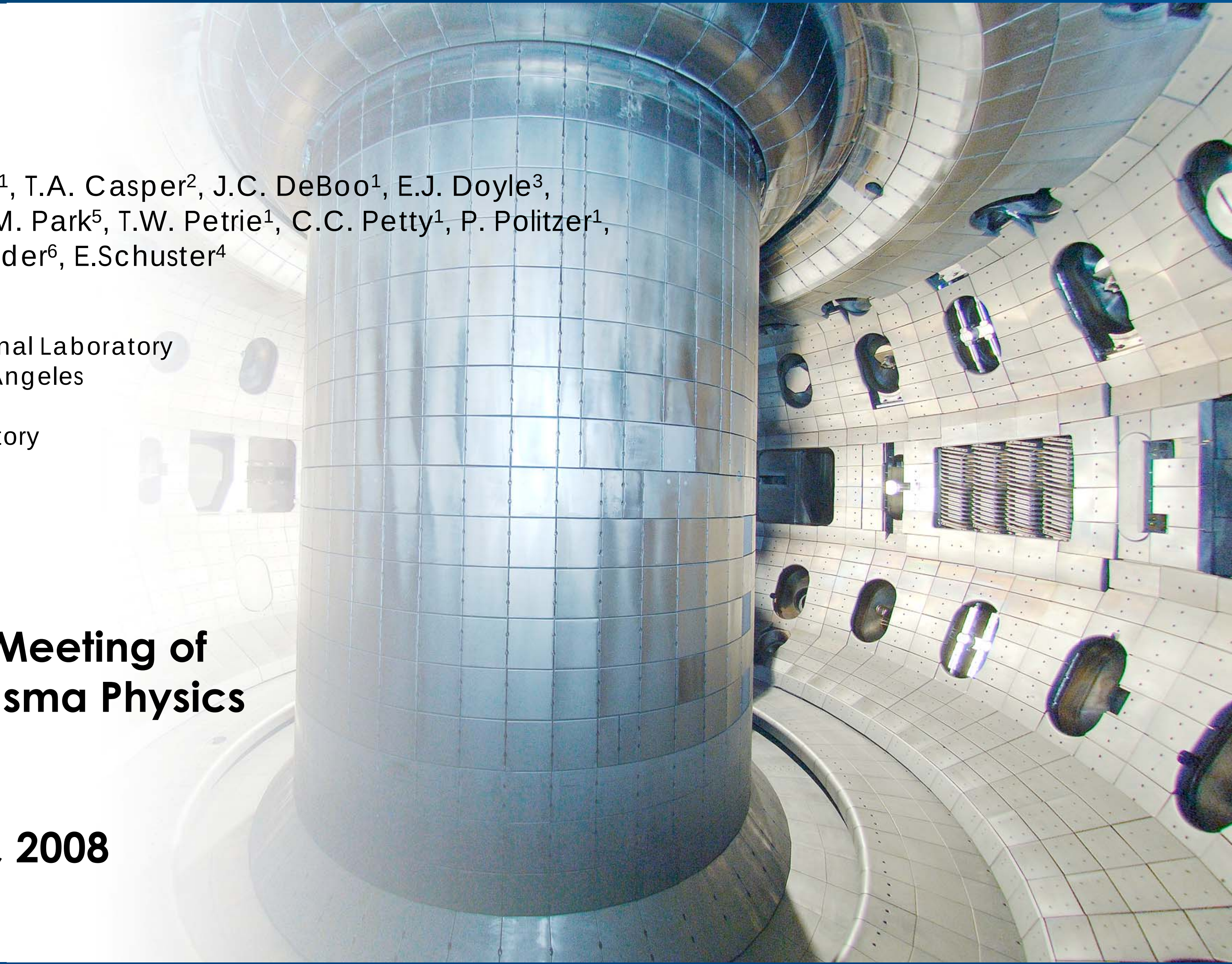
Studies in DIII-D of High Beta Discharge Scenarios Appropriate for Steady-State Tokamak Operation With Burning Plasmas



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DIII-D
NATIONAL FUSION FACILITY

Multiple steady-state scenarios are under study at DIII-D with different current profiles and β_N operating ranges

Common goals:

- $f_{NI} = 1$ (steady-state)
- high β_T (fusion power density)

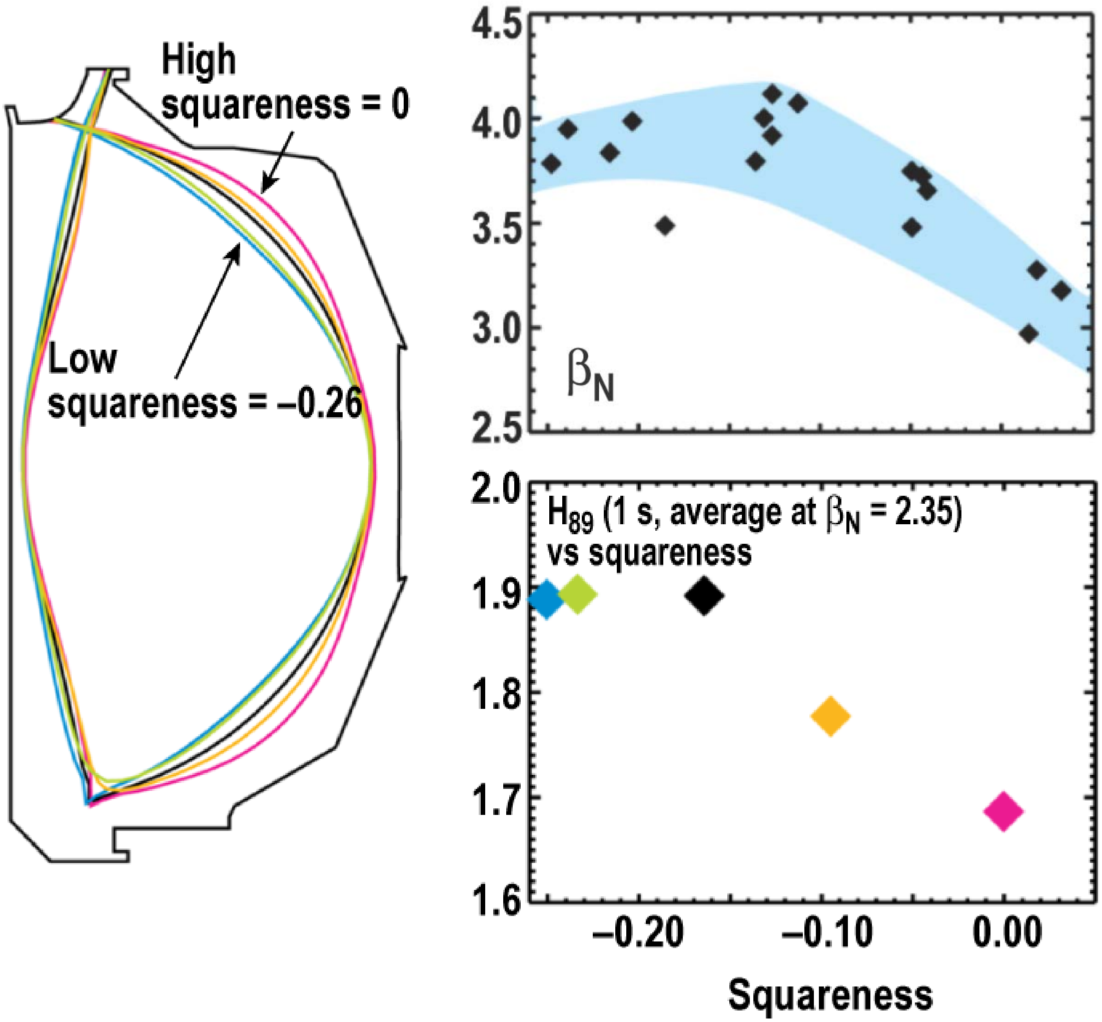
In this talk:

- **Optimization of elevated q_{min} discharges (Holcomb,CI1.3)**
  - Motivation for increased $q_{min} \approx 1.5\text{-}2$: $J_{BS} \propto 1/B_\theta$
- **Discharges with increased $l_i \approx 1.1\text{-}1.4$**
  - Motivation: the increased β limit without wall stabilization and better confinement at higher l_i
- **Comparison of ideal stability and current density profiles**

Other DIII-D steady-state scenarios not discussed here:

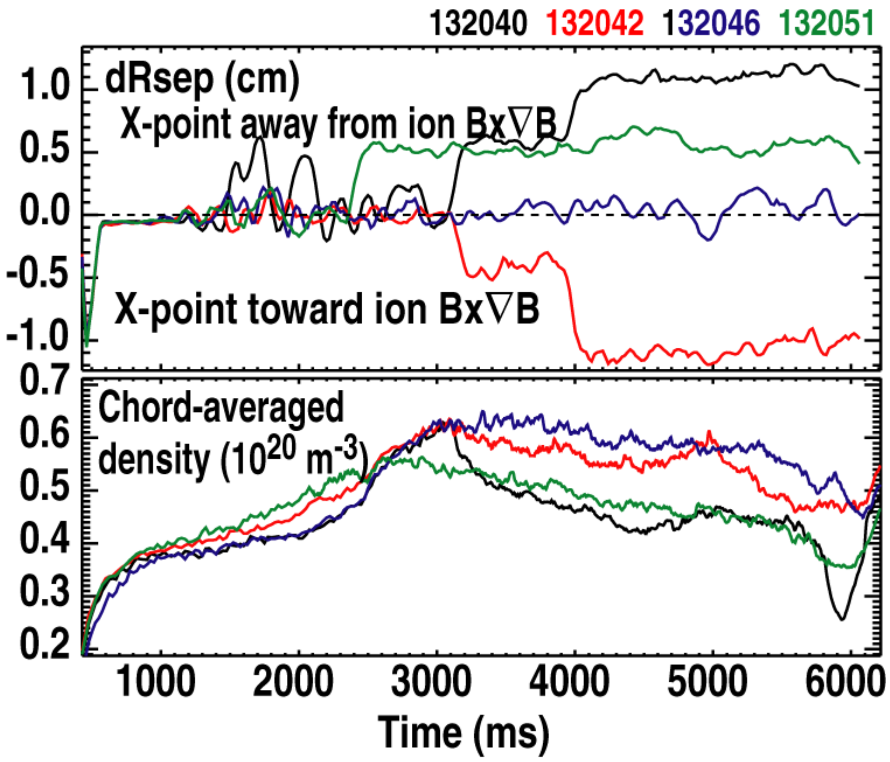
- **Very broad current profile, $q_{min} > 2$ (Garofalo PoP 2006)**
- **Hybrid with on-axis current drive (Petty, IAEA 2008)**

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

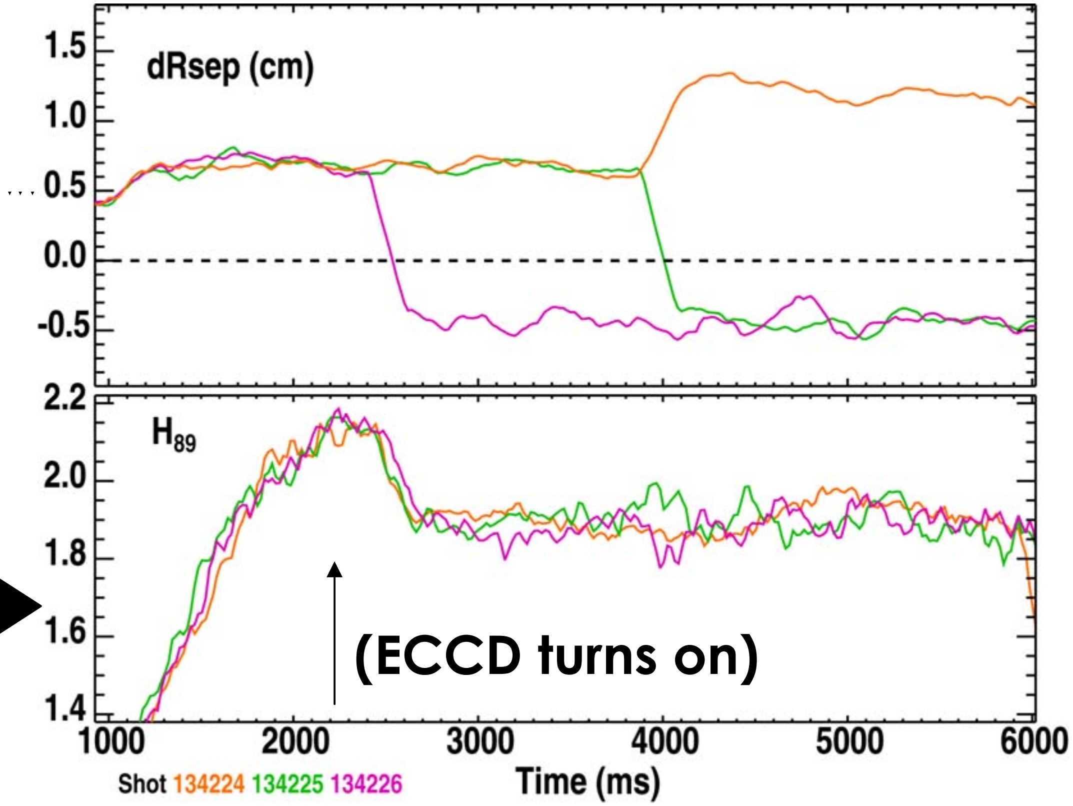


- **Observed change in maximum achieved β_N is in agreement with ideal MHD modeling of low-n kink (Holcomb, CI1.3)**
- **In the reduced confinement at higher squareness:**
  - ELMs are smaller, less regular
  - Core rotation is lower
  - Density fluctuation level is higher

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



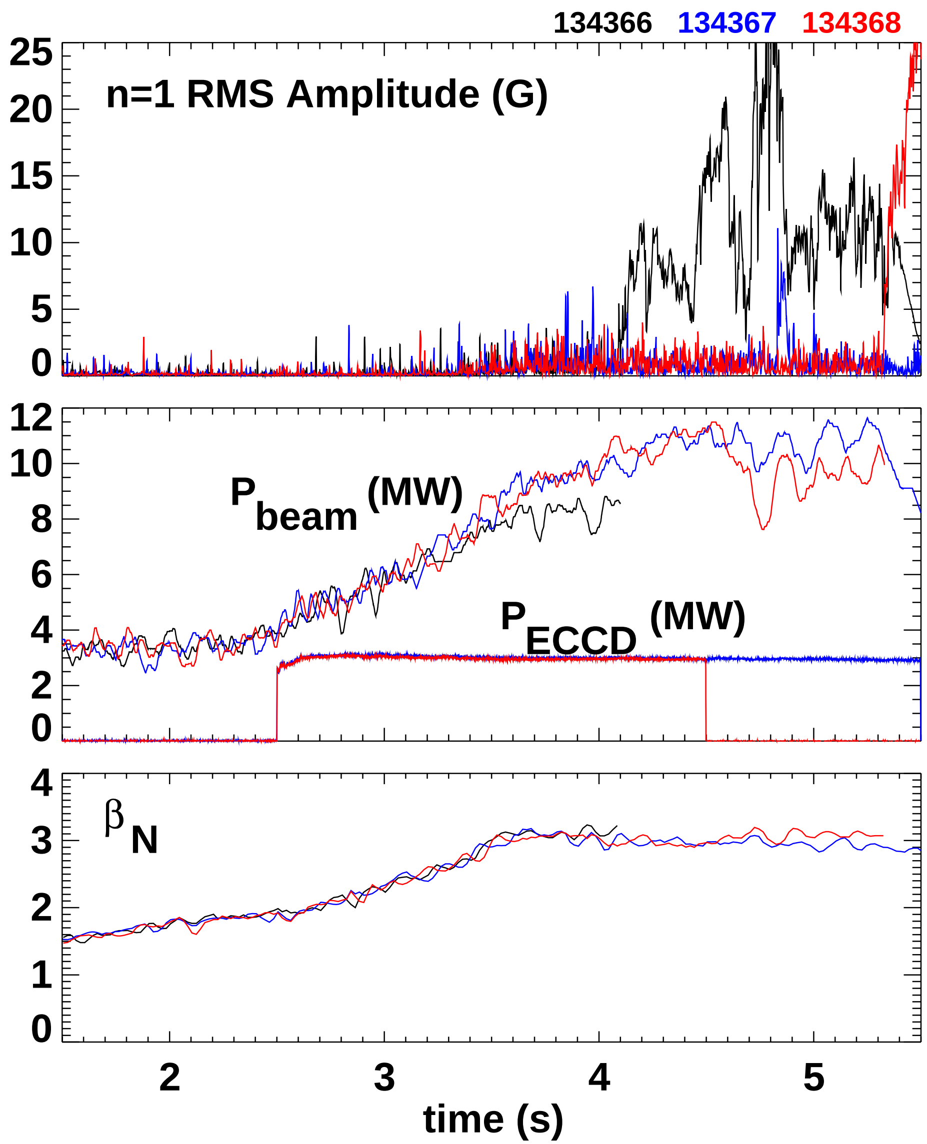
- Small bias away from ion Bx∇B direction results in lower density than a balanced shape or a bias toward Bx∇B



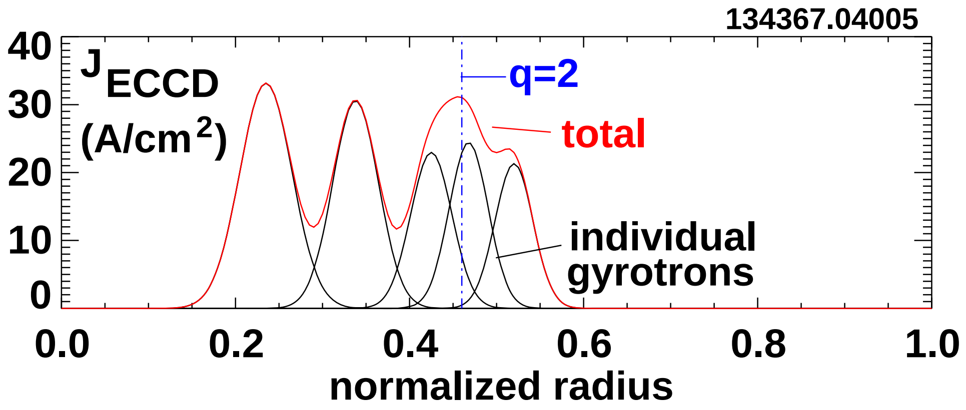
- These dRsep changes do not affect confinement

Petrie PO3.8

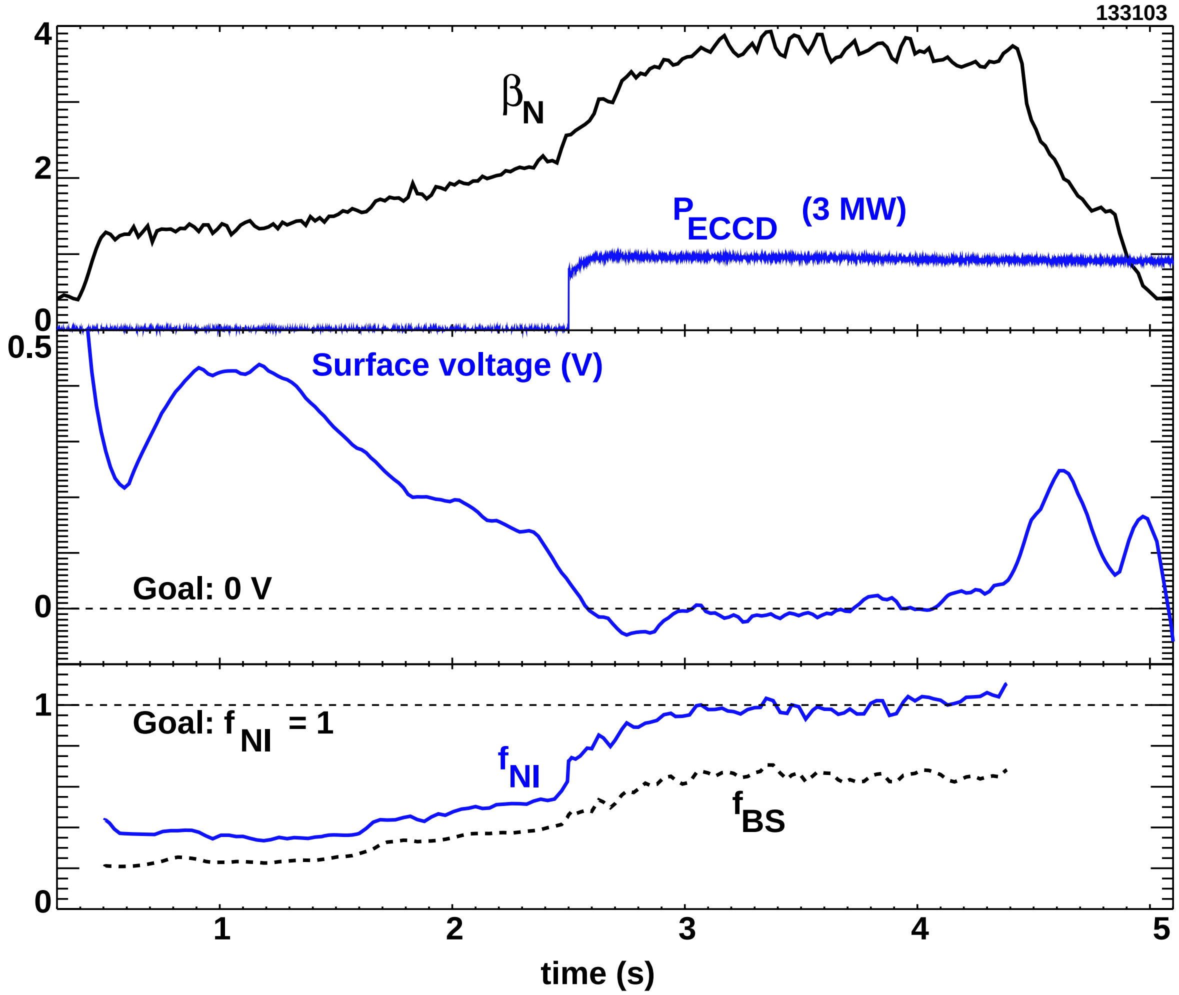
ECCD with a relatively broad deposition profile enhances stability to the 2/1 tearing mode at high beta



- n = 1 mode avoided in discharge with ECCD (blue)
- n = 1 appears after ECCD is turned off (red)
- Alignment of broadly deposited ECCD with q = 2 surface not necessary for improved 2/1 stability
- See Turco TP6.3

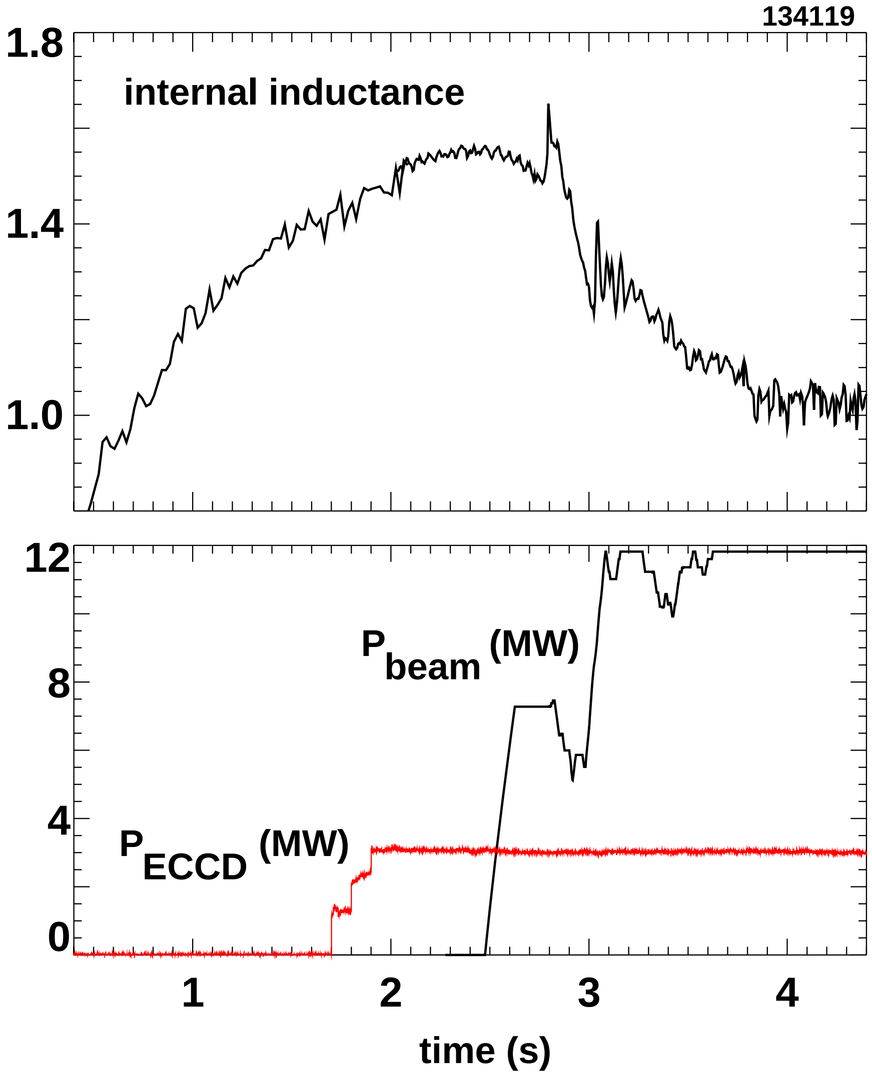


Duration of f_{NI} near 1 extended through operation at increased β_N without termination by a 2/1 NTM



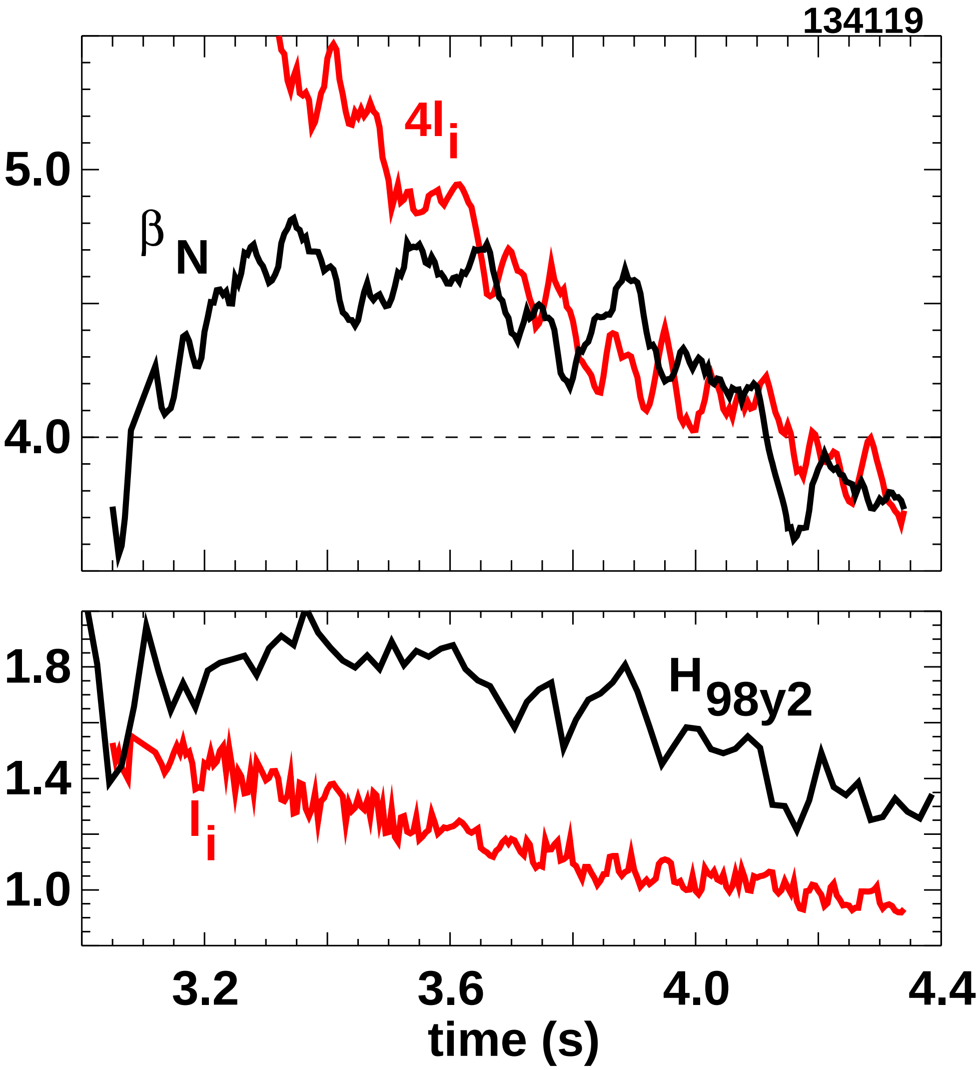
- β_N = 3.5-3.7
- Surface voltage ≈ 0, indicating $f_{NI} \sim 1$, for $\sim 0.7\tau_R$
- Calculated $f_{NI} \approx 1$ and $f_{BS} \approx 0.65$
- Present limitations:
  - Available neutral beam energy limits duration
  - Neutral beam and ECCD power limit I_{NI}

High initial l_i obtained using long ohmic phase to allow current to penetrate to the axis



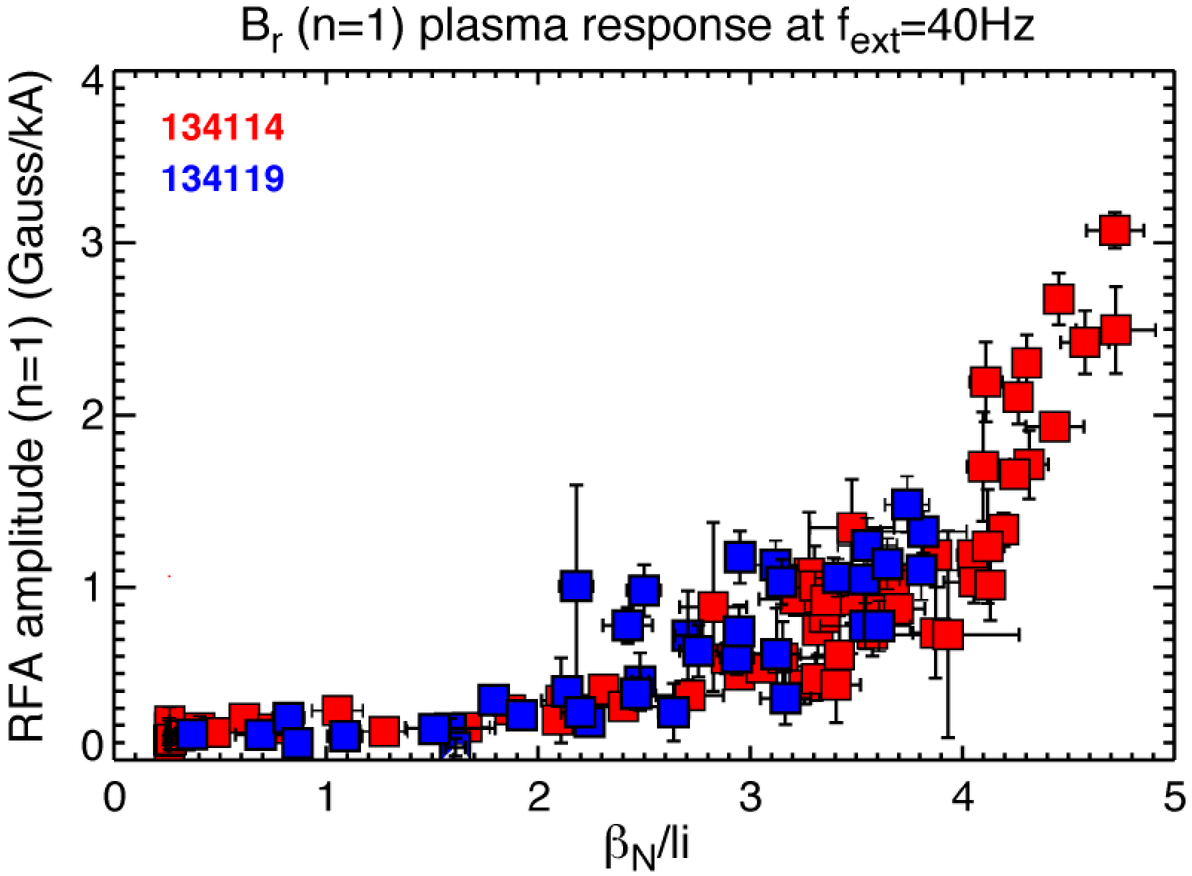
- **After H-mode transition, l_i decreases**
  - Broad J_{BS} profile
  - J_{BS} peak in the H-mode pedestal
- **All co-injection P_{beam} used to maximize β_N**
- **$q_{min} \approx 1$**

β_N remains above 4 for 1 s as the current profile evolves



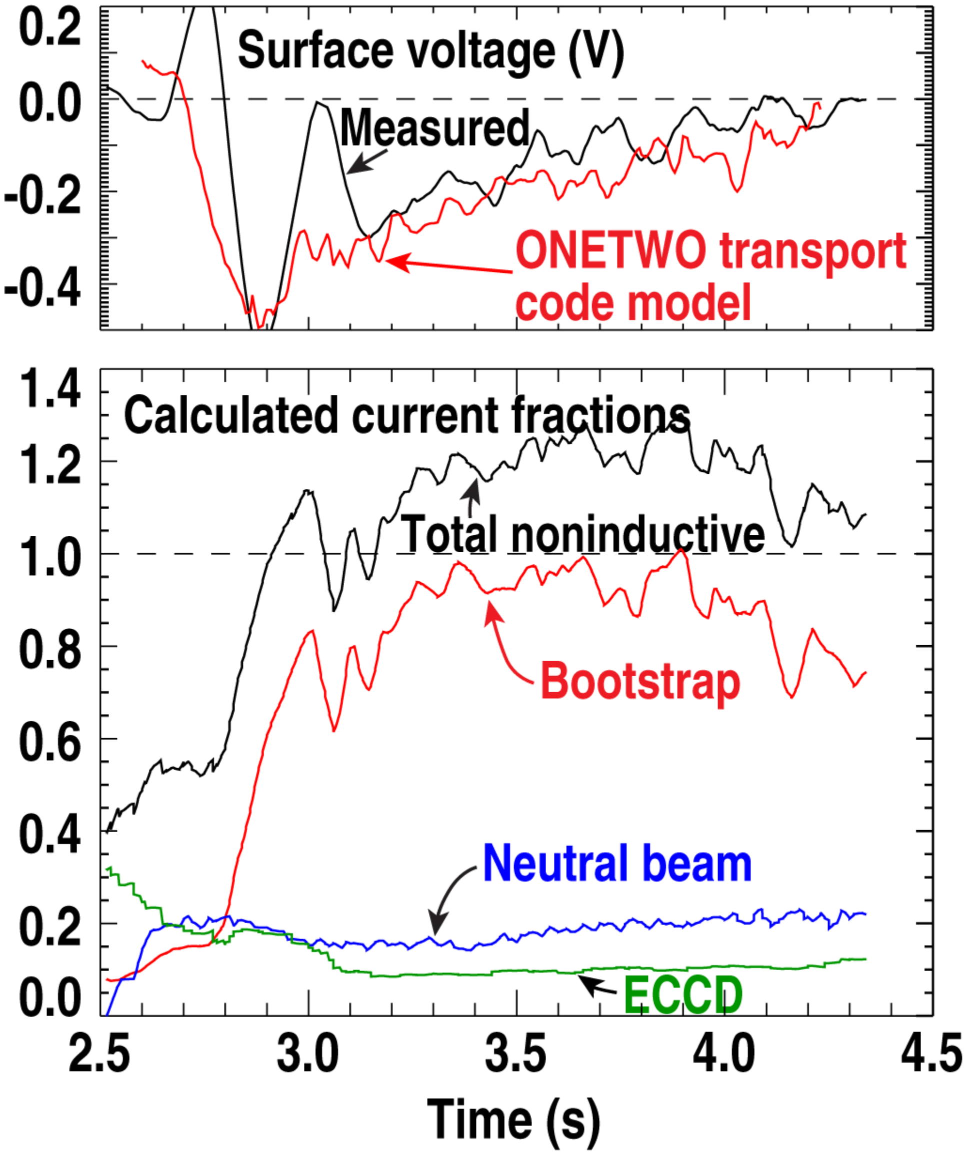
- **Initially $\beta_N \approx 4.5$ is below $4l_i$, the control room estimate for the ideal n = 1 no-wall stability limit**
- **Confinement well above standard H-mode value**
  - Decreases as l_i drops
- **Current profile not yet stationary**
  - Future step in scenario development

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



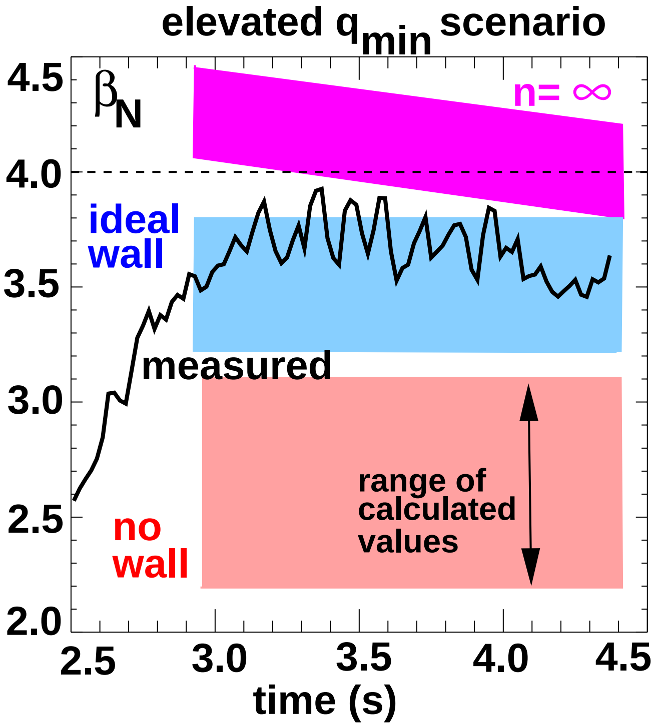
- Indicator is change in slope of response (red points)
- Consistent with the ideal MHD no-wall kink stability limit near $4l_i$

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

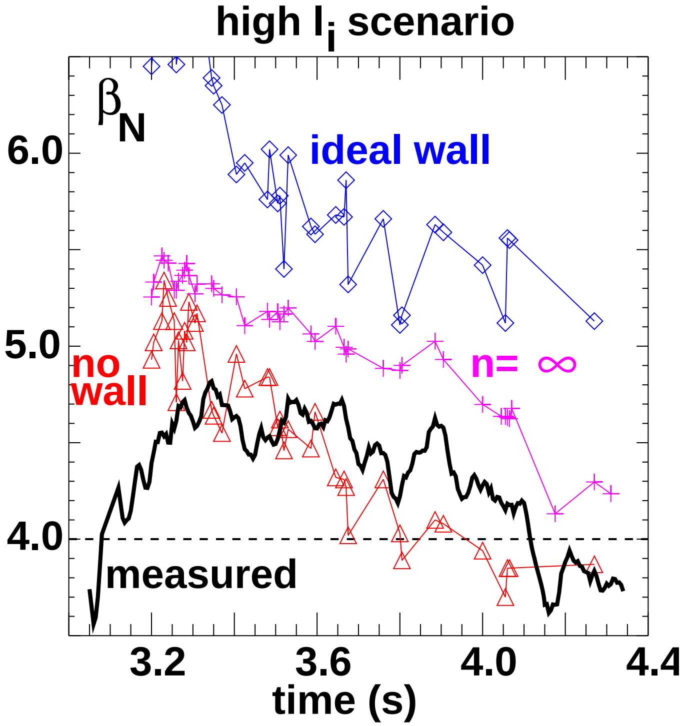


- **Measured surface voltage < 0**
- **Agrees with transport code modeling**
- **Calculated $f_{NI} \approx 1.2$**
- **Calculated $f_{BS} \approx 0.9$**

Stabilization by coupling to an ideal wall is required to obtain high β_N with elevated q_{min} but not at high l_i



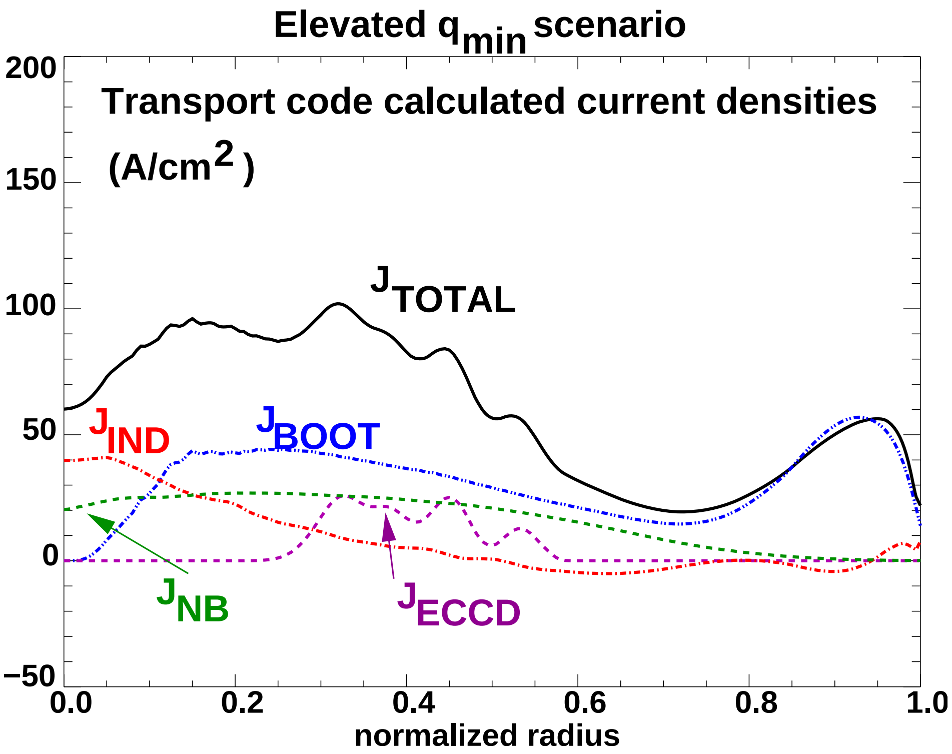
Calculated ideal n = ∞ and n = 1 stability limits

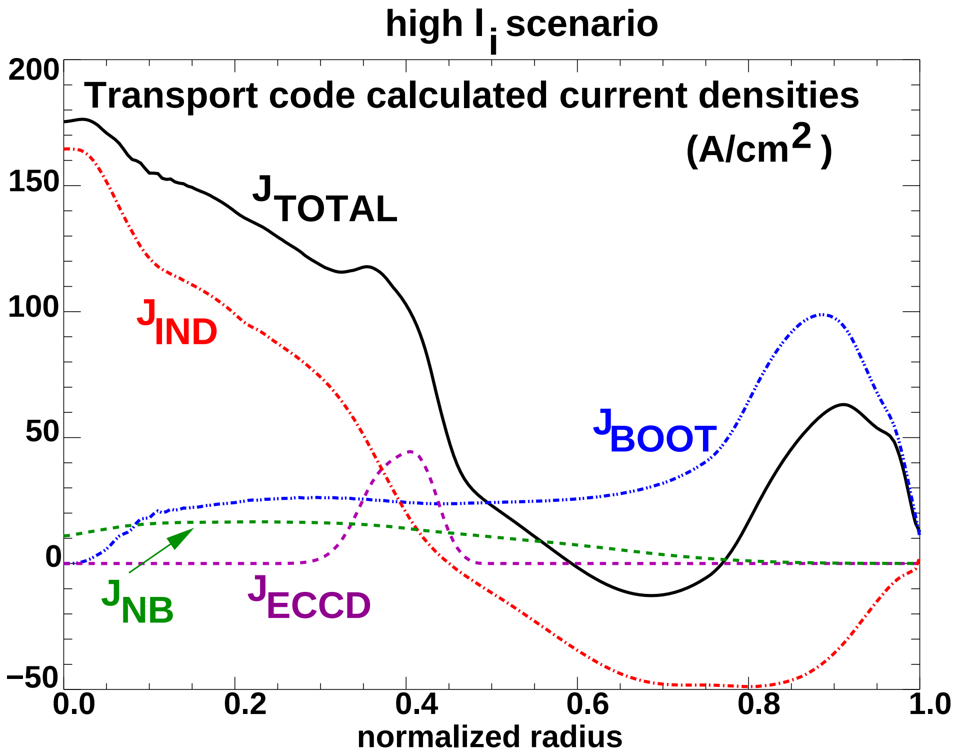


- β_N is at the ideal-wall limit
- Rotation or feedback is required to stabilize resistive wall modes

- β_N is near or below no-wall limit ($\approx 3.8 l_i$)
- $\beta_N = 5$ should be possible at $l_i > 1.4$ without rotation or hardware to stabilize resistive wall modes

Profiles of J_{IND} differentiate the near stationary elevated q_{min} scenario and the still transient high l_i discharge





- **Good alignment between J_{NI} and J_{TOTAL}**
  - Small residual J_{IND}

- **To convert to steady-state:**
  - Replace peaked J_{IND} with efficient on-axis CD
  - Reduce H-mode pedestal J_{BS}

Progress has been made on two different approaches to a steady-state scenario with high fusion gain

- **Elevated q_{min} scenario has been optimized toward long duration operation with high β_N and $f_{NI} = 1$**
  - Details of the discharge shape can have a significant effect on performance
  - Duration with surface voltage ≈ 0 extended at higher β_N without termination by a 2/1 tearing mode
- **In the high l_i scenario, $\beta_N > 4.5$ obtained simultaneously with $f_{NI} > 1$ and $f_{BS} > 0.8$**
  - Peak β_N is less than the ideal no-wall n = 1 stability limit
  - Indicates the possibility of steady-state operation with $q_{min} \approx 1$ without wall stabilization