Localized Electron Cyclotron Current Drive in DIII–D: Experiment and Theory

by
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SCIENTIFIC UNDERSTANDING IS ESSENTIAL FOR ECH AND ECCD TO BE ACCEPTED

- Due to its potential for generating localized off-axis current, electron cyclotron current drive (ECCD) is proposed
  - To sustain hollow current profile in advanced tokamak (AT) discharges
  - To suppress neoclassical tearing modes (NTM)
FOR STEADY STATE ADVANCED TOKAMAK, NON-INDUCTIVE CURRENT NEEDS TO BE SUPPLIED AT THE HALF RADIUS

- Analysis of high performance DIII-D discharge with $\beta_N H_{89} \sim 10$ for $5 \tau_E$
- $E_{||}$ measured; with assumption of neoclassical conductivity, gives $J_{OH}$
- ECCD at the half radius need to be supplied for steady-state
NEOCLASSICAL MHD INSTABILITIES CAN DEGRADE PERFORMANCE BELOW IDEAL $\beta$-LIMIT

$\beta_N$ increases with time as the 23 MW NBI is applied, reaching a peak and then decreasing.

DD neutron rate shows a peak at around 4.5 s.

$\frac{d\beta}{dt}$ (outside plasma) indicates a mode with $m/n = 3/2$.

- ECCD replaces missing bootstrap current to suppress NTM

Z. Chang
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  - To sustain hollow current profile in advanced tokamak (AT) discharges
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- This talk will discuss results from recent study of ECCD in the DIII–D tokamak
  - To demonstrate controllable localized off-axis ECCD
  - To validate wave optics and ECCD physics
CYCLOTRON RESONANCE LEADS TO LOCALIZED POWER DEPOSITION AND CURRENT GENERATION

- Cyclotron resonance and Doppler shift: \( \omega - \ell \omega \gamma - k_{||} v_{||} = 0 \)

\[\Delta \Omega \text{ (half-width)} \sim 1.7\degree\]

\[\phi \text{ (Toroidal injection angle)} \sim 27\degree\]
LONGER COLLISION TIME AT HIGHER ENERGY IS A KEY FOR CURRENT GENERATION

- Fisch-Boozer current drive mechanism

\[ \delta v_\perp \]

\[ v_{\parallel 0} \quad v_{\parallel} \]

\[ e^{-\frac{t}{\tau_e (v + \delta v)}} \]

\[ e^{-\frac{t}{\tau_e (v)}} \]
TRAPPING EFFECTS IN TOROIDAL GEOMETRY REDUCE ECCD EFFICIENCY

- Fisch-Boozer current drive mechanism
- Electron trapping effects in toroidal geometry (Ohkawa effect)
FOKKER-PLANCK CODE IS THE STANDARD THEORETICAL MODEL FOR ECCD

- Quasi-linear Fokker Planck Equation

\[ \mathbf{v}_\parallel \cdot \mathbf{b} \cdot \nabla f - C_{e}f = S_{rf}(f) - \frac{e}{m} E_\parallel \frac{\partial f}{\partial u_\parallel} \]

- Bounce average

\[ -C_{e}f = S_{rf}(f) - \frac{e}{m} E_\parallel \frac{\partial f}{\partial u_\parallel} \]

- Linearized equation + Green’s function techniques

\[ f \cong f_M + f_{rf} + f_E \]

- Modeling Tools

1. ONETWO/TORAY-GA
   - Raytracing based on cold plasma dispersion
   - Weakly relativistic absorption
   - Cohen’s CD package (linear)
   - GA new CD package (linear)

2. CQL3D (2-velocity + 1 radial)
   - Fokker Planck code
   - \( E_\parallel \) effects included
DIII-D HAS A FLEXIBLE ECH SYSTEM

- New steerable launcher (PPPL) has between-shot toridal and poloidal steering capability
- The experimental results described here use two gyrotrons with up to 1.3 MW injection power
- The system has flexibility for experimental setup to test theory
MSE MEASUREMENTS ARE CRUCIAL FOR DETERMINATION OF ECCD PROFILE

- MSE (motional Stark effect) diagnostic measures magnetic field pitch angles at different major radii, so $B_Z = B_t \tan^{-1}$ (pitch angle)

- From Ampere’s law $j_\phi \approx -\frac{1}{\mu_0} \frac{\partial B_Z}{\partial R}$

so the local change in $j_\phi$ due to ECCD is proportional to the change in $\Delta B_Z/\Delta R$, where $\Delta B_Z$ is the difference in $B_Z$ between adjacent MSE channels and $\Delta R$ is the spatial separation

- The measured $\partial B_Z/\partial R$ are compared to simulations to include the effects of small changes in bootstrap, NBCD, and Ohmic currents

- Total driven current is determined from a best statistical fit to the data, varying the location, width, and magnitude of the driven current in the simulation
### LOOP VOLTAGE ANALYSIS AND MSE SIMULATION APPROACH
**ARE COMPLEMENTARY FORMS OF CURRENT DRIVE ANALYSIS WITH DIFFERENT STRONG AND WEAK POINTS**

<table>
<thead>
<tr>
<th>Loop voltage analysis:</th>
<th>Better for extended current drive sources</th>
<th>Inductive and non-inductive currents are separated</th>
<th>MSE data is used only as fit constraint for EFIT</th>
<th>No assumptions about current drive sources are needed</th>
<th>But</th>
<th>Current profile shapes are limited by EFIT basis functions</th>
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<td>MSE simulation approach:</td>
<td>Better for localized current drive sources</td>
<td>Only net change in current density is analyzed</td>
<td>Raw (or slightly manipulated) MSE data are utilized</td>
<td>A specific current drive model must be assumed</td>
<td>But</td>
<td>Model parameters can be varied to find best fit to MSE data</td>
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MSE MEASUREMENTS SHOW THAT THE INCREASE IN CURRENT DENSITY FROM ECCD IS AS LOCALIZED AS RAY TRACING CALCULATIONS PREDICT
ELECTRON CYCLOTRON CURRENT DRIVE PROVIDES LOCALIZED CURRENT WITH GOOD CONTROL

- Observed changes in MSE signals consistent with ray tracing calculations

![Diagram showing Experimental Profiles of $\Delta J_{\text{tot}}$](image)
MEASURED ECCD FROM MSE DATA IS IN GOOD AGREEMENT WITH FOKKER-PLANCK CODE INCLUDING $E_{\parallel}$ EFFECT
MEASURED ECCD INCREASES WITH TOROIDAL INJECTION ANGLE (i.e., $N_{||}$) IN AGREEMENT WITH THEORY EXCEPT FOR THE LARGEST ANGLES.
ECCD EFFICIENCY DECREASES WITH RADIUS (FOR POLOIDAL ANGLE $\approx 90$ deg) AS EXPECTED FROM THEORY DUE TO TRAPPING EFFECTS

$\zeta = \frac{e^3}{\varepsilon_0^2} \frac{I_{ec} n_e R}{P_{ec} T_e}$

- Anomalously high ECCD is observed at largest radius
- Need to verify this at higher ECH power with smaller error bars
FINITE COLLISIONALITY ALLOWS FOR TRAPPING–DETRAPPING PROCESSES

- Effects are more significant at low energies

**Diagram Description**

- **Trapped Electrons (Carry no current)**
  - Located within the shaded region

- **Boundary Layer Electrons (Carry current)**
  - Located on the boundary of the shaded region

- **Wave-Particle Interaction**
  - Arrows indicating the interaction path

- **Cyclotron Resonance**
  - Path highlighted in red

- **Axes**
  - $U_\perp$, $U_0$, $U_\parallel$
Collisionality enhancement of efficiency is appreciable in the off-axis ECCD cases.

- Green's function formulation is extended to calculate ECCD efficiency in finite collisionality regime.

- Lorentz gas model is used to simplify numerical calculations.

- Appreciable enhancement is possible in parameter regimes of the off-axis ECCD experiments:
  - $\omega \approx 2\omega_c$, $n_\parallel = 0.5$
  - $T_e \approx 1.0$ keV, $v_{e*} \approx 0.1$

Enhancement of ECCD efficiency is proportional to $\sqrt{v_{e*}}$. 
LOCALIZED CHANGE IN CURRENT PROFILE DURING ECCD IS CLEARLY OBSERVED IN ELMING H–MODE PLASMAS

![Graph showing localized change in current profile during ECCD](image_url)

- **Major Radius (m)**: 1.6, 1.8, 2.0, 2.2
- **Time (ms)**: 0, 1000, 2000, 3000, 4000
- **Electron Cyclotron Current Drive (ECCD)**

**Note:**

- **D$\alpha$ ECH**
- **SAN DIEGO NATIONAL FUSION FACILITY**

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**Legend:**

- **ECCD (TORAY – GA)**
- **Magnetic Axis**
ECH IS EFFECTIVE AT HEATING ELECTRONS

- 0.8 MW ECH applied at $\rho \sim 0.4$; no NBI
- Measurement of $T_e \approx 15$ keV by ECE roughly supported by Thomson scattering and pulse height analysis

![16 Channels of ECE](image)
SUMMARY

- Localized off-axis ECCD was clearly demonstrated in recent proof-of-principle experiments on DIII–D using the MSE simulation approach.

- Good agreement was observed between the measured ECCD and the theoretical predictions from coupled ray tracing and Fokker-Planck calculations.

- Improved EFIT reconstruction coupled with loop voltage analysis shows promise for directly determining localized ECCD.

- The present study provided a scientific basis for ECCD applications in Advanced Tokamak (AT) operations.
RELATED PRESENTATIONS AT THIS CONFERENCE

- W.R. Fox, HP1.067 (ECCD)
- L.L. Lao, NP1.079
- C.C. Petty, NP1.080
- R.W. Harvey, NP1.081
- J.M. Lohr, MO1.005 (ECH system)
- R. Prater, M01.006 (ECH and ECCD)
- R.J. La Haye, NP1.091 (NTM stabilization)
- F.W. Perkins, NP1.092
- E.J. Strait, MO1.003
- C.M. Greenfield GP1.112 (ITP)
POLOIDAL SCANS SHOW SYSTEMATIC INCREASE IN ECCD EFFICIENCY TO HIGH FIELD SIDE

- Theoretically the increase in ECCD efficiency with poloidal angle is due to (a) reduced trapping effects and (b) wave absorption on higher energy elections from $N_\parallel$ upshift.

\[
\zeta = \frac{e^3}{\varepsilon_0^2} \frac{l_{ec} n_e R}{P_{ec} T_e}
\]
Radial and poloidal scans have been obtained to test the effects of trapped particles.

- \( P_{ECH} = 0.95 - 1.14 \text{ MW} \)
- \( \bar{n} = 1.66 - 1.85 \times 10^{13} \text{ cm}^{-3} \)
- \( q_{95} = 5.95 - 6.33 \)

**Radial Scan**
- Poloidal Scan \( \rho = 0.2 \)
- Poloidal Scan \( \rho = 0.34 \)
- Poloidal Scan \( \rho = 0.47 \)
THE MOTIONAL STARK EFFECT (MSE) DIAGNOSTIC MEASURES
THE CHANGES IN THE INTERNAL MAGNETIC FIELDS DURING ECCD

Toroidal Field Coils

360/0°

15 MSE

30° Left Neutral Beam

45 MSE

1.55 m 2.0 m 2.3 m

Radial Channels

Inner wall

v_b

\( B_T \)

\( \Omega \)

\( \alpha' \)

315 MSE

2.3 m

2.0 m

1.55 m

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

NATIONAL FUSION FACILITY
SAN DIEGO

GENERAL ATOMICS

056–00/CCP/wj
CENTRAL ECCD CASES SHOW THAT EFFICIENT CURRENT DRIVE IS ACHIEVED WITH $E_{||} \approx 0$
(RELEVANT SITUATION FOR STEADY STATE ADVANCED TOKAMAKS)

- Quasilinear effects, although moderate, are required to bring theory and experiment into agreement.
OFF-AXIS ECCD TO SUSTAIN NEGATIVE CENTRAL MAGNETIC SHEAR

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