RECENT ECCD EXPERIMENTAL STUDIES ON DIII–D

by

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Presented at
28th European Physical Society Conference
on Controlled Fusion and Plasma Physics
Madeira, Portugal

June 18–22, 2001

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GENERAL ATOMICS

122-01/CCP/wj

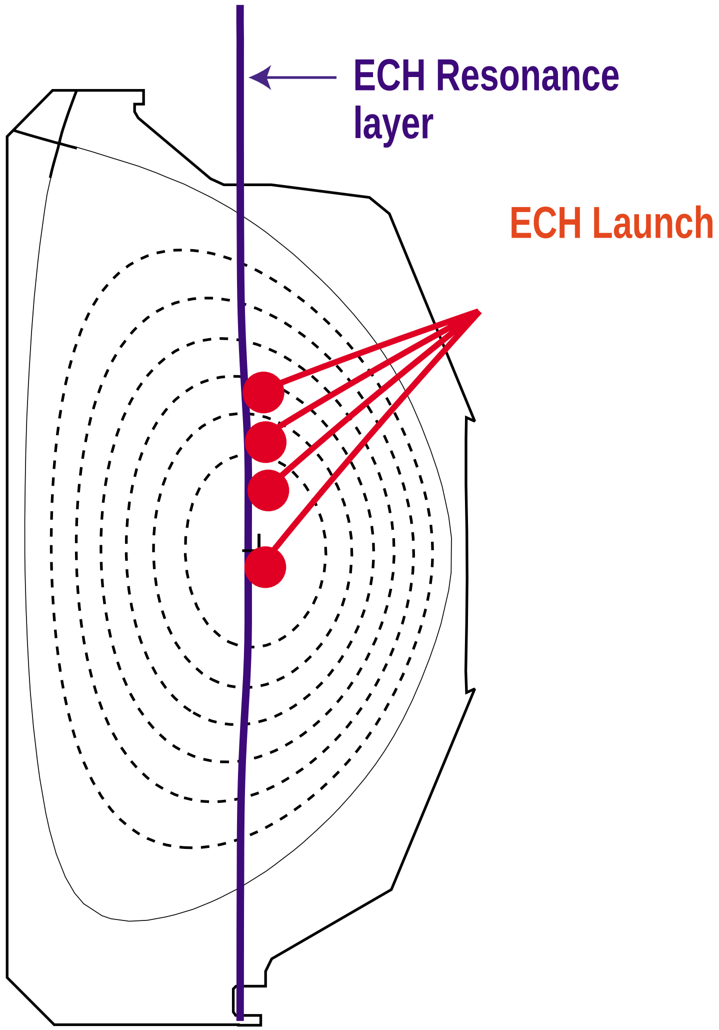
ABSTRACT

The DIII–D program is making excellent progress towards experimentally validating a predictive model of electron cyclotron current drive (ECCD). The measured ECCD is in good agreement with quasi-linear Fokker-Planck calculations over a wide range of toroidal and poloidal injection angles, although the measured counter ECCD is less than theoretically predicted. Tests of electron trapping show that the measured ECCD efficiency decreases rapidly with radius in low beta plasmas, but the ECCD efficiency does not decrease much with radius in high beta plasmas. This shows that the detrimental effects of electron trapping on the ECCD efficiency are greatly reduced at high beta (relevant for advanced tokamaks).

FEATURES OF ECH PROGRAM ON DIII–D TOKAMAK

- Experimental program uses electron cyclotron waves to
  - Probe transport properties (e.g., heat pulse propagation)
  - Control instabilities (e.g., neoclassical tearing modes)
  - Modify current profile (e.g., advanced tokamaks)
- In addition, electron cyclotron current drive (ECCD) experiments seek to validate a predictive model of ECCD

DIII–D HAS A FLEXIBLE ECH SYSTEM

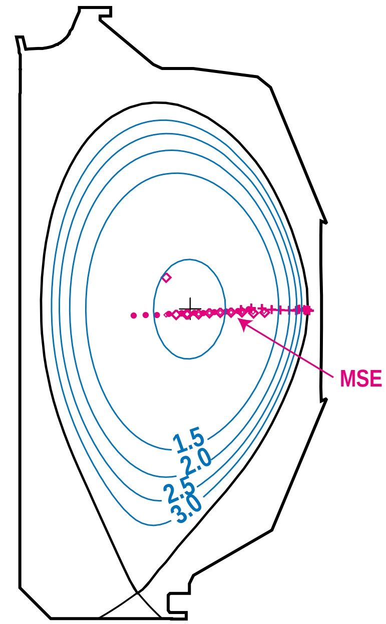


- New steerable launcher (PPPL) has between-shot toroidal and poloidal steering capability
- The experimental results described here use four gyrotrons with up to 2.1 MW injection power
- The system has flexibility in the experimental setup to test theory

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 $j_\phi \cong -\frac{1}{\mu_o}\frac{\partial B_z}{\partial R}$

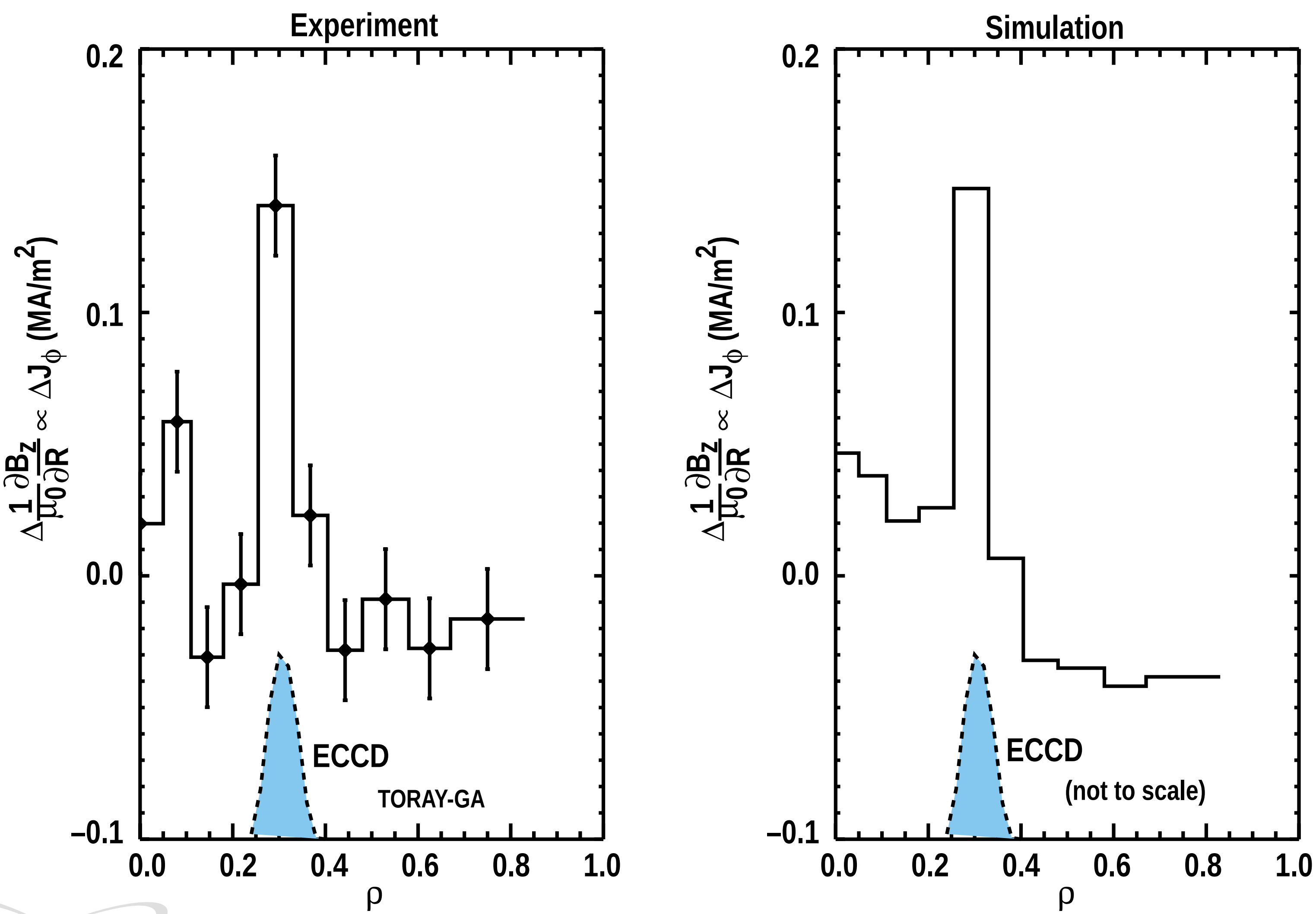


so the local change in j_ϕ due to ECCD is proportional to the change in $\Delta B_z/\Delta R$, where ΔB_z is the difference in B_z between adjacent MSE channels and ΔR is the spatial separation

- 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

MSE MEASUREMENTS SHOW THAT THE INCREASE IN CURRENT DENSITY FROM ECCD IS AS LOCALIZED AS RAY TRACING CALCULATIONS PREDICT



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THEORETICAL DEPENDENCES OF ECCD

- Using the standard theoretical current drive efficiency

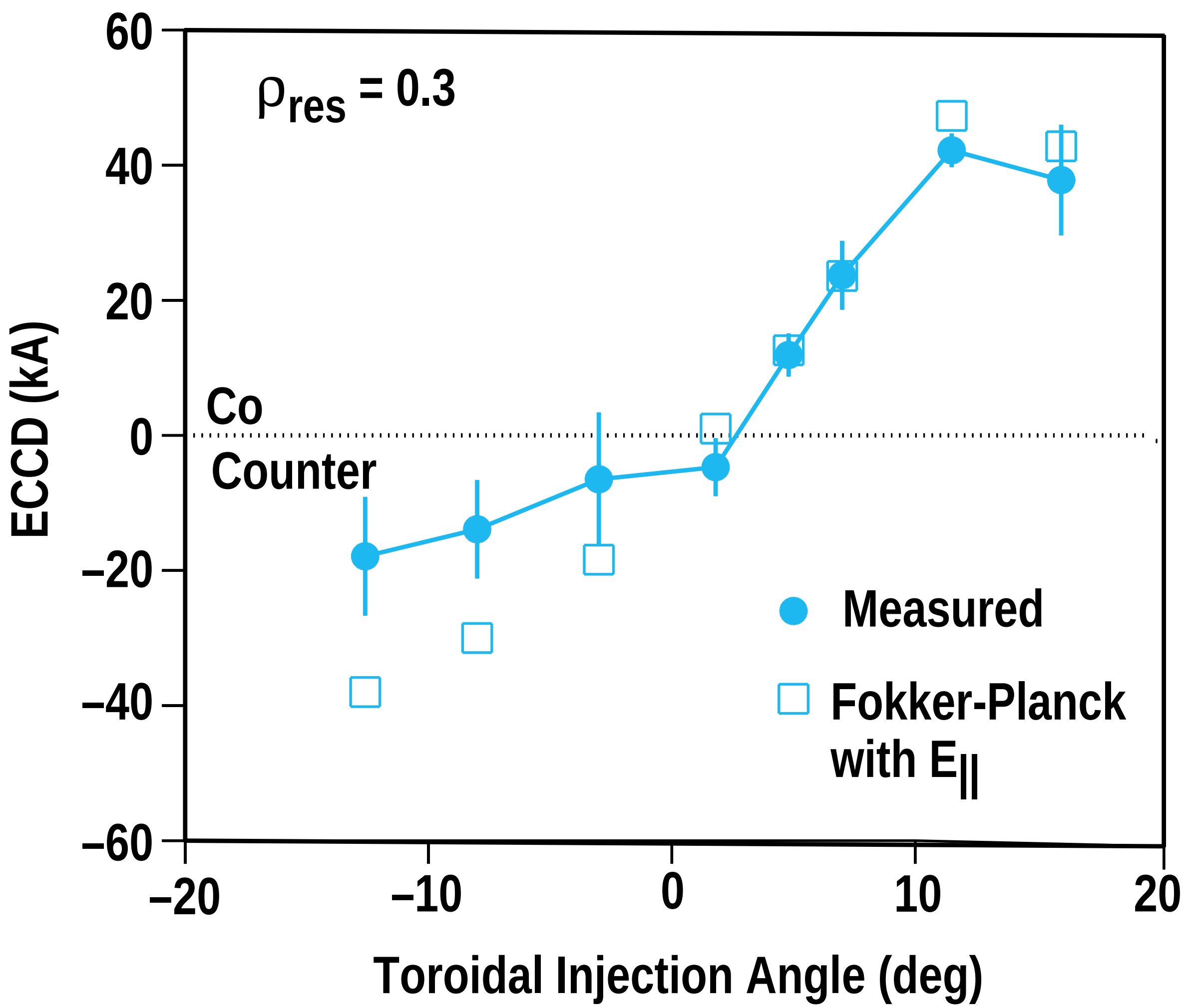
$$\frac{J_{ec}}{P_{ec}} = \frac{e\nu_e}{\upsilon_e T_e} \; F\left(N_{||}, \theta_{pol}, \rho, \beta_e, \cdots\right) ,$$

a dimensionless current drive efficiency can be derived:

$$\frac{e^3}{\varepsilon_o^2} \; \frac{I_{ec} n_e R}{P_{ec} T_e} \equiv \zeta \left(N_{||}, \theta_{pol}, \rho, \beta_e, \cdots\right)$$

- ECCD experiments on DIII–D have measured ζ as a function of
  - Parallel index of refraction ($N_{||}$)
  - Poloidal angle $\left(\theta_{pol}\right)$
  - Normalized radius (ρ)
  - Electron beta (β_e)

VARYING $N_{||}$ CLEARLY CHANGES ECCD FROM CO TO COUNTER DIRECTION, ALTHOUGH COUNTER ECCD IS BELOW THEORETICAL PREDICTIONS



- ECCD increases with $N_{||}$ since waves interact with higher parallel velocity electrons

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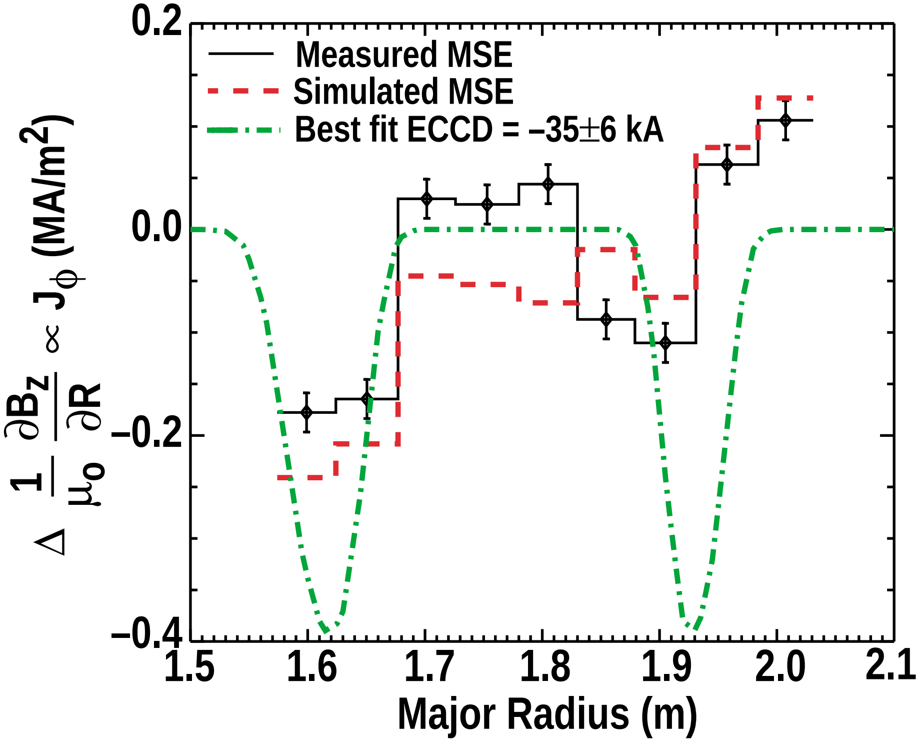
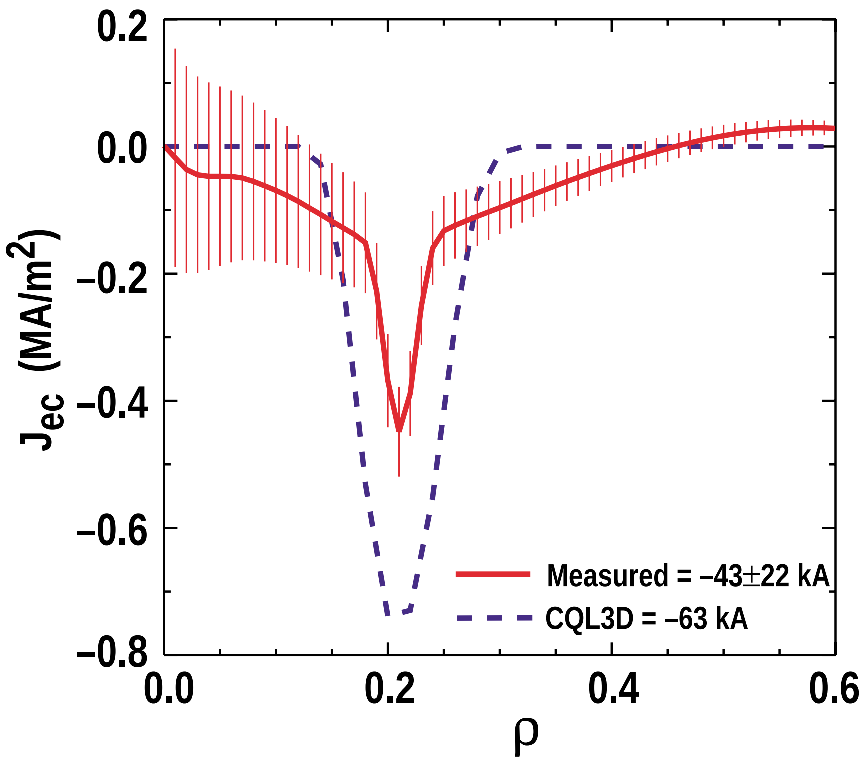
A CLOSER LOOK AT COUNTER ECCD USING TWO ANALYSIS METHODS CONFIRMS THAT THE MEASURED COUNTER ECCD IS LESS THAN PREDICTED BY 1σ OR MORE

MSE Simulation Method



Loop Voltage Analysis Method



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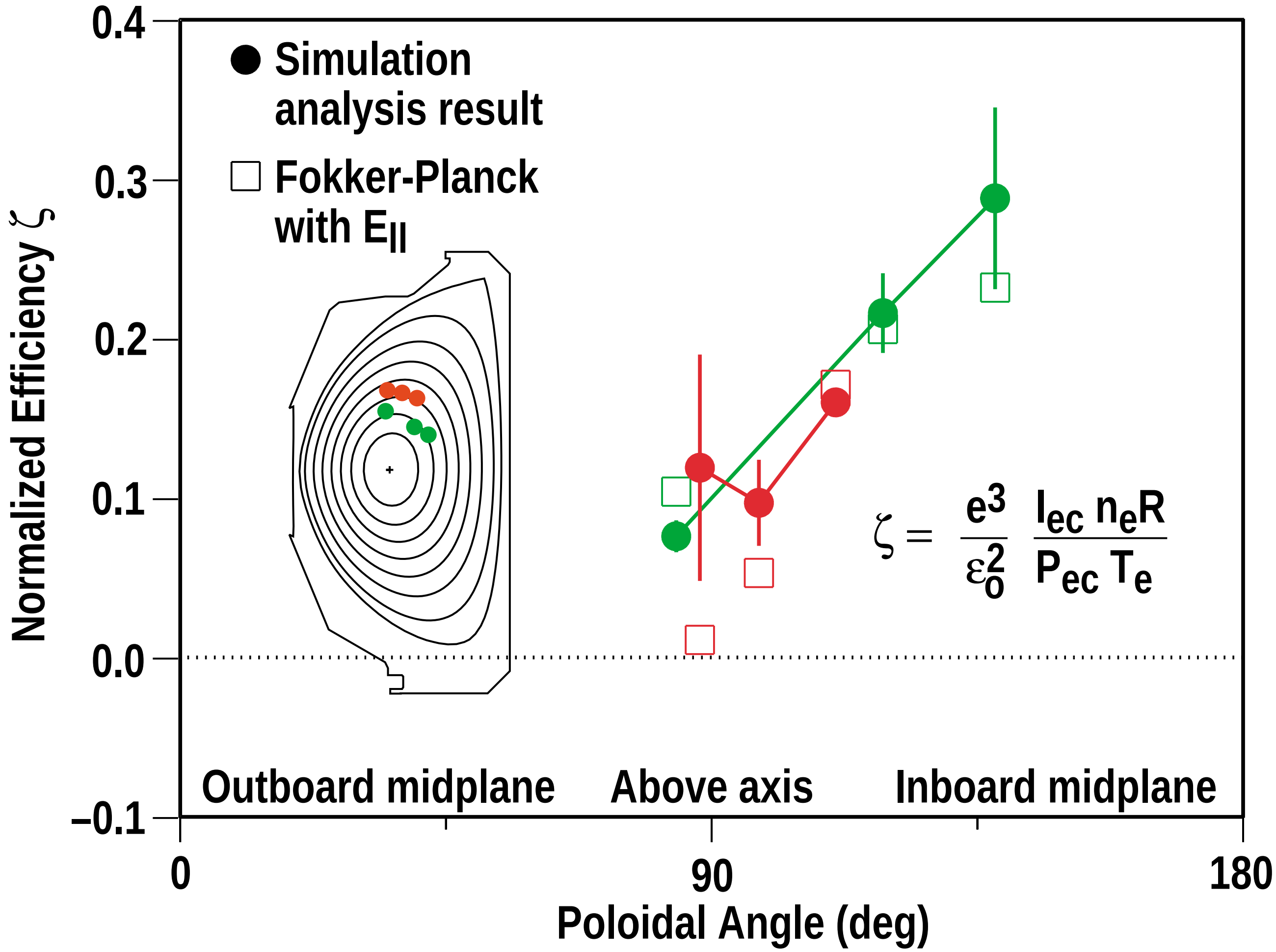
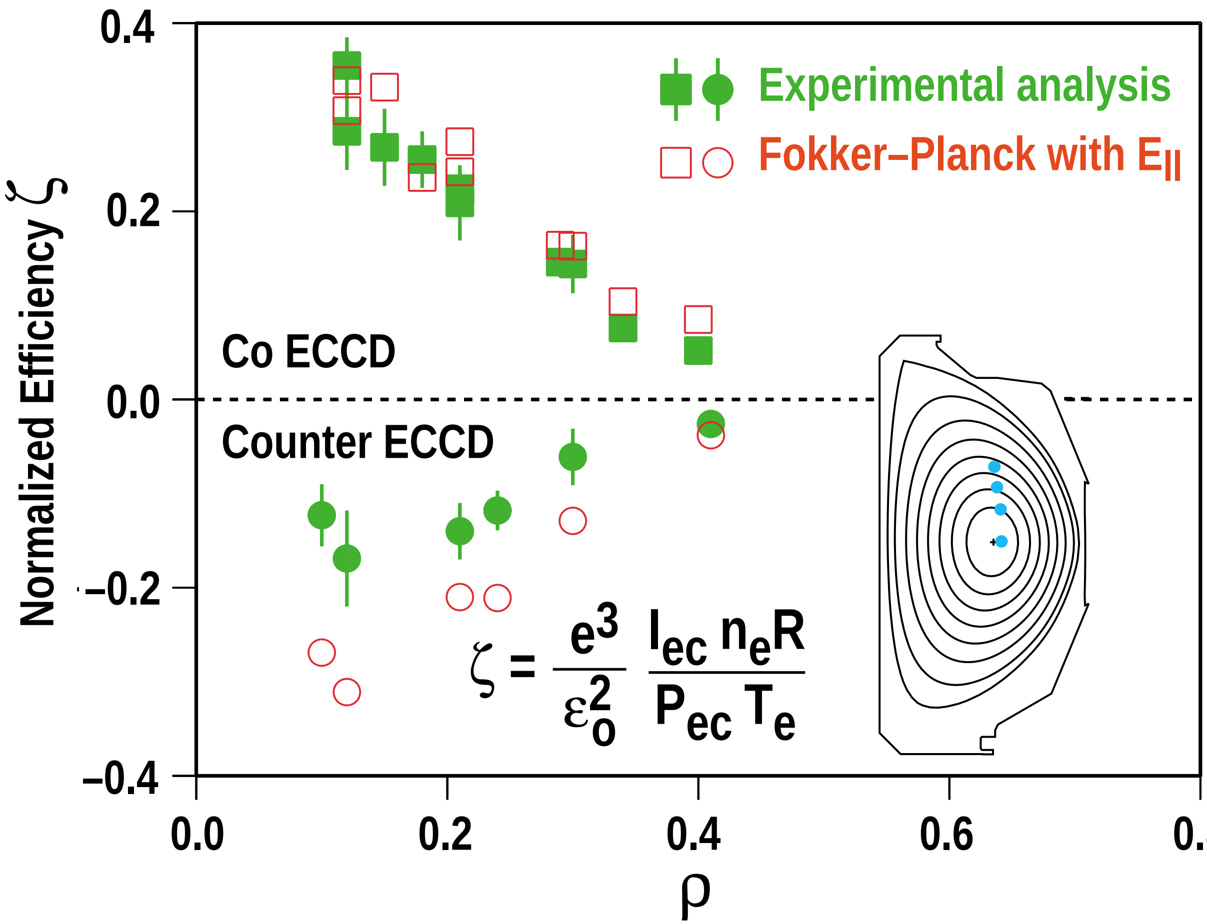
POLOIDAL SCANS SHOW SYSTEMATIC INCREASE IN ECCD EFFICIENCY TO HIGH FIELD SIDE



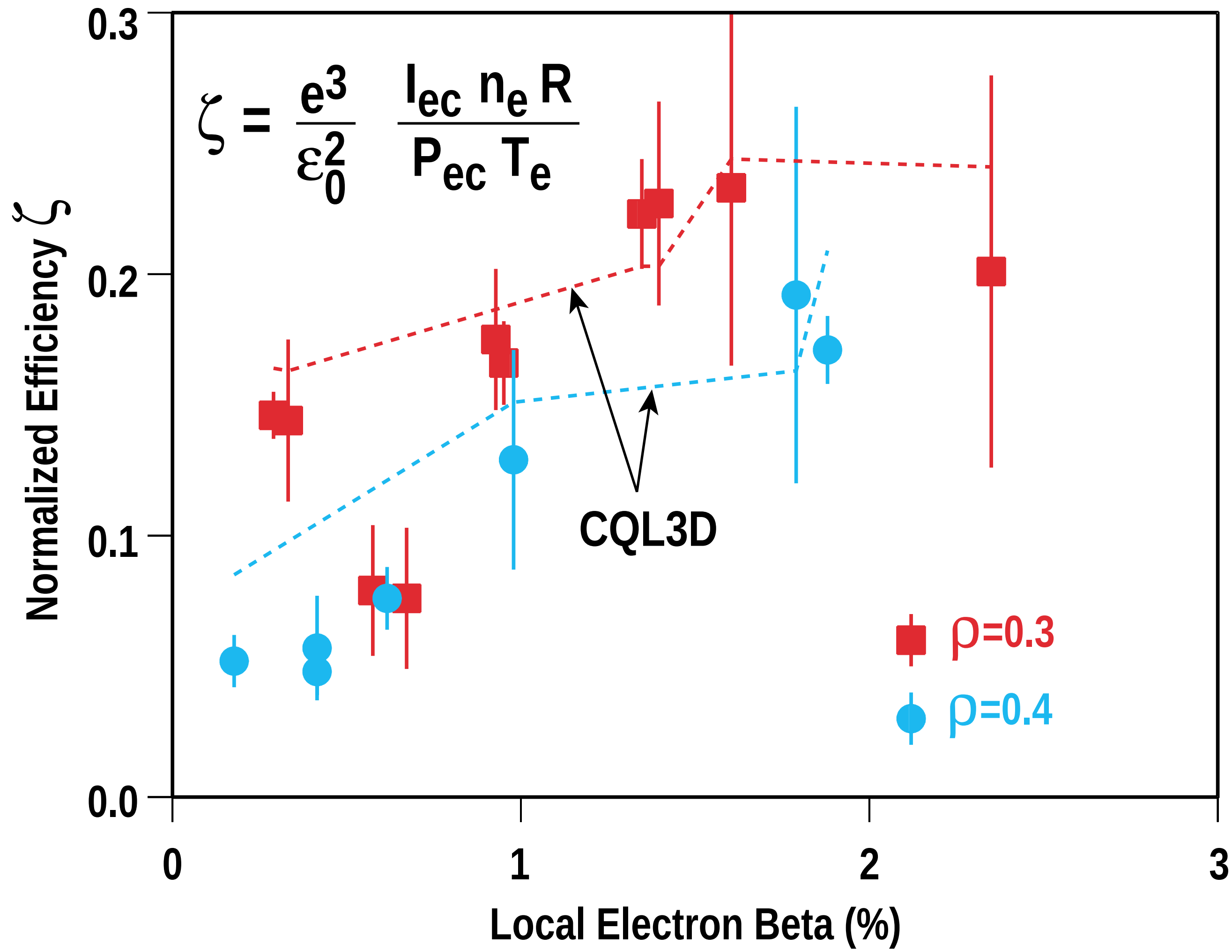
- Theoretically the increase in ECCD efficiency with poloidal angle is due to (a) reduced trapping effects and (b) wave absorption on higher energy elections from $N_{||}$ upshift

ECCD EFFICIENCY DECREASES RAPIDLY WITH RADIUS (FOR POLOIDAL ANGLE ≈ 90 deg) AS EXPECTED FROM THEORY FOR LOW BETA PLASMAS



- Fraction of trapped electrons increases with increasing radius, leading to larger electron trapping which reduces the ECCD

MEASURED OFF-AXIS ECCD EFFICIENCY INCREASES WITH ELECTRON BETA, INDICATING REDUCED TRAPPING EFFECTS



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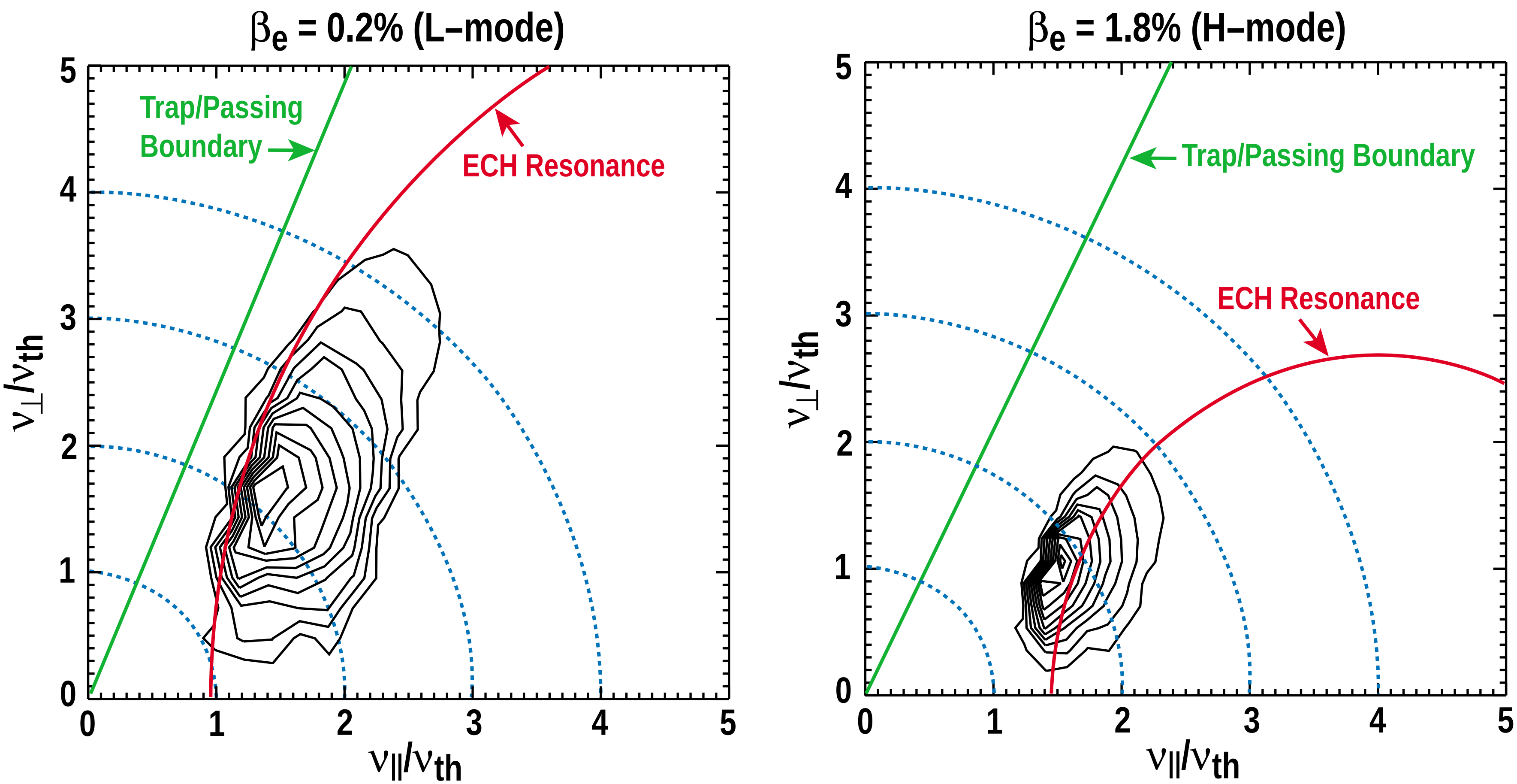
OFF-AXIS ECCD EFFICIENCY INCREASES WITH HIGHER ELECTRON BETA BECAUSE RESONANCE MOVES AWAY FROM TRAPPING BOUNDARY IN VELOCITY SPACE

- Contours of ECH driven flux in velocity space



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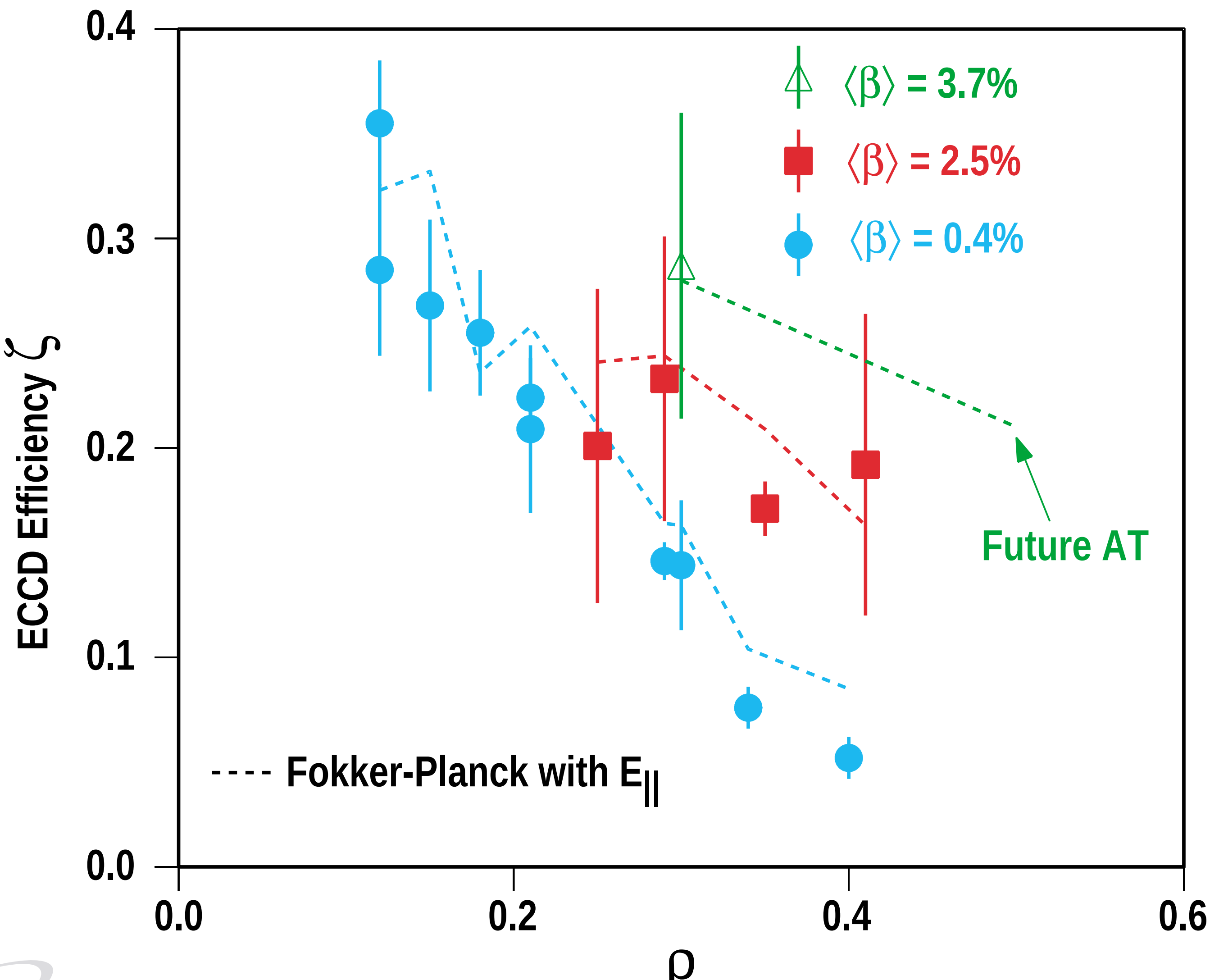
OFF-AXIS ECCD IS MORE FAVORABLE IN HIGH-β PLASMAS SINCE ECCD EFFICIENCY DOES NOT DECREASE MUCH WITH RADIUS



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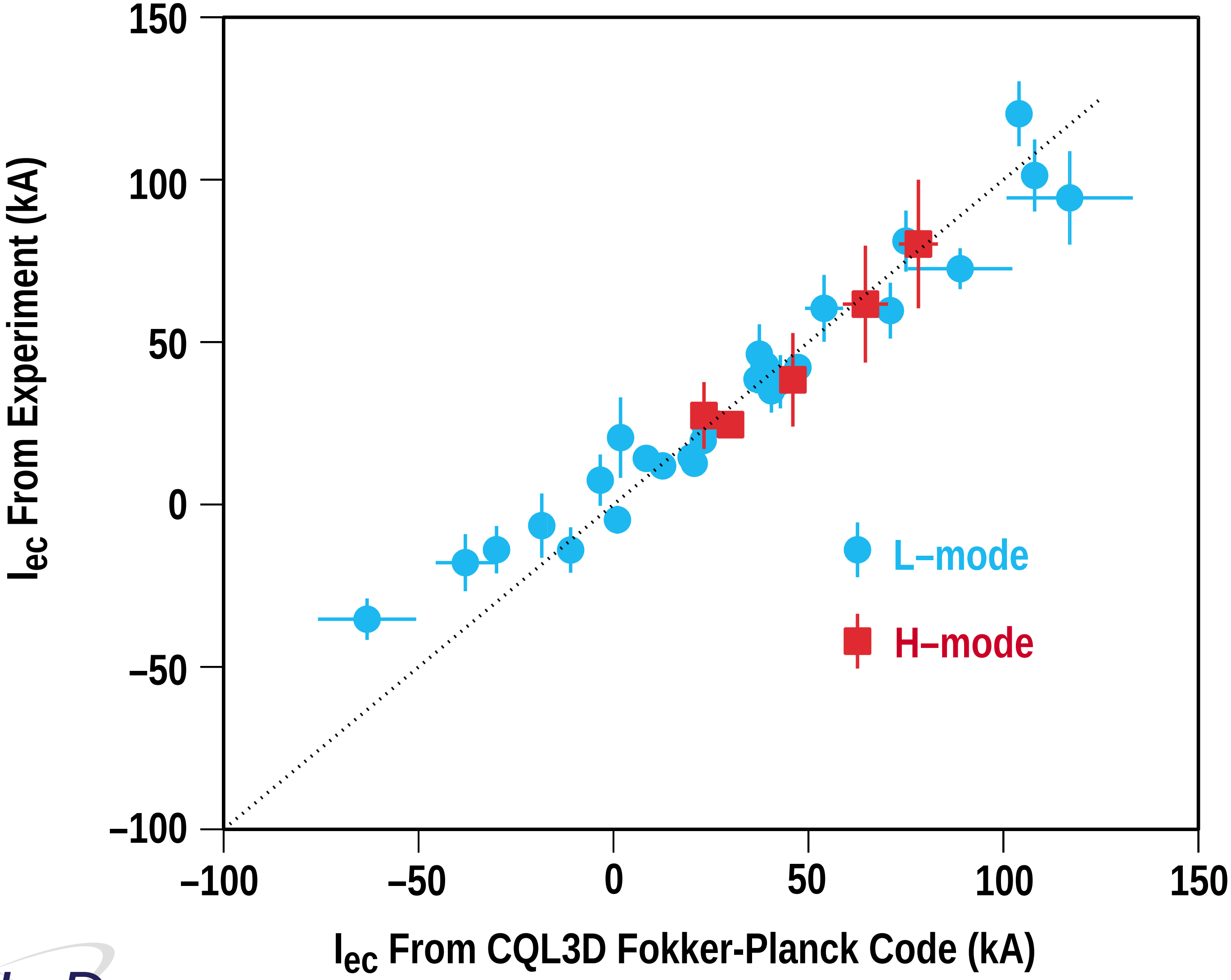
MEASURED ECCD FROM MSE DATA IS IN GOOD AGREEMENT WITH FOKKER-PLANCK CODE INCLUDING $E_{||}$ EFFECT EXCEPT FOR COUNTER ECCD



CONCLUSIONS

- For central deposition, experimental current drive figure-of-merit is

$$\gamma_{ec}\left[Am^{-2}/W\right] = 0.01 \times 10^{20} \times T_e[keV]$$

- Experimental dependence of ECCD efficiency on $N_{||}$, poloidal angle, and radius is generally in agreement with Fokker-Planck code calculations, but measured counter ECCD is lower than expected

- Measured ECCD efficiency increases with electron beta, as expected owing to reduced trapping effects

- Other posters on ECCD: P4.007 La Haye, P4.009 Wade