments have been done on TCV tokamak using top launch ECH\(^1\)

- Launch EC wave with nearly zero toroidal steering
- Use X3 to heat high density (> X2 cutoff) plasmas
- Current drive not studied

\(^1\) S. Alberti, et al, NF 45 (2005) 1224
• **New top launcher can be switched into existing waveguide**
  - Dedicated gyrotron is not needed
  - 2\textsuperscript{nd} harmonic X-mode damping
  - 117.5 or 110 GHz gyrotron can be used
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EC source and $T_e$ response are related through Fourier-transformed energy conservation equation. In high frequency limit,

$$\tilde{S}_{ECH} = \frac{3\pi}{4} \omega_M n_e \tilde{T}_e$$

$T_e$ response measured by Electron Cyclotron Emission (ECE) with high spatial and temporal resolution.

Experiments utilized various gyrotron modulation frequencies ($\omega_M$).
Measured Power Deposition of Top Launch ECCD Generally Agrees with TORAY and CQL3D Predictions

- Ray tracing code TORAY models the Gaussian EC beam using a number of rays.

- Quasi-linear Fokker-Planck CQL3D code calculates bounce-averaged electron distribution function and velocity-space fluxes.

- Good agreement found between experimental and theoretical locations of top launch EC absorption.

- Measured EC power deposition profile is in better agreement with theory for higher modulation frequencies (weaker transport effects).
Broader Power Deposition Profile of Top Launch Confirms the Predicted Longer Absorption Zone

- Theory predicts a longer absorption path for top launch, a result of EC waves approaching the resonance more gradually than for conventional outside launch.
- Along ray path, the FWHM of EC power deposition profile measured by ECE is ~3x longer for top launch than outside launch ECCD.

110 GHz Gyrotron

TORAY

Experiments

11.6 cm

29.4 cm

110 GHz Gyrotron
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Top Launch ECCD Wave Interacts with Higher $V_{||}$ Electrons for Lower Magnetic Fields

- Magnetic field ($B_t$) is scanned with fixed-injection to move the cold resonance location closer to or further away from the EC trajectory.

- With fixed-injection, varying the magnetic field alters the wave-electron interactions in velocity space:
  - Lower $B_t$ pushes resonance to higher $V_{||}$
    \[
    \omega - \omega_{ce}/\gamma = k_{||}V_{||} \quad \text{where} \quad \omega_{ce} \propto B
    \]
  - Wave-Electron interaction follows

CQL3D calculations

Higher $V_{||}$ electrons
Measured absorption fraction decreases with lower $B_t$ (higher $V_{||}/V_t$), in agreement with TORAY, when the damping on tail electrons is too weak.

Since higher energy electrons drive current more efficiently, there is an optimum (optimal $B_t$) for top launch ECCD:

- High $V_{||}/V_t$ electrons + sufficient absorption $\rightarrow$ High ECCD efficiency
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Larger Change in MSE Pitch Angles Observed for Top Launch Than For Outside Launch ECCD

- Motional Stark effect (MSE) polarimetry measures vertical component of magnetic field (Bz) as a function of plasma radius.

- Change in MSE signal compared to similar “no ECH” discharge shown.
ECCD Profile Determined from Difference Between Oblique Launch and Radial Launch

• Non-inductive current drive determined using Ohm’s law:
  \[
  J_{\text{NI}} = J_\| - \sigma_{\text{neo}} E_\|
  \]
  \[
  E_\| \sim \frac{1}{R_0} \frac{\partial \psi}{\partial t}
  \]
  neoclassical conductivity

• Pure heating effect eliminated by
  \[
  J_{\text{EC}} = J_{\text{NI}} (\text{ECCD}) - J_{\text{NI}} (\text{ECH})
  \]

• Two analysis methods used:
  A determining $J_\|$ and $E_\|$ from equilibrium reconstruction with MSE data
  ➢ narrow ECCD profile measured by using $\cos^2(k\psi)$ term in current reconstruction
  
  B determining $J_\|$ and $E_\|$ directly from MSE data
  ➢ direct application of Ampere’s and Faraday’s laws to $B_z$ profile

Measured Off-axis Current Profile via Top Launch ECCD is Generally Consistent with Theoretical Prediction

Loop voltage analysis for MSE EFITs with local $\cos^2(k\psi)$ representation

![Graph showing J_EC vs. \rho for different simulations and experimental data.]

- CQL3D÷2
- TORAY÷2

ELMing H-mode plasma, $I_p = 0.6$ MA, $T_e(0) = 3.3$ keV, $n_e = 1.7 \times 10^{19}$ m$^{-3}$

Direct MSE analysis method

![Graph showing \rho vs. \rho for 117.5 GHz and 110 GHz gyrotrons.]

- Experiment
- TORAY

ELMing H-mode plasma, $I_p = 0.6$ MA, $T_e(0) = 2.5$ keV, $n_e = 1.7 \times 10^{19}$ m$^{-3}$
Integrated ECCD Magnitude in Good Agreement with Theory

![Graph showing the comparison between experimental and theoretical $I_{EC}$ values. The graph includes data points for Top launch and Outside launch with error bars. The x-axis represents $I_{EC}$ from TORAY (kA), and the y-axis represents $I_{EC}$ from Experiment (kA). The line of best fit is also shown.]
For Top Launch, Highest ECCD Predicted for Optimal Tail Electron Absorption

- TORAY modeling of typical DIII-D ‘AT’ plasma predicts highest ECCD with absorption < 100%

High $V_\parallel/V_t$ electrons + sufficient absorption $\rightarrow$ High ECCD efficiency

Based on shot 147634, using 117.5 GHz gyroton
Highest ECCD via Top Launch Obtained for Bt Optimized for Sufficient Damping on Tail Electrons

Absorption

ELMing H-mode plasma $\langle I_p \rangle = 0.6$ MA, $\langle T_e(0) \rangle = 2.3$ keV, $\langle n_e \rangle = 1.5 \times 10^{19}$ m$^{-3}$

110 GHz Gyrotron
Greatly Enhanced ECCD at Mid-Radii Observed via Top Launch ECCD Compared to Outside Co-ECCD Launch

Loop voltage analysis for MSE EFITs with local $\cos^2(k\psi)$ representation

ELMing H-mode plasma, $I_p = 0.6$ MA, $T_e(0) = 2.3$ keV, $n_e = 1.6 \times 10^{19}$ m$^{-3}$

ELMing H-mode plasma, $I_p = 0.6$ MA, $T_e(0) = 3.0$ keV, $n_e = 1.8 \times 10^{19}$ m$^{-3}$
Direct MSE Analysis Confirms ECCD is More than Double for Top Launch, Consistent with TORAY and CQL3D

ELMing H-mode plasma, $I_p = 0.6$ MA, $T_e(0) = 3.5$ keV, $n_e = 1.9 \times 10^{19}$ m$^{-3}$. $P_{EC} = 0.60$ MW

Gyrotron

<table>
<thead>
<tr>
<th>ECCD (kA/MW)</th>
<th>Top launch</th>
<th>LFS co-ECCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>70</td>
<td>25</td>
</tr>
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<td>TORAY</td>
<td>63</td>
<td>27</td>
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<tr>
<td>CQL3D</td>
<td>68</td>
<td>31</td>
</tr>
</tbody>
</table>

117.5 GHz
EC Wave via Top Launch Interacts with Higher $V_{||}$ Electrons, Farther From Trapping Boundary

CQL3D calculations at peak current drive

- **Outside co-ECCD**
- **Top launch ECCD**
CQL3D calculations at peak current drive

RF flux contour

Outside co-ECCD

Top launch ECCD

#179169
#179173
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Two New Top Launch Lines Planned in DIII-D to Advance Towards High-$\beta$ AT Scenario Physics Goals

- Most DEMO design studies (e.g. Aries-AT, ACT1, CAT-DEMO) operate at $\beta_N=4$-6, $q_{95}=4$-6
- Traditional approach with outside launch 110 GHz gyrotrons predicted to require 6+ MW for DIII-D to reach target range of DEMO designs

FASTRAN Modeling: Steady State Highest Stable $\beta_N$

\[ \begin{align*}
\beta_N & \quad q_{95} = 5.2 \\
\beta_N & \quad q_{95} = 6.0 \\
\beta_N & \quad q_{95} = 6.9
\end{align*} \]

1 J.M. Park, et al., POP 25 (2018) 012506
Two New Top Launch Lines Planned in DIII-D to Advance Towards High-\(\beta\) AT Scenario Physics Goals

- Most DEMO design studies (e.g. Aries-AT, ACT1, CAT-DEMO) operate at \(\beta_N=4-6\), \(q_{95}=4-6\)

- Traditional approach with *outside launch* 110 GHz gyrotrons predicted to require 6+ MW for DIII-D to reach target range of DEMO designs\(^1\)

- Instead, apply the same power using ~2x more efficient top launch, broader \(j\), higher \(\beta_N\), lower \(q_{95}\) can be accessed
  
  - Nearly the same performance with 3 MW TOP as 6 MW OUTSIDE
  - 3 MW TOP 117.5 GHz + 3 MW OUTSIDE

  110 GHz would be a reasonable alternative to 9 MW OUTSIDE

- Two new top launch installations planned: first in FY22 campaigns

\(^1\) J.M. Park, et al., POP 25 (2018) 012506
Predictions for FNSF-AT, DEMO, CFETR Suggest Substantial Improvement in Efficiency via Top Launch ECCD

- Studies of many tokamak reactors show current drive around $\rho \sim 0.5-0.7$ is required for steady-state AT regime

- Modeling for FNSF-AT shows > 50% higher off-axis CD efficiency for top launch ECCD\textsuperscript{1}, similarly for DEMO\textsuperscript{2}

- 35% improvement in ECCD efficiency at $\rho \sim 0.5$ found in initial modeling for CFETR baseline scenario\textsuperscript{3}

Doubling of Off-axis ECCD Achieved on DIII-D via Reactor-relevant ‘Top Launch ECCD’ Approach

- New top launch ECCD system installed on DIII-D to test this high-ECCD-efficiency approach

- Experiments validated main tenets of top launch ECCD
  - Geometry allows selective wave interaction with high $V_{||}$ electrons yielding high CD efficiency
  - Long absorption path compensates for inherently weak damping at high $V_{||}$
  - Highest ECCD efficiency for optimal absorption on high $V_{||}$ tail electrons

- Simulations of FNSF-AT, DEMO and CFETR support top launch ECCD as an improved efficiency off-axis current drive technique for future reactors