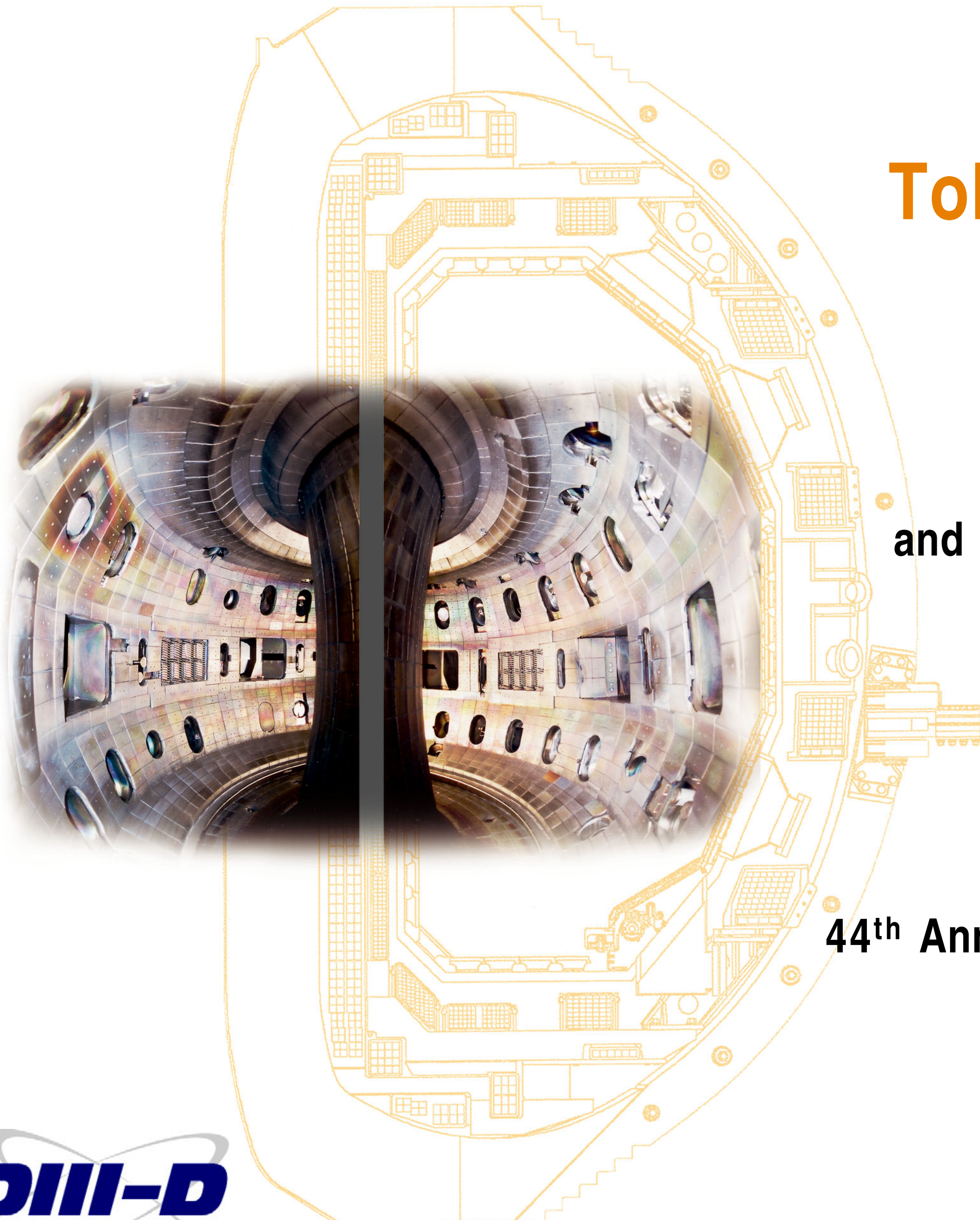

Progress in Advanced Tokamak Development in DIII–D

by

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and the Advanced Tokamak Thrust Group

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GENERAL ATOMICS

287-02/CMG/cmg

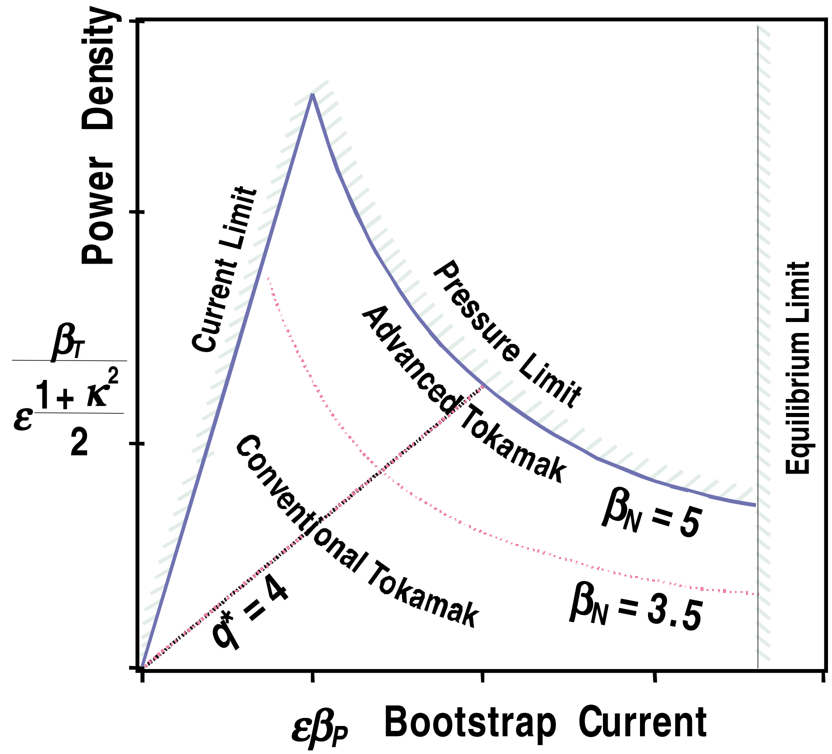
ADVANCED TOKAMAK RESEARCH ON DIII–D

Realizing the Ultimate Potential of the Tokamak

- Improvement of the tokamak concept toward
  - High duty factor (ideally, steady state)
    - > Self-generated bootstrap current ⇒ high β_P
    - > Current drive
  - High power density ⇒ high β_T
    - > Improved stability
  - Compact (smaller)
    - > Improved confinement ⇒ high τ_E

Simultaneously integrated

- A self-consistent optimization of plasma physics through
  - MHD stability control
    - > Magnetic geometry (plasma shape)
    - > Pressure and current profiles
    - > Resistive wall mode mitigation [Garofalo, L01.004]
    - > NTM avoidance via high q_{min}
  - Plasma profile control
    - > Current, pressure, density, rotation, radiation,...
  - *Strong experiment – simulation coupling*



Competing requirements of high power density and high bootstrap fraction necessitate operating near the pressure limit (high β_N)

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EFFORTS IN 2002 FOCUSED ON IMPROVED CONTROL OF ADVANCED TOKAMAK PLASMAS

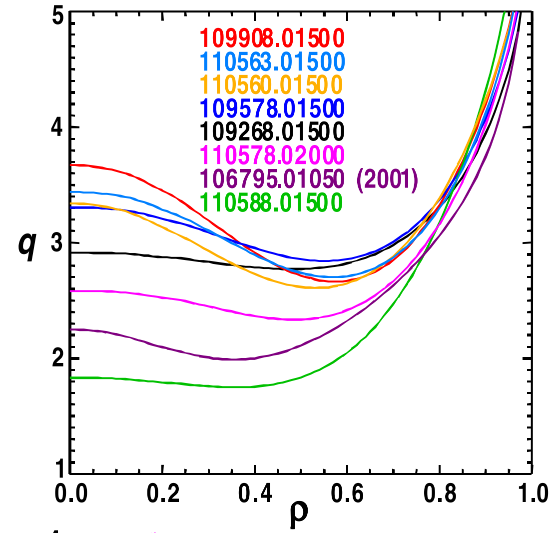
- **Previously (2001): High β Advanced Tokamak plasmas demonstrated:**

  $\beta = 4.2\%$ $\beta_{N—\_\_} \geq 10$ for 600 ms (~4 τ_E)

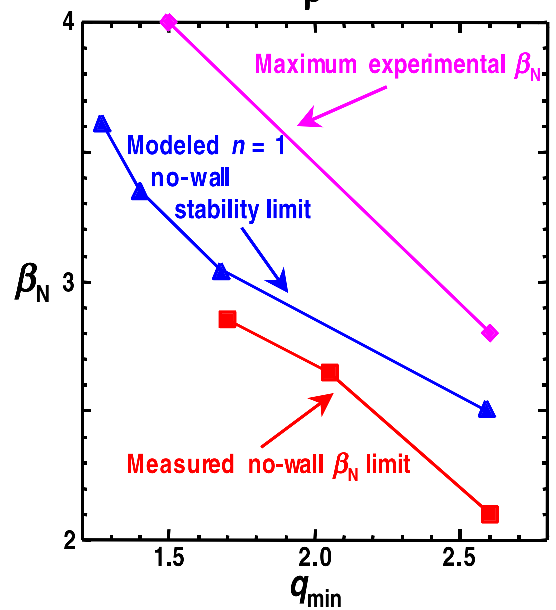
- **Emphasis in 2002: Profile control looking towards steady-state:**
  - Optimize target *q* profile for simultaneous high β and high noninductive current fraction
    - > Evaluate MHD stability at high β and high *q*
  - Current profile control with ECCD in two different *AT* regimes
    - > **Discharges with $\beta_N > 3$ and $f_{NI} > 90\%$ obtained.**
  - Control of kinetic profiles with ECH
    - > Feedback control of T_e
    - > Density profile control in QDB regime

A RANGE OF *q* PROFILES ARE EVALUATED TO DETERMINE THE BEST *q* PROFILE FOR *AT* REGIMES

- **Demand for high bootstrap fraction makes high q_{min} appear favorable.**
  - Wide variety of current profile shapes available via control of L–H transition and heating during current ramp



- **However, no-wall β_N limit and achievable β_N decrease as q_{min} increases with typical DIII–D *AT* pressure profiles.**



- **Further optimization:**
  - Consider competing requirements of high beta and high bootstrap fraction.
  - Improved pressure and current profile control and plasma shaping may allow access to higher β with high *q*.

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Ferron, L01.005 Makowski, QP1.061 (Thursday morning)

PROGRESS IN 2002 UTILIZED EXPANDED ELECTRON CYCLOTRON HEATING (ECH) AND CURRENT DRIVE (ECCD) CAPABILITIES

- **Definitions:**
  - Electron Cyclotron Heating (ECH): *Radially launched EC waves, localized heating with no current drive.*
  - Electron Cyclotron Current Drive (ECCD): *Tangentially launched EC waves, localized heating + current drive.*

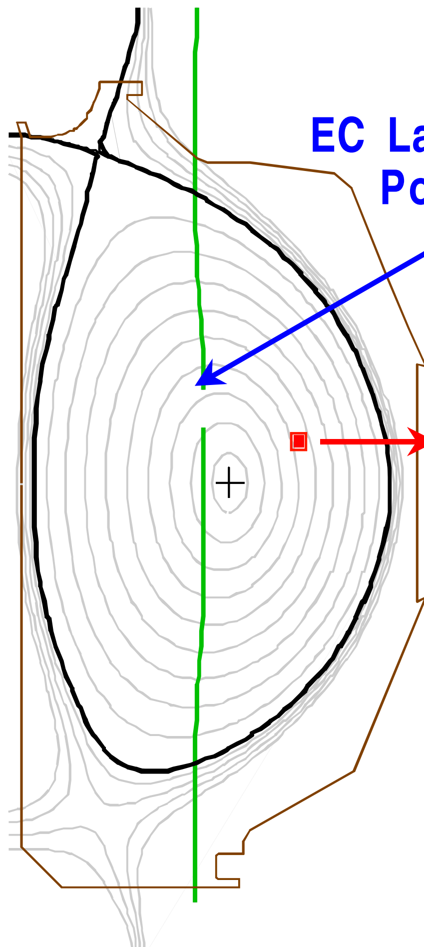
- **Flexible launchers allow waves to be launched in a variety of directions:**
  - Vertical adjustment → radial position control.
  - Toroidal adjustment → co- or counter-ECCD or ECH.

- **Gyrotrons supply up to 2.7 MW of EC power at 110 GHz.**
  - Up to 4 MW anticipated available in 2003

- **Flexible Plasma Control System → feedback control of gyrotrons for real-time profile control.**

EC 2nd Harmonic Resonance (f = 110 GHz)

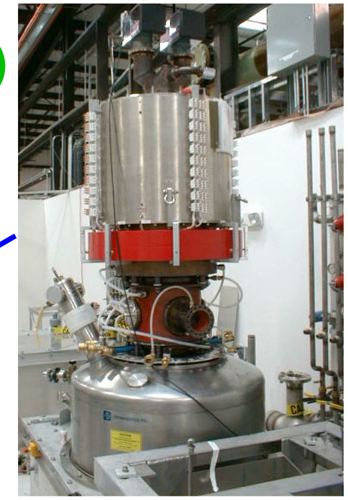
EC Launched Power



T_e measured by ECE

Lohr, L01.006

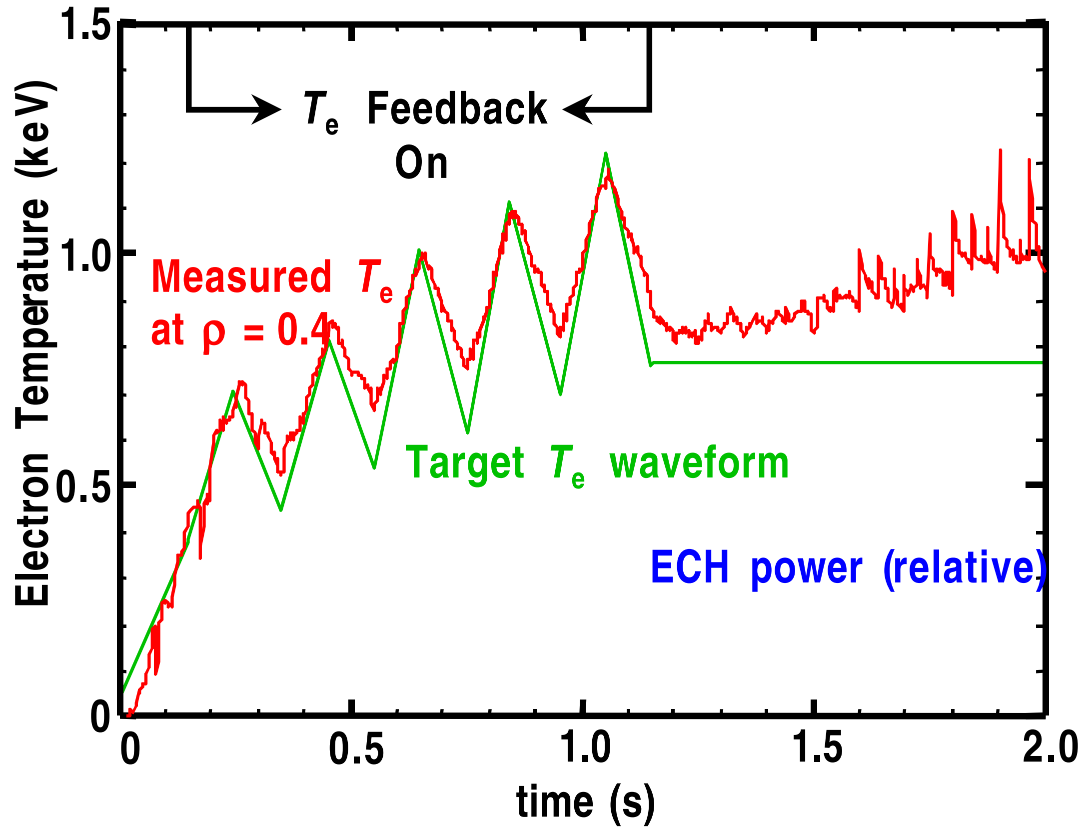
3 (6) gyrotrons (power separately controlled)



Plasma Control System

REAL-TIME CONTROL OF T_e HAS BEEN DEMONSTRATED WITH BOTH ECH AND NBI

- Demonstration of real-time T_e control:
  - ECH deposition at $\rho \approx 0.4$
  - PCS feedback using ECE measurement at $\rho \approx 0.4$ as sensor
- *Applications include improved control over AT target plasma formation.*
  - T_e control $\rightarrow$ q profile evolution control
  - More reproducible
  - Wider density range available
- Capability can be extended using multiple ECE channels and ECH launchers.



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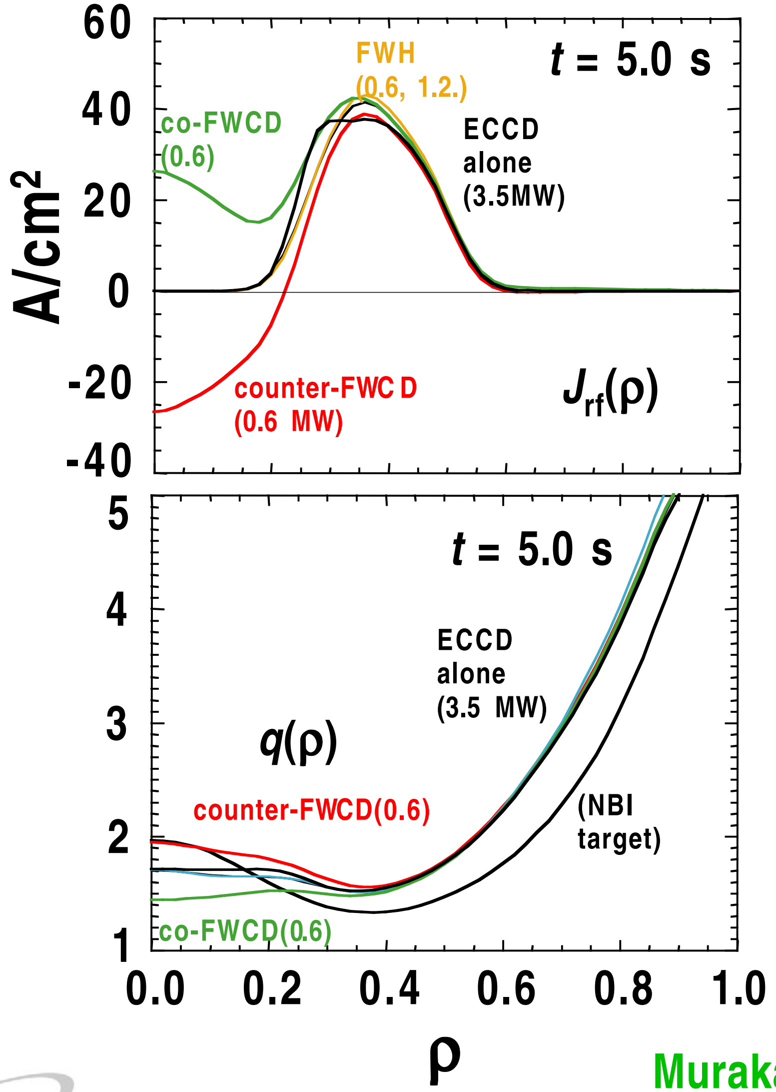
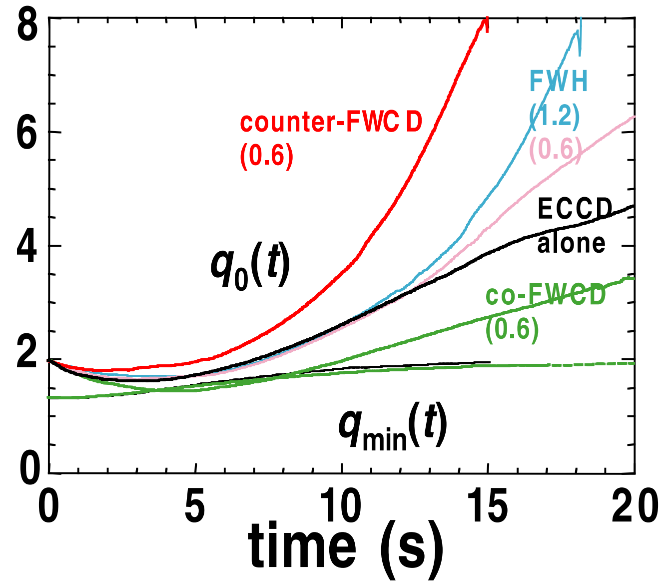
Wade, L01.008

AT EXPERIMENTS ARE DESIGNED WITH THE AID OF SIMULATIONS BASED ON THEORY AND PREVIOUS EXPERIMENTS





- **Integrated modeling predicts control over the current profile using realistic values of EC and FW power.**

Murakami, FI1.002 (Tuesday morning)
Casper, L01.003
St. John, RP1.032 (Thursday afternoon)

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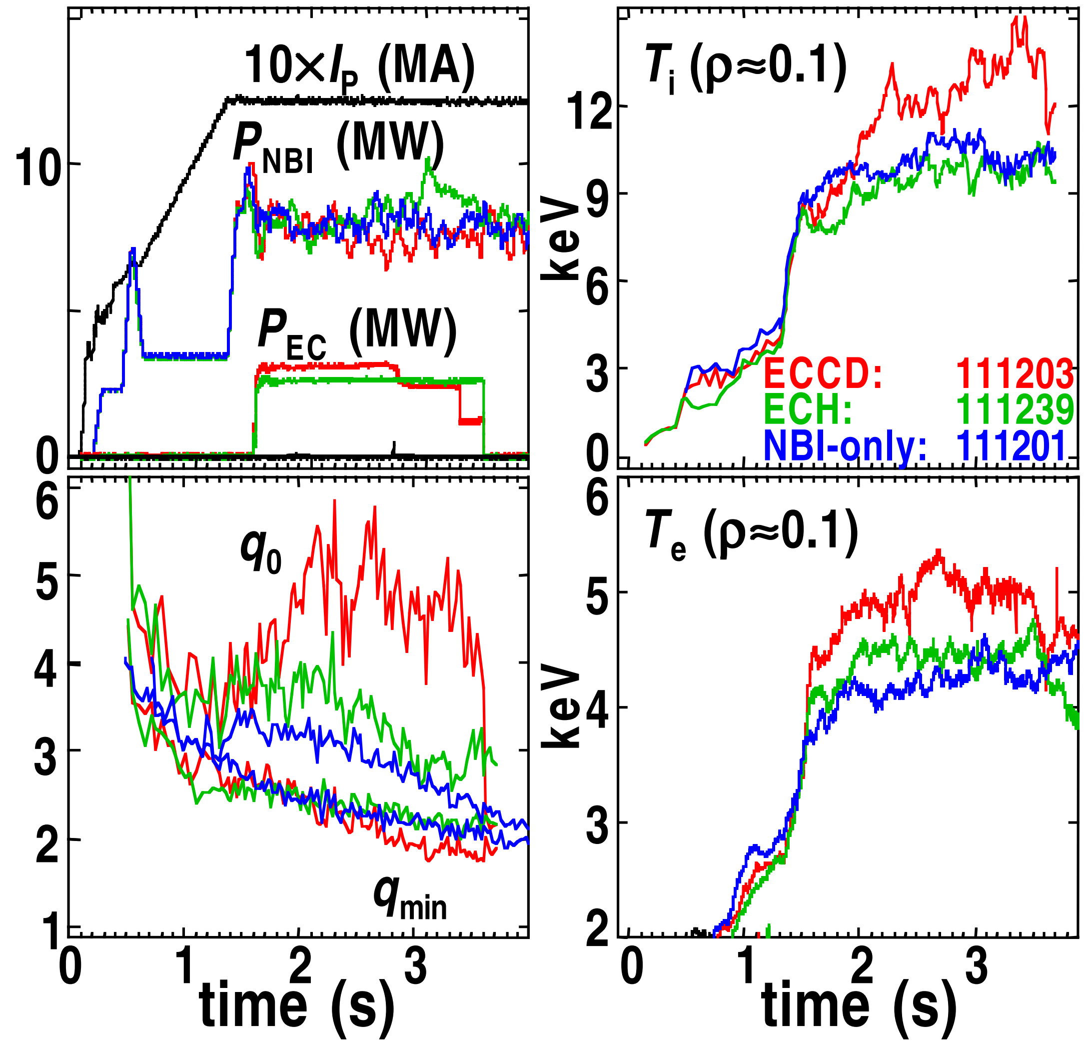
ECCD CURRENT PROFILE CONTROL DEMONSTRATED IN HIGH BOOTSTRAP *AT* REGIME

- **ECCD results in:**
  - Current profile control consistent with simulations.
    - > *Also seen in QDB regime.*
  - ITB formation.
    - > Facilitated by changes in *q* profile due to current drive.

- **Profile changes not seen in NBI-only and ECH cases.**



(Five gyrotrons for 2 sec aimed at ρ ≈ 0.4)

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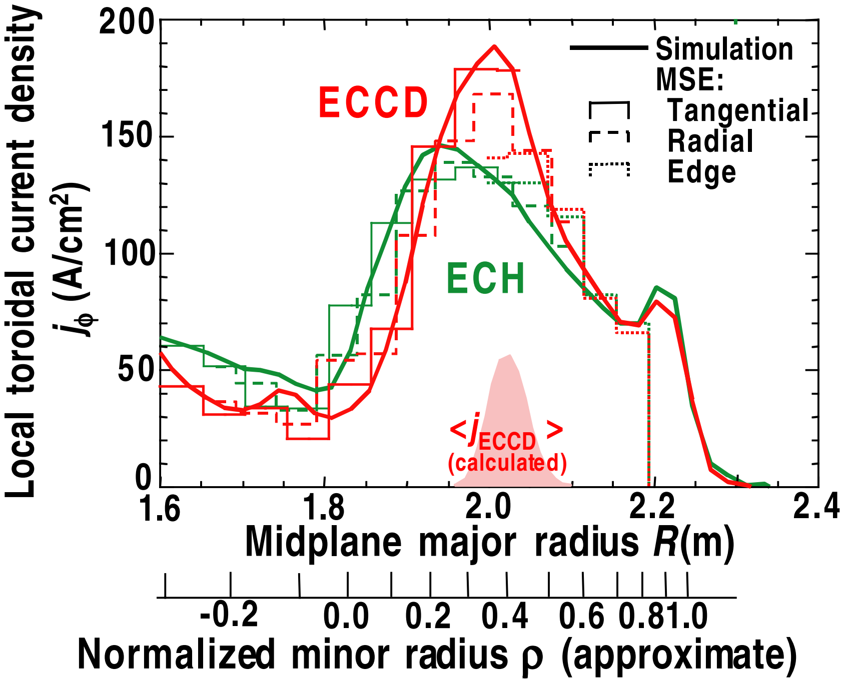
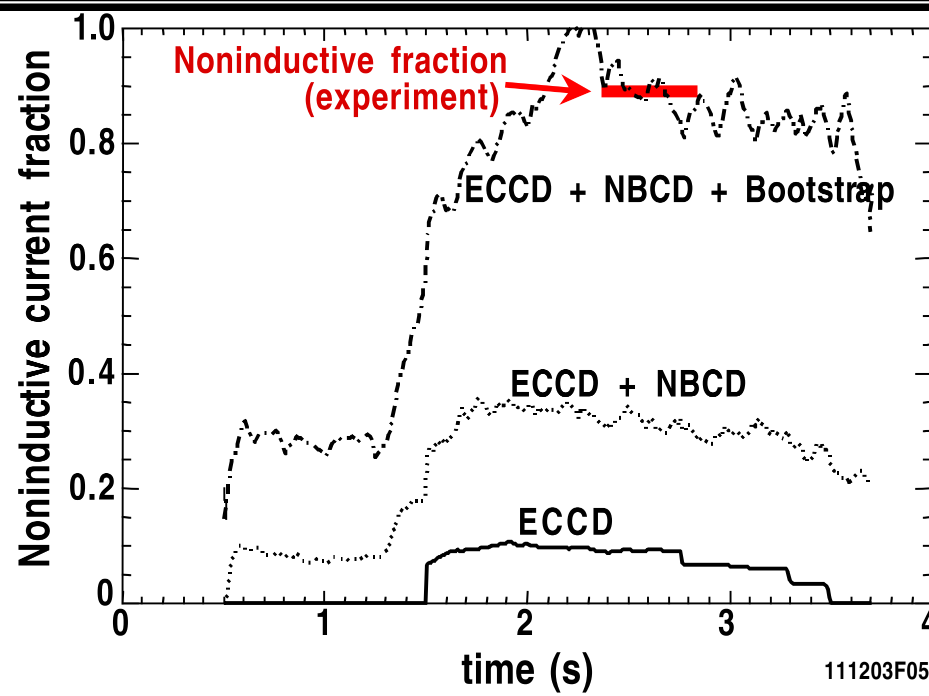
Murakami, FI1.002 (Tuesday morning)

CONTROL OF THE CURRENT PROFILE VIA ECCD FACILITATES OPERATION WITH f_{NI} > 85%





- Simulated current profiles are consistent with MSE measurements.
- Current density increases in vicinity of ECCD absorption location.
  - $I_{ECCD} \approx$ 140 kA with $P_{ECCD} \approx$ 2.5 MW.
- Noninductive current drive fraction maintained with f_{NI} > 85% for 0.5 s.
  - Nearly stationary discharge with f_{NI} > 85% maintained for 1 s with lower $q_{min} \approx$ 1.5.

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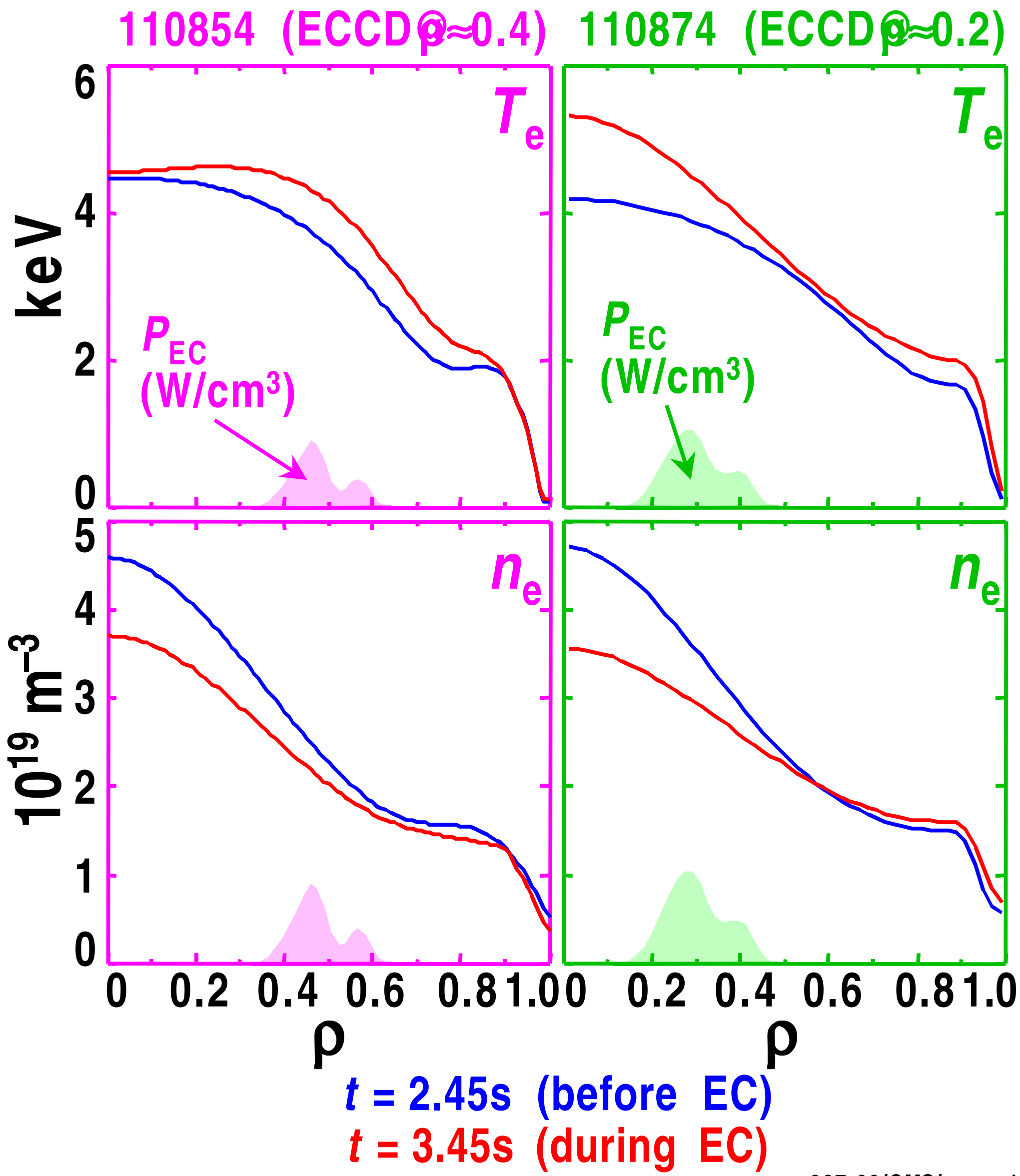
CORE ECH CONTROLS DENSITY PROFILE IN THE QUIESCENT DOUBLE BARRIER REGIME

- **Strongly peaked density profiles limit performance in QDB plasmas.**
  - Core impurity confinement
  - Beta limit: $\beta_N \approx 2.9$ due in part to peaked pressure profile
  - Bootstrap alignment

- **Core ECH can broaden density profile.**
  - Not strongly dependent on antenna aiming: primarily a heating effect.

- **Impact:**
  - Core impurities significantly reduced
  - Effect on β limit and bootstrap alignment not yet evaluated



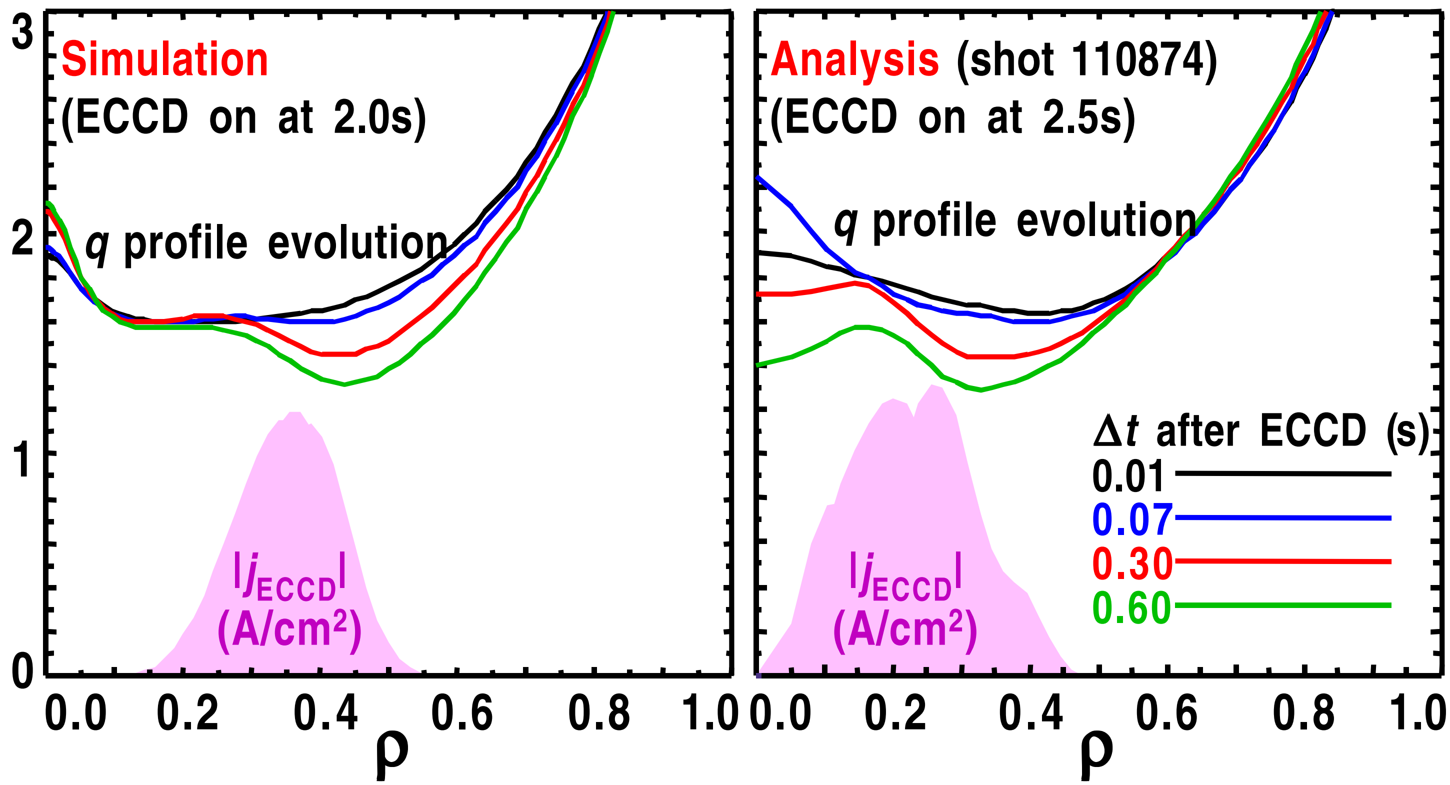
SUMMARY: ADVANCED TOKAMAK PROGRESS IN 2002

- **Progress made on understanding beta limits in AT regimes.**
  - Open issue: Determination of optimal target *q* profile.

- **ECH/ECCD: a versatile and powerful profile control tool.**
  - Feedback control (ECH and NBI) employed during current ramp to control T_e and current profile evolution.
  - ECCD used to make significant modifications to current profile in *two* different AT regimes:
    - > High Bootstrap Fraction AT
    - > Quiescent Double Barrier Regime
  - Control of density (electron and impurity) profiles demonstrated in QDB discharges using ECH.

- **Future capabilities will allow further development toward ultimate goal of 100% noninductive, very high beta discharges:**
  - Increased ECH power
  - Fast-wave system reactivation
  - Internal coils for MHD control decoupled with rotation
  - Possible longer-term additions include high(er) triangularity, double-null divertor pump.

ECCD CAN ALSO CONTROL CURRENT PROFILE IN QUIESCENT DOUBLE BARRIER DISCHARGES



- Simulation and analysis with CORSICA both indicate current profile modification with off-axis ECCD in QDB discharges.
- ECCD's viability as a current profile control tool not limited to single *AT* regime.

Casper, L01.003 Doyle, RP1.029 (Thursday afternoon)