Advanced Tokamak Profile Evolution in DIII–D

by

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ATTRACTIVENESS OF ANY FUSION POWER SYSTEMS RELIES ON PROVIDING HIGH POWER DENSITY AND HIGH DUTY FACTOR (OR STEADY STATE)

- Goal of DIII–D Advanced Tokamak (AT) Program: Develop physics basis and plasma control methods needed for steady state, high performance operation
- Steady-state operation requires:
  - Plasma current driven noninductively
  - High bootstrap current fraction (f_{BS})
- Self-consistent solution to achieve simultaneously high performance and high f_{BS} requires:
  - Moderately high q
  - High β_N
- Both experimental experience and simulations suggest that:
  - A relatively small (~10%) amount of current driven at ρ ~ 0.5
  - Combined with bootstrap current and NBCD

$\Rightarrow$ steady state current profile compatible with a high β equilibrium

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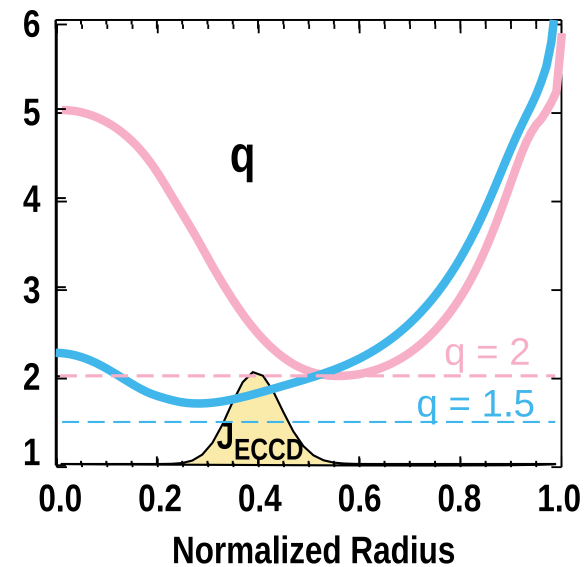
RECENT DIII-D EXPERIMENTS HAVE DEMONSTRATED OFF-AXIS ECCD AS AN EFFECTIVE TOOL TO CONTROL THE CURRENT PROFILE IN ADVANCED TOKAMAK OPERATION

- The experiment using off-axis ECCD has demonstrated integrated AT operation, combining:
  - High β (> 3%) at high q (q_{95} ~ 5)
  - Good energy confinement (H_{89} ~ 2.4)
  - High noninductive current fraction (f_{BS} ~ 55%, f_{NI} ~ 90%)
- Clear evidence of the effectiveness of off-axis ECCD demonstrated in high β plasma with q_{min} > 2
  - Internal transport barrier formed even in the presence of type I ELMs
  - Improvements observed in all transport channels
  - Increased peaking of profiles lead to higher bootstrap current in core



- In a separate experiment, current profile at high β has been sustained with q_{min} >1.5
  - Nearly steady-state current and pressure profiles maintained for 1 s
  - Good access to the regime demonstrated where higher f_{BS} possible with higher β_N

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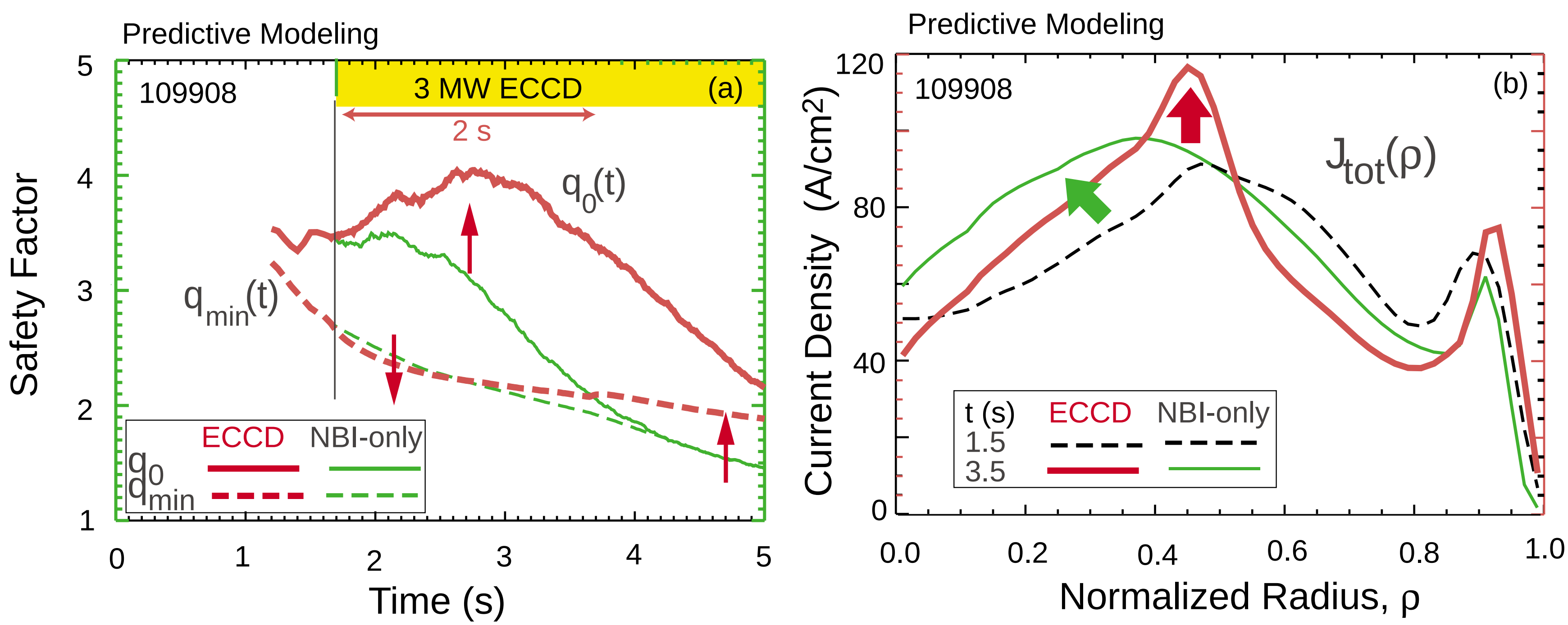
MODELING AND SIMULATION HAVE BECOME ESSENTIAL TOOLS FOR THIS EXPERIMENTAL PROGRAM



- **Predictive modeling prior to the experiment based on an existing DIII–D discharge:**
  - **Used to develop detailed experimental plans**
  - **Successfully predicted main features of the experiment with delightful surprises**
- **Simulations allow detailed comparison with theory and experiment**
- **Predictive modeling indicates that full noninductive sustainment is possible in near future**

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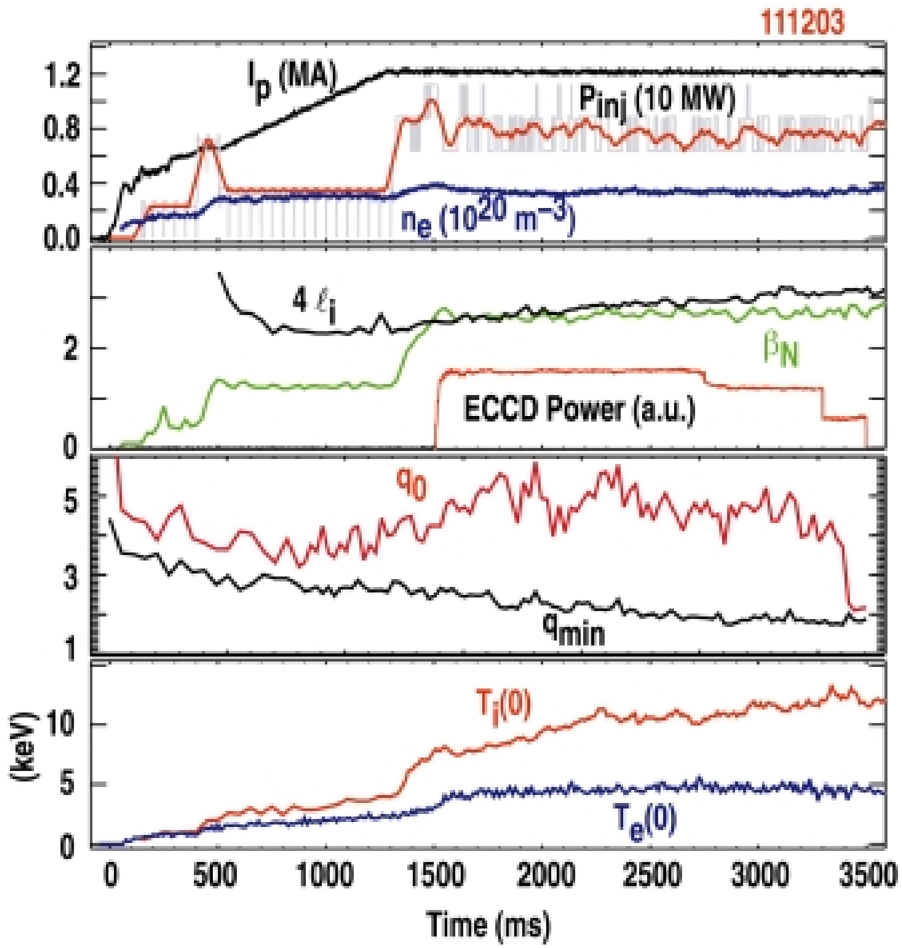
OUTLINE

- Current profile modification with q_{min} >2
  - ECCD
  - Experiment versus Simulation
    - MSE
    - J_{OH}
- Sustainment of current profile with q_{min} >1.5
- Predictive modeling for full noninductive operation

APPLICATION OF ECCD IN HIGH β WITH $q_{min} > 2$ DISCHARGE RESULTS IN FAVORABLE CHANGES TO CURRENT PROFILE AND TRANSPORT



- Early H-mode used to access high q_{min}
- $\beta_N \approx 2.8$, $H_{89} \approx 2.4$ maintained by NBI feedback
- Robust operation at $\beta_N > \beta_N^{\text{no-wall}}$ ($\approx$2.5) made possible by RWM stabilization
- ECCD causes increase in central magnetic shear
- Both T_e and T_i increases with application of ECCD

S. Allen: LO1.001
C. Greenfield: LO1.002
A. Garofalo: LO1.004
J. Ferron: LO1.004

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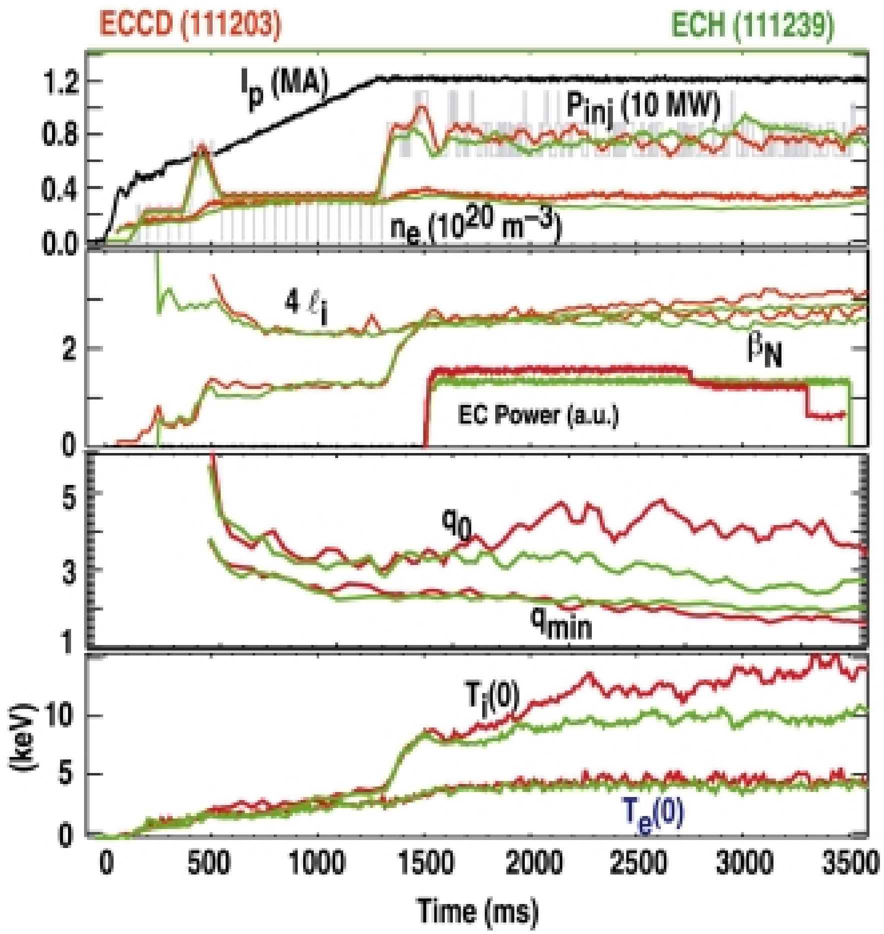
CURRENT PROFILE MODIFICATION IS DUE TO CURRENT DRIVE RATHER THAN TO HEATING



- **ECH: Radial launch; Heating only**

  ECCD: Tangential launch; Heating and CD

- **$\beta_N \approx 2.8$ maintained in both cases**

- **ECCD increases q_0 and reduces q_{min} relative to reference case**

- **Local transport improves with increases in central T_e and T_i observed with ECCD**

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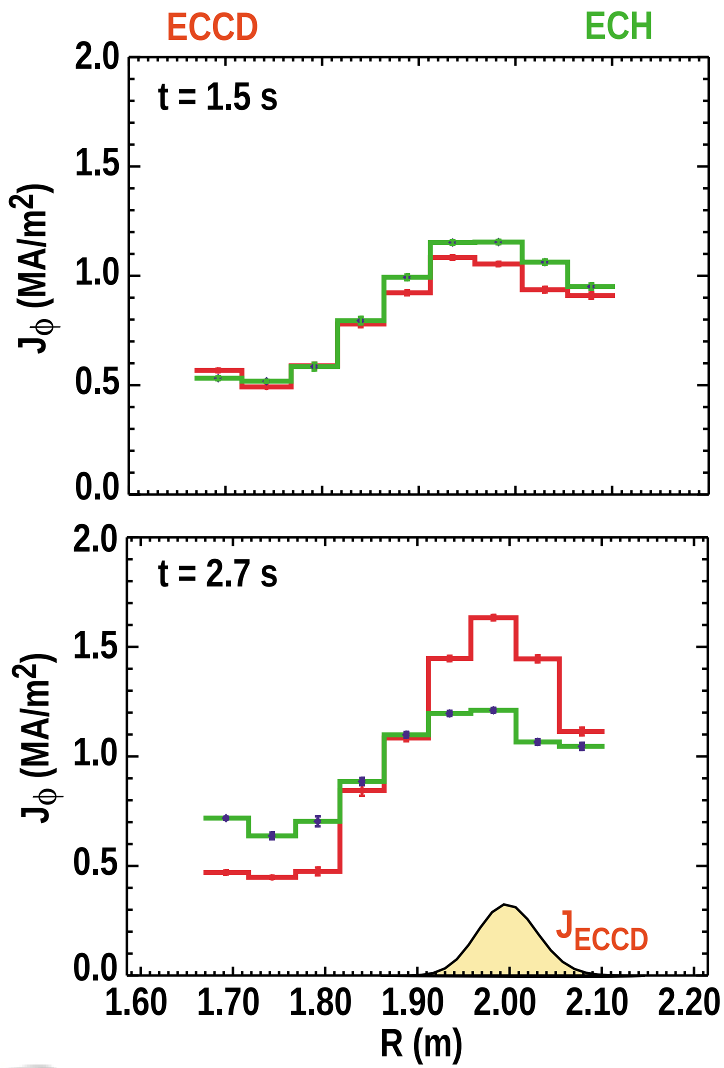
MSE MEASUREMENT OF J_ϕ SHOWS AN INCREASE IN CURRENT AT THE ECCD LOCATION



- Mortional Stark effect spectroscopy to measure magnetic pitch angle (B_{pol}/B_{tor})
- At start of ECCD, current profiles are identical
- At 2.7 s
  - J_ϕ increased at ECCD location
  - Analysis indicates 130 kA ECCD, consistent with CQL3D prediction (120 kA)
  - Normalized CD efficiency consistent with that required for AT target scenario

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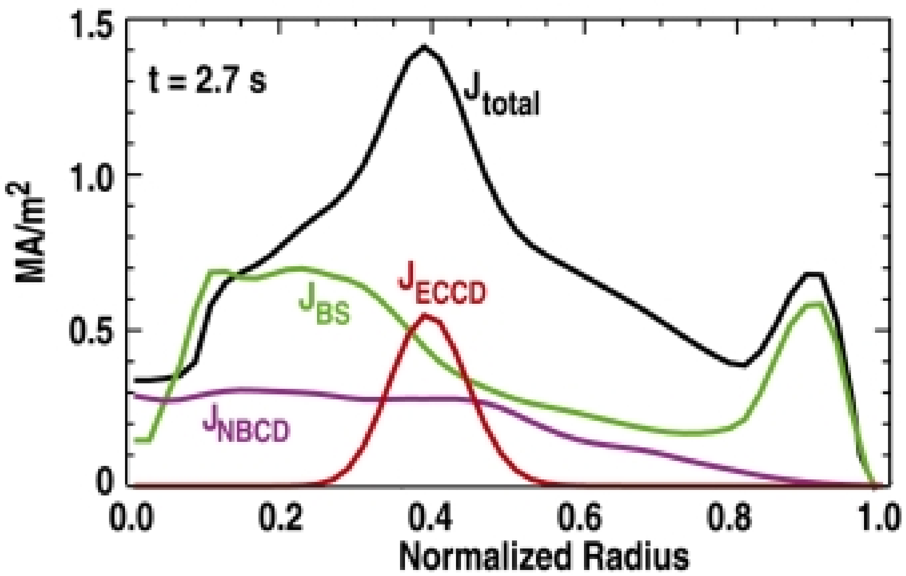
MODELING AND SIMULATION ARE ESSENTIAL FOR THE EXPERIMENTAL PROGRAM

- **TRANSP and ONETWO codes:**
  - **Simulation:** Solve J [$B_p(\rho,t)$ diffusion equation] with experimental kinetic profile inputs
  - **Predictive modeling:** Solve J, T_e and T_i equations with experiment-based χ_e and χ_I



- **TRANSP run using the Fusion Grid created by the National Fusion Collaboratory Project**
- **ECCD/ECH**
  - — Used $1.2 \times J_{ECCD}$(TORAY-GA)
- **NBCD**
  - — Monte-Carlo slowing down with a modest spatial diffusion of beam ions
- **Bootstrap current**
  - — Used Hirshman 78 model (Large R/a approx.)
  - — Underestimate by ~10% compared with NCLASS and Sauter models

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FusionGRID

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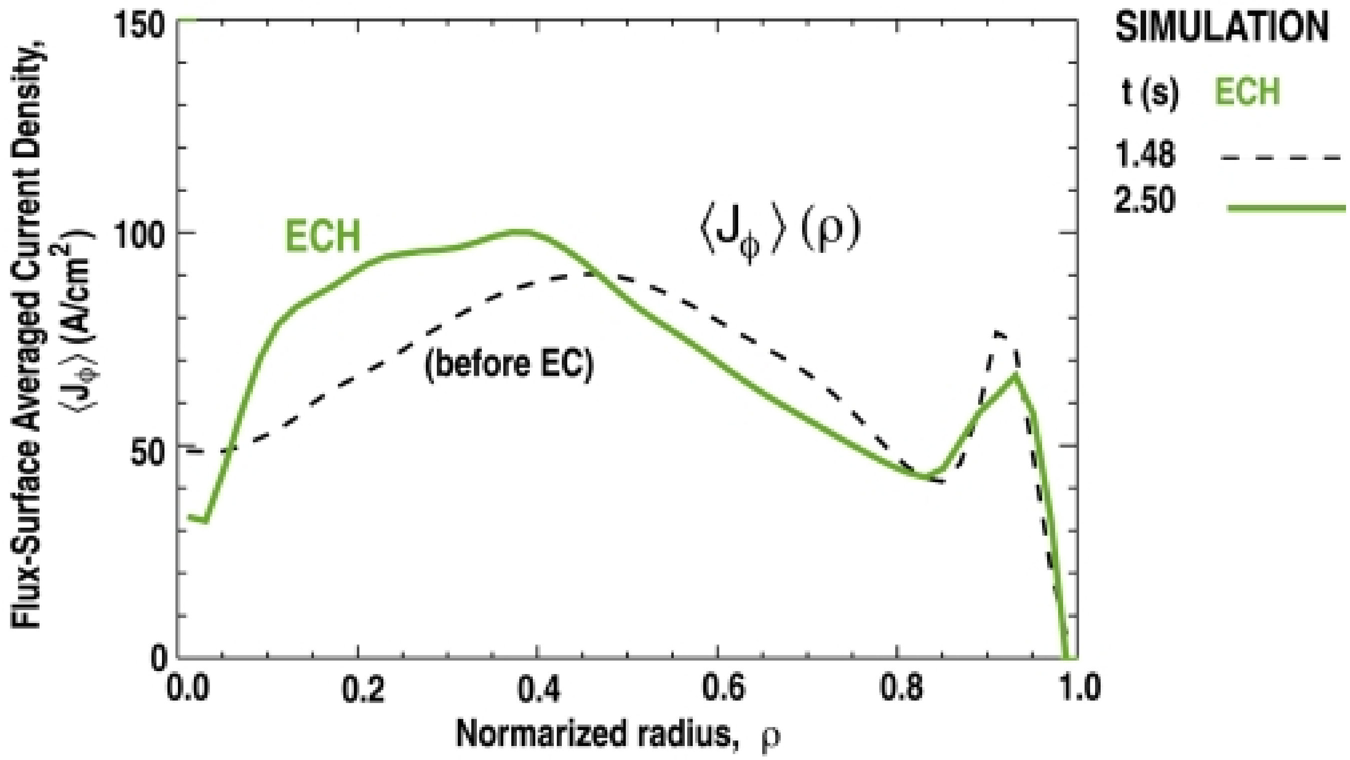
SIMULATIONS SHOW THAT ECCD PREVENTS INWARD CURRENT PENETRATION



- With ECH (no CD), the current peak continued to move in

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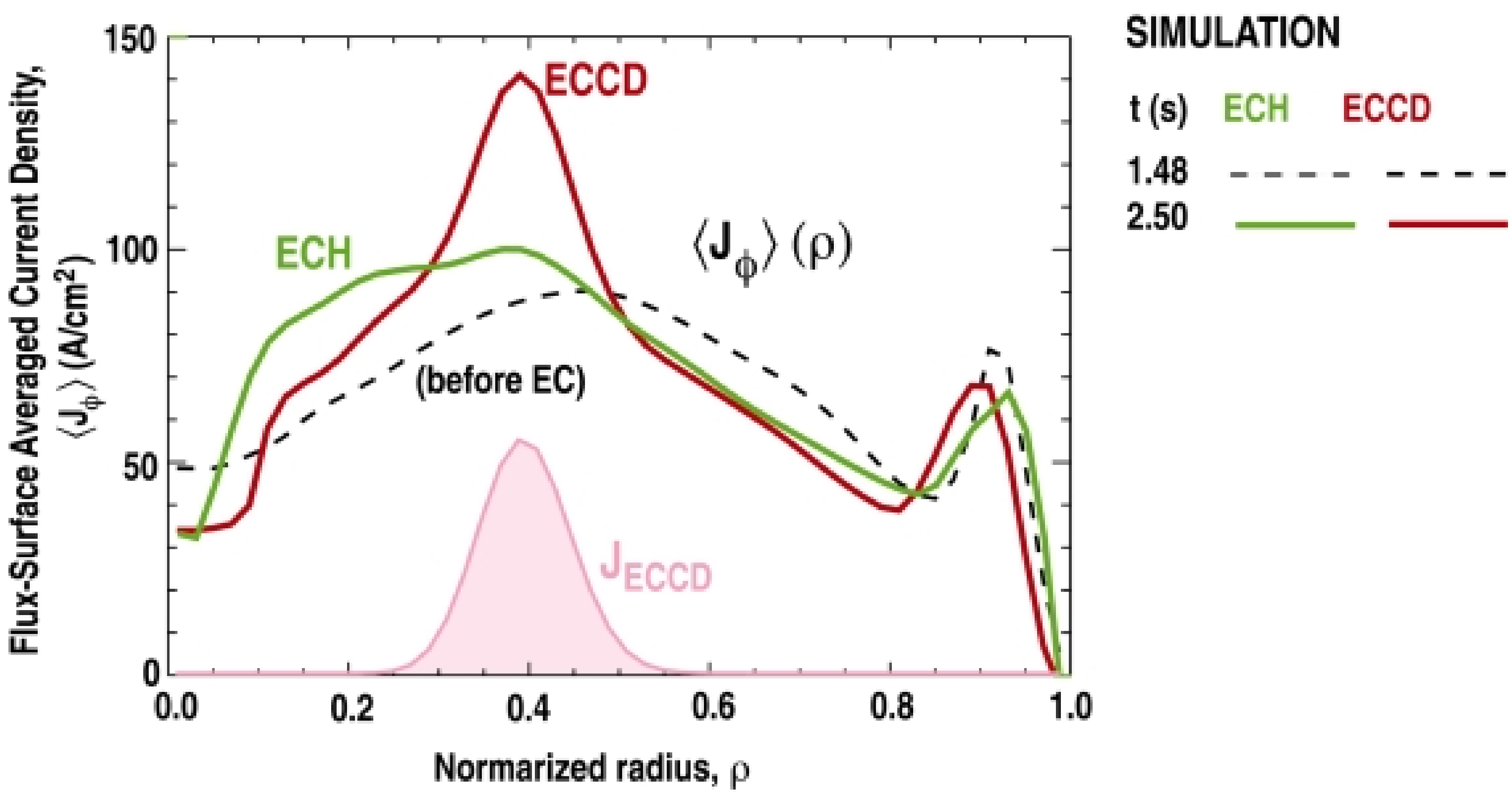

- With ECH (no CD), the current peak continued to move in
- ECCD clearly produced an off-axis peaked J_ϕ
- Slight shift of the current peak position from the ECCD peak due to bootstrap current at $\rho < 0.35$

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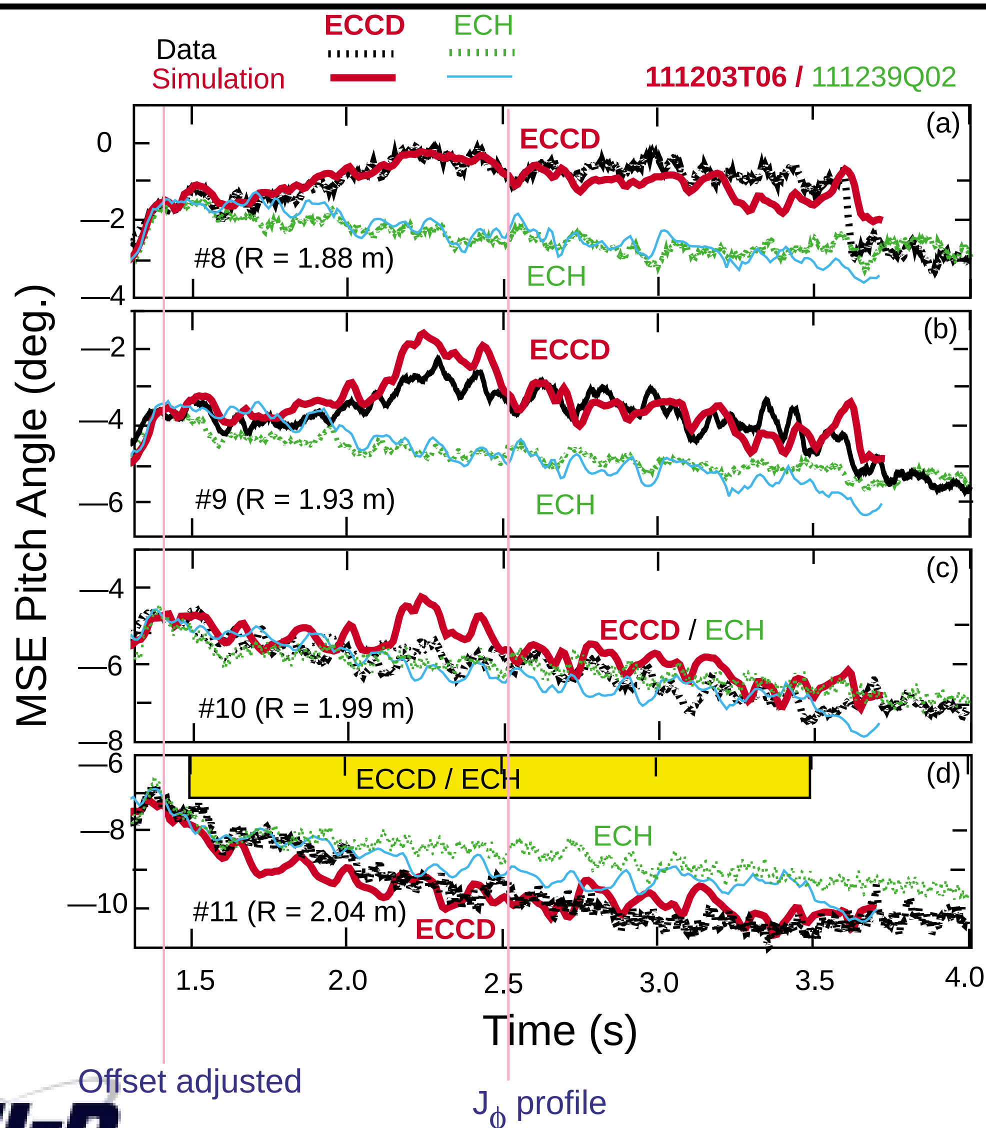
SYNTHETIC MSE SIGNALS GENERATED BY THE SIMULATION AGREE WELL WITH EXPERIMENTAL MSE SIGNALS



- **Two procedures implemented:**
  - Offset calibration adjusted at one early time
  - $E_r(\rho)$ from CER measurement

- **Agreement in nearly all channels throughout the discharge**

M. Makowski

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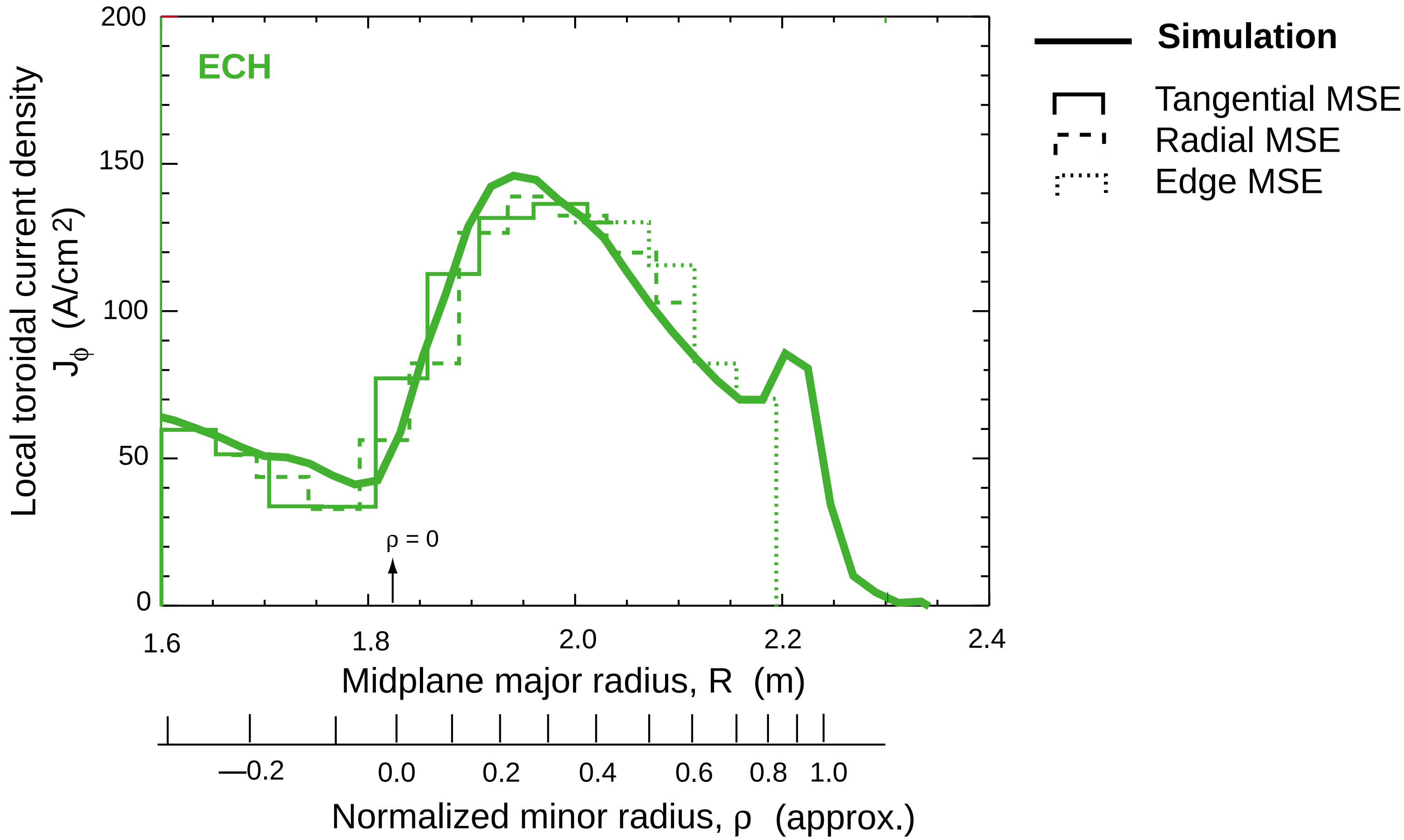
LOCAL TOROIDAL CURRENT DENSITY PROFILE PREDICTED BY SIMULATION AGREES WELL WITH MSE INFERRED CURRENT PROFILE



- Broad current profile with ECH

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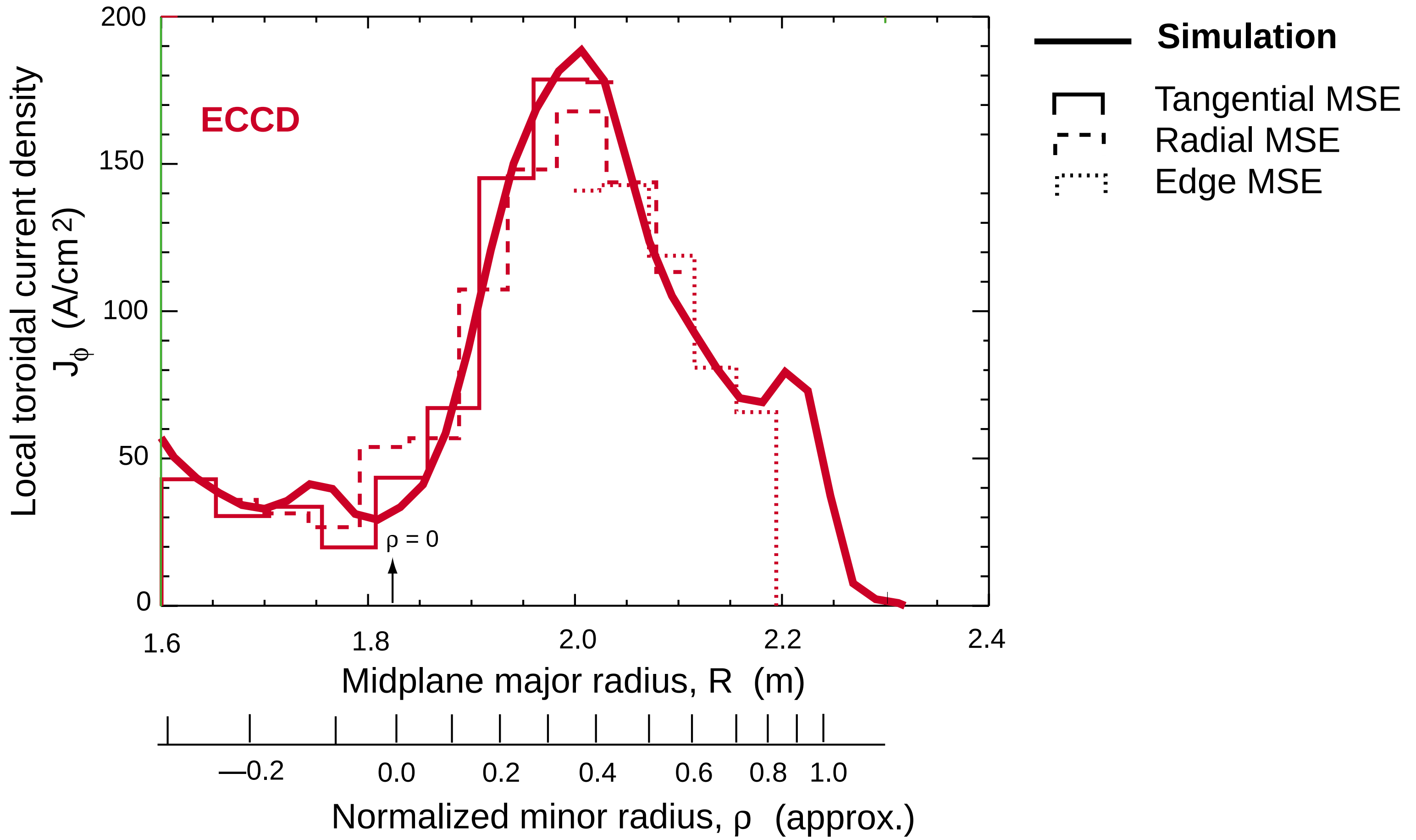

- Broad current profile with ECH
- More off-axis peaked with ECCD

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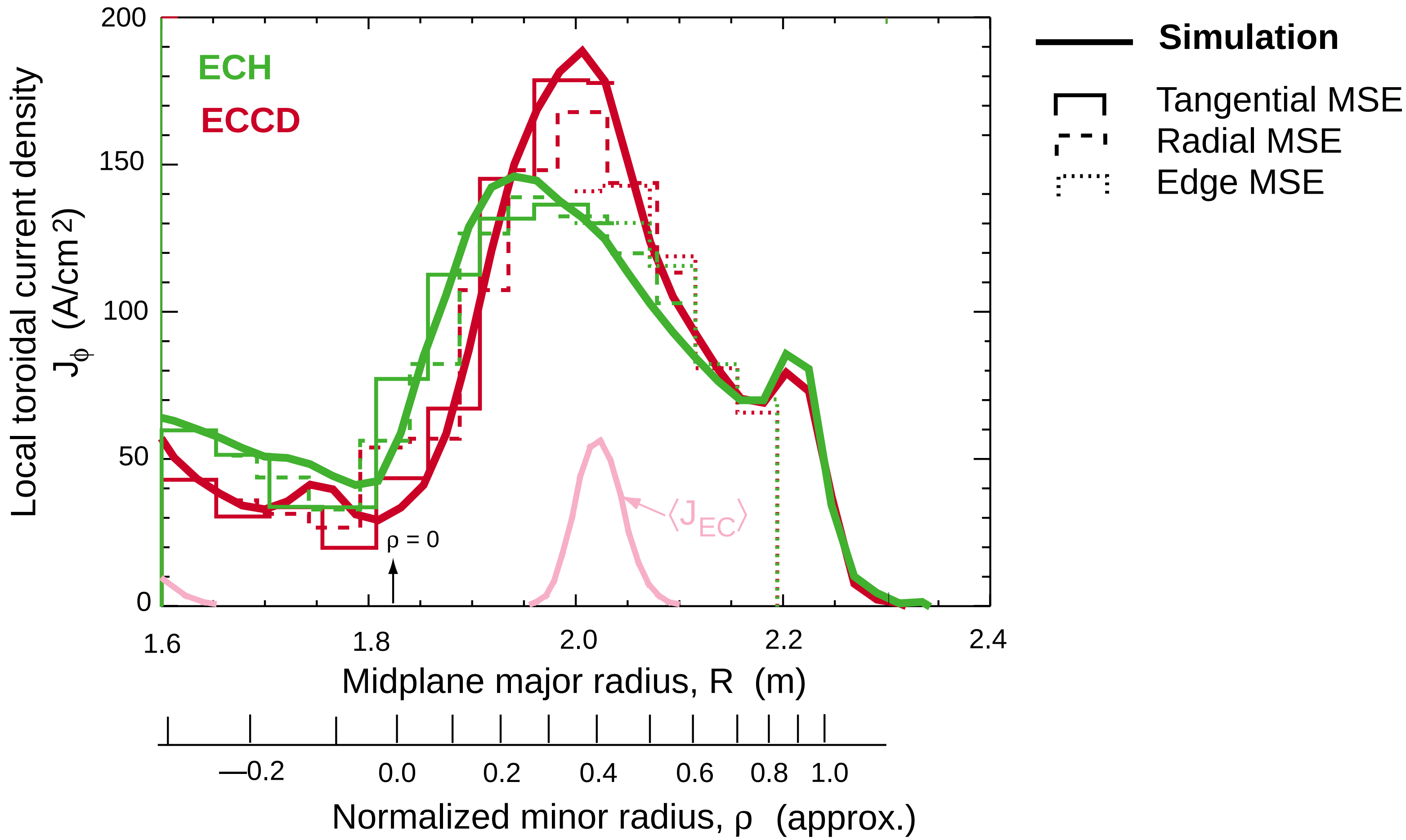

- Broad current profile with ECH
- More off-axis peaked with ECCD
- The current peak is broader than the ECCD driven current due to:
  - Substantial Phirsch-Schlüter current component which is averaged out in $\langle J_\phi \rangle$
  - Bootstrap current

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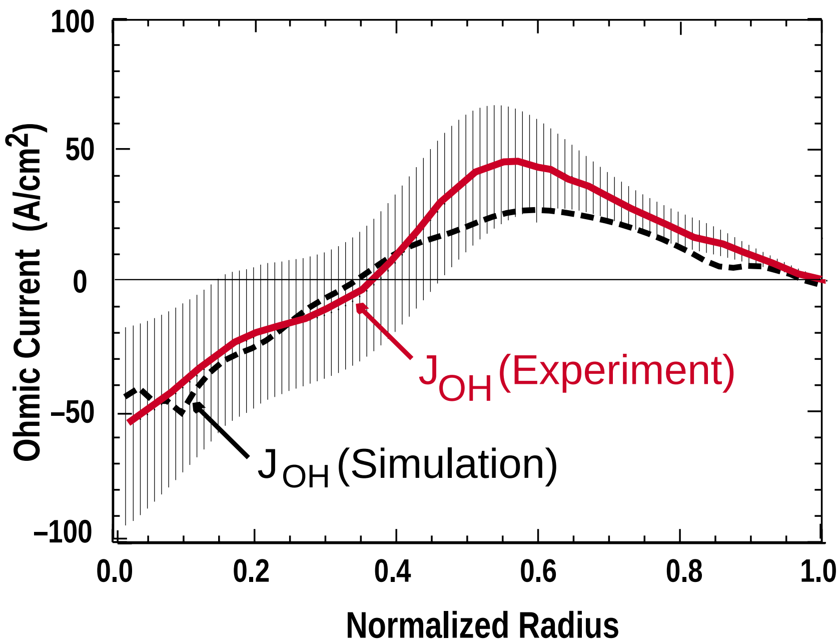
ALTHOUGH ECCD CONTRIBUTION TO TOTAL NONINDUCTIVE CURRENT IS SMALL, ITS EFFECT ON BOOTSTRAP CURRENT REDUCES OHMIC CURRENT TO LESS THAN ~15%



- **Experimental J_{OH} from the loop voltage analysis:**
  - $E_{||} = \frac{d\Psi_{pol}}{dt} \Rightarrow J_{OH} = \sigma_{neo} \bullet E_{||}$

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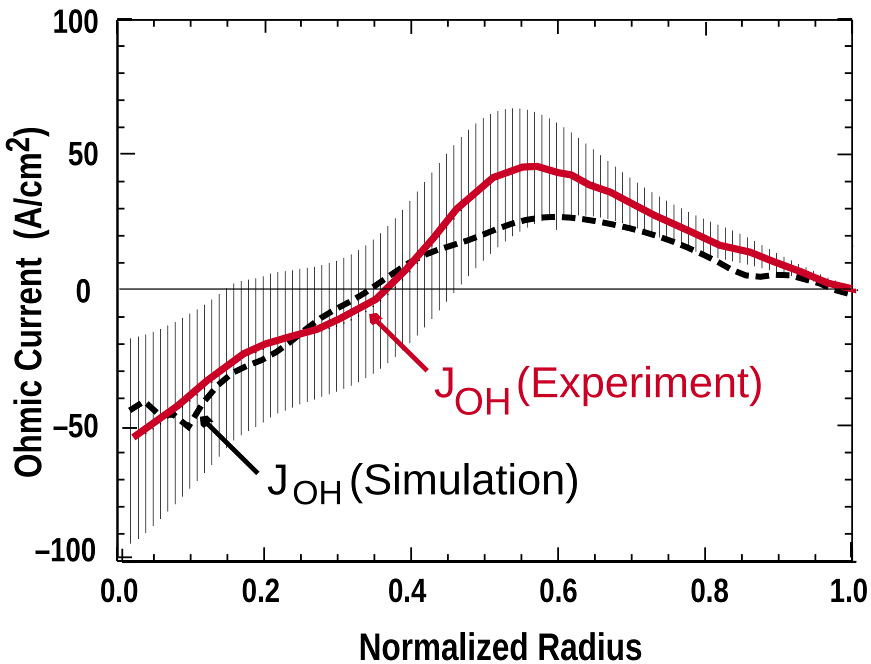

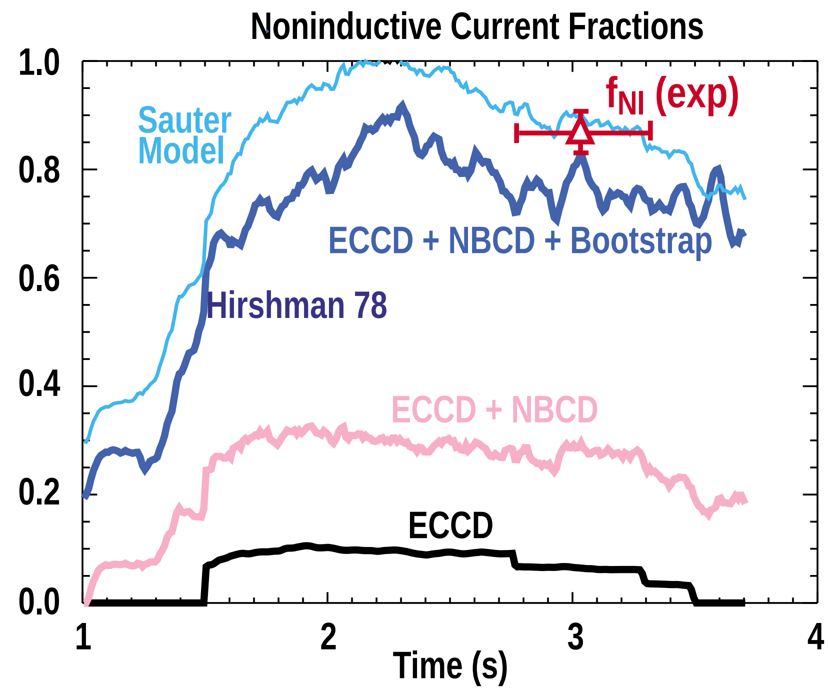

- Experimental J_{OH} from the loop voltage analysis:
  - $E_{||} = \frac{d\Psi_{pol}}{dt} \Rightarrow J_{OH} = \sigma_{neo} \bullet E_{||}$
- f_{BS} increased by 10% when ECH $\Rightarrow$ ECCD

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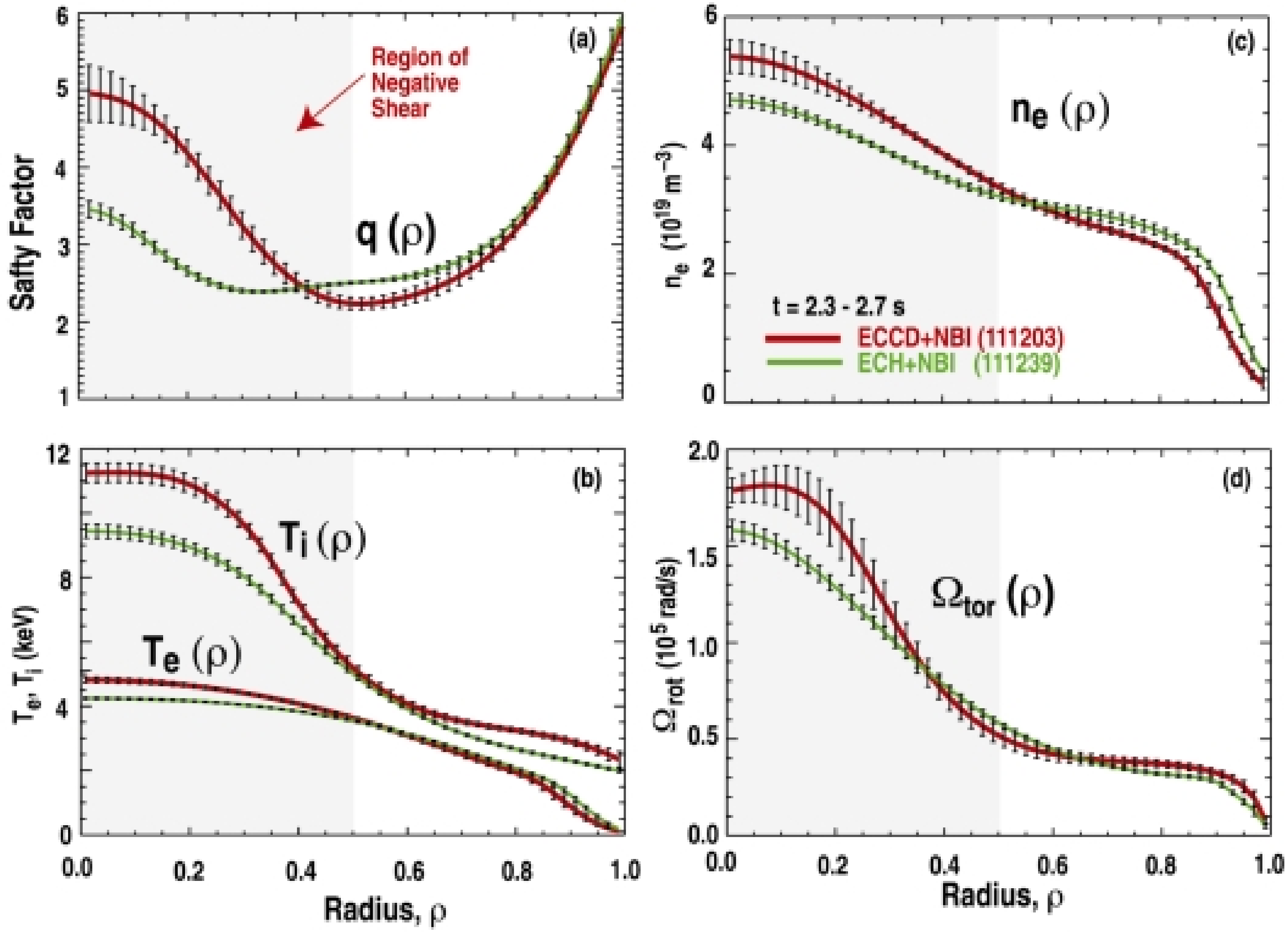
IMPROVEMENT IN BOOTSTRAP CURRENT ARISES FROM INCREASED PEAKING OF DENSITY AND TEMPERATURE



- Strong NCS triggered a weak internal transport barrier (ITB)

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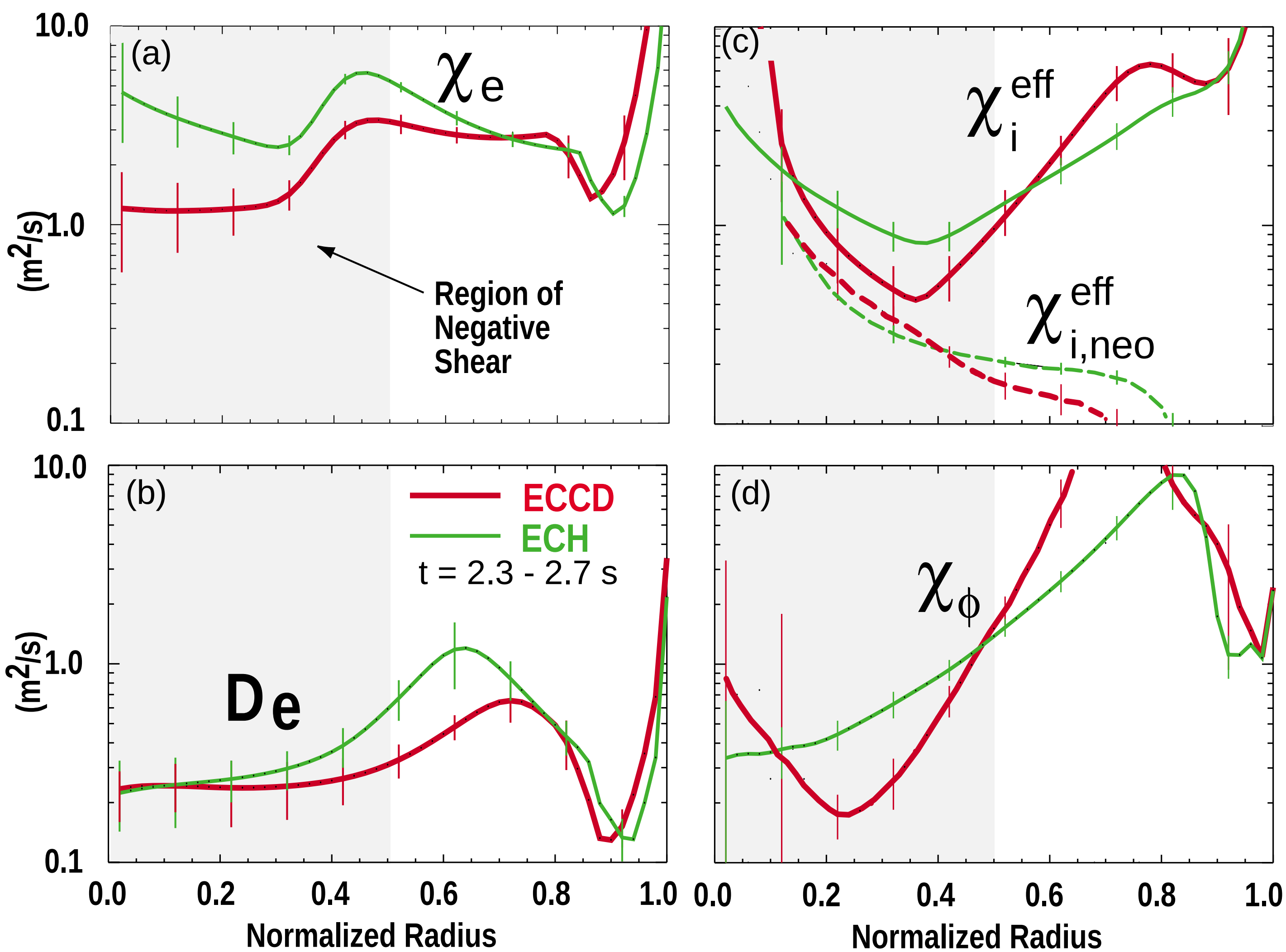
REDUCED TRANSPORT COEFFICIENTS OBSERVED IN ALL TRANSPORT CHANNELS IN CORE



- χ_i^{eff}(convective + conductive) ≈ χ_i^{eff}(neoclassical) at $\rho < 0.35$ with ECCD

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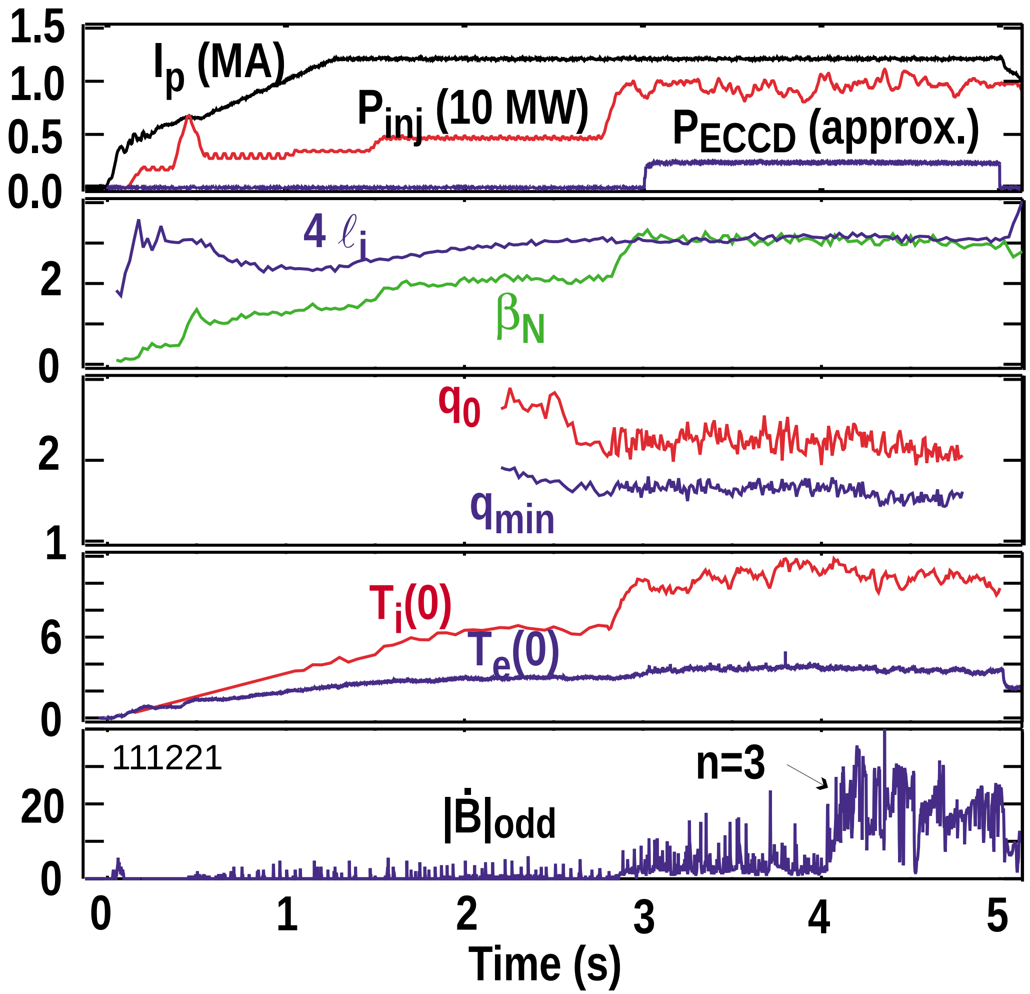
IN SEPARATE EXPERIMENTS, ECCD HAS BEEN USED TO SUSTAIN A STATIONARY CURRENT DENSITY PROFILE FOR UP TO 1.0 S with q_{min}>1.5



- High power phase delayed until q_{min} < 2.0
- β_N ~ 3.1, β ~ 3.3 %, H_{89} ~ 2.4
- q_0 > 2.0, q_{min} < 2.0 maintained for 1.0 s
- Duration limited by onset of small m=5/n=3 NTM

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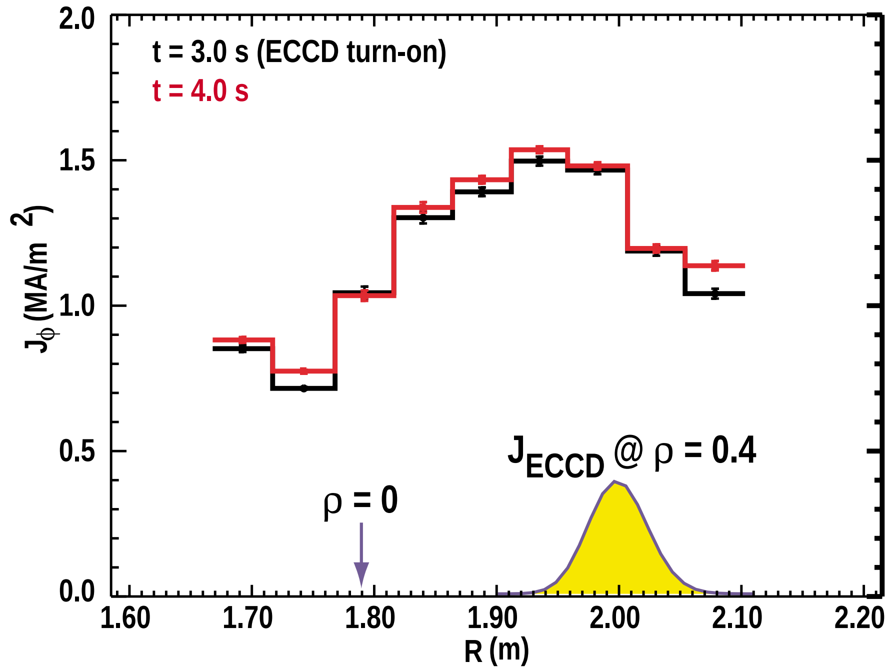
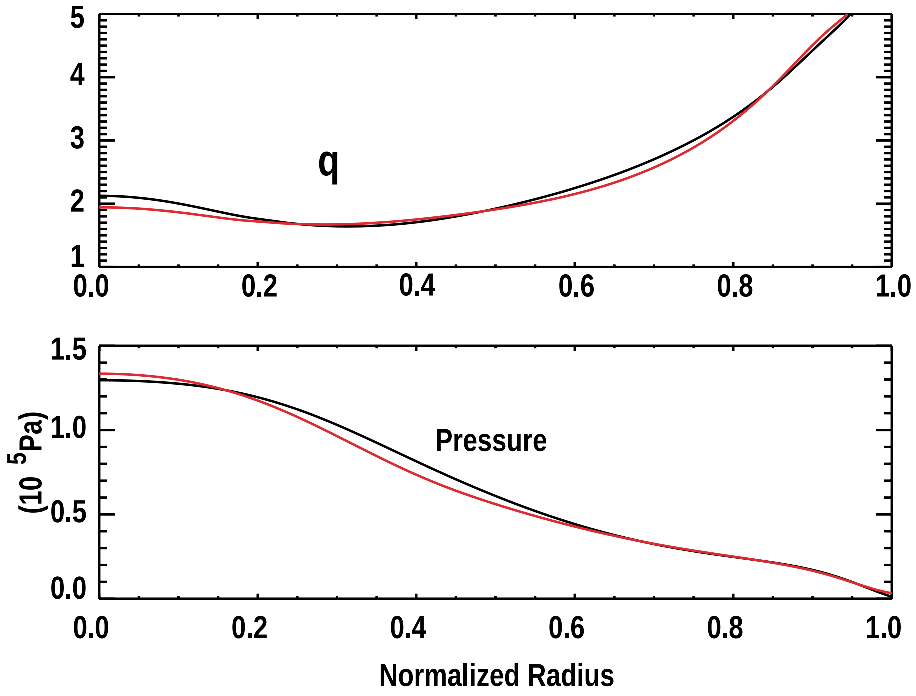
CURRENT PROFILE IS STATIONARY FOR FIRST SECOND OF ECCD

- Direct inference of J_ϕ using MSE data



- EFIT reconstruction of equilibrium



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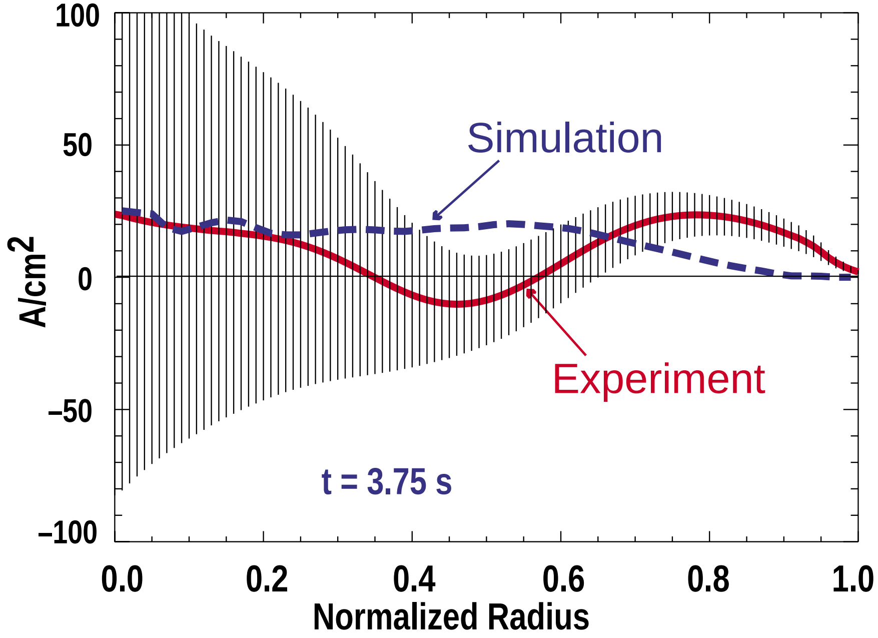
NONINDUCTIVE CURRENT FRACTION OF ~85% WAS OBTAINED IN THE $q_{min} \gtrsim 1.5$ REGIME



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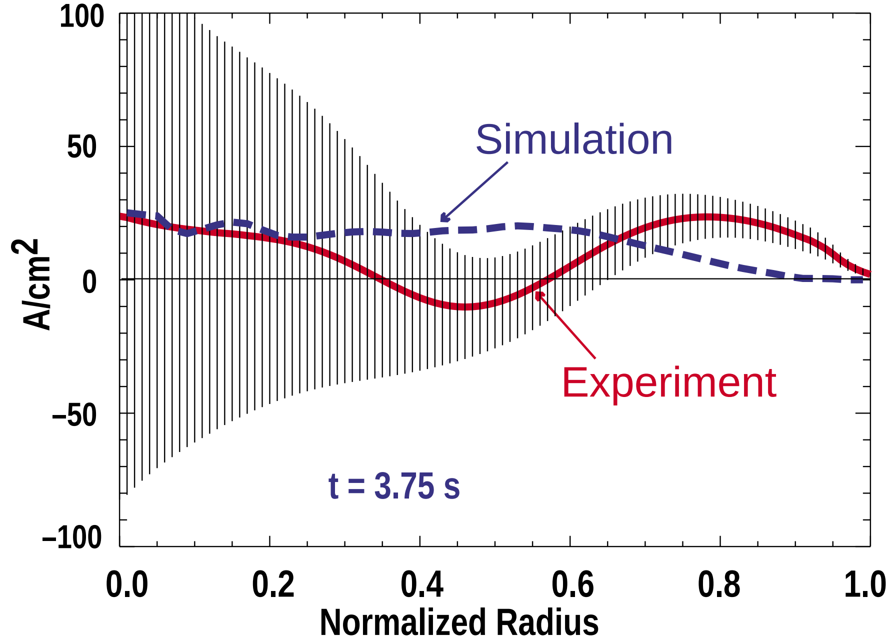

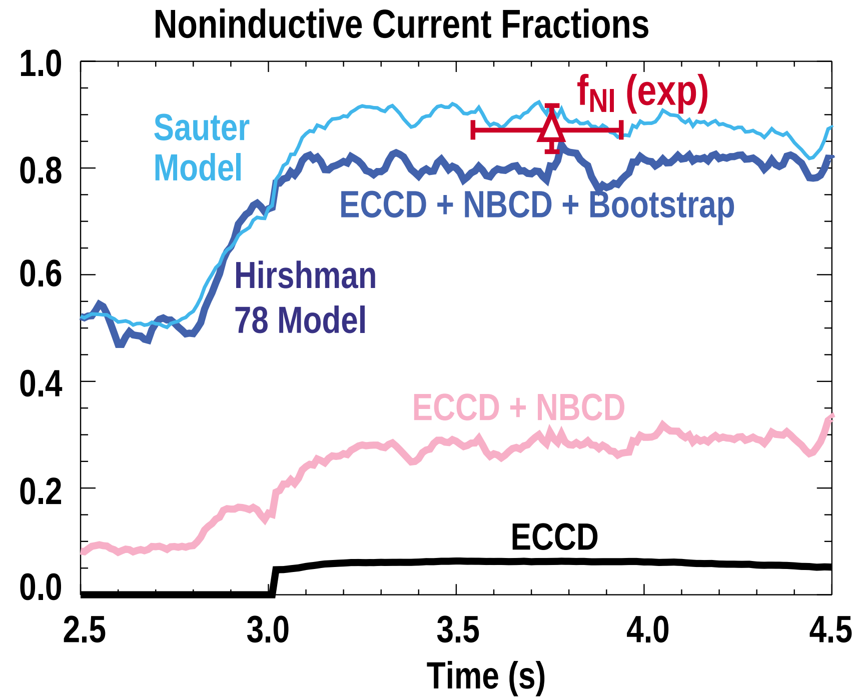

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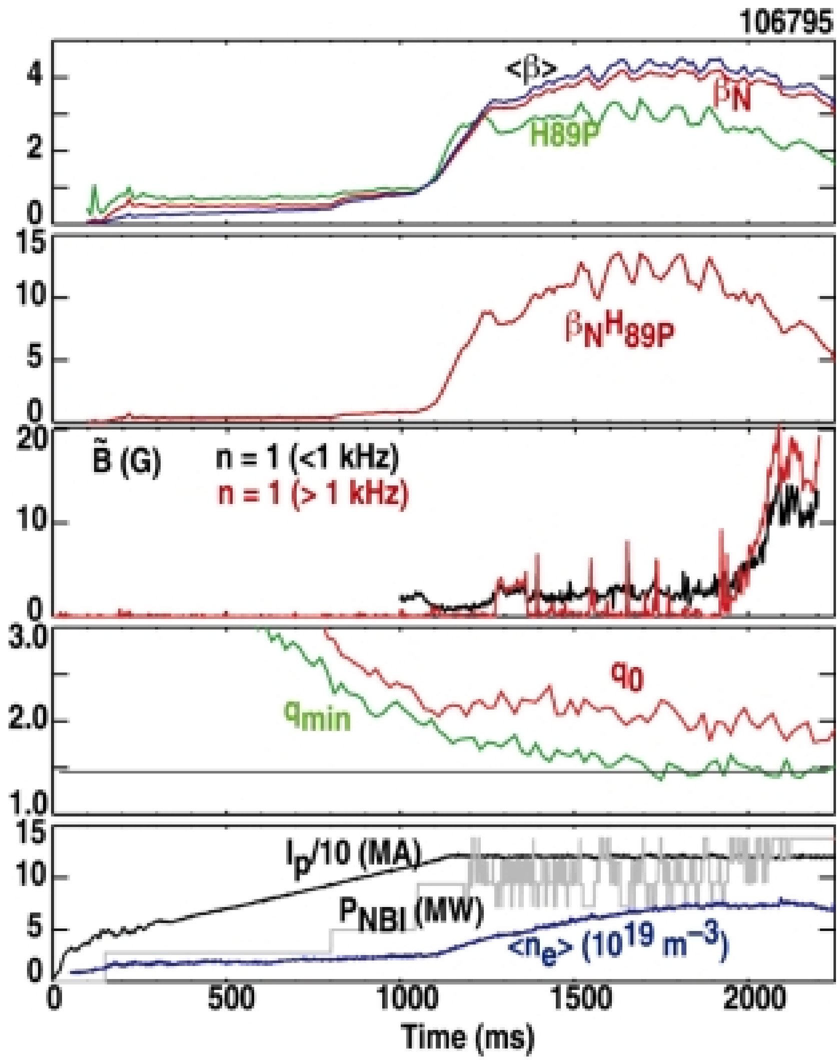
DISCHARGE WITH β_N ~ 4 HAS BEEN OBTAINED WITH NBI IN THE q_{min} ~ 1.5 REGIME



- β_N ~ 4
- $\beta_N H_{89}$ > 10 for $4\tau_E$
- Minimal MHD activity
- Small RWM amplitude due to sustained plasma rotation

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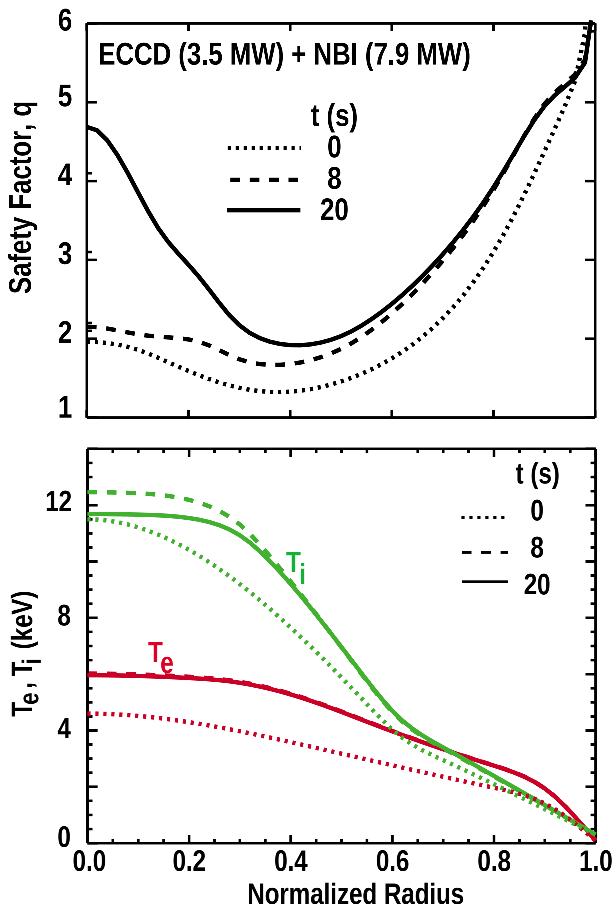
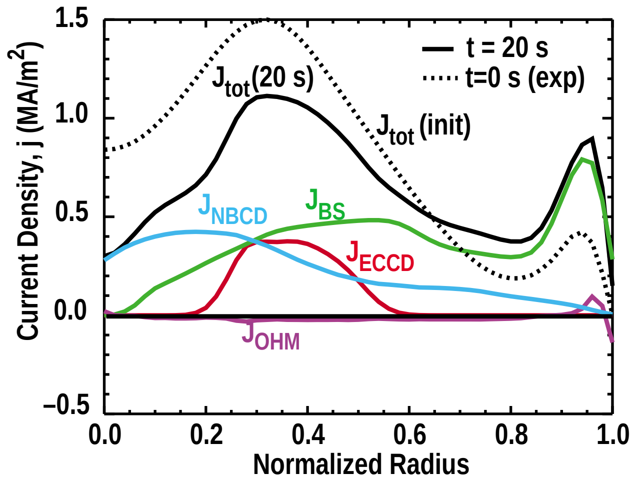
PREDICTIVE MODELING BASED ON ONE OF THE HIGH β_N TARGET DISCHARGES WITH q_{min} ~ 1.5 INDICATES THAT THE FAVORABLE CURRENT PROFILE CAN BE MAINTAINED INDEFINITELY





β_N = 4.0

H_{89} = 3.1

f_{BS} = 80%

f_{NI} = 100%

- Assumed a broadly distributed off-axis ECCD at P_{EC} = 3.5 MW
- Sustaining this high β_N value requires reliable RWM stabilization which we are still developing

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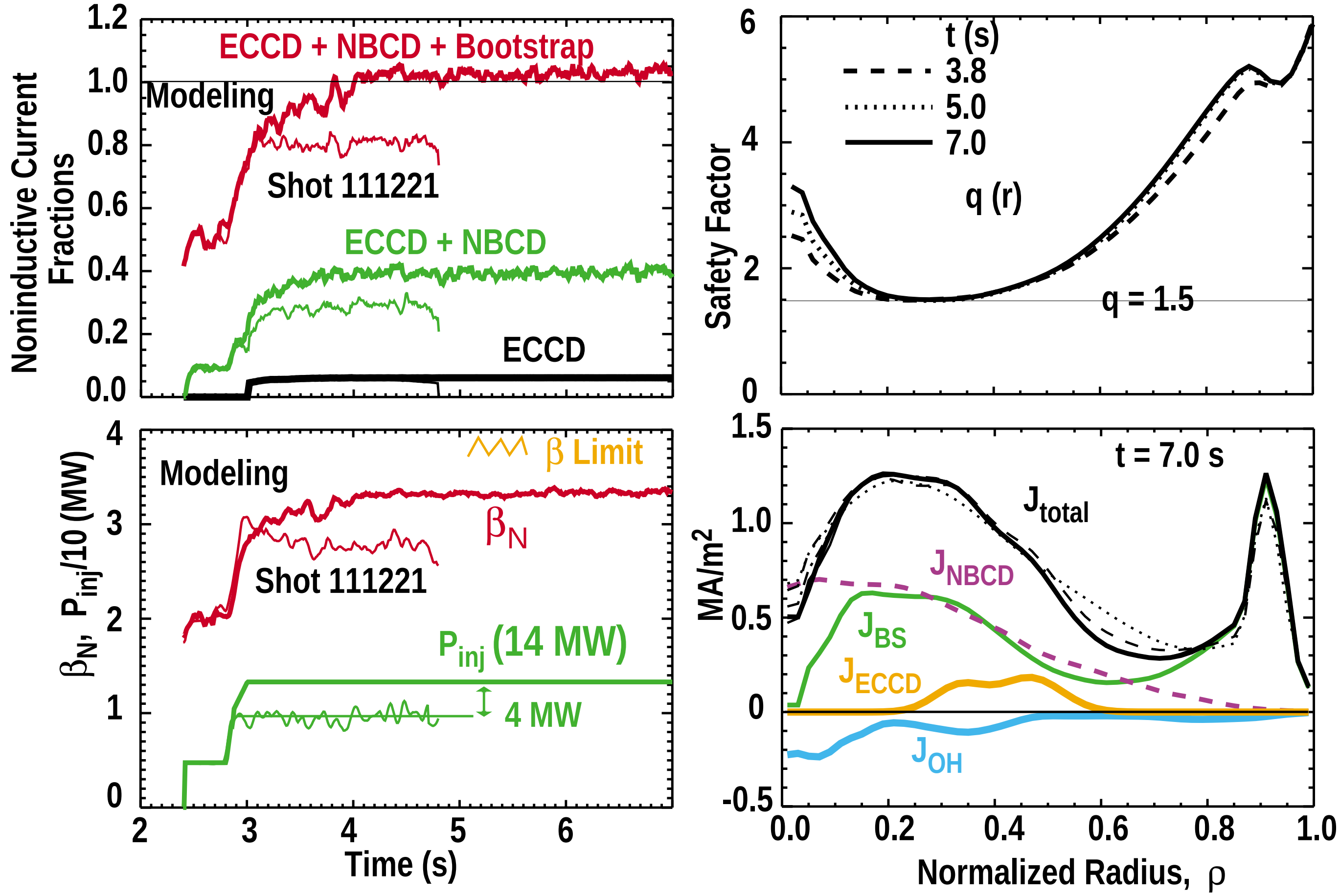
PREDICTIVE MODELING SHOWS THAT THE EXISTING q_{min} > 1.5 ECCD DISCHARGE CAN BE EXTENDED TO FULL NONINDUCTIVITY USING THE HARDWARE CAPABILITIES AVAILABLE IN THE NEAR TERM



- Estimated power requirements are conservative: H98y2 scaling power degradation ($\chi \propto \chi_{exp} \cdot P^{0.69}$); kinetic (not magnetic) β_N; and bootstrap model
- The DIII–D ECCD capability expected in 2003 includes 4 s (> τ_{CR}) of ECCD at P_{EC} ~ 2.5 MW

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J. Lohr: LO1.006

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SUMMARY

- Current profile at high β has been modified using off-axis ECCD with q_{min} >2
  - Strong negative central shear produced
  - Improvements observed in all transport channels
  - f_{BS} ~ 55%; f_{NI} ~90% achieved; higher values limited by attainable β_N

- Current profile at high β has been sustained with q_{min} >1.5
  - Nearly steady-state current and pressure profiles maintained for 1 s
  - Good access to the regime demonstrated where higher f_{BS} possible with higher β_N

- Predictive modeling validated for full noninductive operation with q_{min} > 1.5 using near-term hardware capabilities

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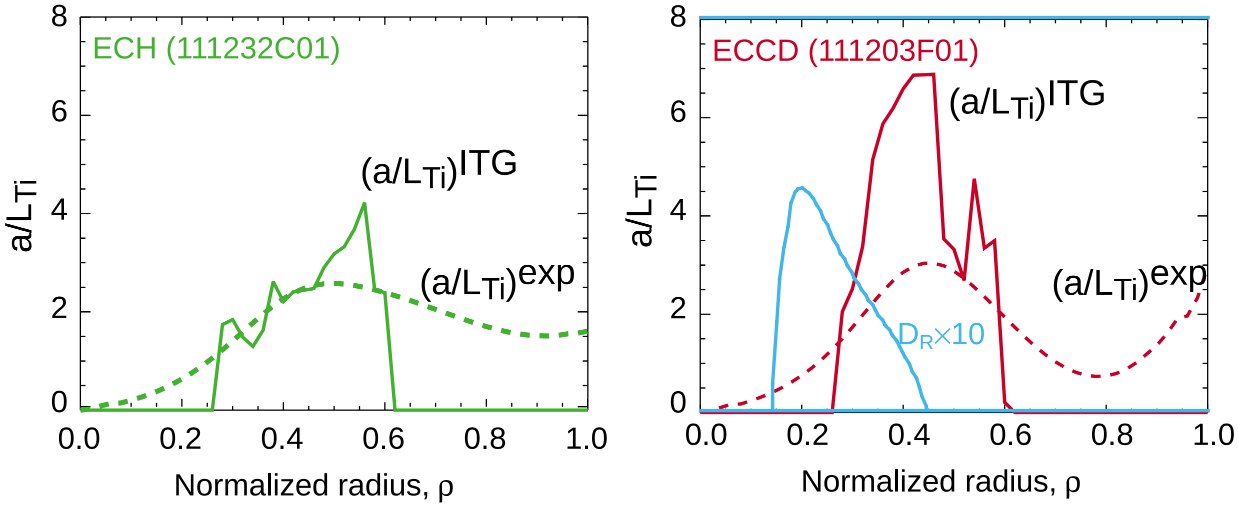
THE CORE REGION OF THE ECCD DISCHARGE MAY BE LIMITED BY RESISTIVE INTERCHANGE MODES



- GKS ⇒ a/L_{Ti}(exp) limited by a/L_{Ti}(ITG) in the ECH case
- Stronger NCS, α-stabilization (and ExB shear) stabilize ITG in the ECCD discharge
- Why not a/L_{Ti}(exp) goes up as high as a/L_{Ti}(ITG)?
- Resistive interchange modes are found to be unstable in core (ρ = 0.15 - 0.41) with ECCD, as shown by D_R >0 there
  - — Some bursts observed in Mirnov signals
- Since GKS code uses the ballooning representation, the code calculation in this region is invalid
- We also note that χ_i^{eff}(exp) ~ χ_i^{eff}(neo) in region ρ < 0.35 for the ECCD case

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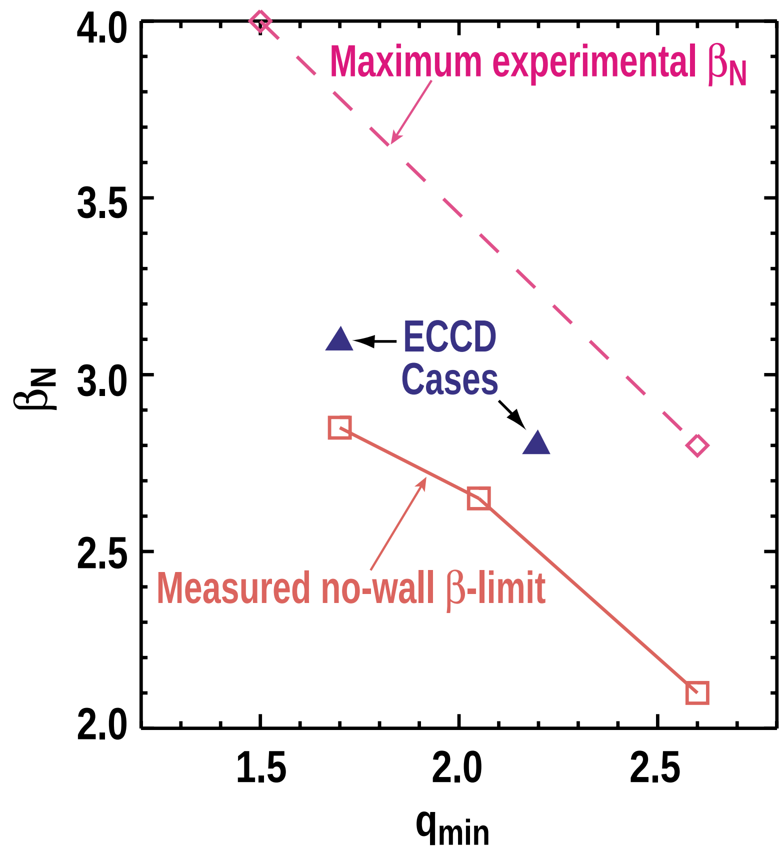
ATTAINABLE β_N OBSERVED TO DECREASE AS q_{min} INCREASES

- So far, β_N = 3.5 - 4.0 possible with q_{min} <2
- Robust operation above no-wall, ideal n = 1 limit made possible by RWM stabilization
- Stability calculations ⇒ with suitable broad pressure profiles and RWM stabilization, higher β_N may be possible with q_{min} >2



J. Ferron: LO1.005
A. Garofalo: LO1.004

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