Development in DIII-D of high beta discharges appropriate for steady-state tokamak operation with burning plasmas

Presented by
J.R. Ferron

Presented at
22nd IAEA Fusion Energy Conference
Geneva, Switzerland
October 13-18, 2008

Introduction

Reliable production of high beta discharges with $f_{NI} = 1$ for duration τ_R has been the recent research focus

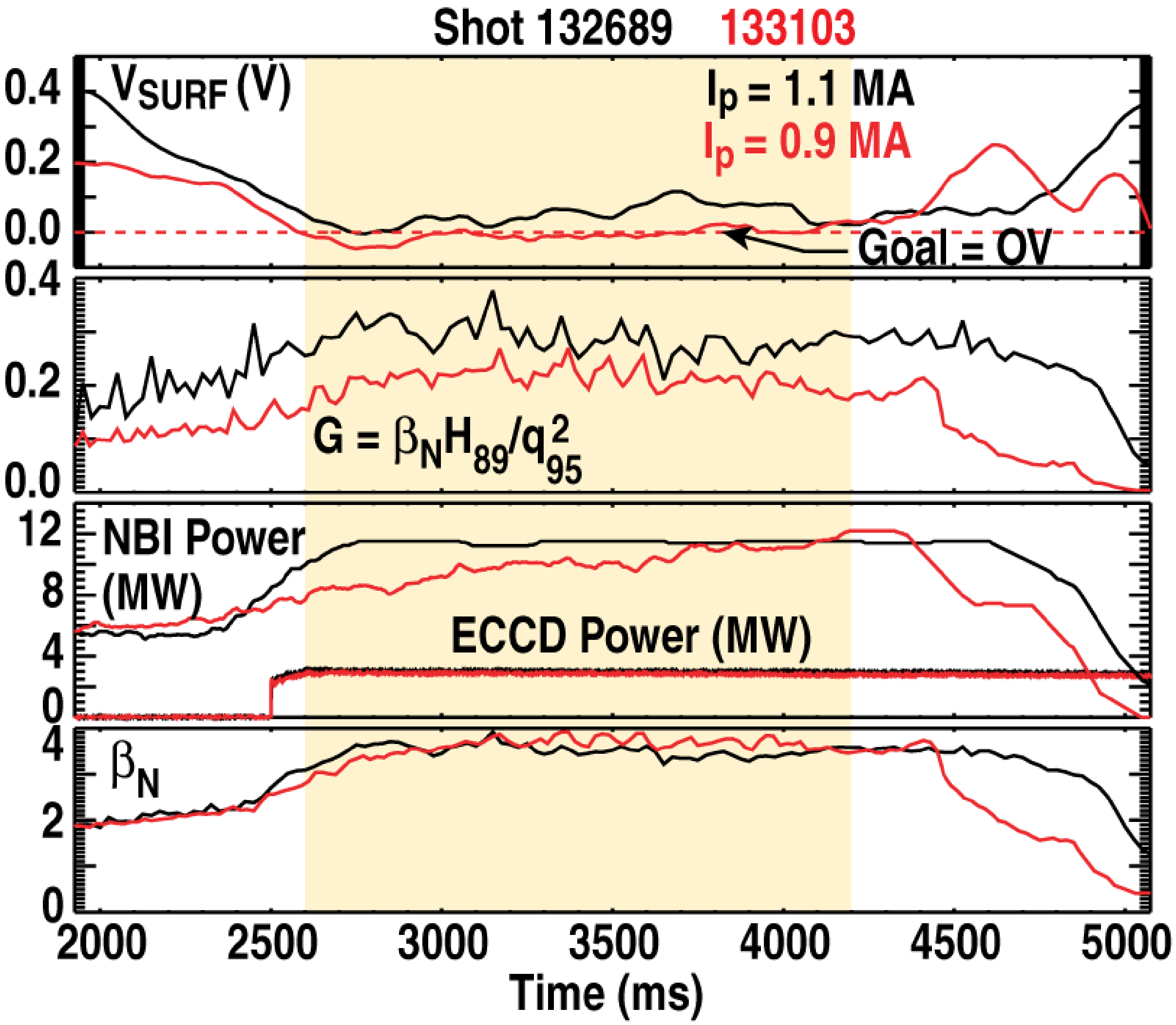
- **Stationary discharges with $f_{NI} = 0.9$ are now straightforward**
- **$f_{NI} = 1.0$ previously demonstrated for < 1 s**
- **Reproducible, long pulse generation of that last 10% of noninductive current requires careful discharge optimization**
  - Maximize β_N to increase bootstrap current
    - Achievable β_N and τ_E vs. discharge shape
  - Increase noninductively driven current
    - Divertor pumping vs. discharge shape, minimize n_e
    - 3 MW long pulse ECCD power now available
  - Avoid 2/1 tearing mode to increase duration
    - Broad ECCD deposition profile

Exploration for a scenario with $\beta_N = 5$ and profiles appropriate for steady-state is underway

- **Motivated by the high power density and neutron fluence required in a demonstration power plant**
- **Goal is operation near the ideal MHD stability limit**
- **Two approaches modeled and tested experimentally**
  - High internal inductance plasmas that remain below the no-wall n = 1 limit
    - $\beta_N = 4.6$ achieved for 0.4 s ($\beta_N > 4$ for 1 s) at $l_i > 1$
  - Wall-stabilized plasmas with elevated q_{min} that require stabilization of RWMs by rotation or active feedback
    - $\beta_N = 4$ achieved for 2 sec
- **Priority is experimental verification that these pressure and current profiles can be produced**

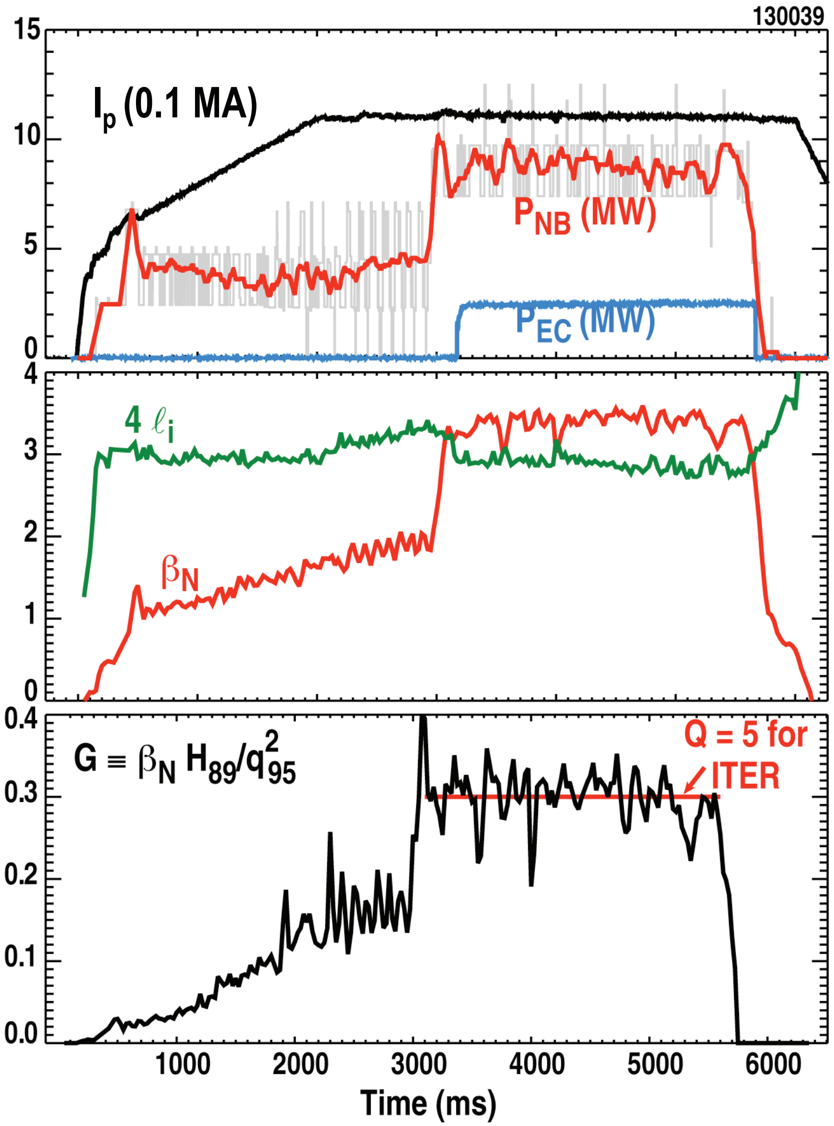
High noninductive fraction discharges with q_{min} >1.5

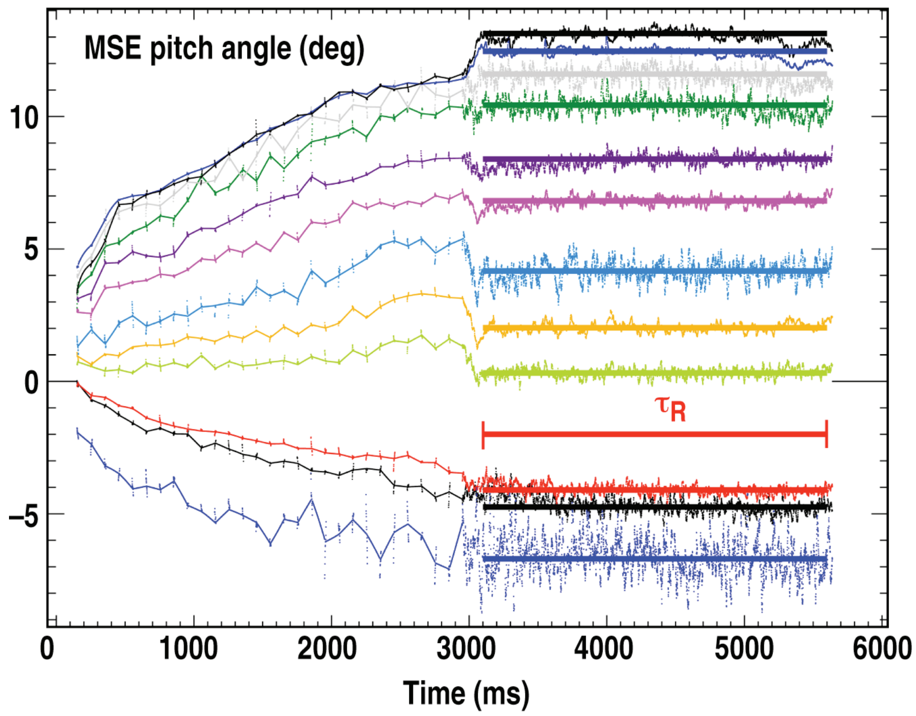
Duration of f_{NI} Near 1 Extended to 0.7 τ_R Through Operation at Increased β_N Without Termination by a 2/1 NTM



- β_N = 3.5-3.7
- **Surface voltage ~0 indicates f_{NI}~1**
- **Reducing I_p to match the available I_{NI} increased f_{NI}**
  - Reduces fusion gain parameter G
- **Present limitations:**
  - Neutral beam energy limits duration
  - Neutral beam and ECCD power limit I_{NI}

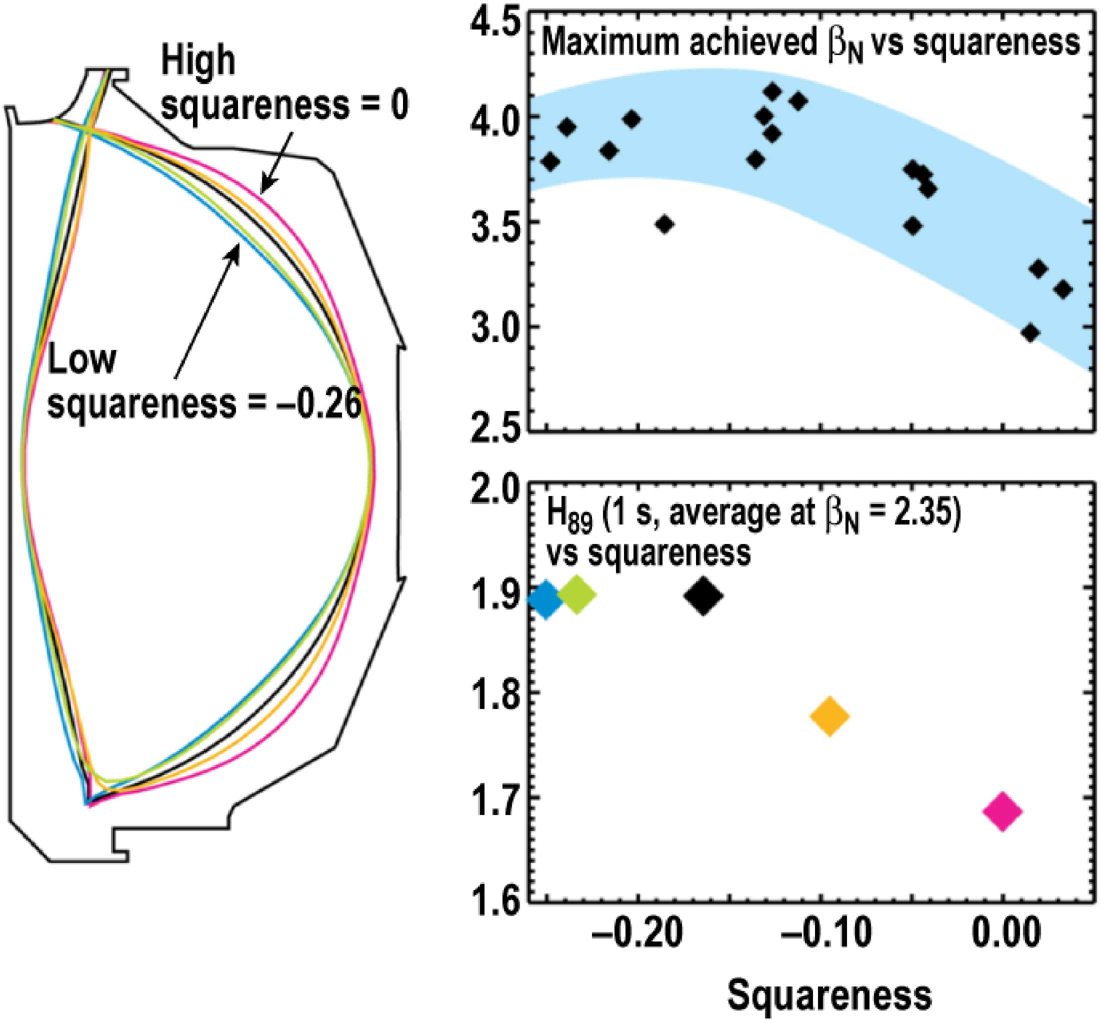
f_{NI} = 0.9 Discharges Stationary for τ_R, Limited by Deliverable Co-NB Energy, Not ECCD





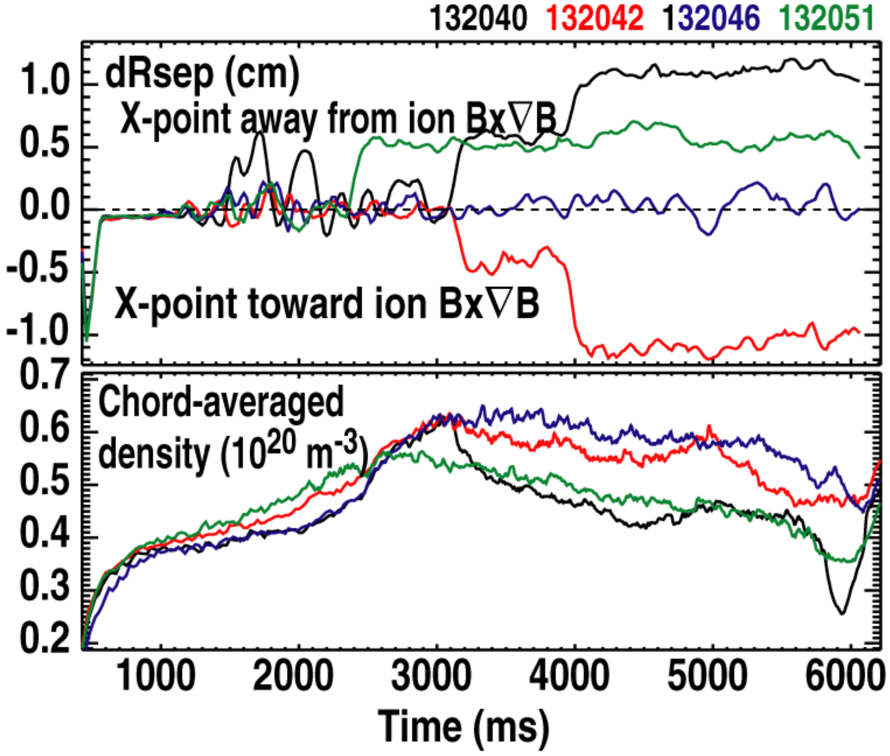
- **Constant MSE pitch angle indicates current density profile is not evolving**
- **H_{89} = 2.3, H_{98y2} = 1.4**

Confinement and Achievable β_N are Optimized at Intermediate Values of the Shape Squareness



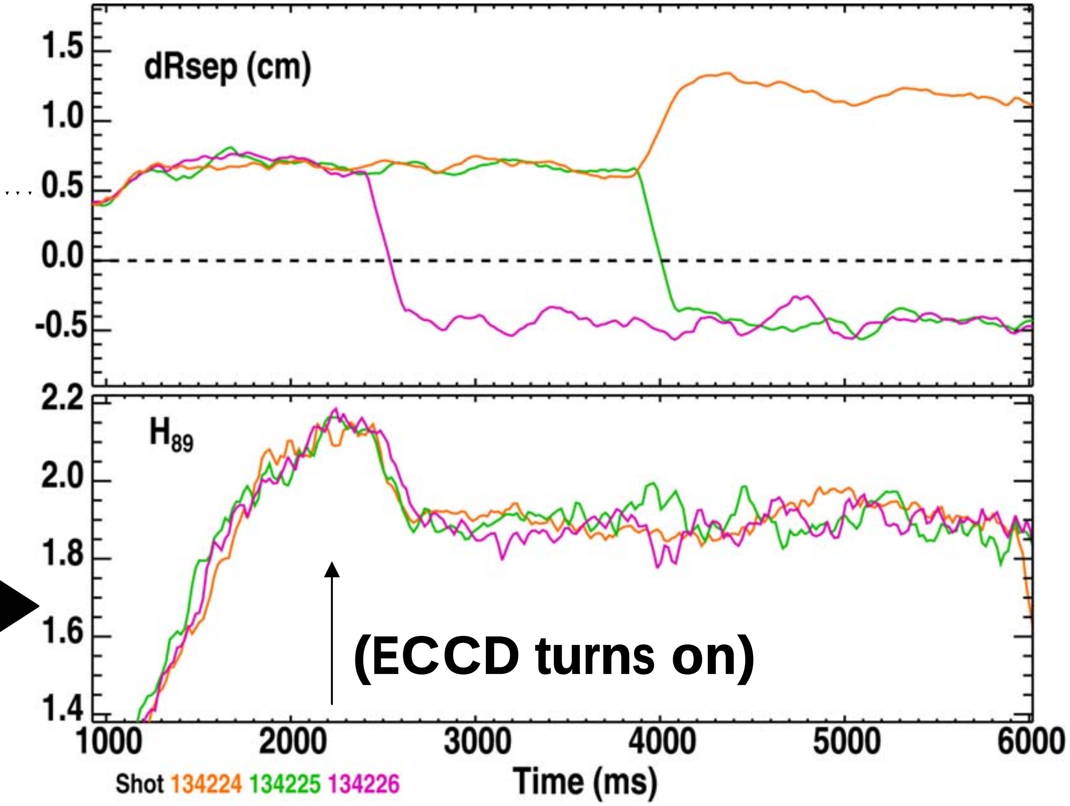
- **2006 experiments determined stability is best at low to intermediate values of squareness**
  - Agrees with ideal MHD modeling of low-n kink
- **2008 squareness scans show confinement is reduced at higher squareness:**
  - ELMs are smaller, less regular
  - Core rotation is lower
  - Density fluctuation level is higher

Unbalanced Double-null Minimizes n_e for Efficient Current Drive with Little Impact on Confinement

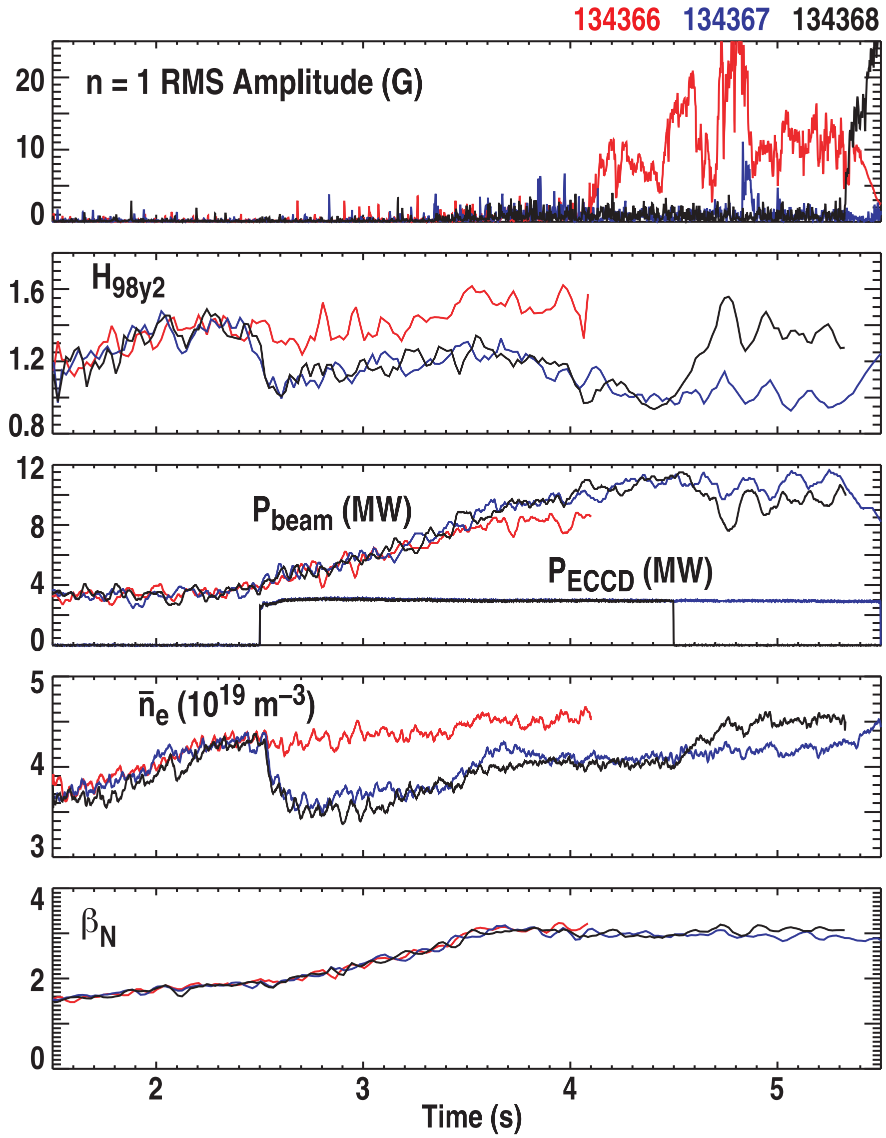


- Small bias away from ion Bx∇B direction reduces density more than balanced, or toward-Bx∇B case

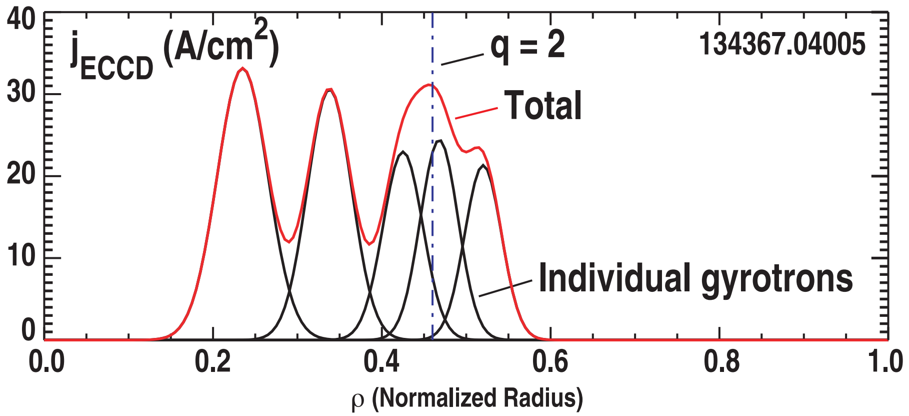
- These dRsep changes do not affect confinement
- dRsep changes made with approximately constant squareness



ECCD with a Relatively Broad Deposition Profile Enhances Stability to the 2/1 Tearing Mode at High Beta

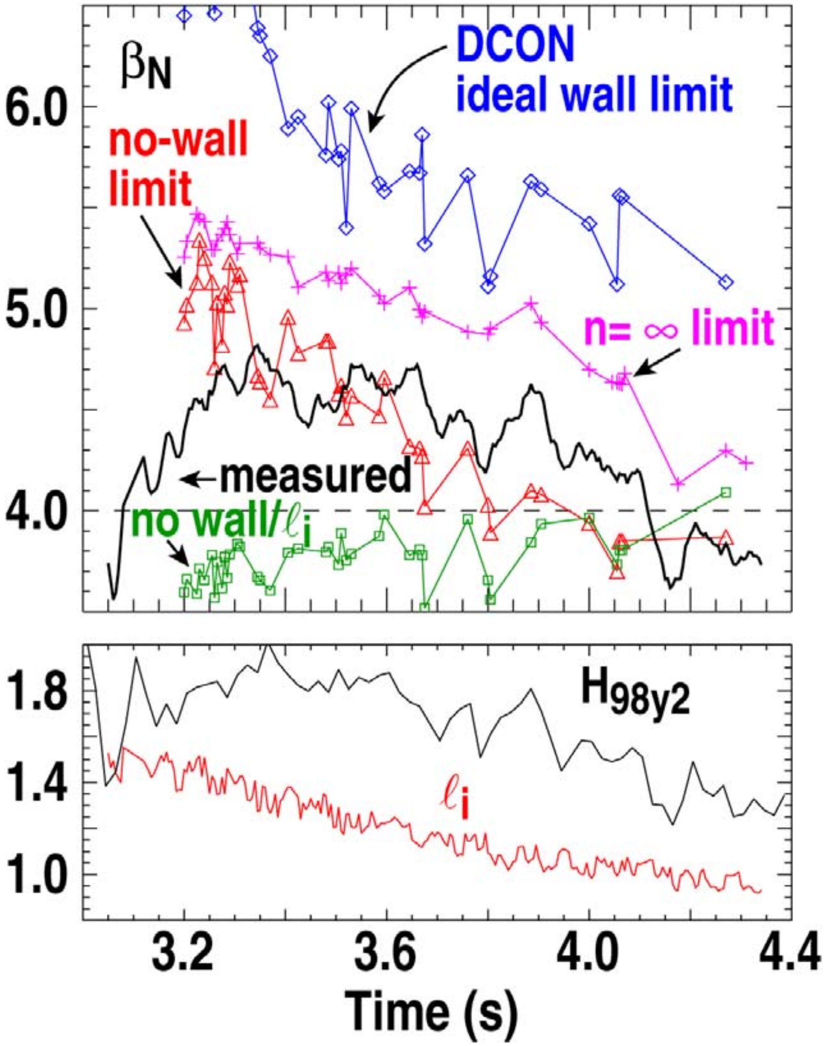


- n = 1 mode avoided in discharge with ECCD
- n = 1 appears after ECCD is turned off
- Alignment of broadly deposited ECCD with q = 2 surface not necessary for improved 2/1 stability
- Application of ECCD reduced τ_E and n_e



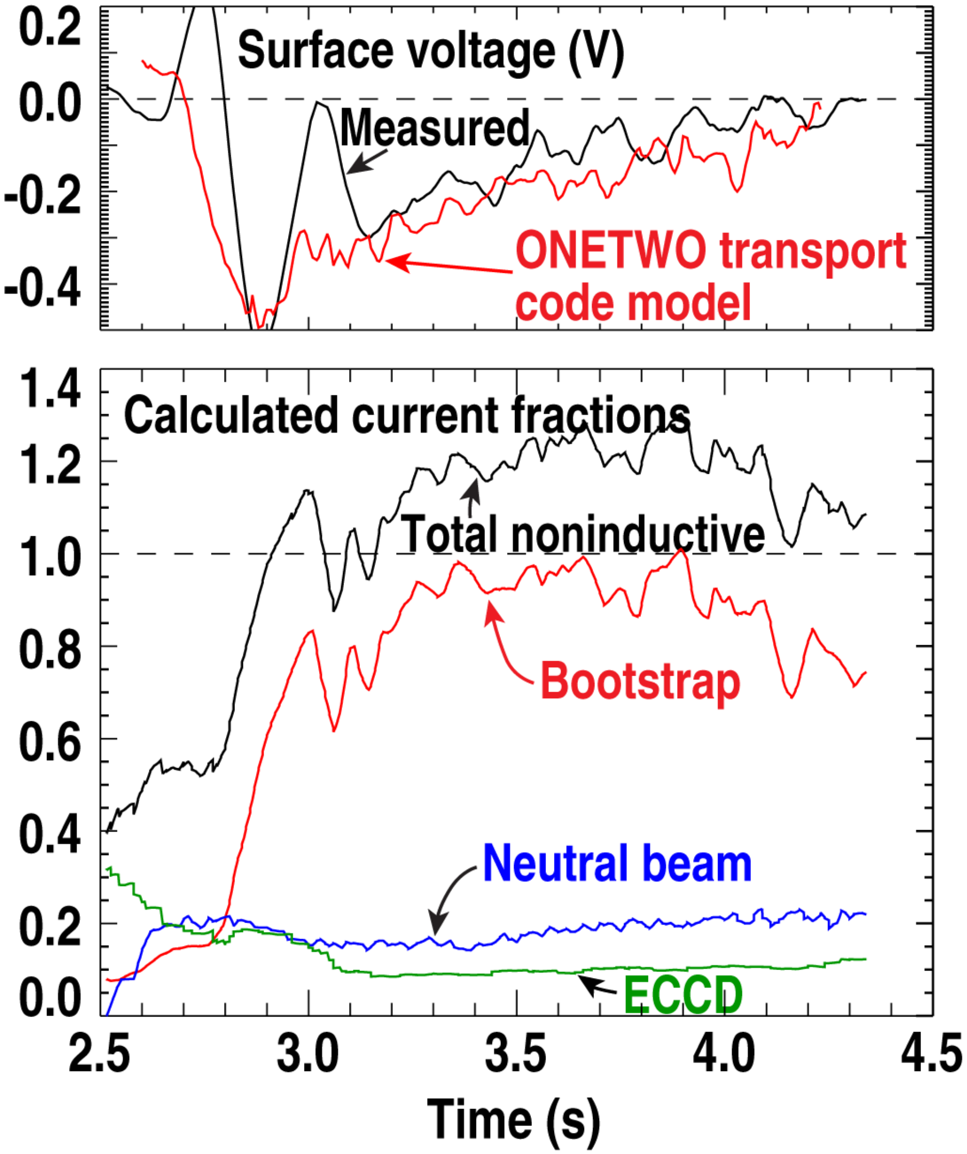
High β_N Discharges with Increased Internal Inductance

β_N Remains Above 4, Near the No-wall n = 1 Stability Limit, for 1 s



- **No-wall stability limit: β_N/l_i = 3.7-4.0**
- **Indicates β_N= 5 should be possible at l_i>1.4 without rotation or hardware to stabilize resistive wall modes**
- **Confinement well above standard H-mode value**
- **Current profile not yet stationary**
  - Future step in scenario development

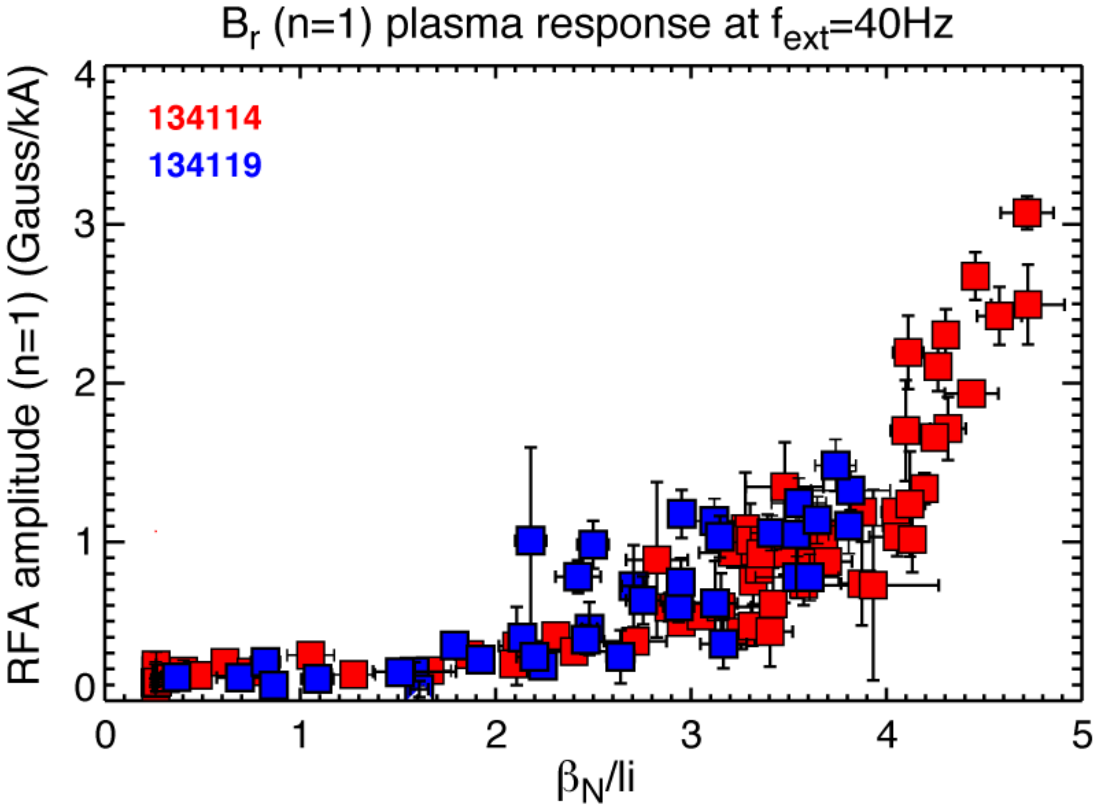
With f_{NI} at or Above 1, the l_i >1 Scenario is a Candidate for Steady-state Operation



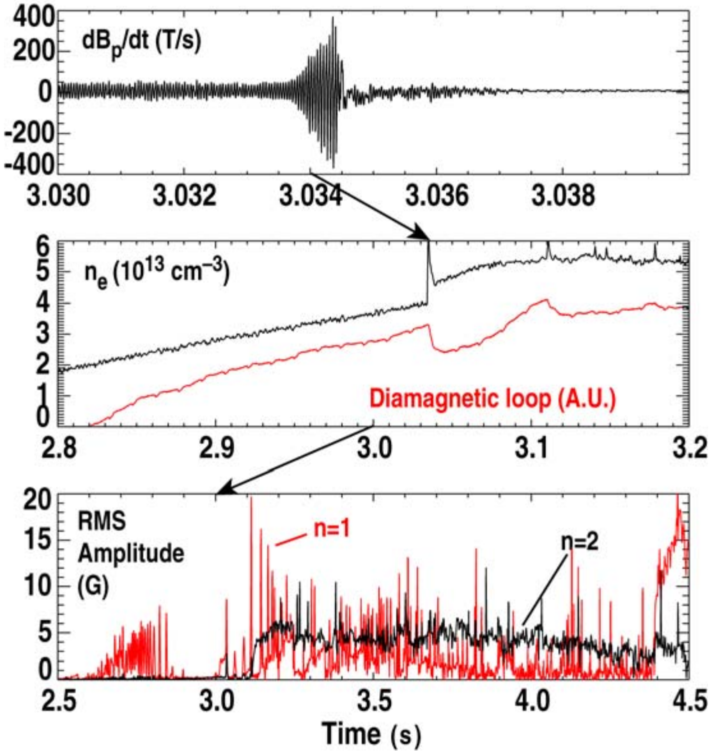
- **Measured surface voltage < 0**
- **Agrees with transport code modeling**
- **Calculated $f_{NI} \approx 1.2$**
- **Calculated $f_{BS} \approx 0.9$**

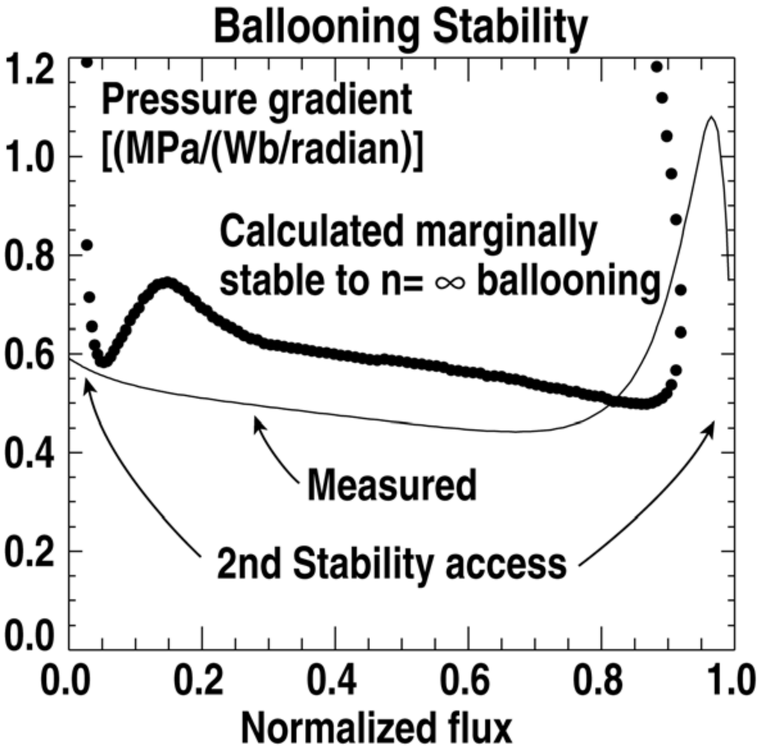
MHD spectroscopy indicates a reduction in n = 1 kink mode stability at $\beta_N/l_i = 4$

- **Indicator is change in slope of response (red points)**
- **Suggests discharge exceeds the ideal MHD no-wall kink stability limit**
- **Approximate agreement with calculated limit**



Fast-growing Bursts of 1/1 Mode Cause Drops in β_N and Trigger Tearing Modes

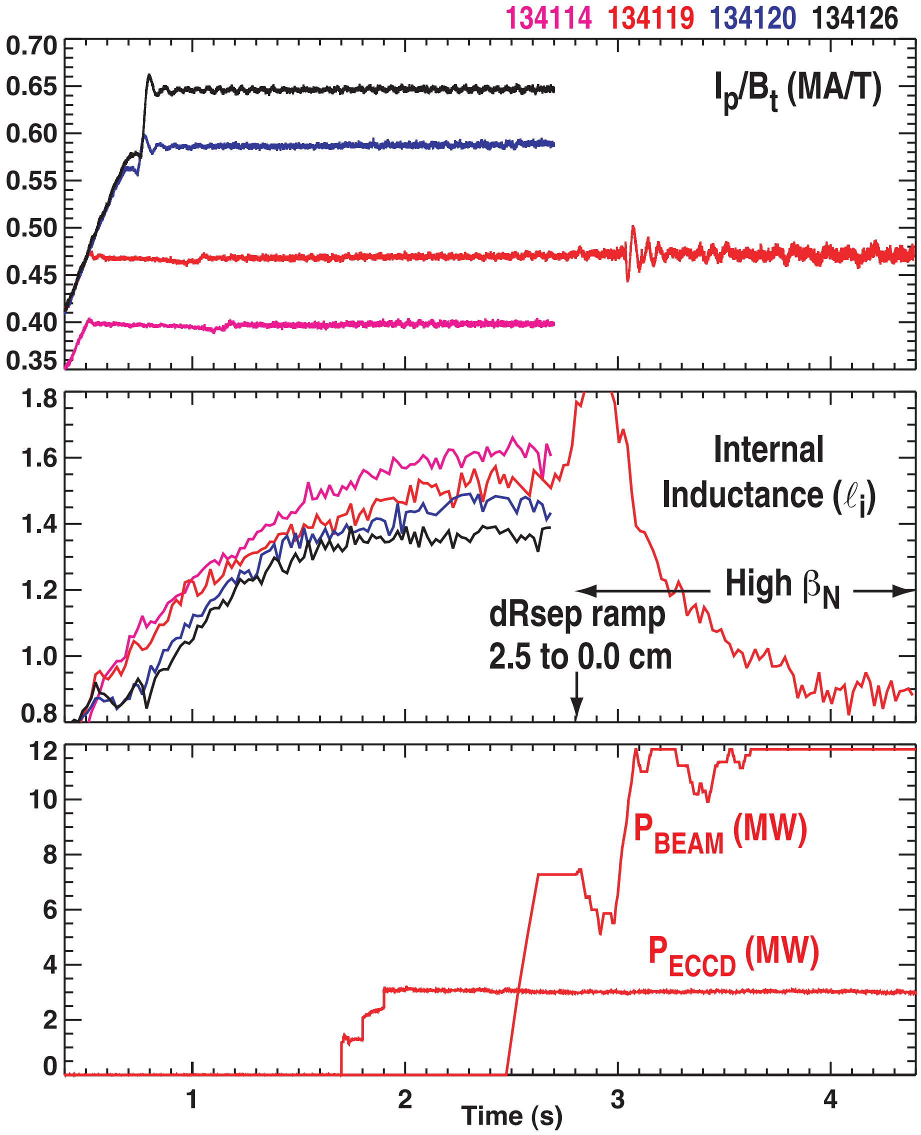




- **After 1/1 burst:**
  - n_e profile broadens, possibly improving stability
  - n = 2 mode begins
- **High-performance terminated by 2/1 mode**
- **P' slightly below calculated ballooning mode limit**

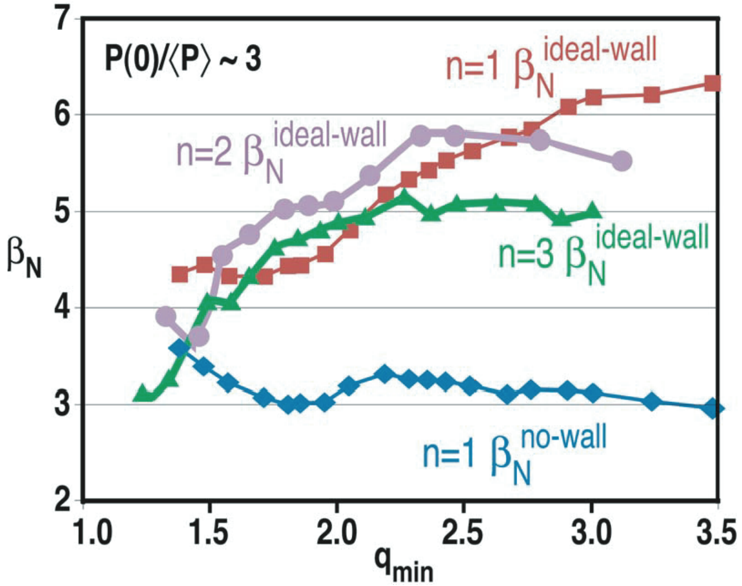
High Initial ℓ_i Obtained Using Long Ohmic Phase to Allow Current to Penetrate to the Axis

- **Stationary ℓ_i depends on I_p/B_t**
  - I_p/B_t scan performed
  - Best performance at $I_p/B_t = 0.47$ ($q_{95} \approx 7.5$)
  - Standard AT operation is at $I_p/B_t = 0.65$
- **Transition to double null is a small κ ramp, increases ℓ_i**
- **During high β_N phase, broad J_{NI} profile results in lower ℓ_i**

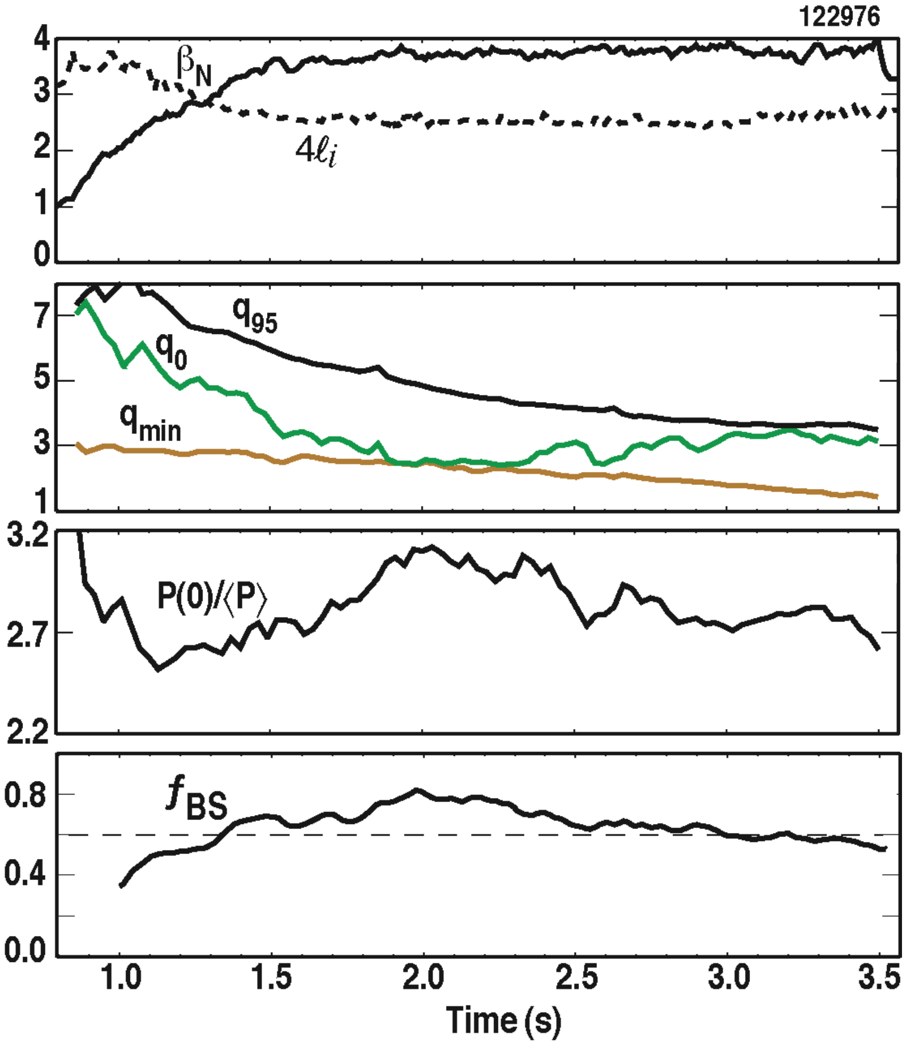


High β_N discharges with a very broad current profile

Off-Axis Current Driven by I_p and B_t Ramps Enabled β_N~4 with an ITB at q_{min}~2



- Computed β_N limits for kink modes with P(0)/<P> = 3 and ρ_{qmin}=0.5
- In experiment, $\rho_{q_{min}}$ did not exceed ~0.5, and q_{min} evolved too quickly



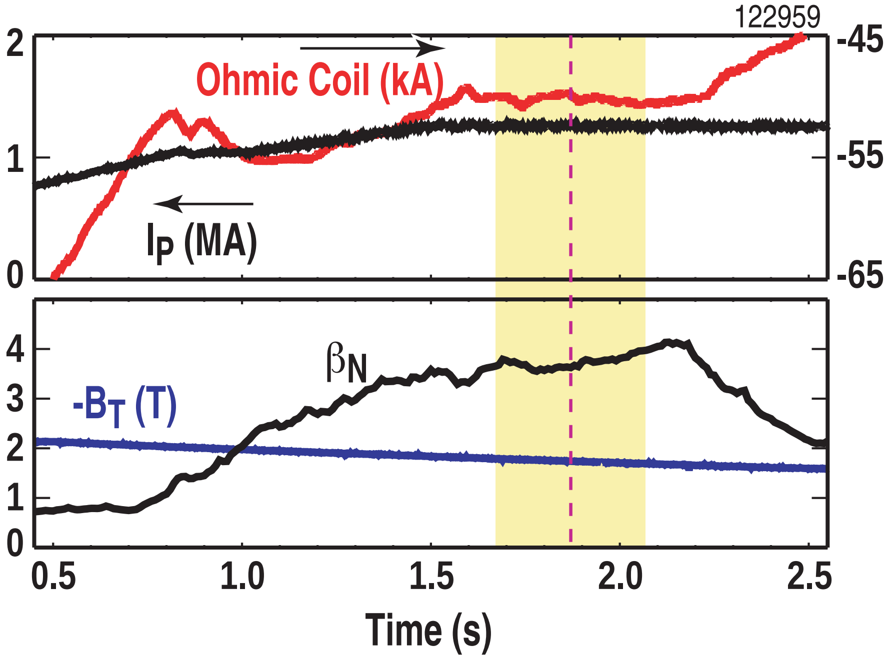
From: Garofalo, Phys. Plasmas, 2006

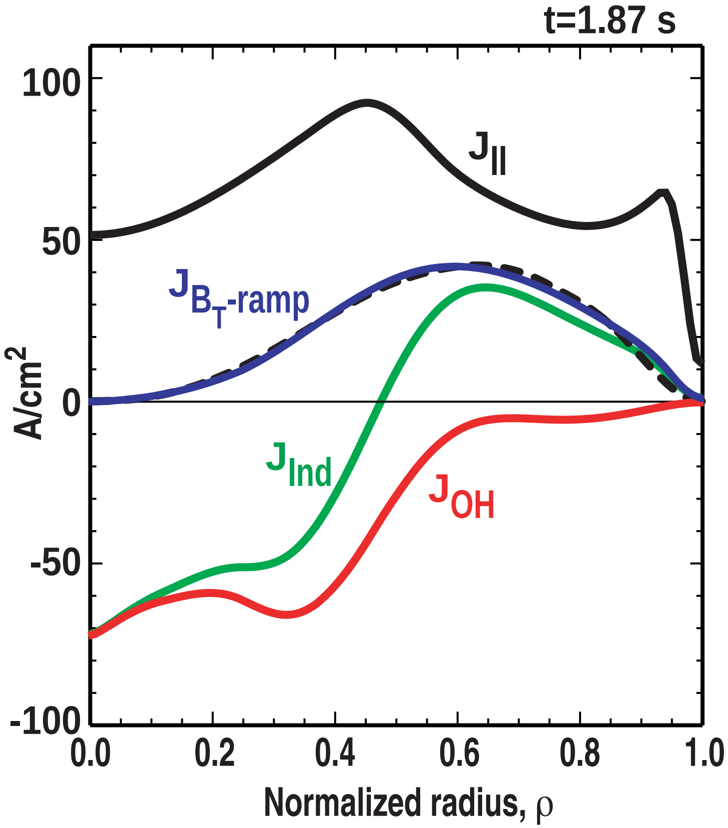
Toroidal Field Ramp-down Drives Large, Off-axis, Parallel Current

- **Two components of the flux-averaged, parallel, inductive current density**

$J_{\mathrm{OH}} \sim \sigma\, d\psi/dt$ (poloidal flux evolution)

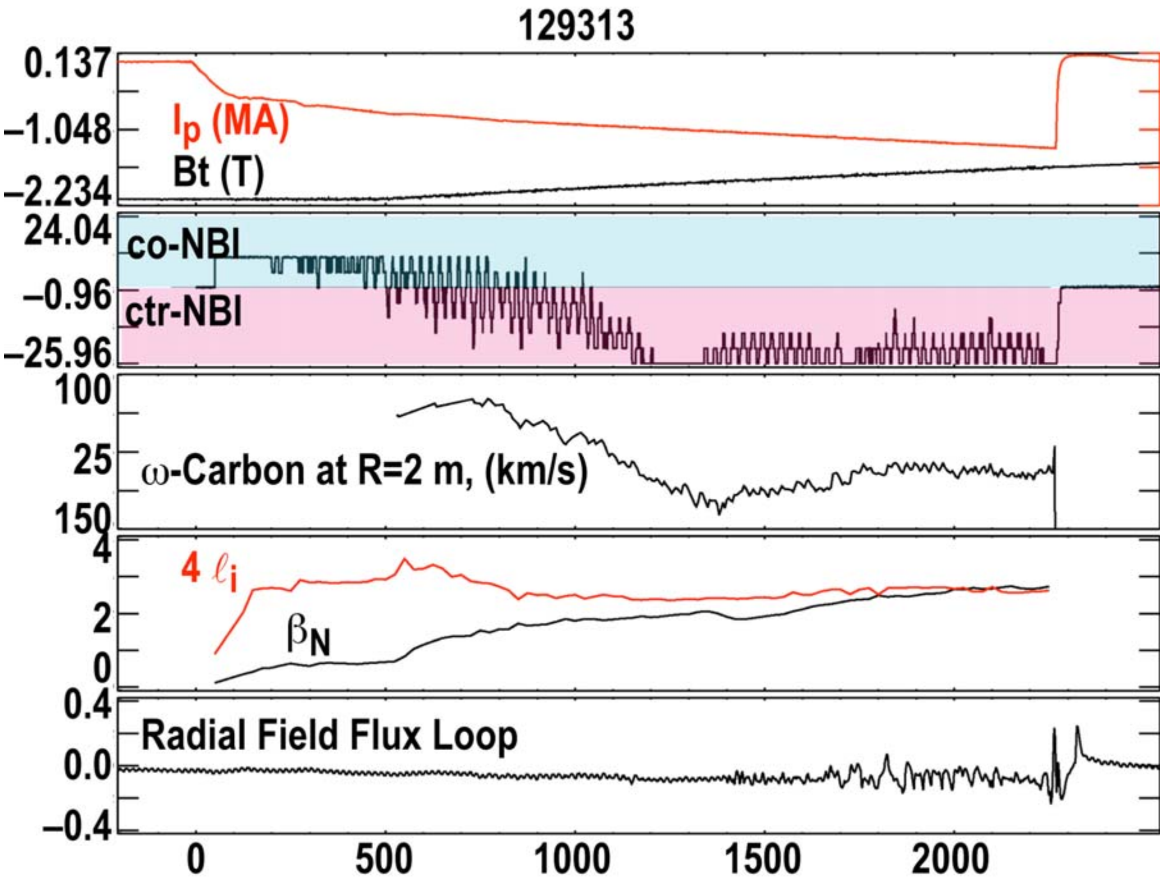
$J_{\mathrm{B_T}} \sim \sigma\, d\phi/dt$ (toroidal flux evolution)





2007 Experiment Attempted to Increase β_N>4 Using Reverse I_p and Counter-NBI for Slower q_{min} Evolution and Higher ρ_{qmin}

- Previous fast q_{min} evolution due to too much on-axis NBCD and misalignment between j_{BS} and j_{total} peaks
- With counter-I_p, lower on-axis current density at same injected power
- ρ_{qmin} observed to increase slowly with time to ~0.6
- Instability at main ion rotation null prevented increasing β_N beyond $4l_i$
- I_p and Bt ramps for increasing β_N and off-axis current drive

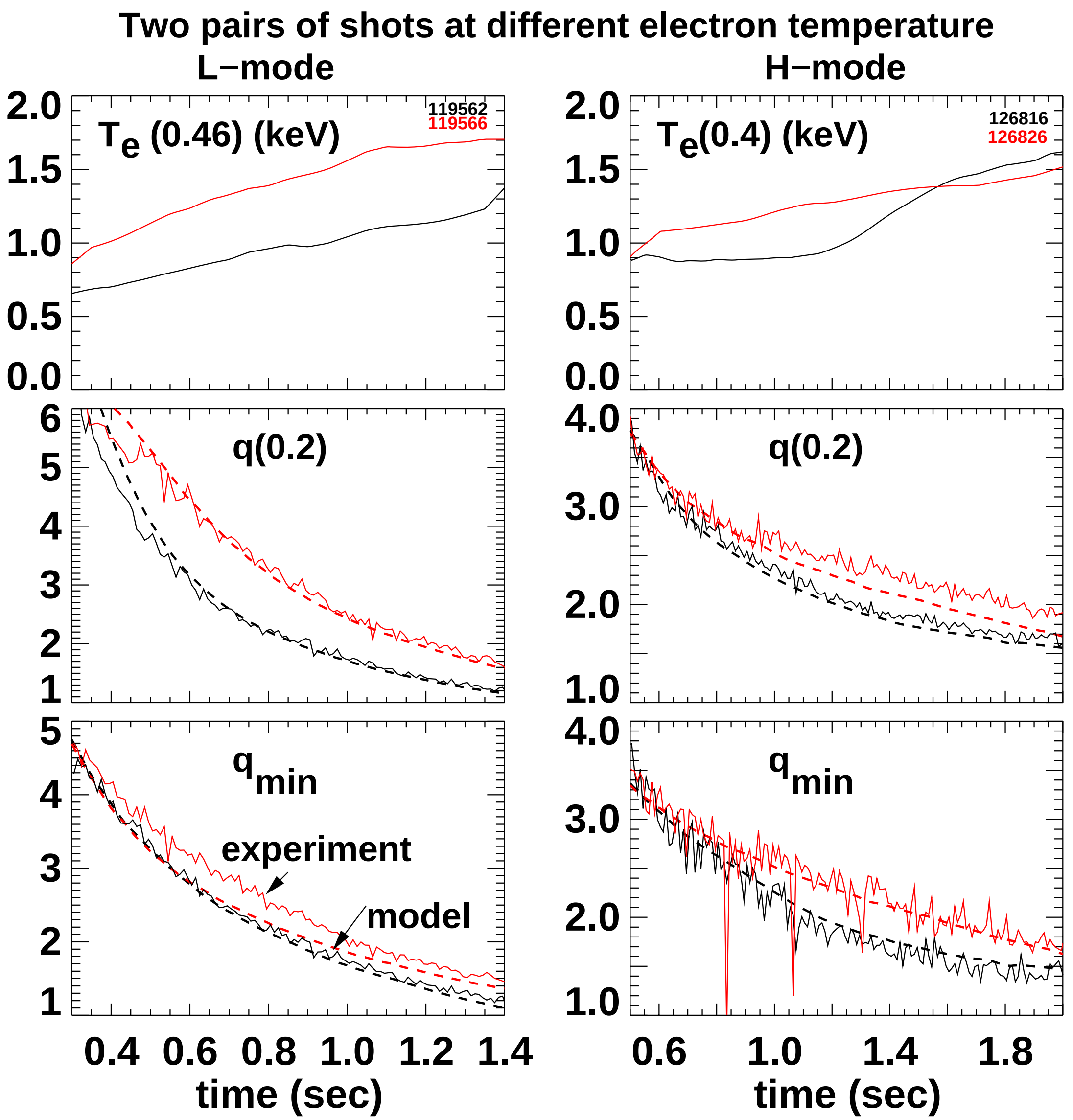


Feedback control of the current profile evolution

Goal: control the q evolution during the discharge formation in order to determine the target profile for the high β_N phase

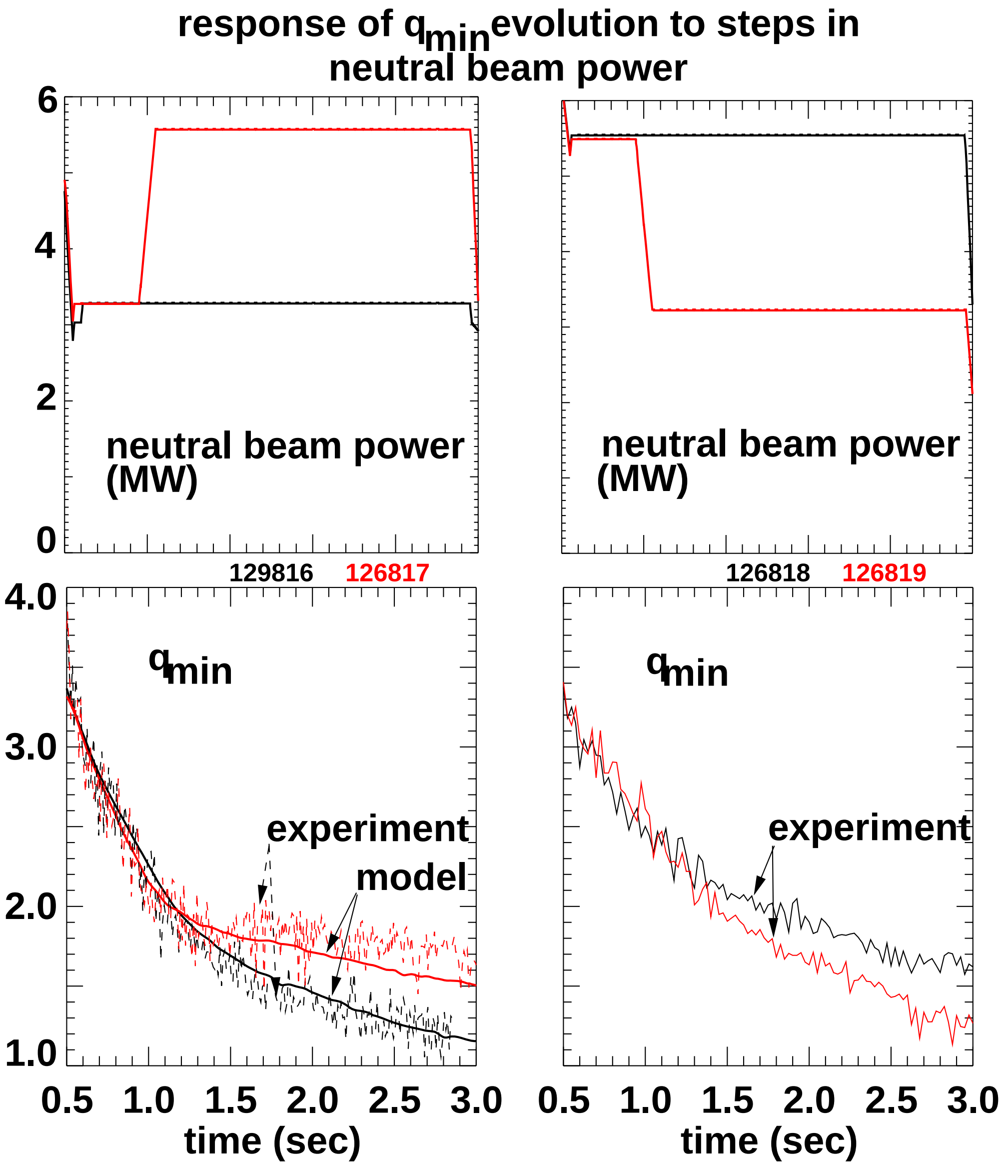
- **Evaluation of transport code ability to model the current profile evolution**
  - Agreement found indicates that the physics models are sufficient for use in development of model-based real-time controllers for the q evolution
- **An empirically designed q_{min} controller is available for routine use**
- **Tests of the efficacy of available actuators**
  - The only sufficiently effective actuator is electron heating
    - Modifies σ and thus the rate of penetration of the ohmic electric field
  - Weak actuators : dI_p/dt, n_e, beam voltage, co/counter beam mixture, ECCD, FWCD

Changes in Te significantly modify the q evolution in agreement with transport code model predictions



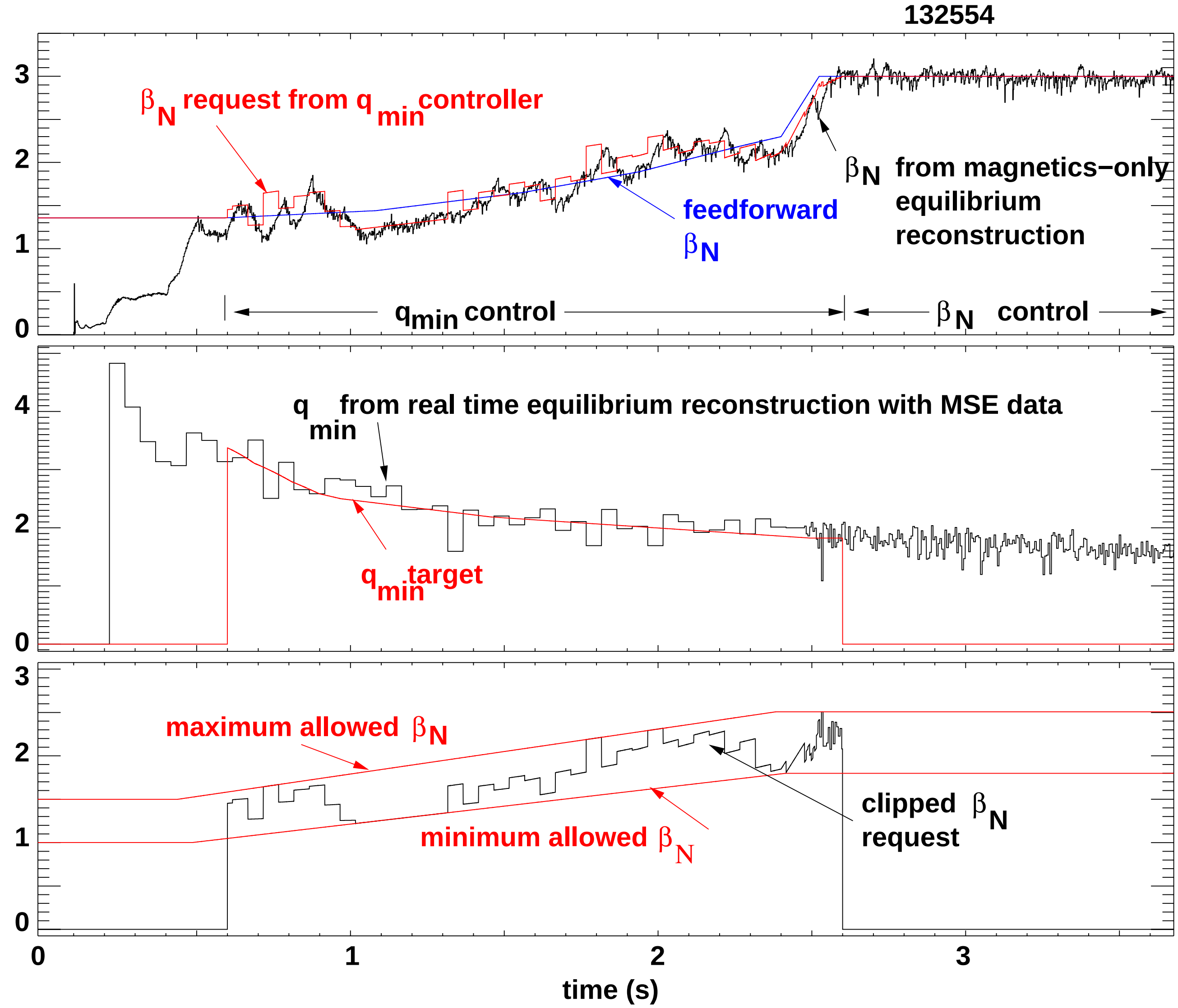
- **q profile evolves more slowly as Te is increased**
  - result of increase in σ
- **Decay of q is slower in H-mode for comparable mid-radius Te**
- **Modeling with the ONETWO transport code**
- **Experiment from EFIT reconstructions**

Transport code modeling successfully reproduces the change in dq_{min}/dt after a step in beam power



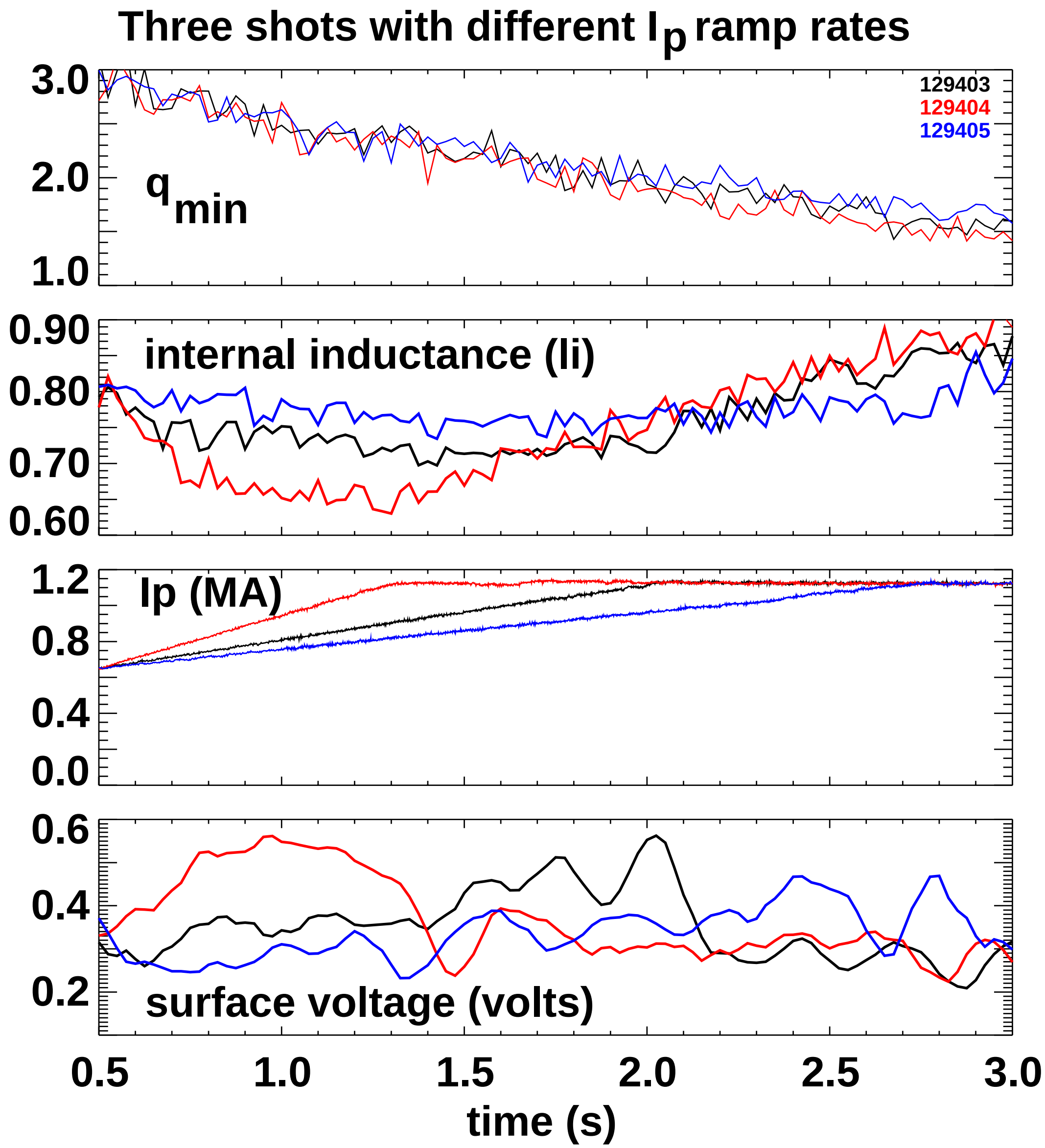
- **Dynamic response to steps in the heating power will provide input to model-based q controller design**
- **Modeling with ONETWO**

Indirect control of q_{min} evolution using β_N as actuator tested for more reliable avoidance of stability limits



- PI controller applied to q_{min} error used to generate a β_N request
- β_N substitutes for $<T_e>$, the true actuator
- Easy to clip the β_N request to help avoid tearing modes
- Envisioned improvement: request $<T> \approx \beta_N / n_e$

Only a small change in the q_{min} evolution is observed with a factor 2.75 change in the plasma current ramp rate



- **H-mode**
- **Equal T_e (feedback controlled)**
- **Ramp rate scan varies the loop voltage**
- **Strong effect on the internal inductance**
- **J differences are outside the J peak at $\rho \approx 0.4$**

Summary

q_{min} > 1.5 scenario has been optimized toward long duration operation with high β_N and $f_{NI} = 1$

- **Duration with surface voltage ≈ 0 extended to $0.7\tau_R$**
- **Intermediate discharge squareness maximizes confinement and achievable β_N**
- **Best discharge shape has dRsep ≈ +0.5 cm**
  - Maximizes divertor pumping
  - Little effect on τ_E
  - Tolerable reduction in β_N limits
  - Shape bias is away from the ion ∇B drift direction
- **Broad ECCD deposition enables 2/1 mode avoidance**
  - Allows operation at increased β_N= 3.5-3.7
- **Feedback control of q_{min} evolution available for use in regulating the high beta target**
  - Transport code q evolution model validated for use in development and testing of model-based controllers
  - Empirically designed controller avoids β_N limits
  - Actuator effectiveness tested

$\beta_N > 4$ has been demonstrated in two scenarios suitable for steady-state operation with $f_{BS} > 0.5$

- **Opens the possibility of a reactor with increased power density or higher q95**
  - Less energy stored in the poloidal field to be released in a disruption
- **$\beta_N > 4.5$ obtained with increased l_i**
  - The peak β_N is less than the ideal no-wall n = 1 stability limit
  - Confinement well above standard H-mode level, $H_{98y2} = 1.8$
  - $f_{NI} > 1$, $f_{BS} > 0.8$ with $q_{min} \approx 1$
- **$\beta_N \approx 4$ obtained in a discharge with a very broad current profile**
  - With wall stabilization, ideal β_N limit increases with q_{min}
  - $f_{BS} > 0.6$ with $q_{min} \approx 2$