HIGHLY LOCALIZED ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE IN DIII–D

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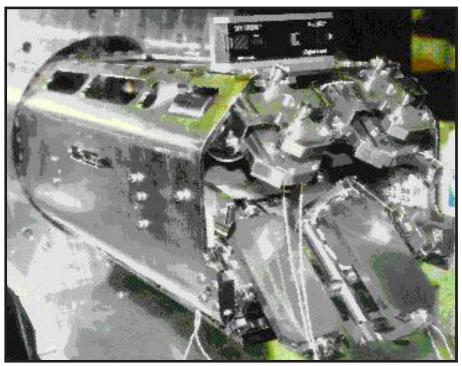
MOTIVATION FOR STUDIES OF ECCD

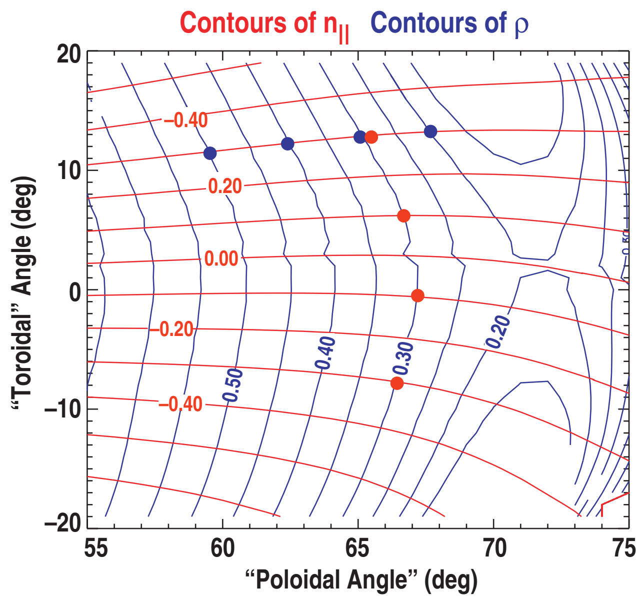
- ECCD (electron cyclotron current drive) needed for
  - Current sustainment and profile control in tokamaks — but high performance discharges have ELMs, tearing modes. . .
  - Stabilization of MHD activity in discharges which have MHD
- Need to validate the theory so codes can be predictive under realistic conditions and to take advantage of the unique localization properties of ECCD
  - MHD suppression
  - Transport barrier generation

ECH SYSTEM

- System with six 1 MW-class gyrotrons under construction
- Launchers for two gyrotrons have control of poloidal and toroidal angles (PPPL)



PPPL Launcher



CPI Diamond Window Gyrotron

- Independent scans of $n_{||}$ and ρ (magnetic well depth) are possible

- Independent control over toroidal and poloidal launch angles facilitates science (independent $n_{||}$ and ρ scans) and applications (high $n_{||}$ gives high I_{CD}, while low $n_{||}$ gives high j_{CD})

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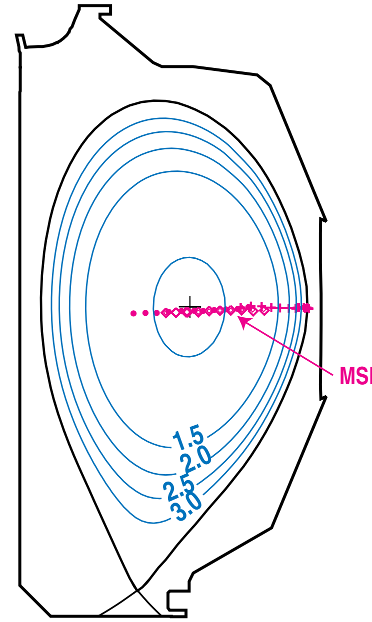
OUTLINE OF RESULTS

- Analysis of ECCD experiments shows that driven current is highly localized, in agreement with theory
  - Behavior of j_{ECCD} with magnetic trapping consistent with theory
  - Successful experimental measurement of off-axis ECCD in ELMing H–mode
- Highly localized nature of ECCD is validated in experiments showing full stabilization of neoclassical tearing modes, under conditions where direct measurement of ECCD is not possible
- Localized nature of ECH may be involved in the observed generation of a strong electron transport barrier in discharges with reversed magnetic shear

ECCD CAN BE MEASURED DIRECTLY FROM MSE SIGNALS

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

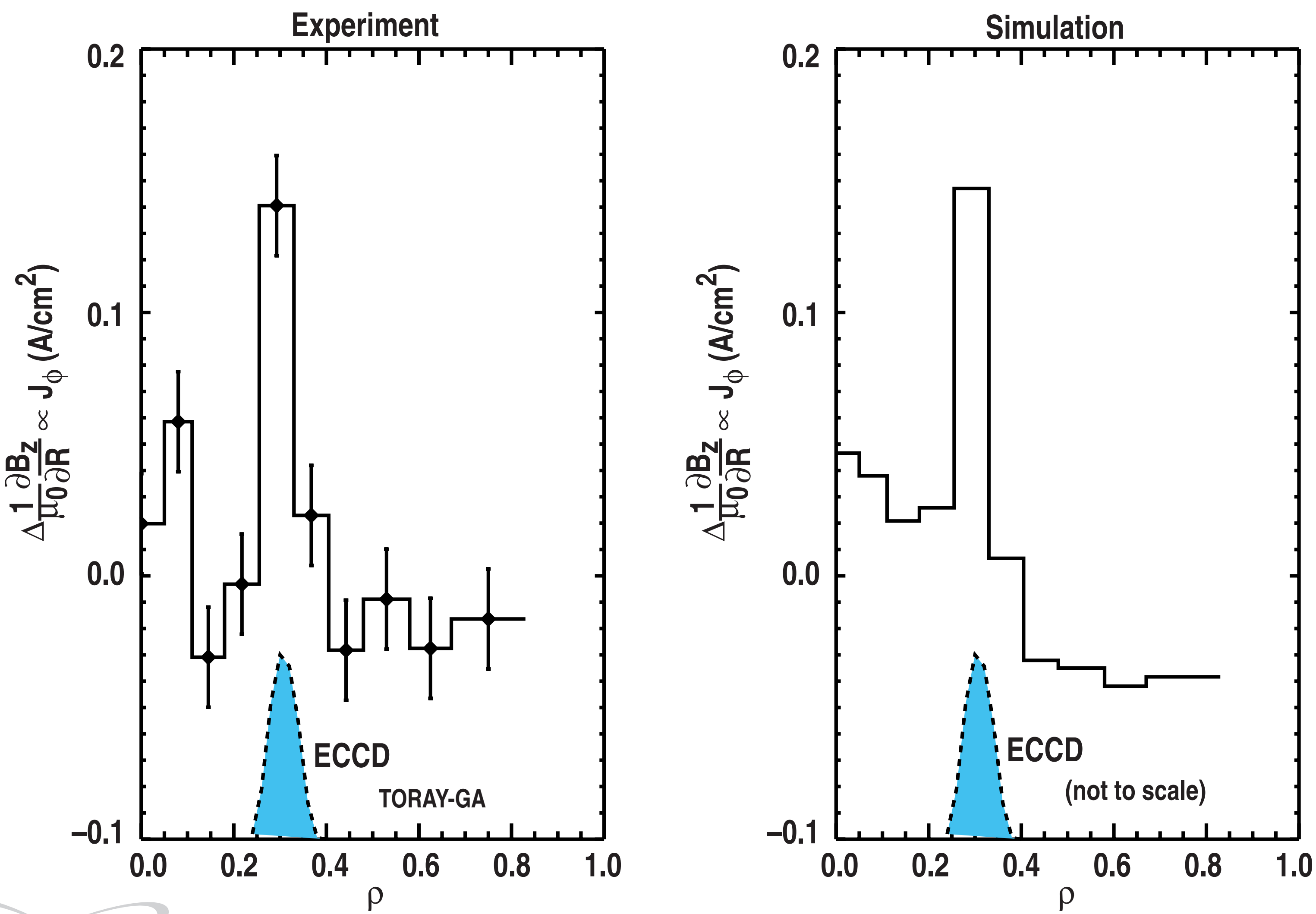


so the local change in j_ϕ due to ECCD is proportional to the change in $\Delta B_Z/\Delta R$, where ΔB_Z is the difference in B_Z between adjacent MSE channels and ΔR is the spatial separation

- 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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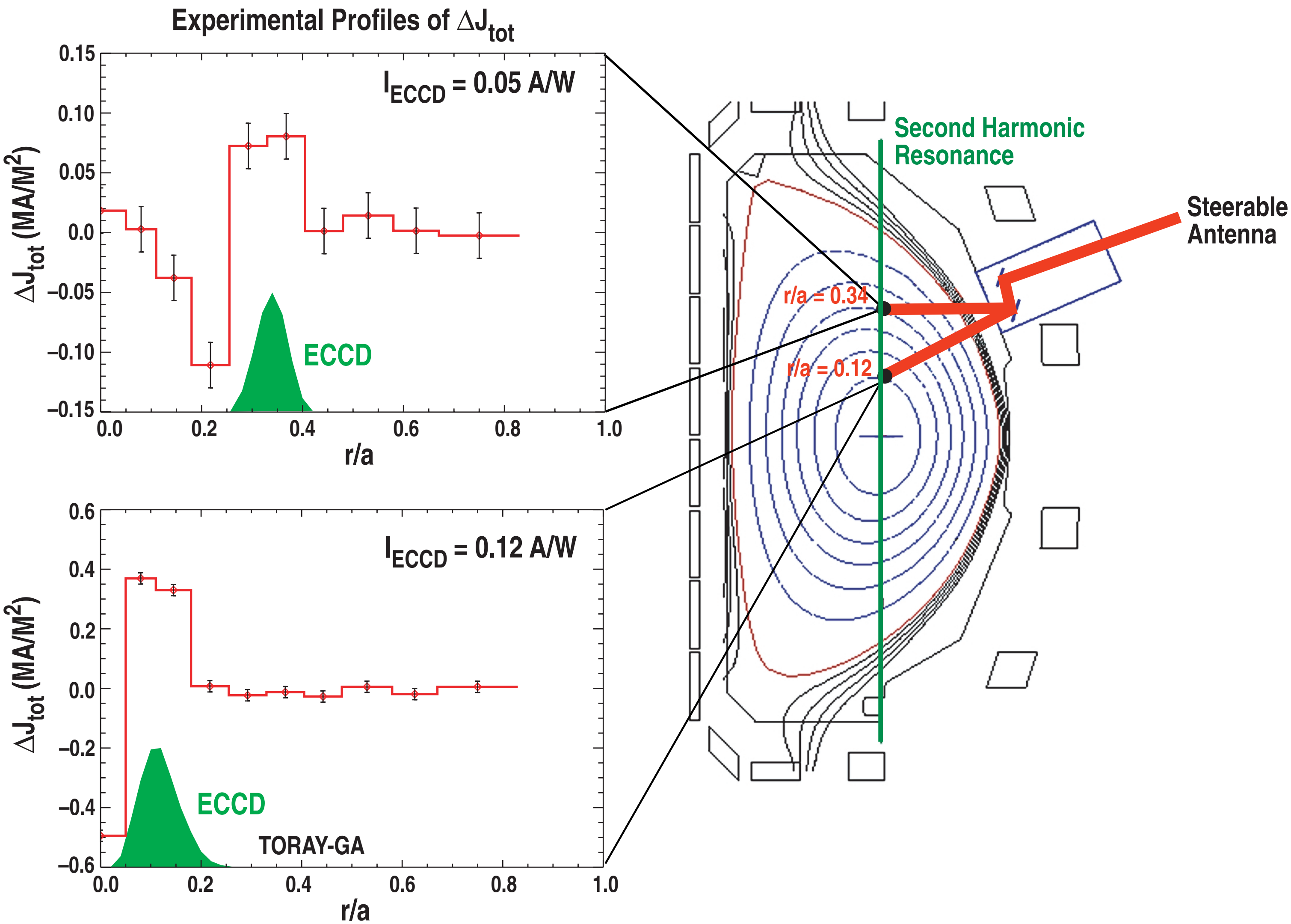
ELECTRON CYCLOTRON CURRENT DRIVE PROVIDES LOCALIZED CURRENT WITH GOOD CONTROL

- Observed changes in MSE signals consistent with ray tracing calculations



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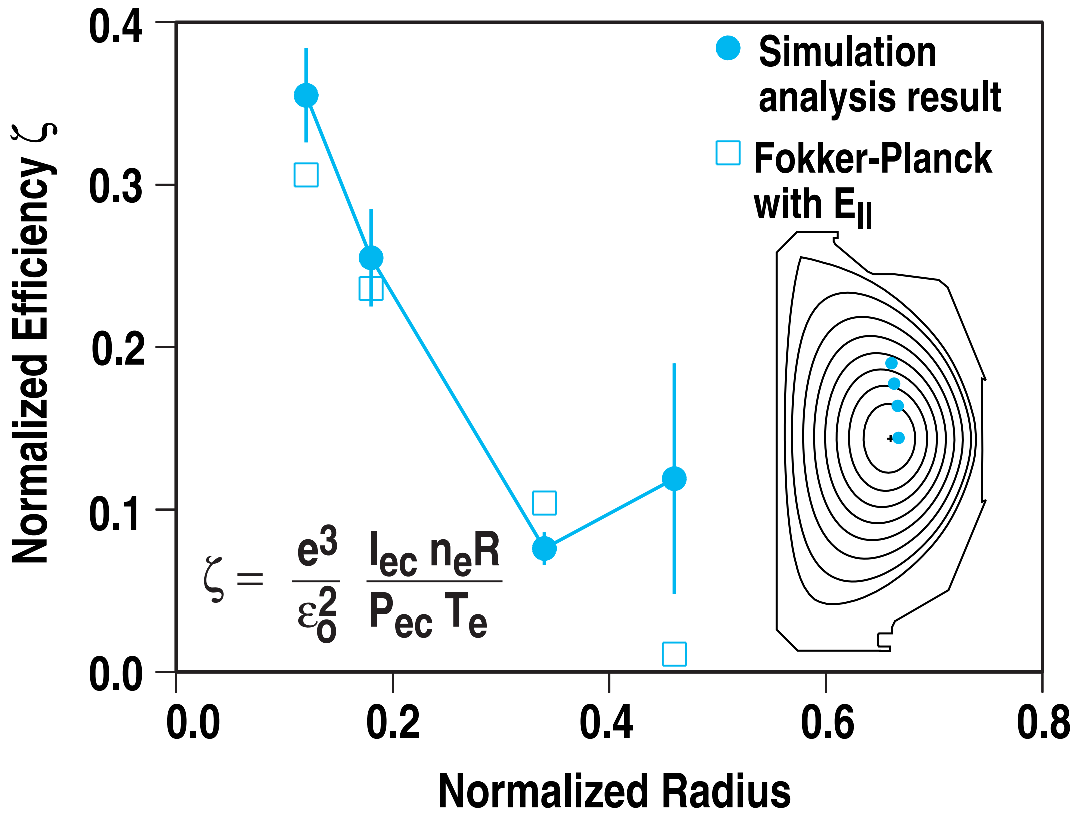
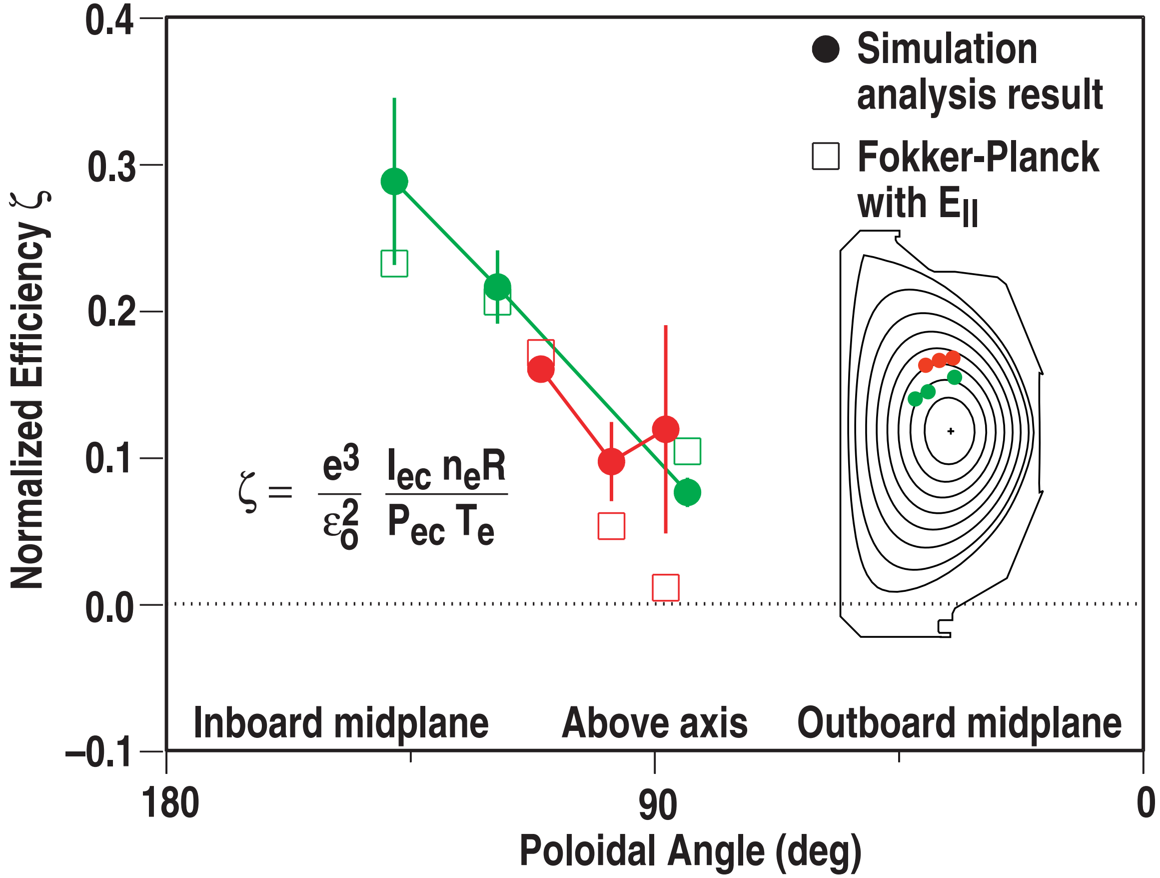
ECCD EFFICIENCY DECREASES WITH RADIUS (FOR POLOIDAL ANGLE ≈ 90 deg) AS EXPECTED FROM THEORY DUE TO TRAPPING EFFECTS



- Excellent agreement with theory except at largest radius
  - Need to test large ρ at higher ECH power with smaller error bars

POLOIDAL SCANS SHOW SYSTEMATIC INCREASE IN ECCD EFFICIENCY TO HIGH FIELD SIDE, IN GOOD AGREEMENT WITH THEORY



- Theoretically the increase in ECCD efficiency with poloidal angle (i.e., magnetic well depth), is due to (a) reduced trapping effects and (b) wave absorption on higher energy electrons from $n_{||}$ upshift

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GENERAL ATOMICS

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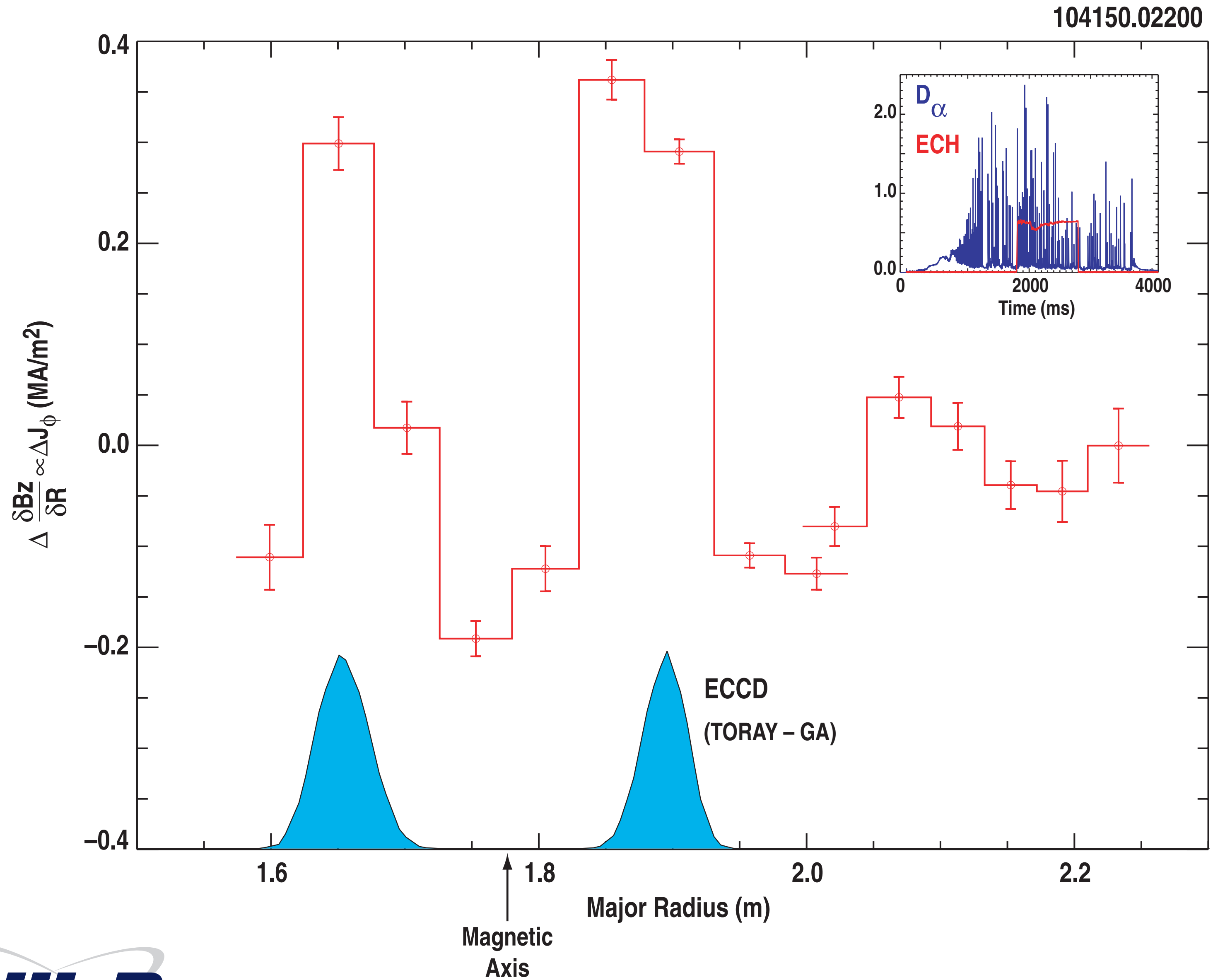
LOCALIZED CHANGE IN CURRENT PROFILE DURING ECCD IS CLEARLY OBSERVED IN ELMING H–MODE PLASMAS



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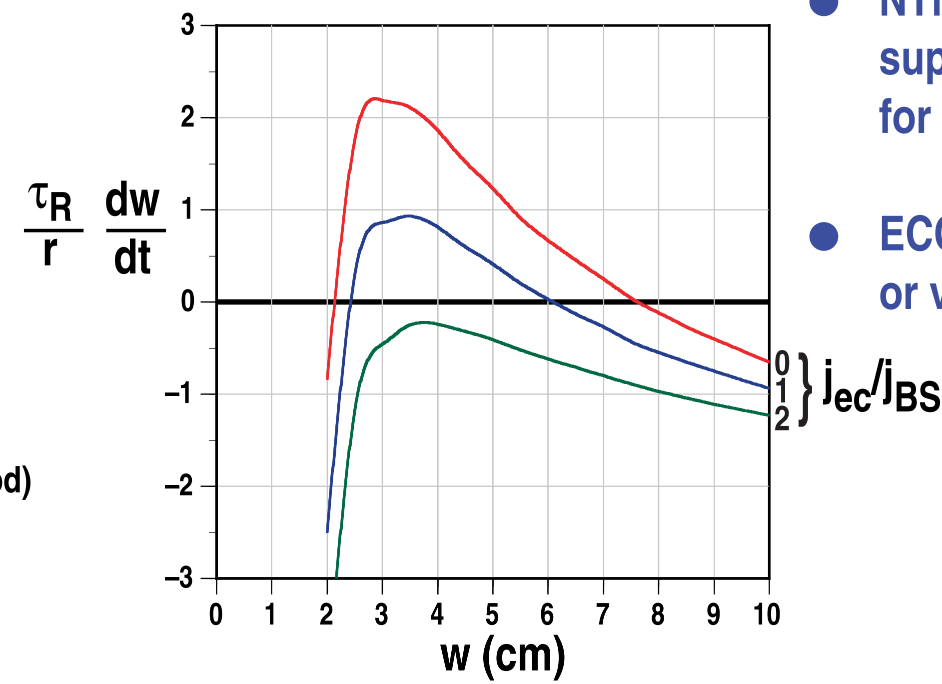
CO-ECCD RADIALLY LOCALIZED AT ISLAND CAN REPLACE THE "MISSING" BOOTSTRAP CURRENT AND COMPLETELY STABILIZE THE NEOCLASSICAL TEARING MODE

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \varepsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{r}{w} - \frac{r w_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2 w^2}\left(\frac{\eta\, j_{ec}}{j_{bs}}\right)\right]$$

$m/n = 3/2$
$\beta_\theta = 0.9$
$\Delta' r = -3$
$r = 0.36$ m
$\varepsilon^{1/2} = 0.5$
$L_q/L_p = 1.5$
$w_{pol}/r = 0.05$
$\delta_{ec}/r = 0.08$
$\eta_0 = 0.4$ (no mod)



- NTM amenable to complete suppression because $\gamma < 0$ for $w < w_{seed}$
- ECCD must lie within island or very near rational surface

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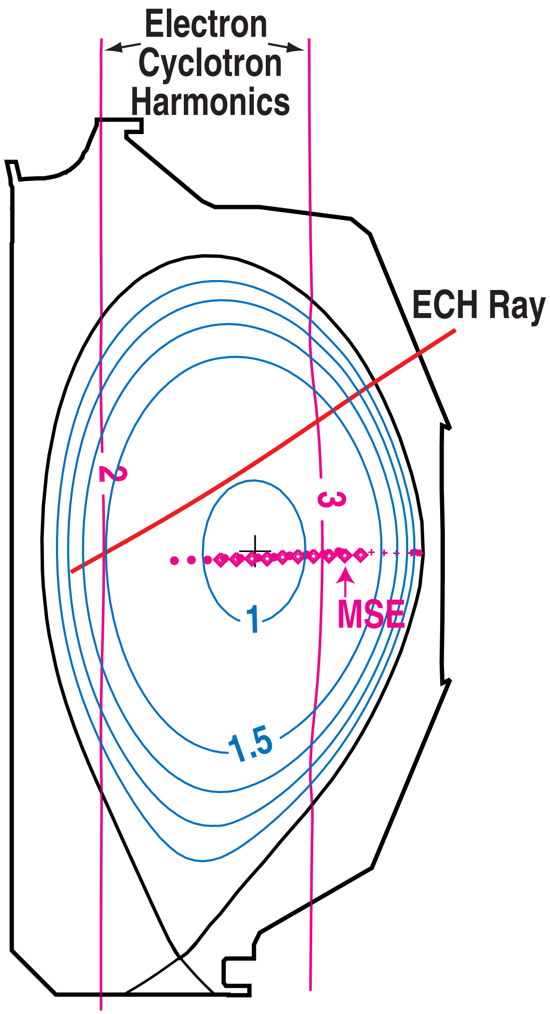
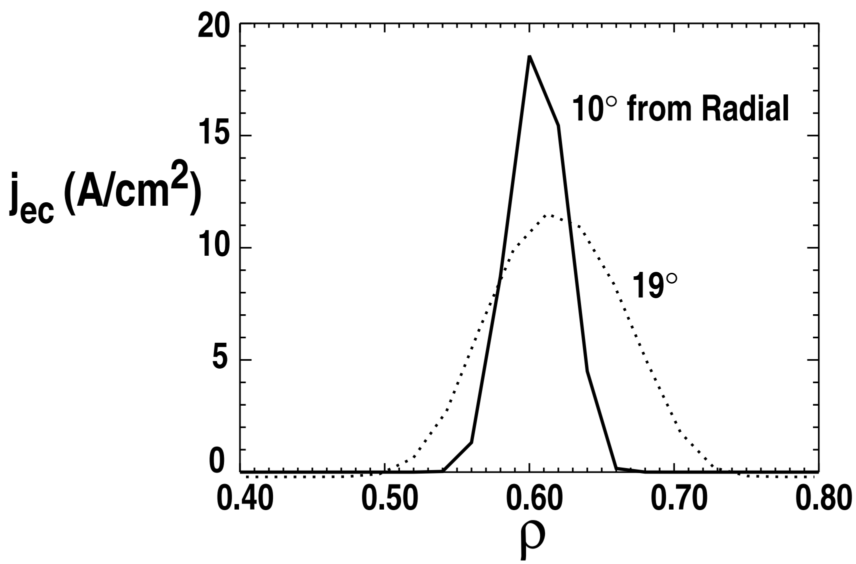
HIGH CURRENT DENSITY OBTAINED THROUGH OPTIMIZATION OF ECCD



- Target plasma is ELMing H–mode discharge with sawteeth and 3/2 tearing mode
- ECCD applied to high field side midplane to minimize trapping effects
- B_T adjusted to place resonance near q = 3/2 surface
- Small toroidal component to ECH rays maximizes j_{ec} rather than I_{ec}



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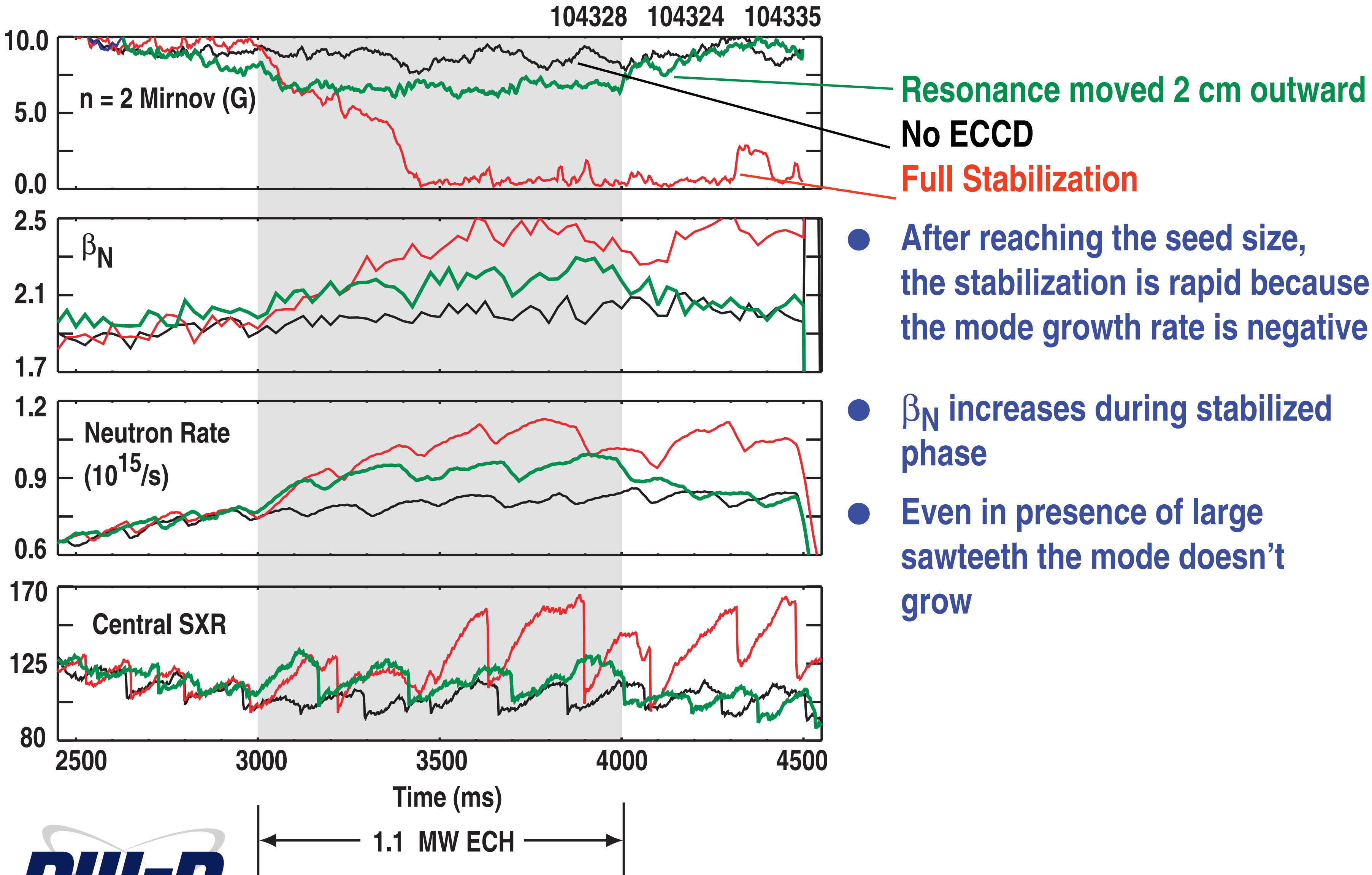
FULL STABILIZATION OF NTM OBTAINED WITH MODEST ECH POWER



- After reaching the seed size, the stabilization is rapid because the mode growth rate is negative
- β_N increases during stabilized phase
- Even in presence of large sawteeth the mode doesn't grow

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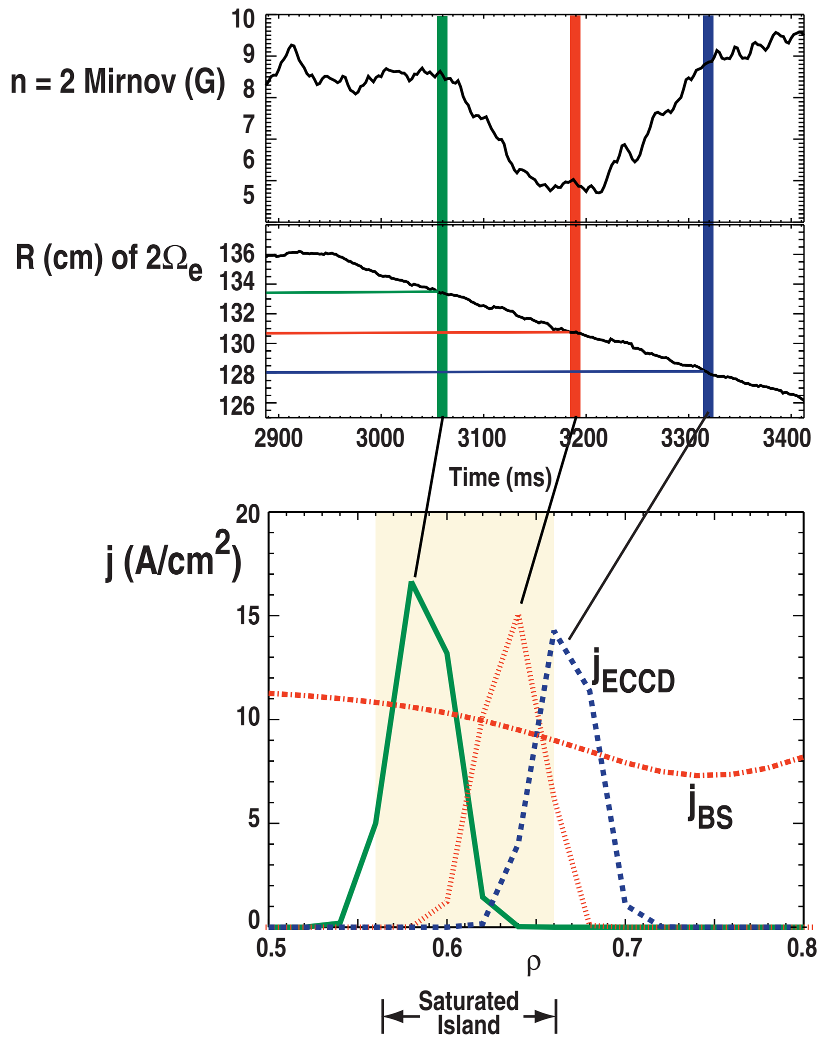
THE LOCATION OF ECCD IS CRITICAL TO FULL STABILIZATION



- Toroidal field was ramped down to scan ECCD past the island
- Alignment within 2 cm is required
- $j_{ECCD} > j_{BS}$ is satisfied
- Sensitivity of effect to location implies that the width of the ECCD is less than the island size, in agreement with ray tracing calculation
- These results show that modeling is accurate even in ELMing H–mode with sawteeth and a tearing mode, at large ρ

- Results similar to those obtained on ASDEX-U and JT-60U

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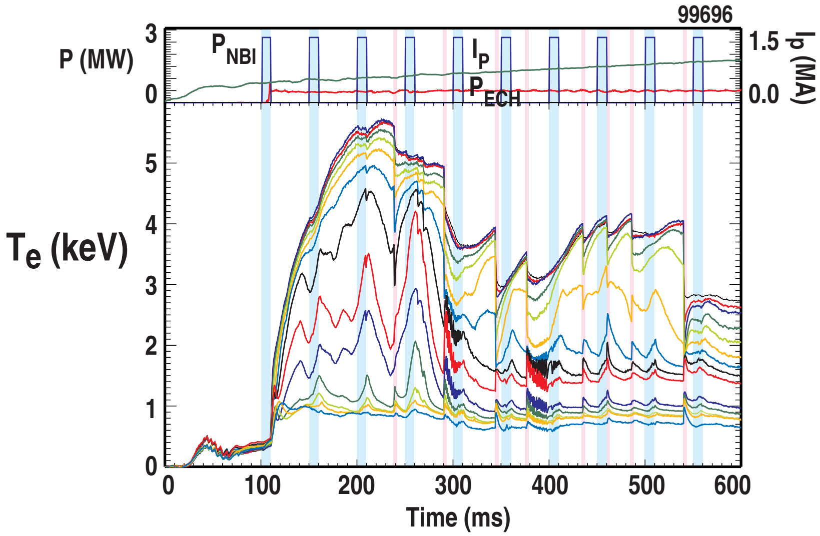
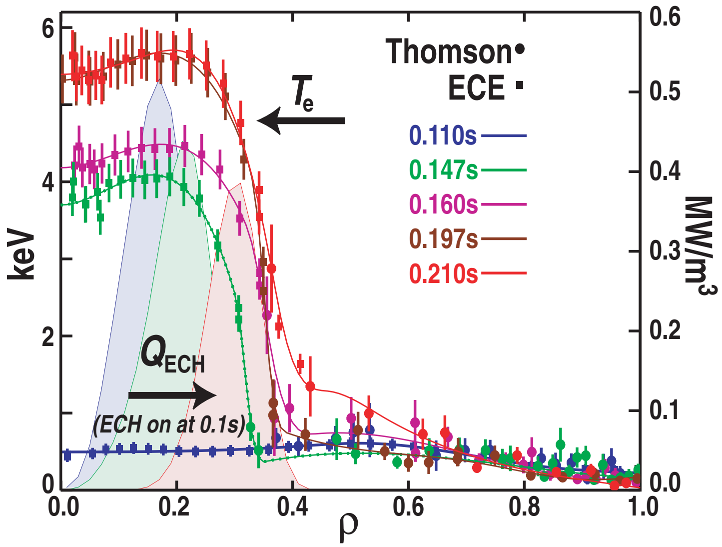
ECH IN DISCHARGES WITH NEGATIVE MAGNETIC SHEAR LEADS TO FORMATION OF AN ELECTRON TRANSPORT BARRIER





- Electron transport barrier forms immediately upon application of ECH power of 0.5 MW
- Barrier location lies just outside heating location
- χ_e more than an order of magnitude smaller than χ_i in the barrier
- Stabilization of ETG mode by Shafranov shift believed responsible for decrease in χ_e
- Barrier found with co-ECCD, counter-ECCD, and radial ECH; also with no NBI

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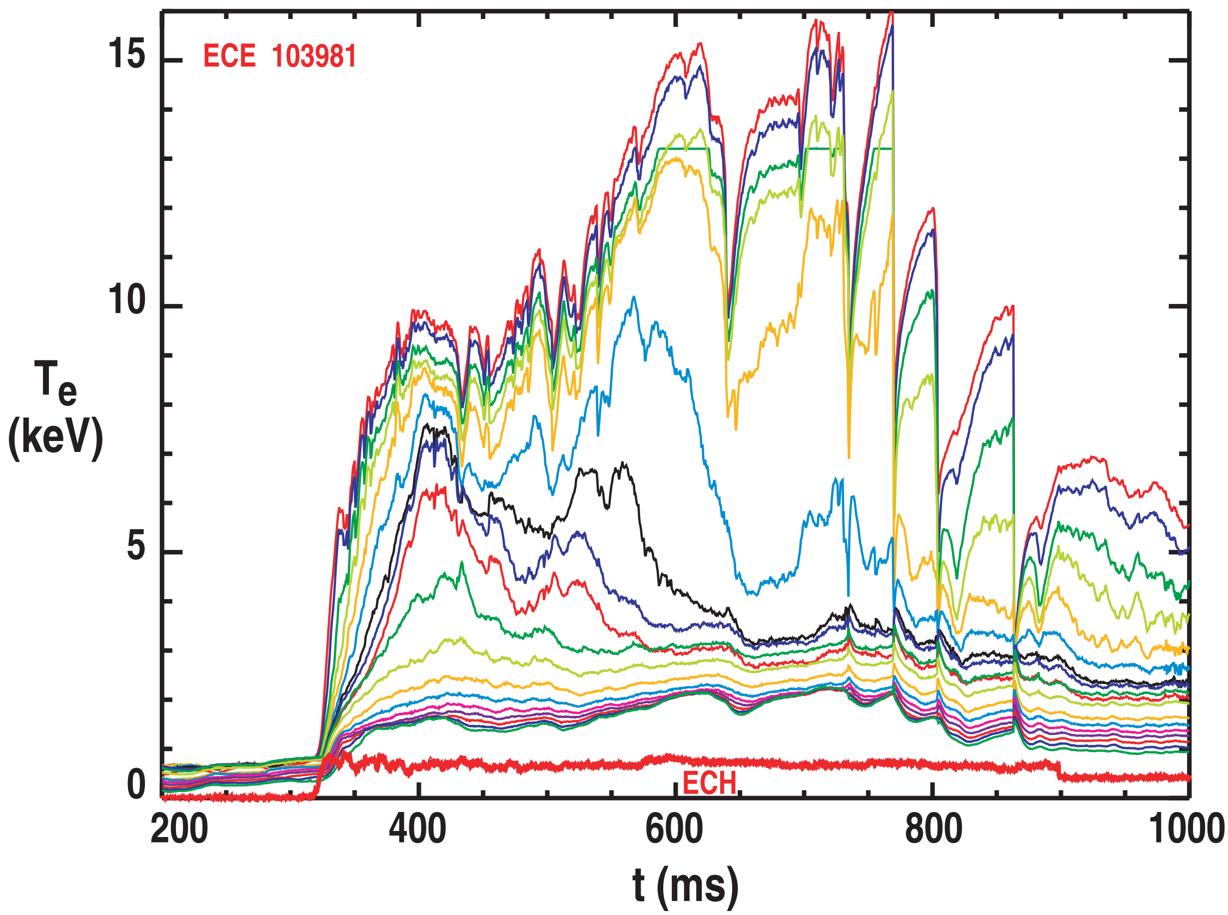
ECH EARLY IN DISCHARGE PRODUCES HIGH T_e AND LARGE PRESSURE GRADIENT WITHOUT NEUTRAL INJECTION

- 0.8 MW ECH applied at ρ ~0.4; no NBI
- Co–ECCD in this case; radial ECH also works
- Measurement of $T_e \gtrsim 15$ keV by ECE roughly supported by Thomson scattering and pulse height analysis



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CONCLUSIONS

- Modeling and experiment have substantially come together for ECH/ECCD
  - Best tested in quiescent L–mode
  - Also tested under realistic conditions of ELMs, sawteeth, and other turbulence
- The narrow current drive profile of ECCD is useful for stabilizing neoclassical tearing modes
  - Full suppression obtained, with increase in pressure and neutron rate
  - Effect very sensitive to location of current drive
  - Success indicates indirectly that the narrowness of the ECCD profile and its magnitude are close to those calculated by ray tracing
- Localized ECH generates an electron transport barrier in the vicinity of the power deposition
- These results strongly support ECCD for detailed control of the current profile needed to realize advanced tokamak discharges