# Feedback Control of the Safety Factor Profile in DIII-D Advanced Tokamak Discharges

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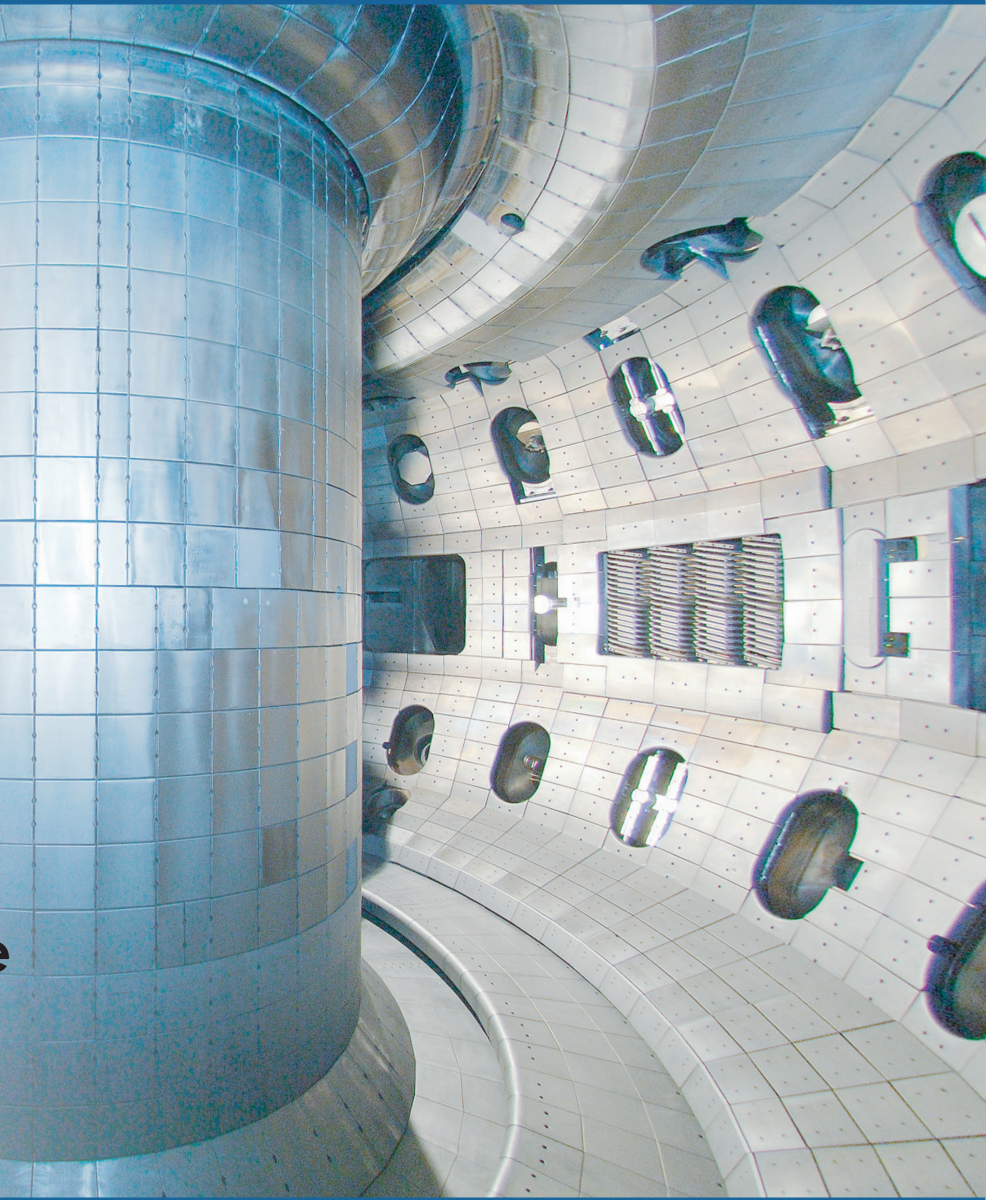

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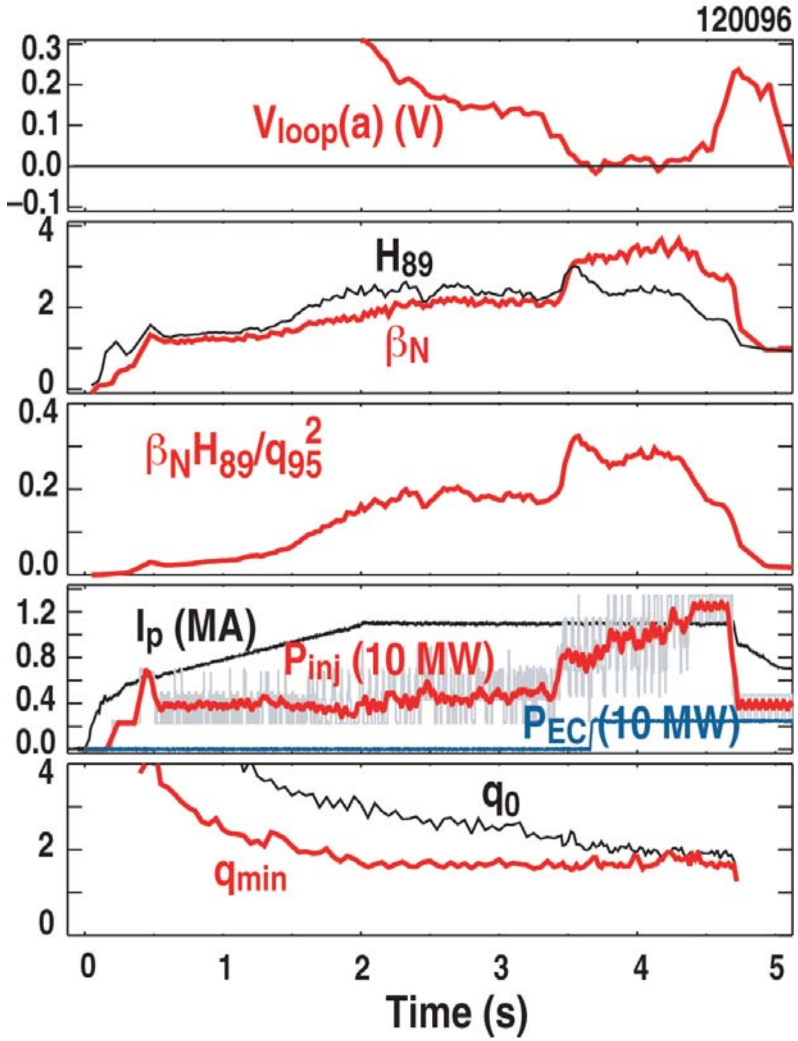
# AT Discharge Goal: Create the Optimum q Profile During the Discharge Formation and Sustain it in Steady State




- **100% noninductive current at high $\beta_N$**
- **$\beta_N$ feedback for reproducibility**
- **H-mode during the $I_p$ ramp**
- **q profile target for high $\beta$ phase:**
  **$1.5 < q_{min} < 2.5$**
  **$q(0) - q_{min} \approx 0.5$**

# Safety Factor Control Experiments on DIII–D Focus on Formation of Initial Current Profile for Advanced Tokamak Discharges

- **Primary control knob for current profile evolution during plasma formation is conductivity ($\sigma$, or effectively $T_e$)**

  $$J = J_{ind} + J_{nonind} = \sigma E_{||} + J_{BS} + J_{EC} + J_{NB} + \ldots$$

- **Noninductive currents are small relative to inductive during current ramp (low $\beta$ and low $T_e$)**

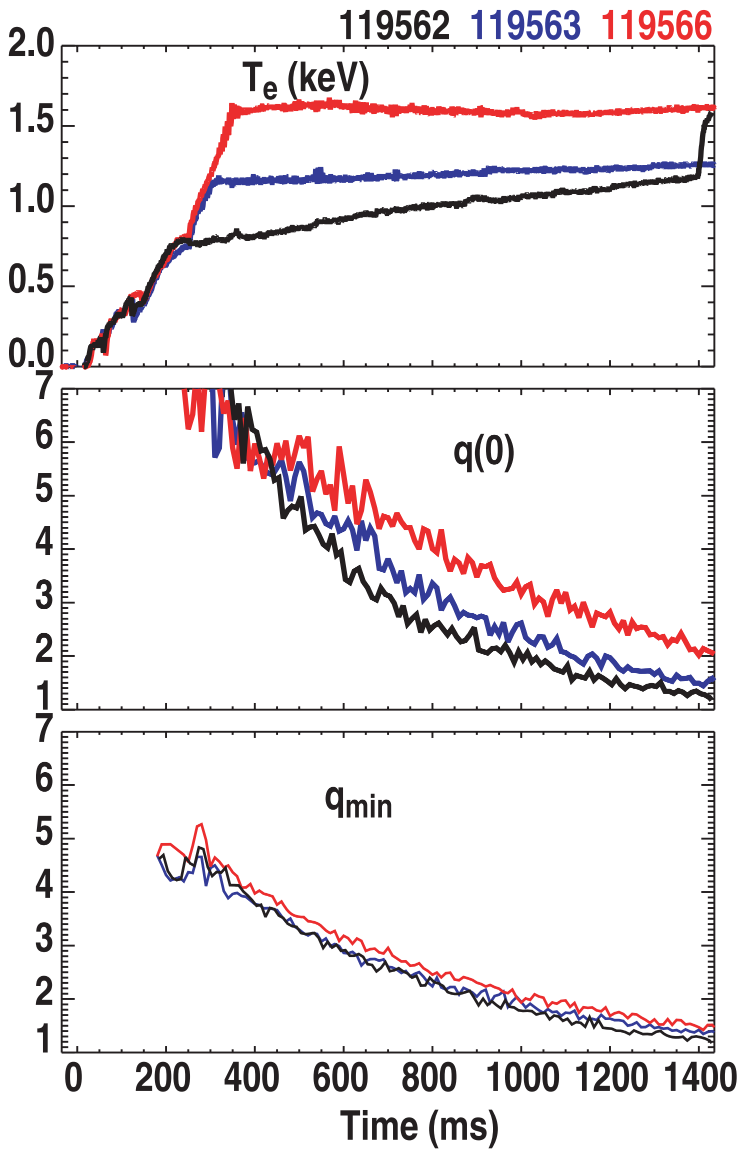
- **Electron heating is strong actuator for q(0) and $q_{min}$ evolution during discharge formation**

- **Off-axis ECH and neutral beam heating are both effective as actuators for changing $\sigma$ profile**
  - 110 GHz long pulse gyrotrons with steerable mirrors inject ~2 MW
  - Neutral beams heat ions/electrons and drive co-current on axis

- **During stationary phase of discharge, localized current drive is needed to control q profile**

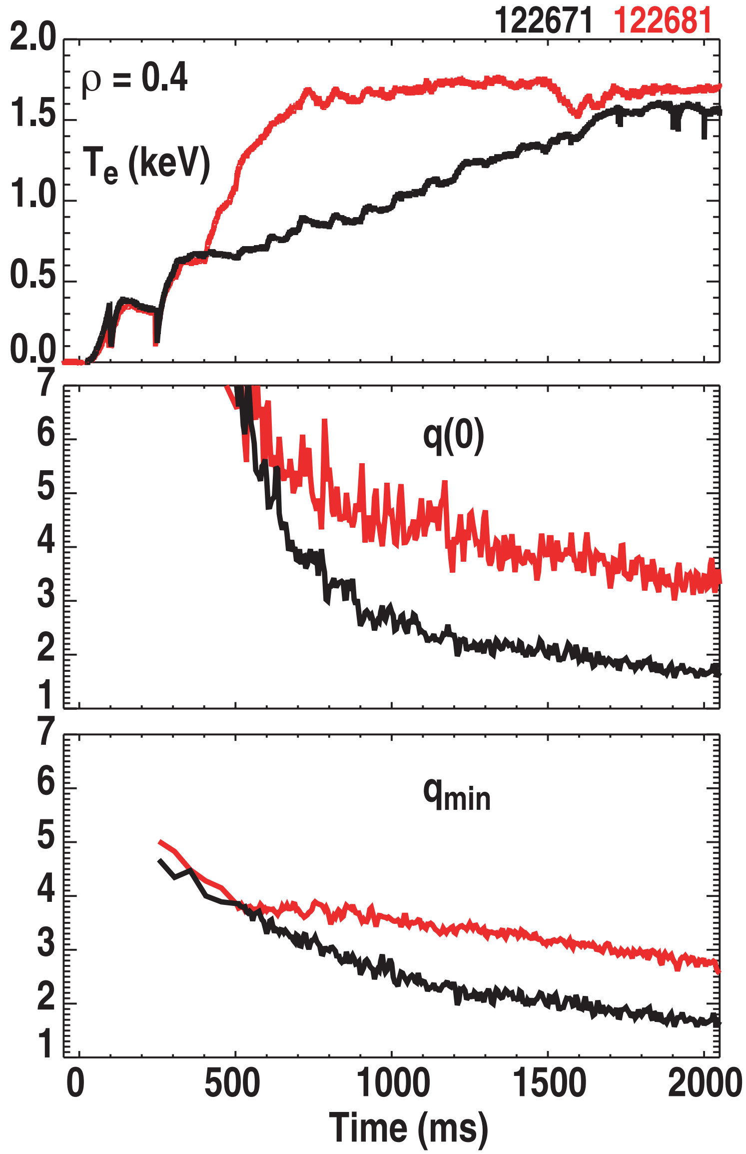
# Experiment

# Open Loop Experiments Demonstrate the Modifications in the q Profile Evolution Resulting From Changes in $T_e$

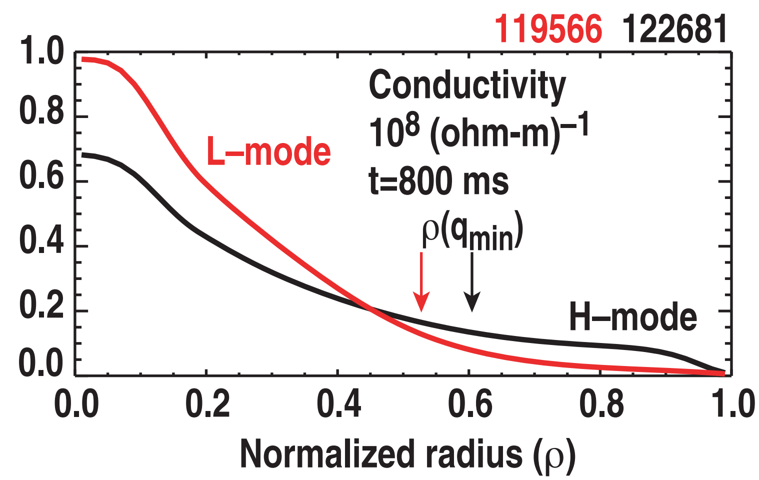



- **L-mode edge, constant $P_{NB}$ =2.6 MW**
- **$T_e$ feedback control using ECH at $\rho$=0.4**
- **Effect is on q(0), not $q_{min}$, because of peaked $T_e$, $\sigma$ profiles [$\rho$ ($q_{min}$) ≈ 0.5]**

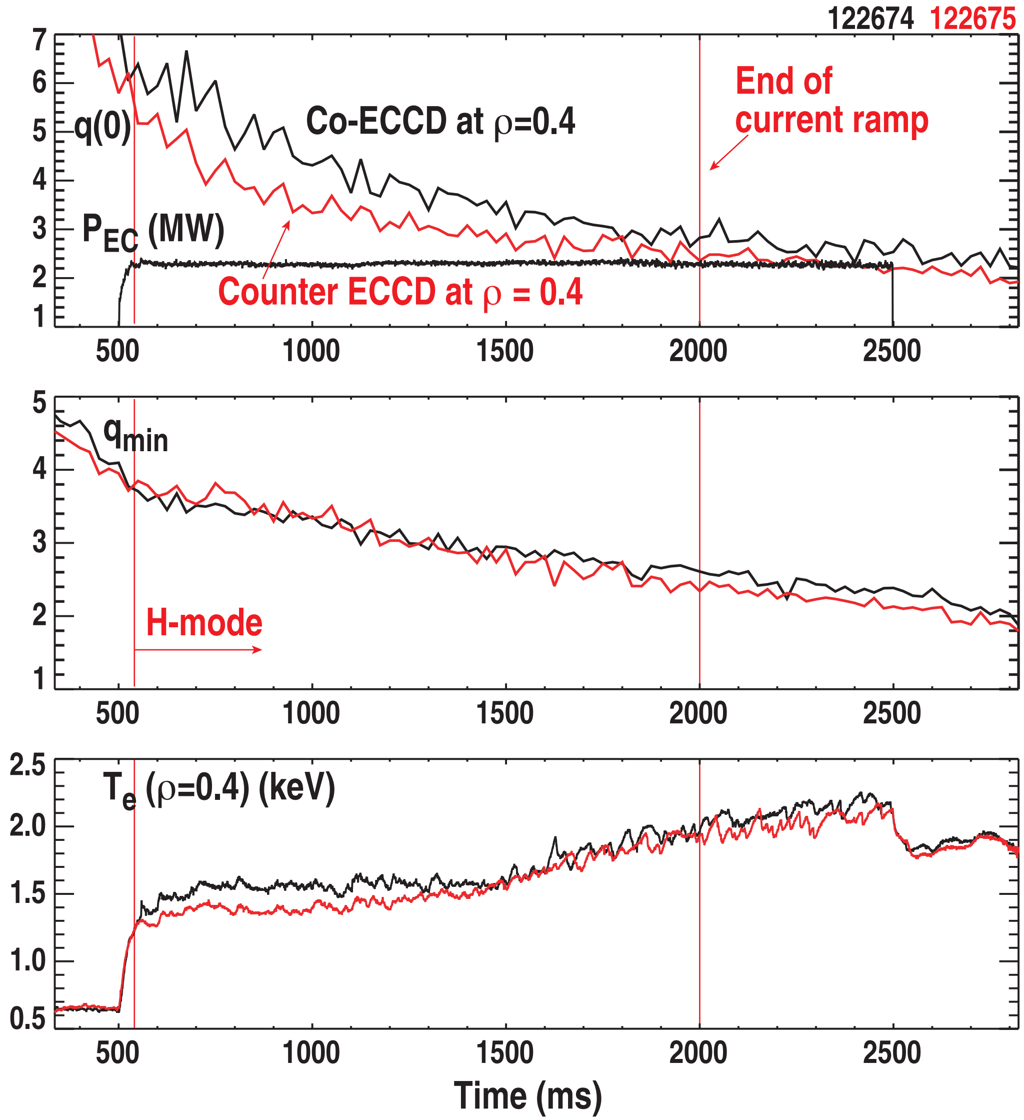
# Broad $T_e$ Profile in H-mode Results in Higher q Values for Longer Duration




- **H-mode, edge $T_e$ pedestal**
- **Both q(0) and $q_{min}$ increase with $T_e$ because of broad σ profile**
- **σ outside radius of $q_{min}$ is 2-4 times larger in H-mode than in L–mode**



# Off-axis Current Drive During the $I_p$ Ramp is a Less Effective Actuator than Conductivity

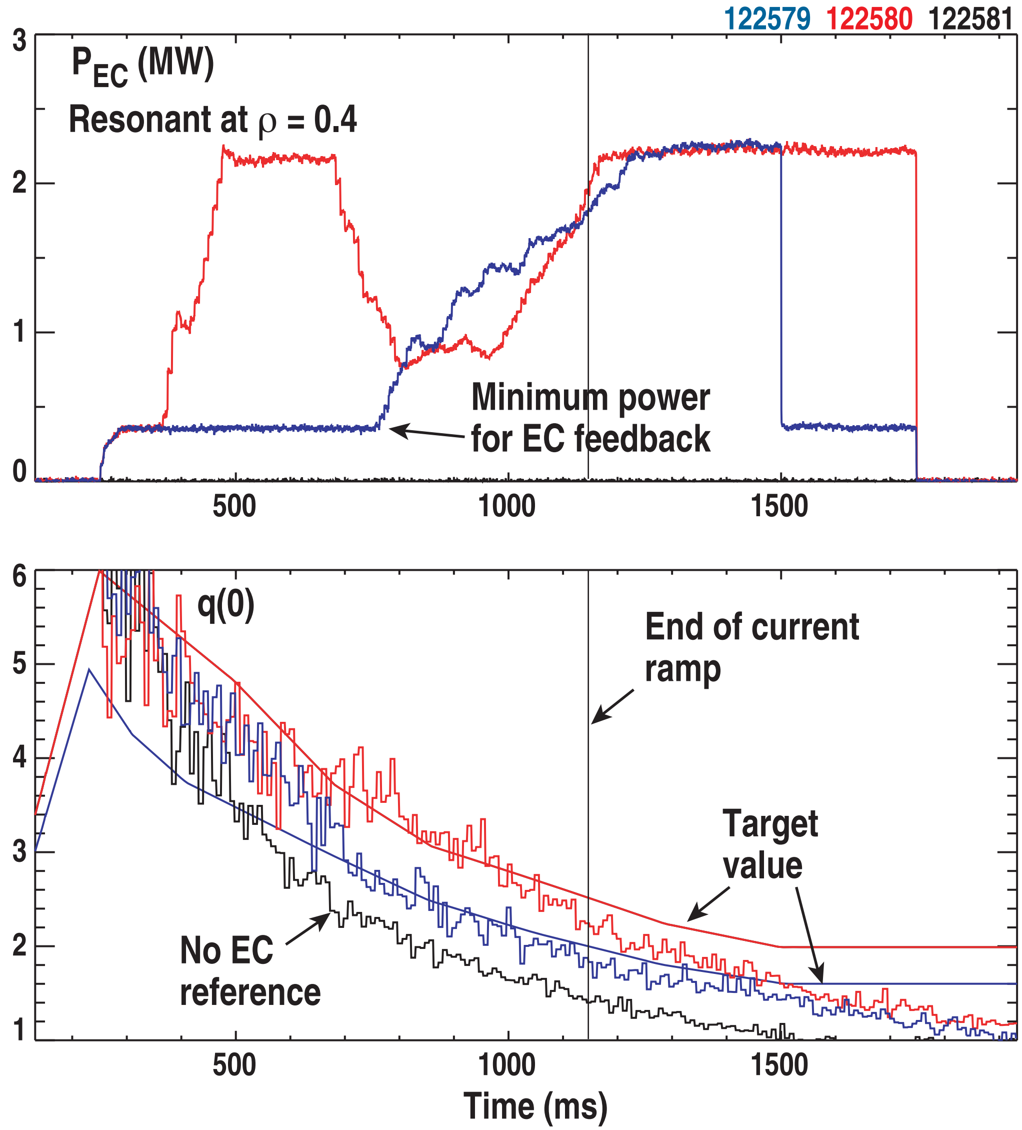



- A comparison between off-axis co–ECCD and counter–ECCD shows only small differences in q evolution
- H-mode edge
- Because of low $T_e$, the ECCD is small compared to the total current density
- Changes resulting from current drive are similar to discharge-to-discharge variations

# Safety Factor Profile is Calculated in Real Time from a Complete Equilibrium Reconstruction

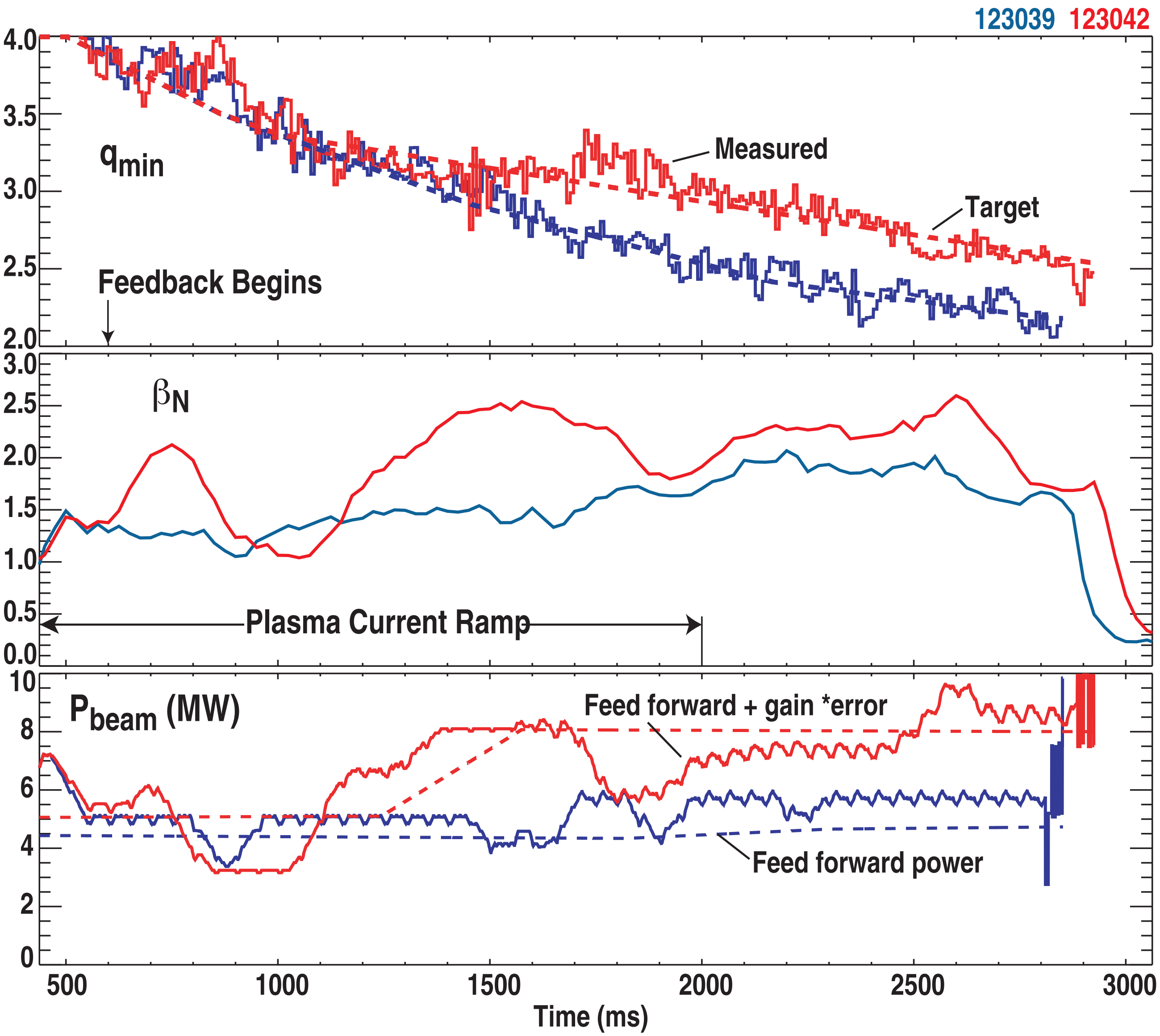
- Data from 26 internal poloidal field measurements from the MSE diagnostic are utilized in the real time EFIT algorithm
- A least squares fit solution to Grad-Shafranov equation is calculated matching the magnetics and MSE measurements
- Solution is consistent with force balance
- Correction for the effect of $E_r$ on MSE
- Spline current profile parameterization for fitting negative central shear q profiles
- Safety factor profile calculation is typically available at 4–8 ms intervals

# Closed-loop Control of q(0) Evolution Using Off-Axis ECH is Effective Until Power Saturates




- L-mode
- Control works during current ramp; insufficient EC power to maintain target in flattop
- Proportional gain only (probably should be higher)
- Two different targets reproduce good (red) and degraded (blue) breakdown conditions

# $q_{min}$ has been Controlled to High Values for Long Duration Using Neutral Beam Heating in H-mode




- **Control works in ramp up and flattop**
- **Proportional gain only**
- **Large power demand on NBI can drive the plasma to β limit**
- **Control of $q_{min}$ and $q(0)$ - $q_{min}$ probably not possible with only NBI**

# Modeling

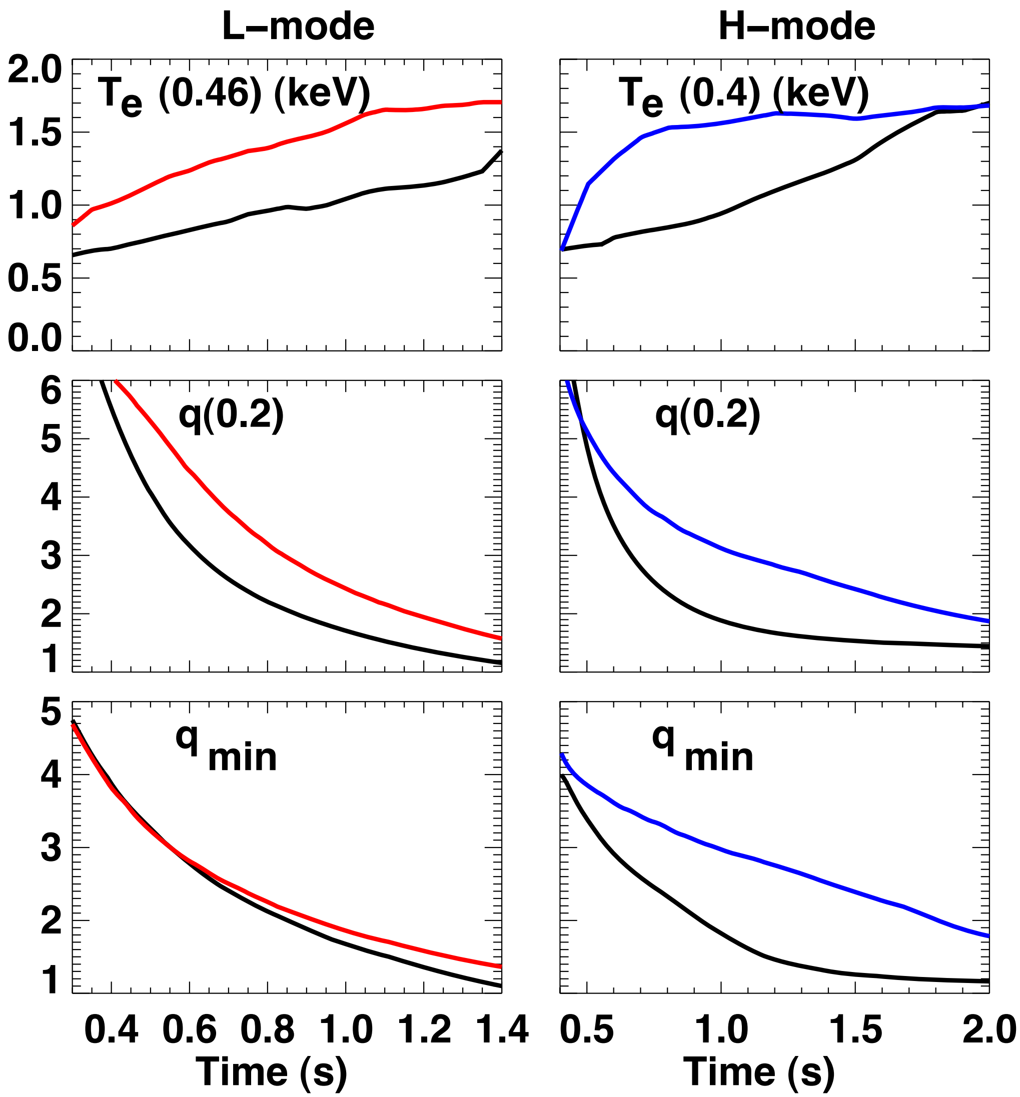
# Simulations of the Current Profile Evolution During AT Discharge Formation are Used to Test the Physics Models

- **Transport codes reproduce changes in current profile evolution achieved by varying conductivity (σ)**
  - $J = J_{ind} + J_{NI} = \sigma E + J_{BS} + J_{EC} + J_{NB}$
- **Inductive current dominates during discharge formation**
- **Models of $B_p$ diffusion, $J_{BS}$ and $J_{NB}$ reproduce experiment in many cases**
- **Transport codes in use to develop and test feedback controllers**

# Transport Code is Used With Measured Density and Temperature Profiles to Predict the q Profile Evolution

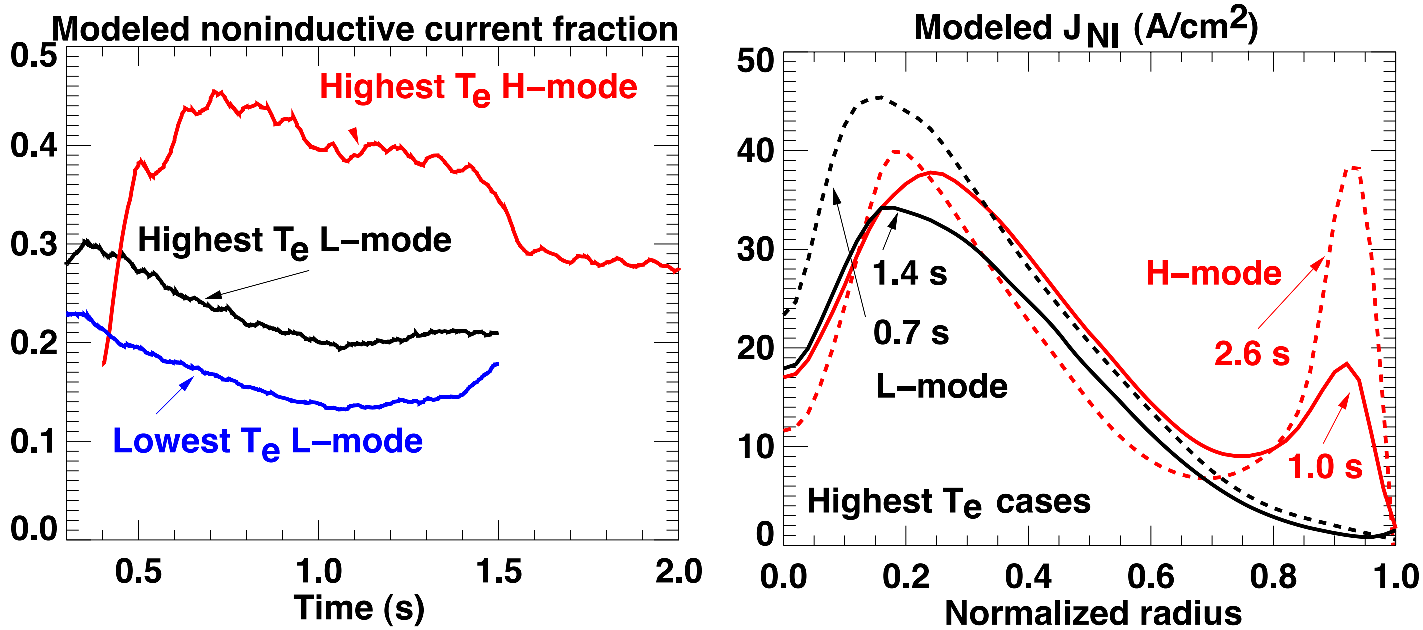
- **ONETWO used primarily, also CRONOS, TRANSP, CORSICA**
- **Starts with an initial current profile obtained by fitting magnetic and MSE data with EFIT**
- **Total plasma current versus time is specified**
- **Experimental values for comparison with simulations are obtained from EFIT equilibrium reconstructions using MSE data**
  - J and q profiles
  - Electric field from $E = d\psi/dt$
  - $J_{IND} = \sigma E$ ($\sigma$ from neoclassical model)
  - $J_{NI} = J - J_{IND}$

# q Evolution Predictions Reproduce the Dependence on $T_e$ and the Choice of L or H-mode Observed in the Experiment



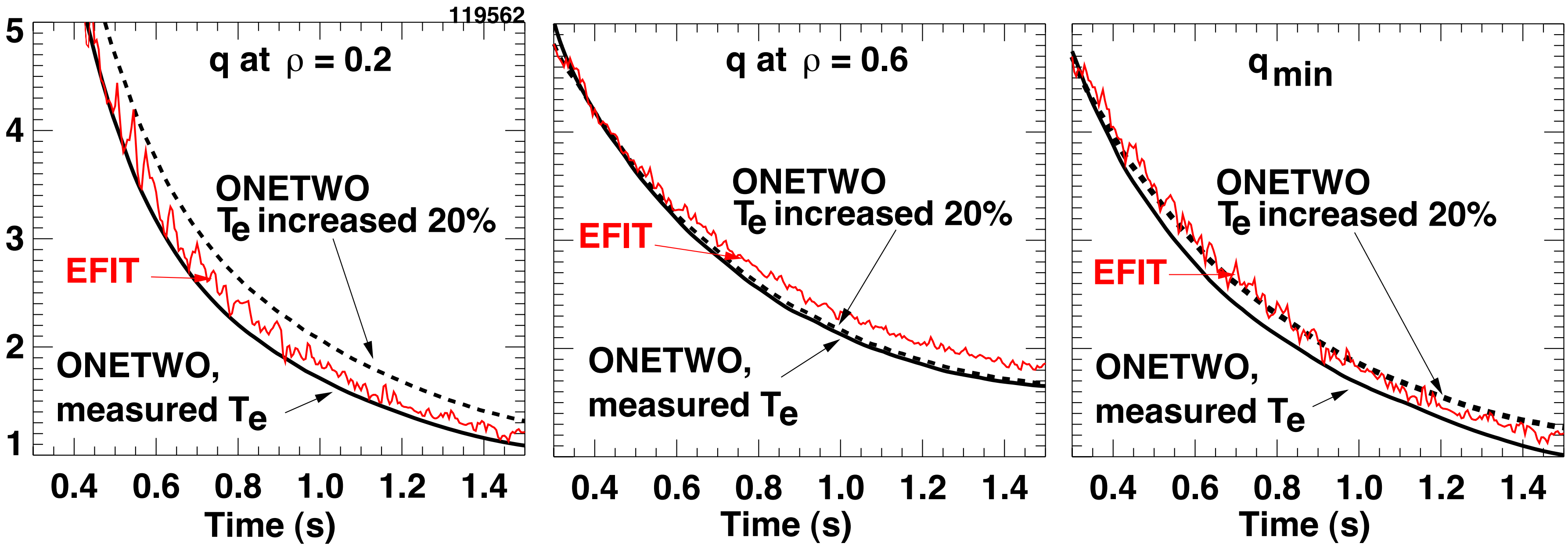

- **q profile evolves more slowly as $T_e$ is increased**
  - Result of increase in σ
- **Decay of q is slower in H-mode for comparable mid-radius $T_e$**

# The Noninductive Current Remains Relatively Low and Shows Little Change in Profile Shape as the q Profile Evolves



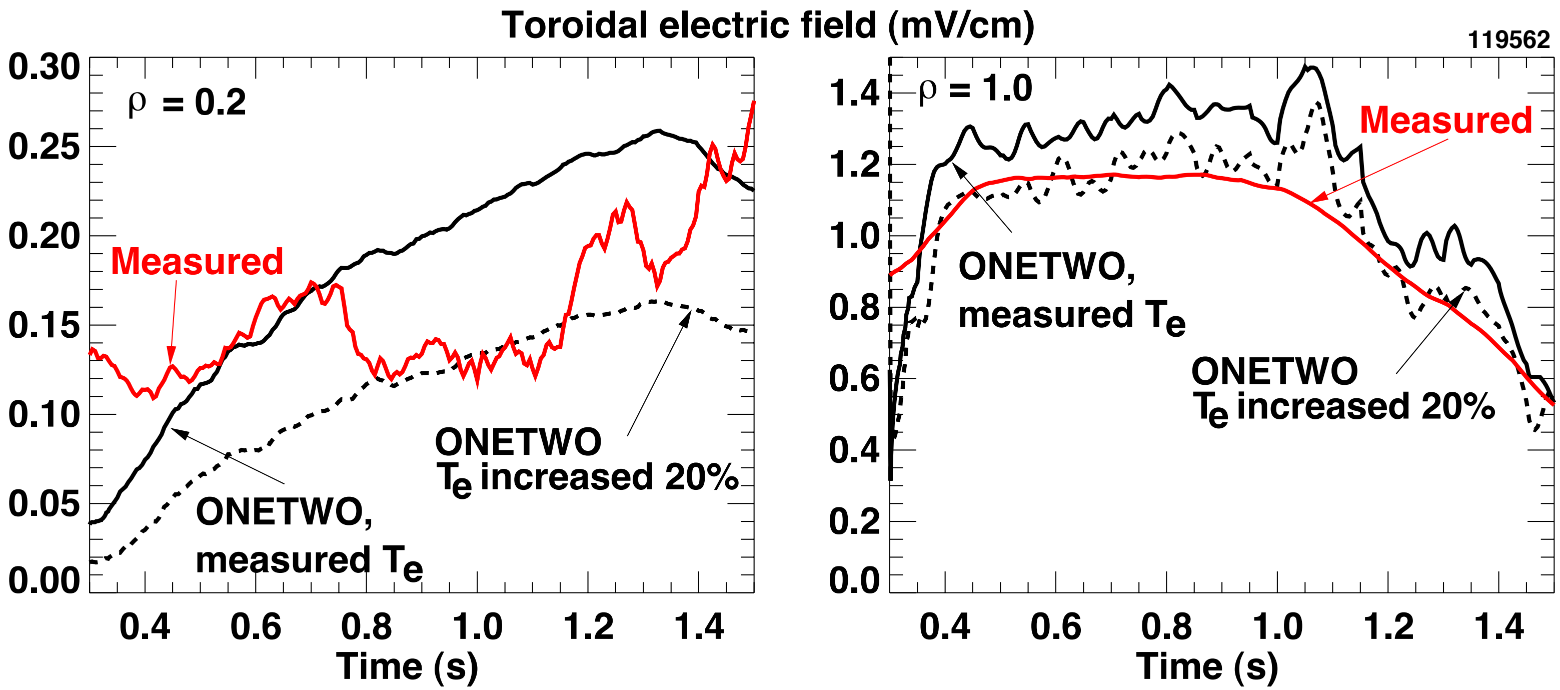

- **$I_{NI}/I_{total}$<0.5: inductive current evolution dominates**
  - But $J_{NI}$ is large enough to change q profile, particularly as $T_e$ increases
- **Predicted profile of $J_{NI}$ nearly constant in time**
  - No practical means to change the profile to change q

# The Simulation Can Reproduce the Measured Time Evolution of the q Profile in L-mode Discharges with Low $f_{NI}$



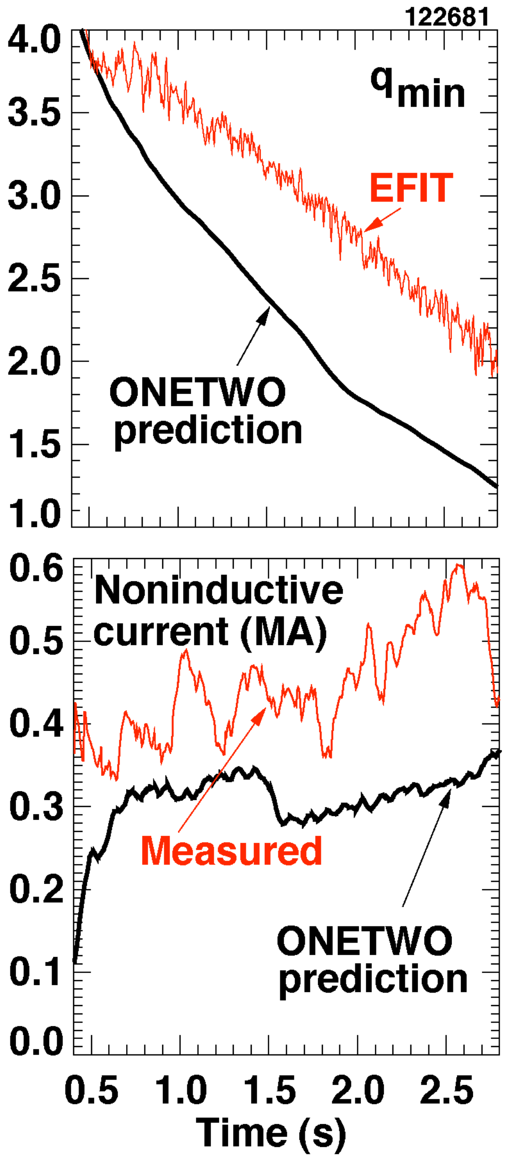

- **This example is the lowest $T_e$ case where $f_{NI} = I_{NI}/I_{total}$ is the smallest.**
- **The two simulations bracket the experimental results**

# Electric Field at the Core and Boundary Show Reasonable Agreement Between Simulation and Experiment

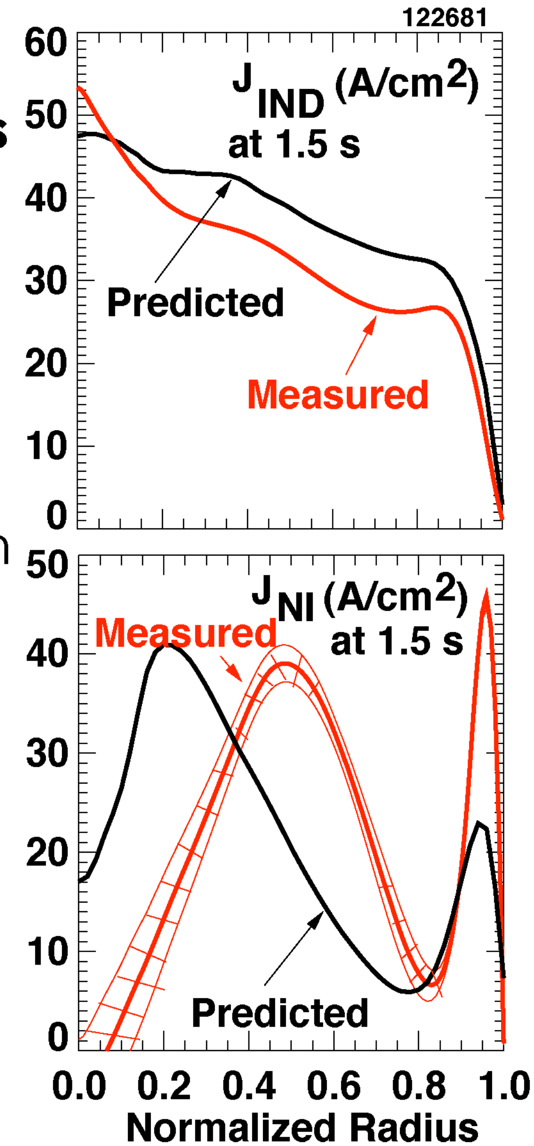



- Rising E in core reflects relaxation of $J_{IND}$ profile
- Predicted E ($\rho$= 1) above the measured value could indicate either the modeled $I_{NI}$ or the modeled $\sigma$ is too low

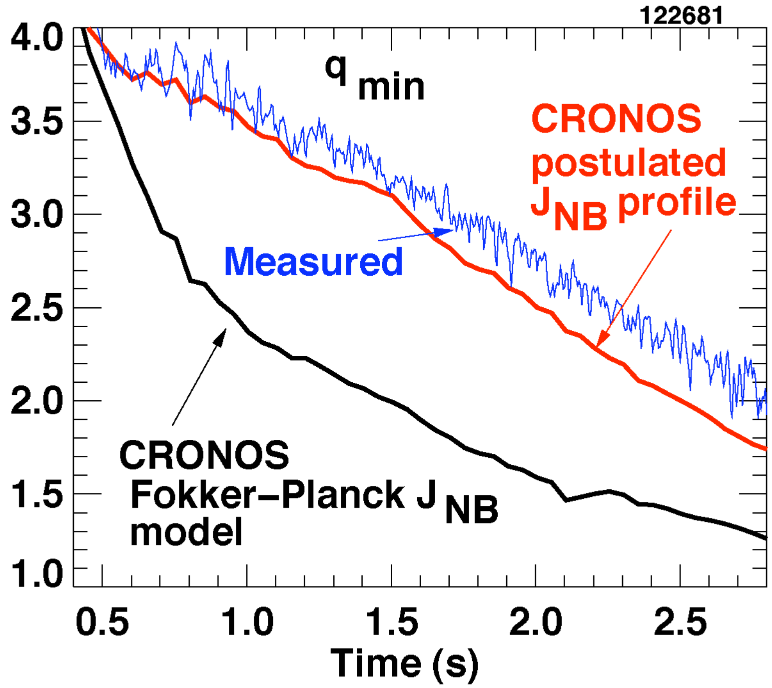
# For many H-mode Discharges, Faster q Profile Evolution than Observed is Predicted by the Transport Code Models

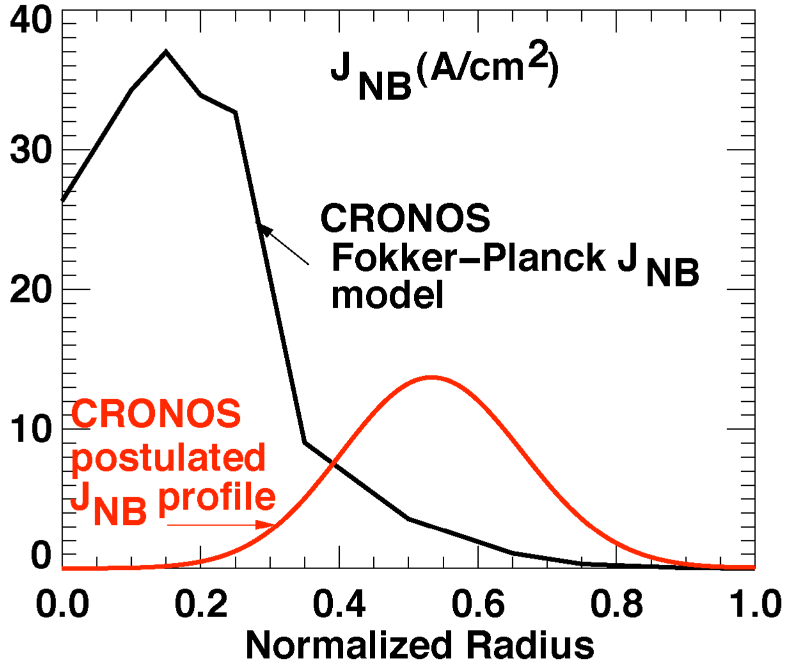



- **Predicted inductive current profile shape roughly matches experiment**
  - Predicted $J_{IND}$ is too large
- **Predicted $J_{NI}$ peaks closer to the axis than measured**
  - Predicted $I_{NI}$ is smaller than measured



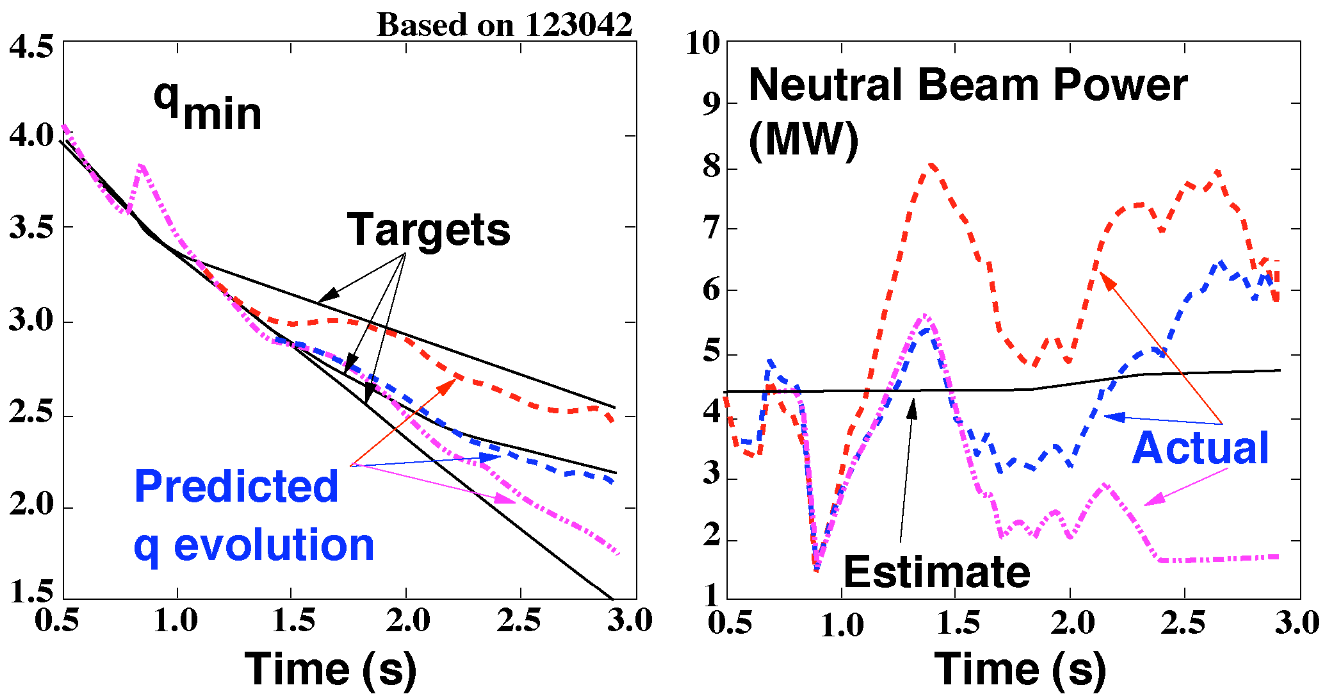
# Postulating that the Neutral Beam-Driven Current is Located Off-Axis Results in a Better Match to the Experiment



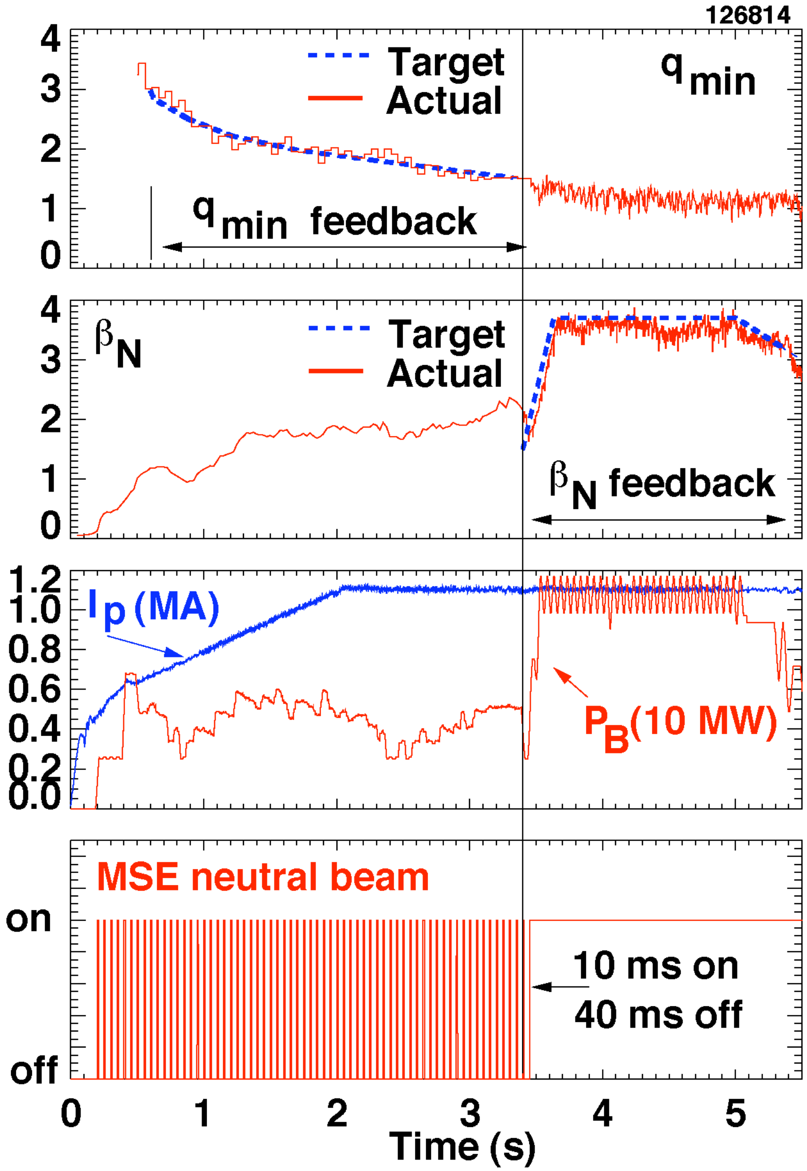

- **Total NB-driven current is the same in both simulations**
- **Redistribution of fast ions by Alfvén eigenmodes could possibly result in an altered $J_{NB}$ profile**
  - See Heidbrink EX6-3

# The CRONOS Code Successfully Models the Capability of the Real-Time Controller to Modify the Time Evolution of $q_{min}$




- $P_{NB}$ = estimate + gain * (actual $q_{min}$ – target $q_{min}$)
- Time evolution of $n_e$, $T_i$, $Z_{eff}$ specified
- $T_e$ profile calculated using an empirical electron heat diffusivity model
- Postulated $J_{NB}$ profile is used

# Summary: Feedback Control of the q Evolution is in Use to Form the Target q Profile for High $\beta_N$ DIII-D AT Discharges




- Goal is to reliably produce the optimal q profile for sustainment in steady-state
- Closed loop feedback control of q evolution is effective with ECH or neutral beam heating
- Changes in σ used to modify the rate of relaxation of the current profile
- Transport code simulation in use for controller testing
- In some cases, the noninductive current is apparently located farther from the axis than predicted by the models

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