Demonstration of the ITER Ignition Figure of Merit at q_{95} > 4 in Stationary Plasmas in DIII–D

by
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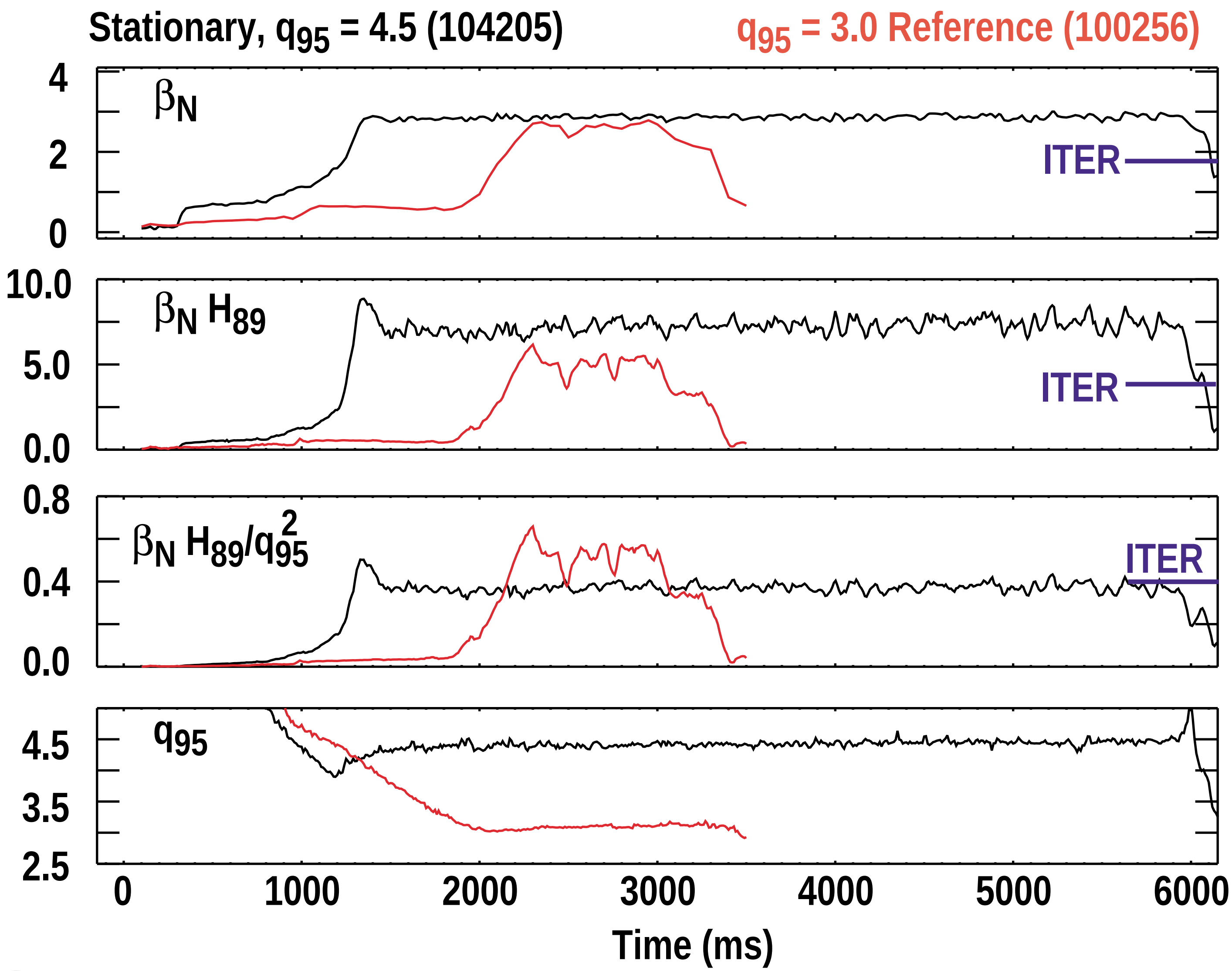
ITER BASELINE SCENARIO IS CONSTRAINED BY β LIMIT IMPOSED BY ONSET OF NEOCLASSICAL TEARING MODES (NTMs)

- NTM scalings limit $\beta_N \lesssim 2.0$ in ITER, 40% below ideal MHD limit
  - Low limit partially due to large seed islands produced by sawteeth
- $\beta_N < 2.0$ forces ITER design to low q_{95} (or high I_p) to achieve desired fusion gain

$$\text{Fusion Gain} \propto \beta\tau \propto \frac{\beta_N}{q_{95}} \; \frac{H}{q_{95}}$$

- Several disadvantages associated with low q_{95} (or high I_p) operation
  - Effect of disruptions increase with increasing I_p
  - ELMs are larger: $\Delta W_{ELM} \propto P_{ped} \propto I_p^2$
  - Peak divertor heat flux increases due to shorter connection lengths
  - Pulse length is reduced since resistive flux consumption $\propto I_p$

STATIONARY PLASMAS WITH $\beta_N H/q_{95}^2 \geq$ ITER DESIGN VALUE AND $q_{95} > 4$ HAVE BEEN DEMONSTRATED ON DIII-D



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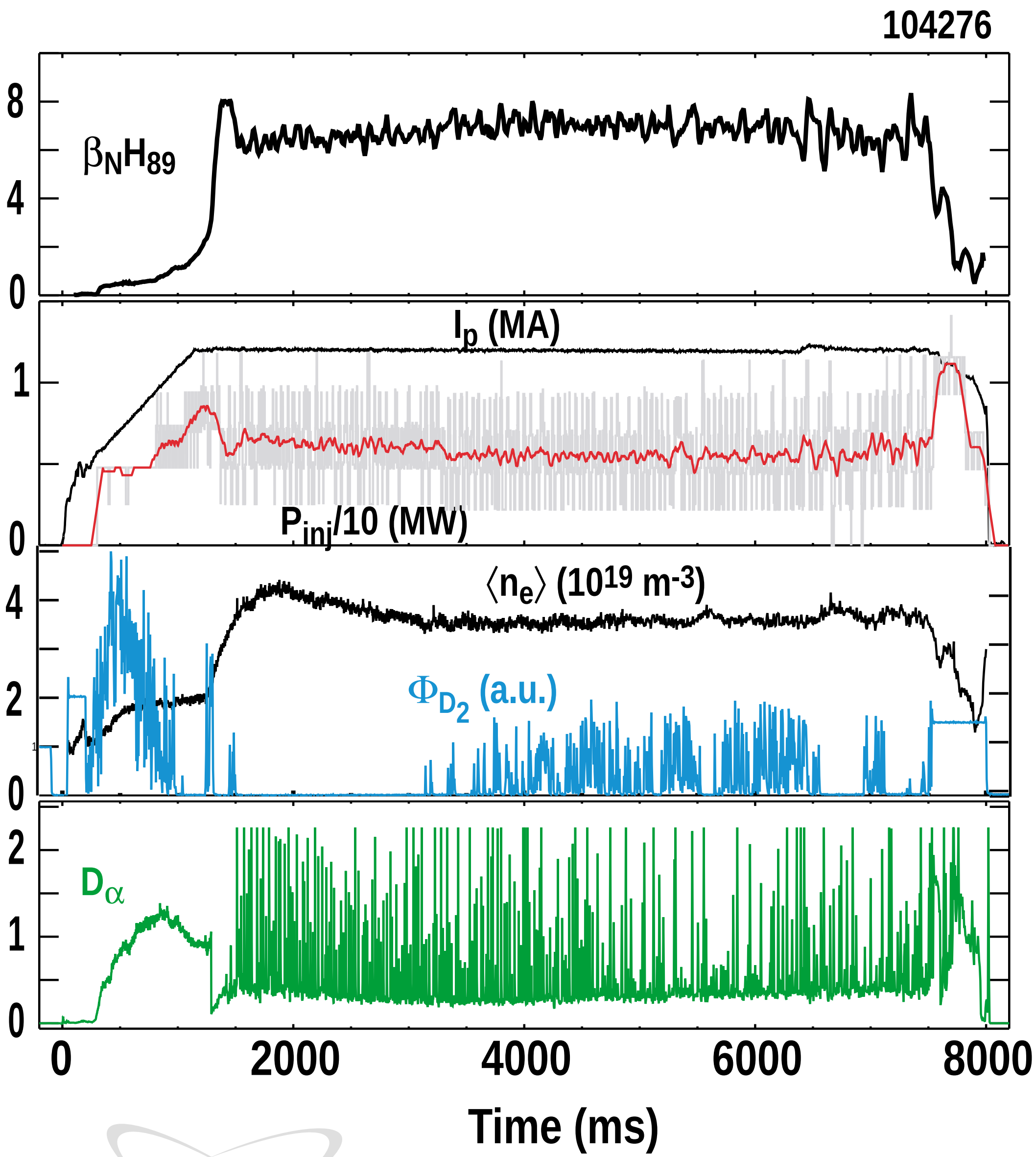
DISTINGUISHING FEATURES OF THESE DISCHARGES

- Stationary on the measured thermal, resistive, and wall equilibration time scales
  - $\tau_{dur} \sim 25\ \tau_E \sim 2.5\ \tau_{CR} \sim 20\ \tau_{weq}$
- $q_0 > 1.0$, no sawteeth or other n=1 activity
  - Results from continuous m=3/n=2 tearing mode at half radius
  - Reduces susceptibility to m=2/n=1 NTM
- $\beta_N \sim \beta_N^{no\text{-}wall}$ achieved without NTM
- Transport significantly better than expected from q scaling projections

THESE STATIONARY DISCHARGES ARE OPTIMIZED AND MAINTAINED THROUGH FEEDBACK CONTROL OF β AND PLASMA DENSITY



- Uses typical AT startup with NBI during current ramp
- High normalized performance maintained through feedback control of stored energy
- Gas injection required to maintain requested density
- Type I ELMing throughout

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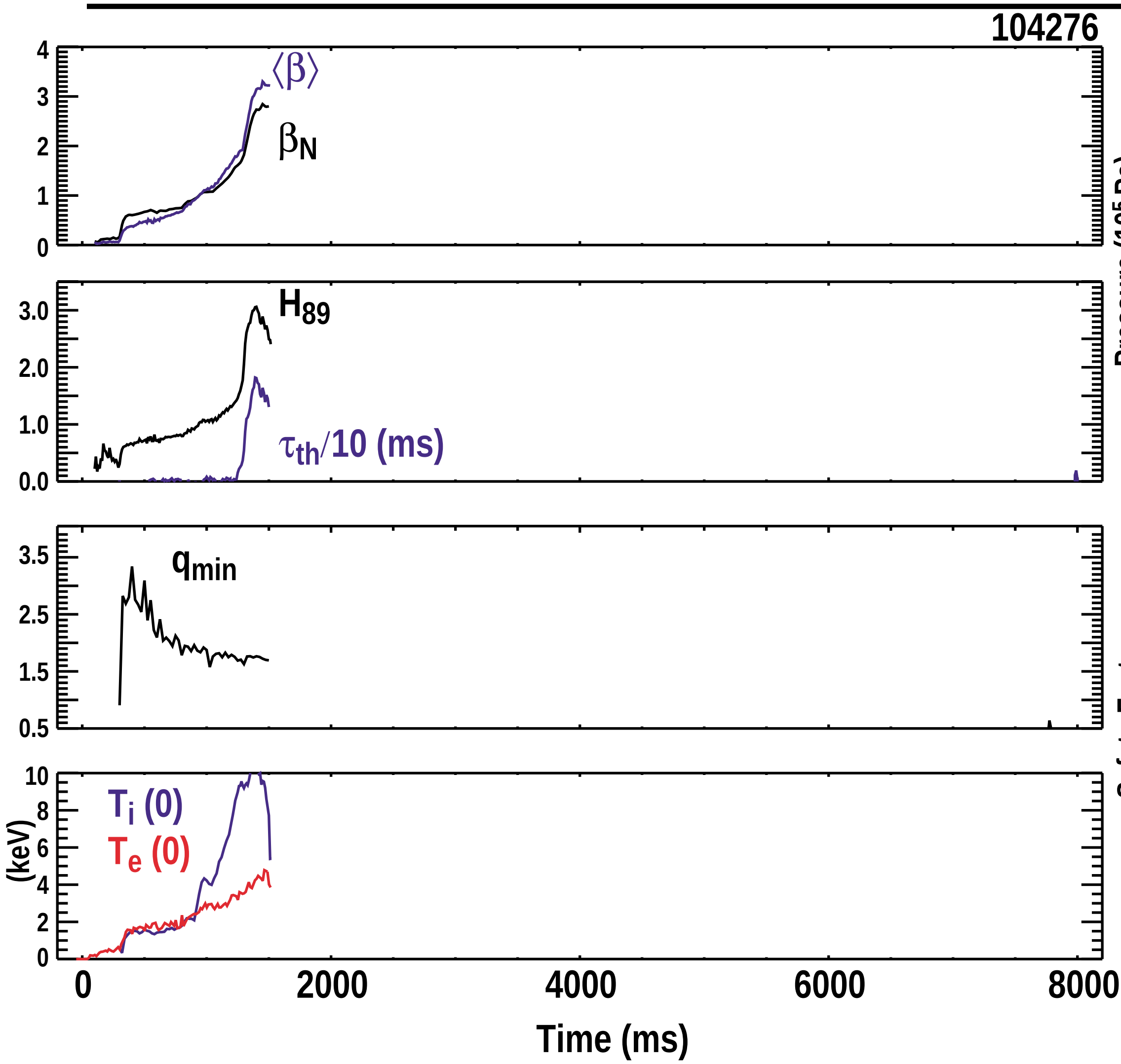
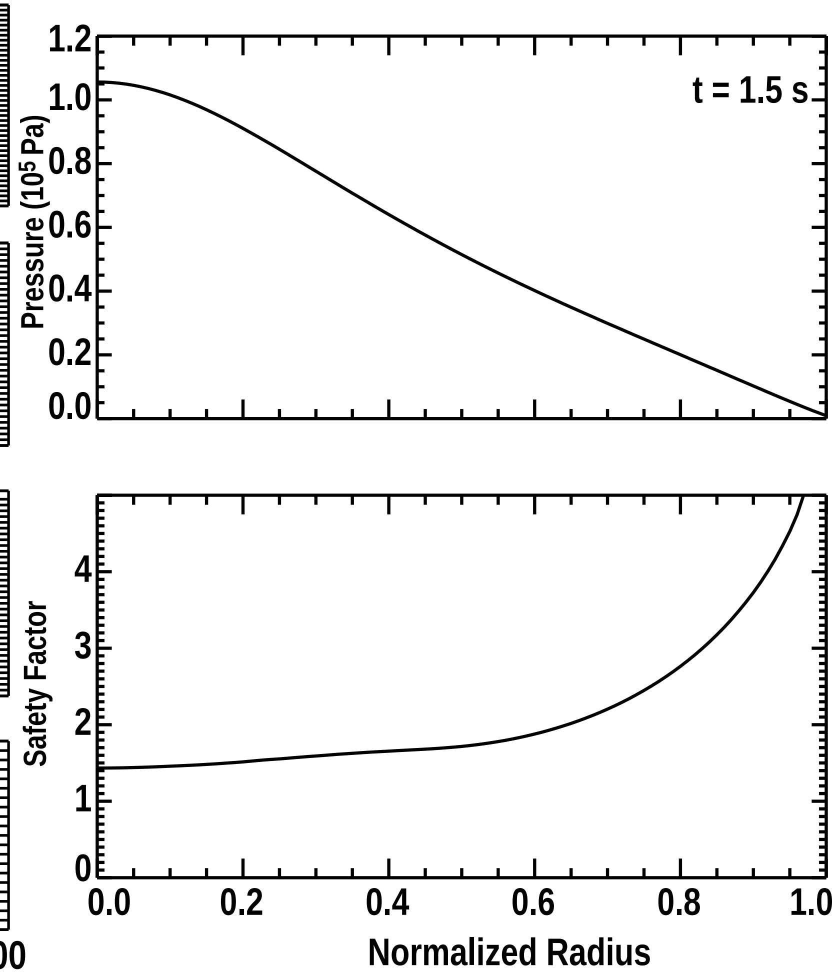
PRESSURE PROFILE EQUILBRATES SOON AFTER L-H TRANSITION; CURRENT PROFILE EQUILIBRATES ON A CURRENT RELAXATION TIME SCALE (τ_{CR} ~ 2.0 s)





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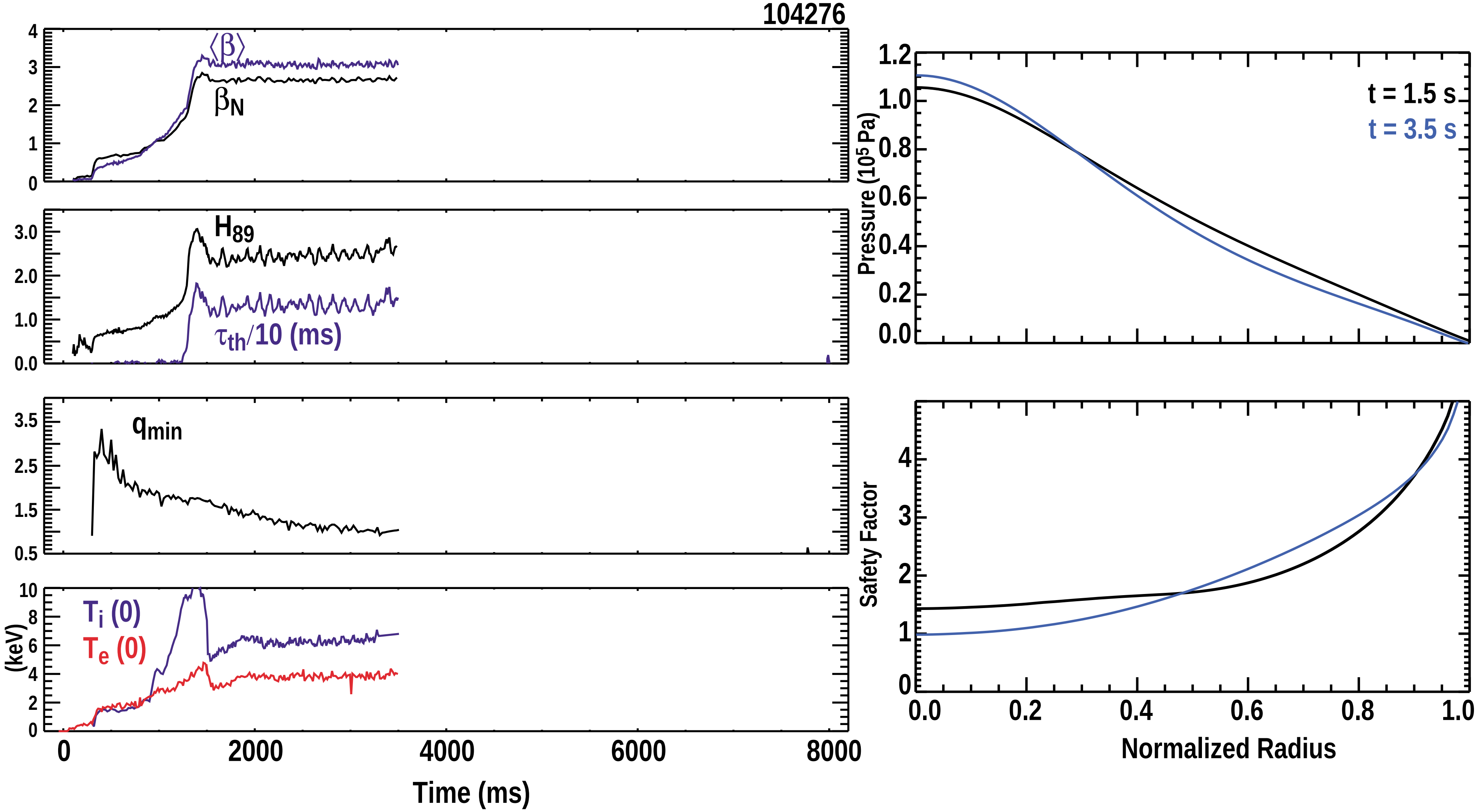

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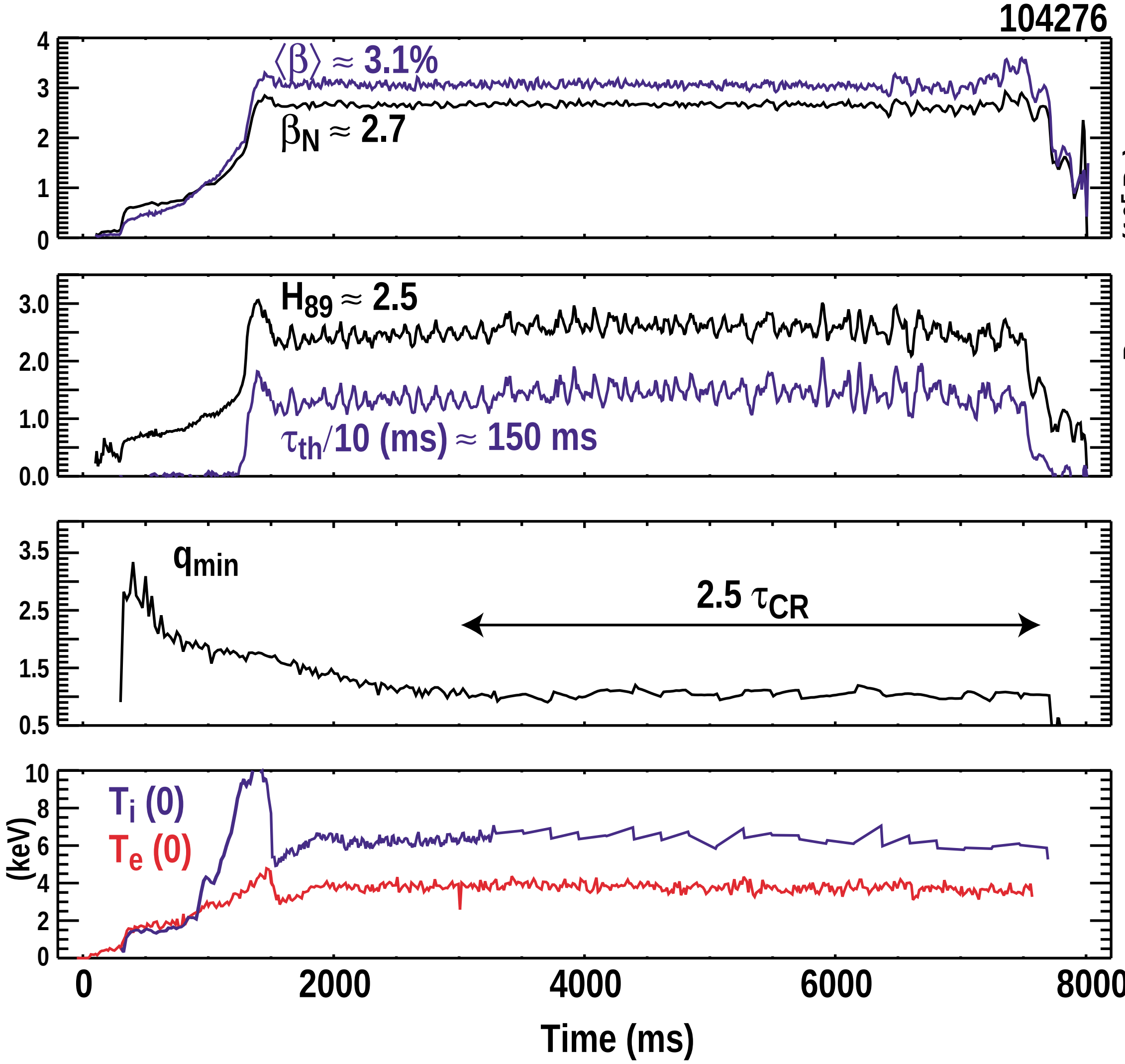

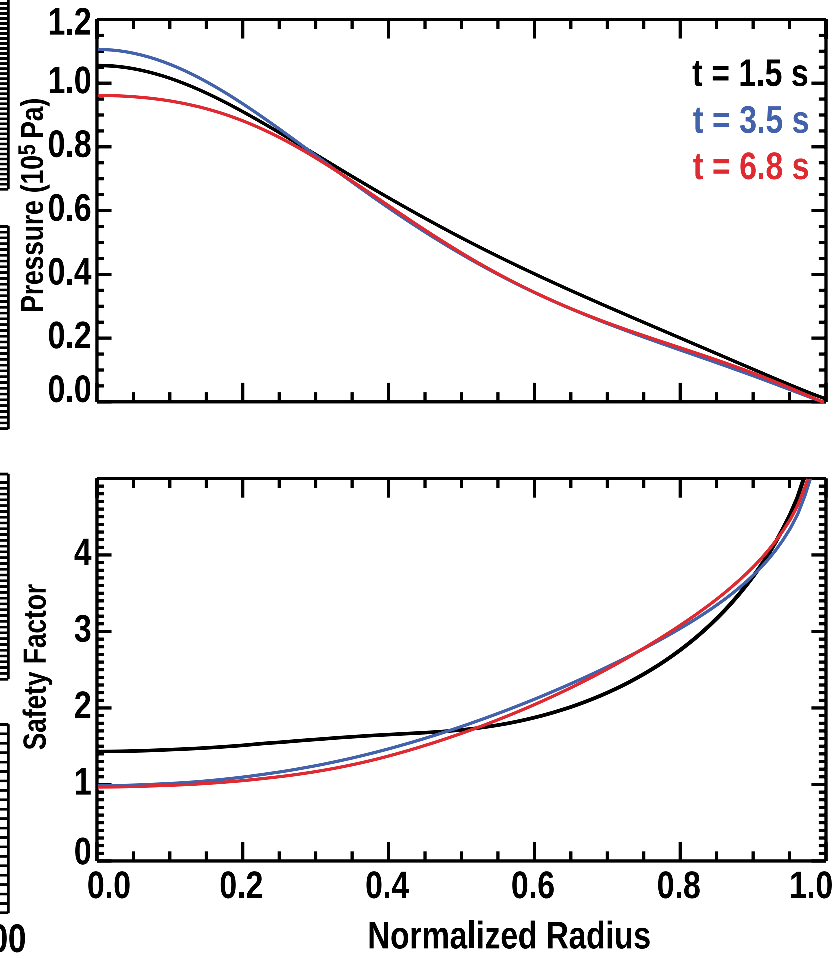

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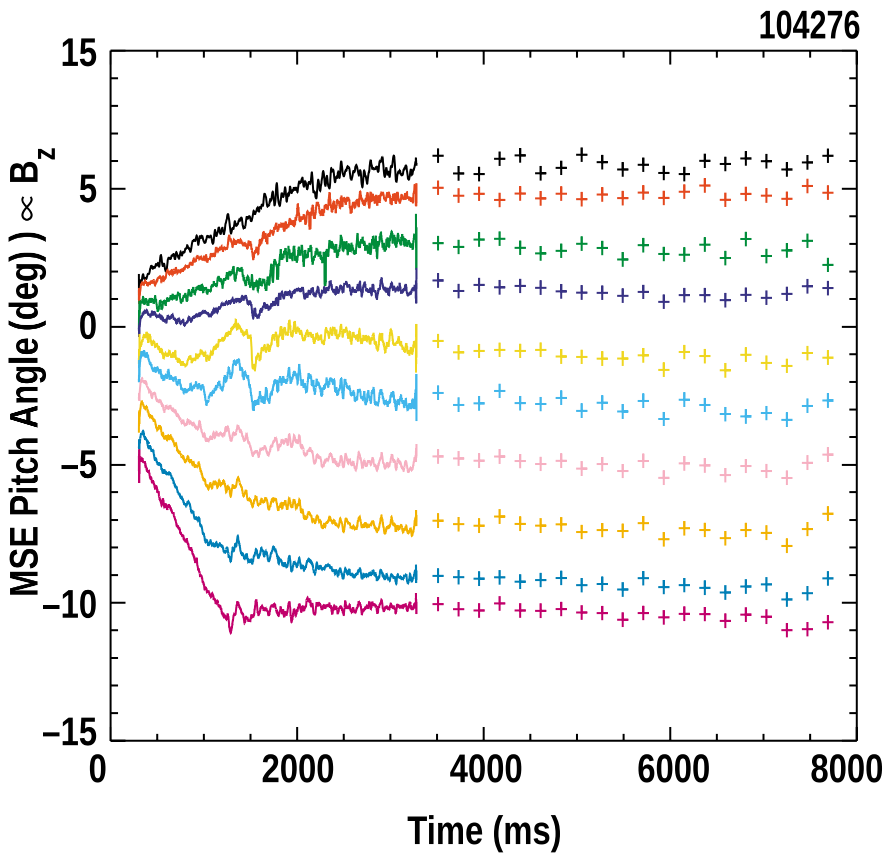
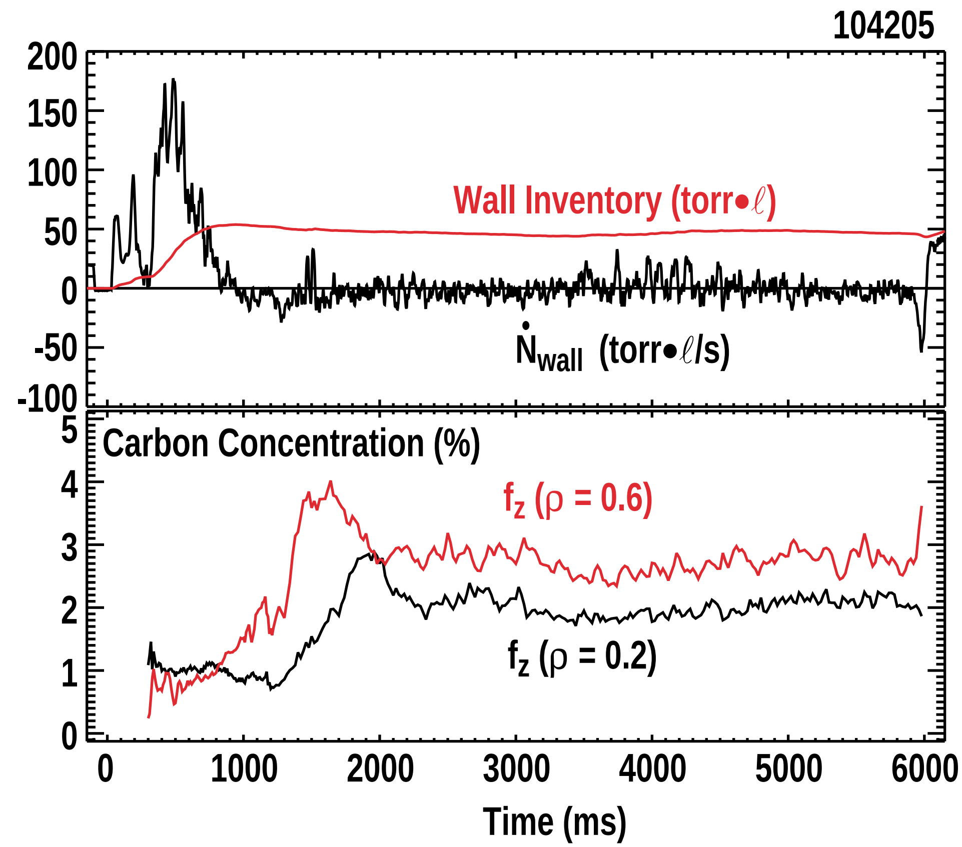
CURRENT PROFILE IS FULLY RELAXED AND WALL PARTICLE INVENTORY IS EQUILIBRIATED AFTER 3.0 s





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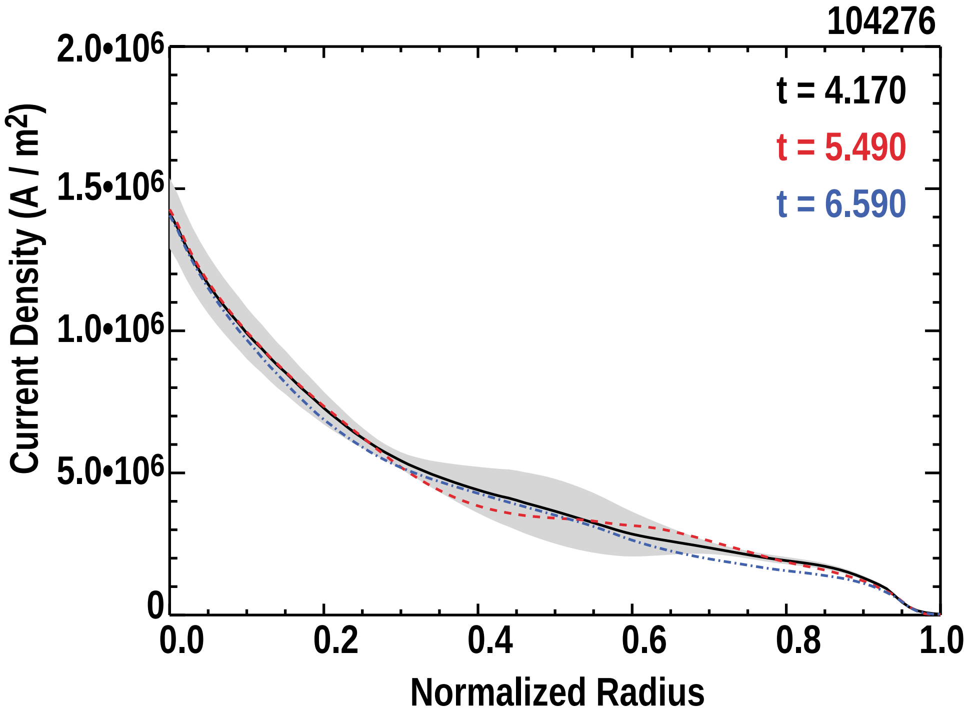
VLOOP ANALYSIS INDICATES DIFFUSION OF OHMIC CURRENT STOPS AT ~ 3.0 s AND SMALL VOLTAGE SOURCE AT ρ = 0.5

- $V_{LOOP} \propto \frac{d\psi}{dt}$; $J_{OHM} = \sigma_{neo} E_{||}$



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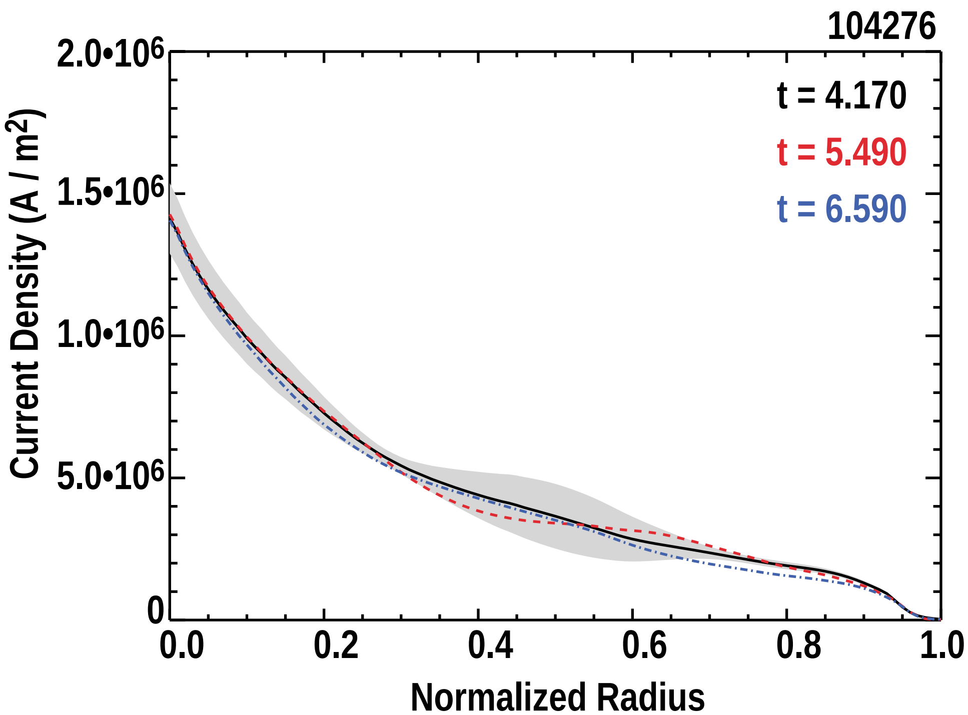

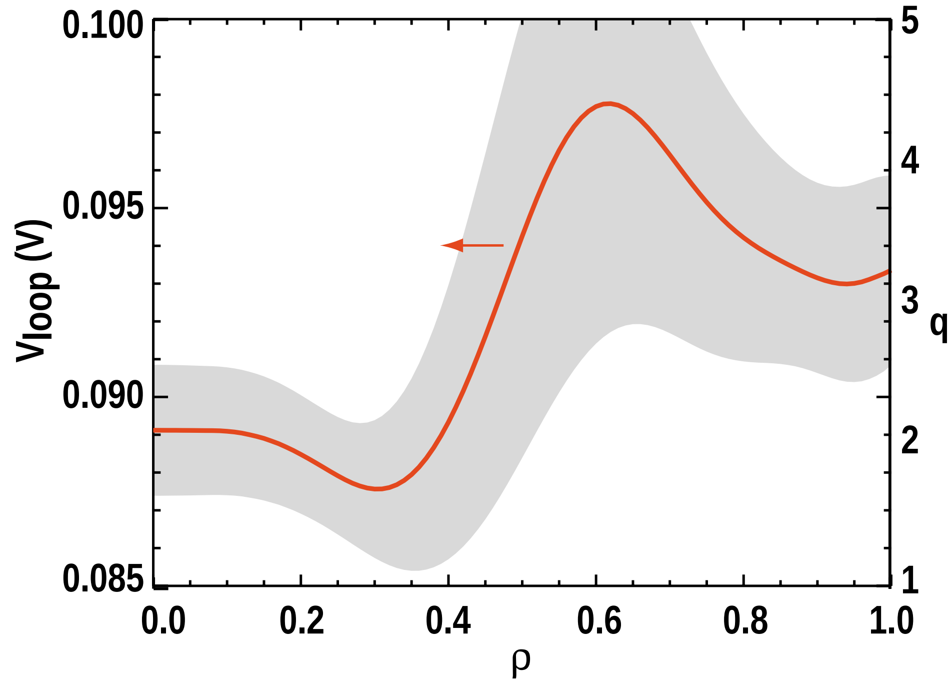

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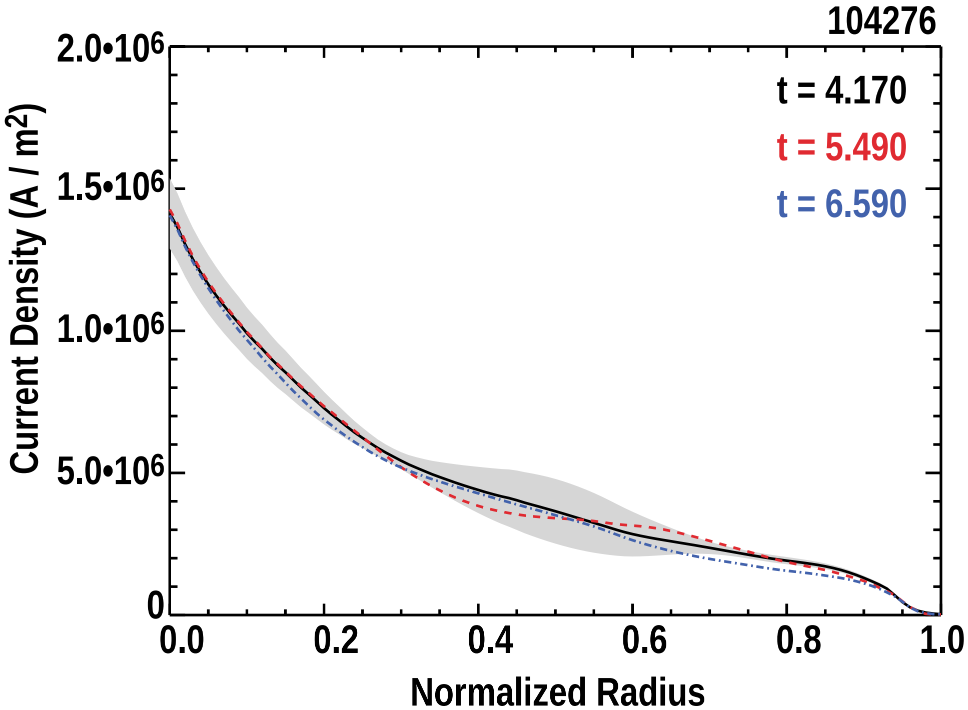

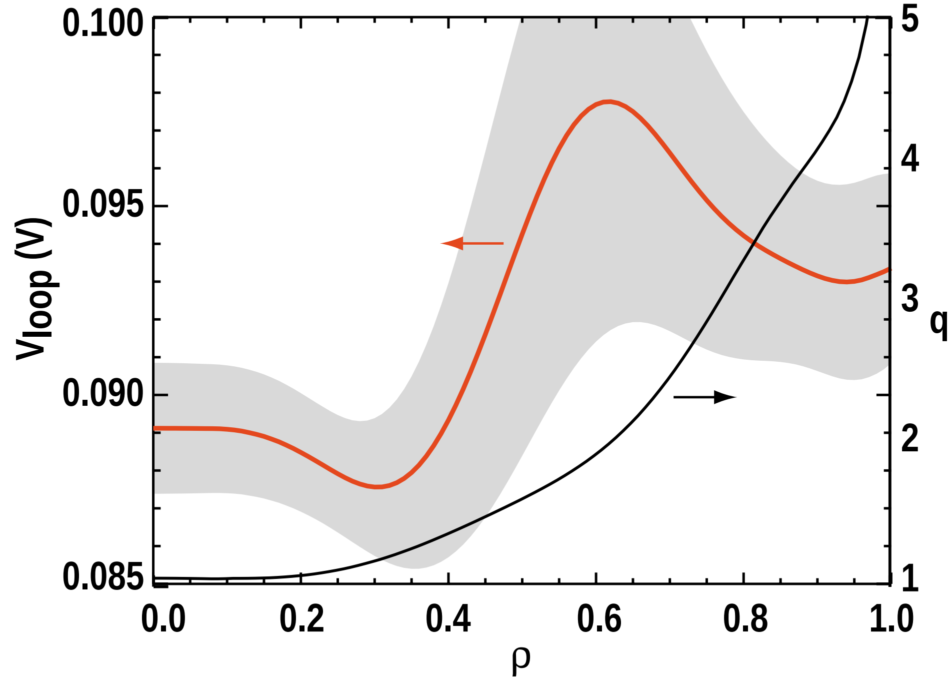

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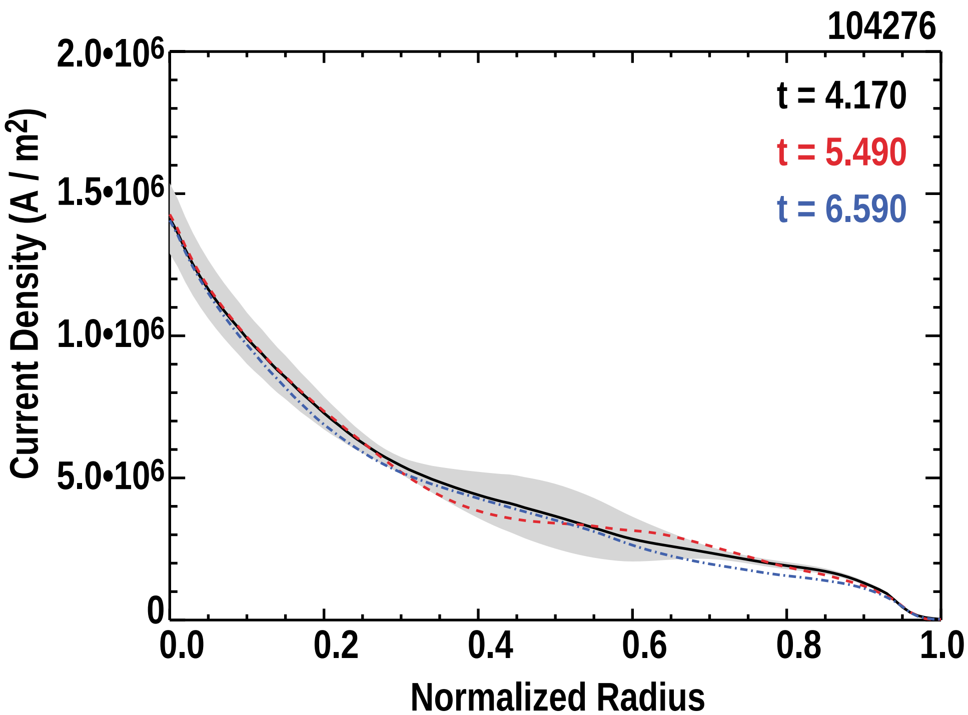

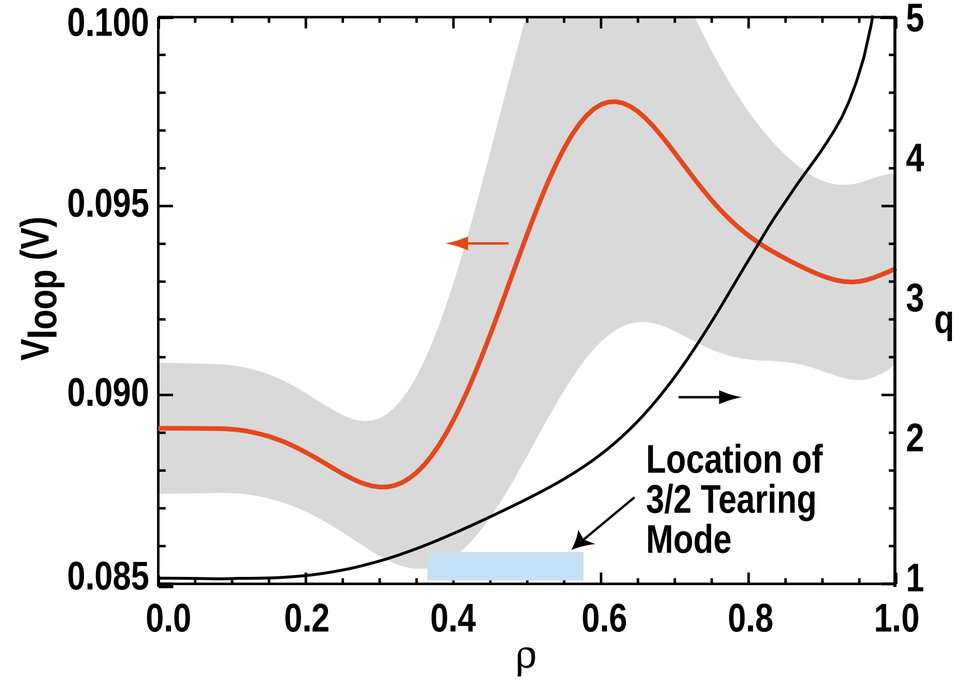

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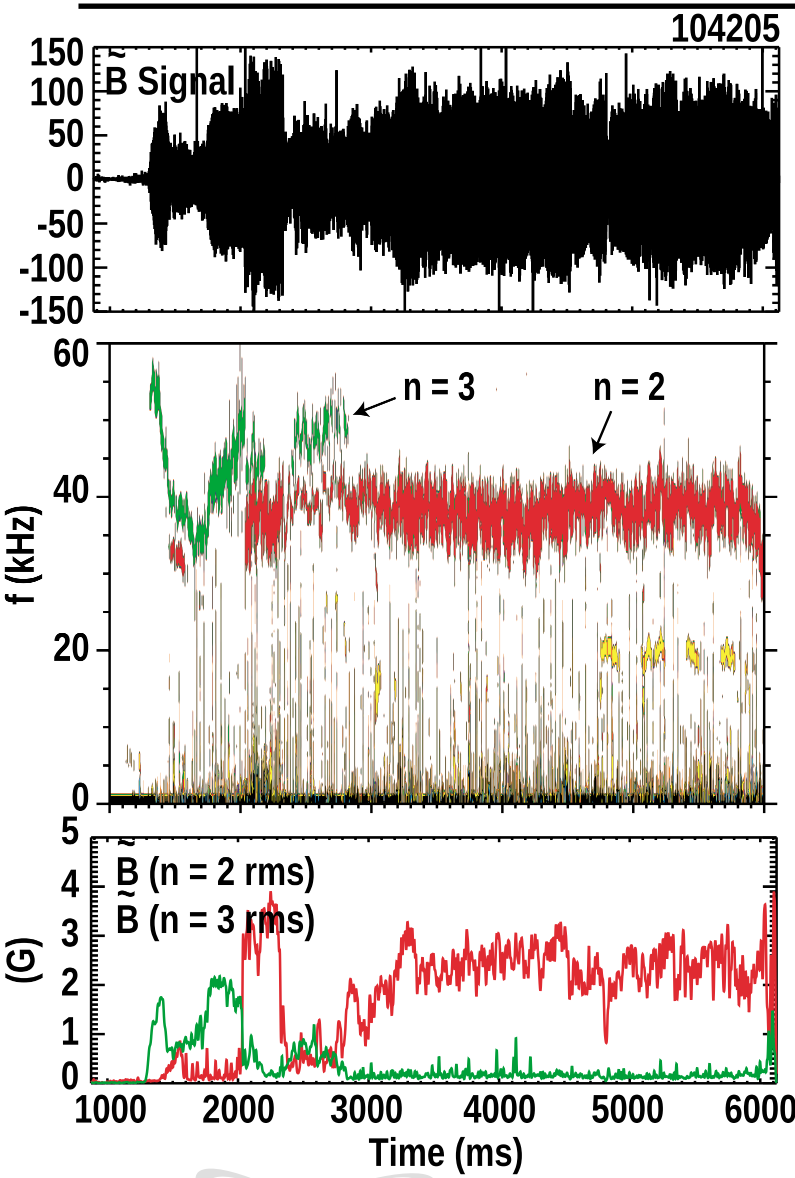
STEADY m = 3/n = 2 TEARING MODE IS PRESENT IN ALL DISCHARGES WITH SUSTAINED, HIGH PERFORMANCE



- Continuous mode starts in earnest at t = 3.0 s
- Identified as m=3/n=2 tearing mode
- Rotation frequency is near 20 kHz, placing mode near p = 0.5
- Mode amplitude is small (<5 G) and confinement is only modestly affected (<10%)
- No sawteeth or fishbones evident

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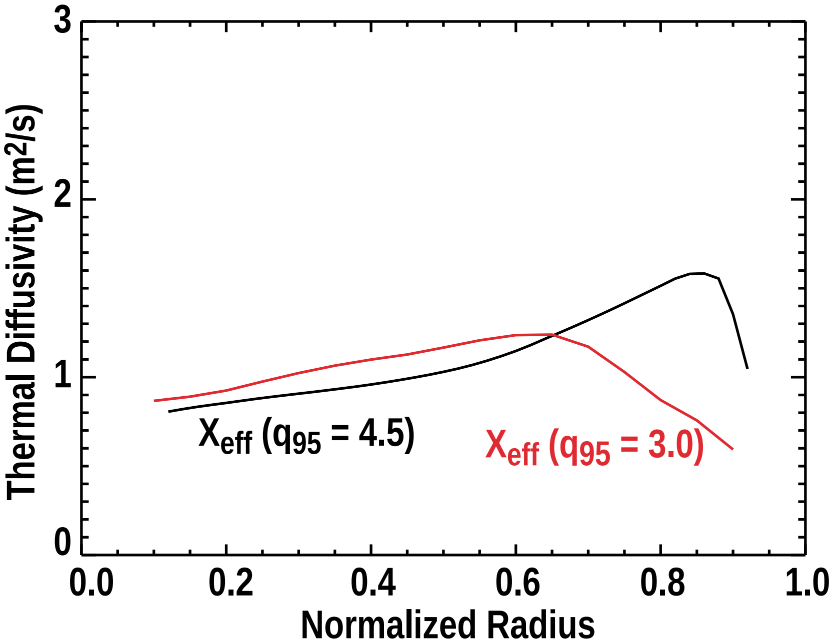
ENERGY TRANSPORT COMPARABLE TO THAT OBTAINED IN LOW q_{95} REFERENCE SHOT

- χ_{eff} substantially lower than that expected by q scaling of transport
  - Global confinement scaling: $\chi_{eff} \propto q^{1.4}$
  - Nondimensional transport studies: $\chi_{eff} \propto q^{2}$



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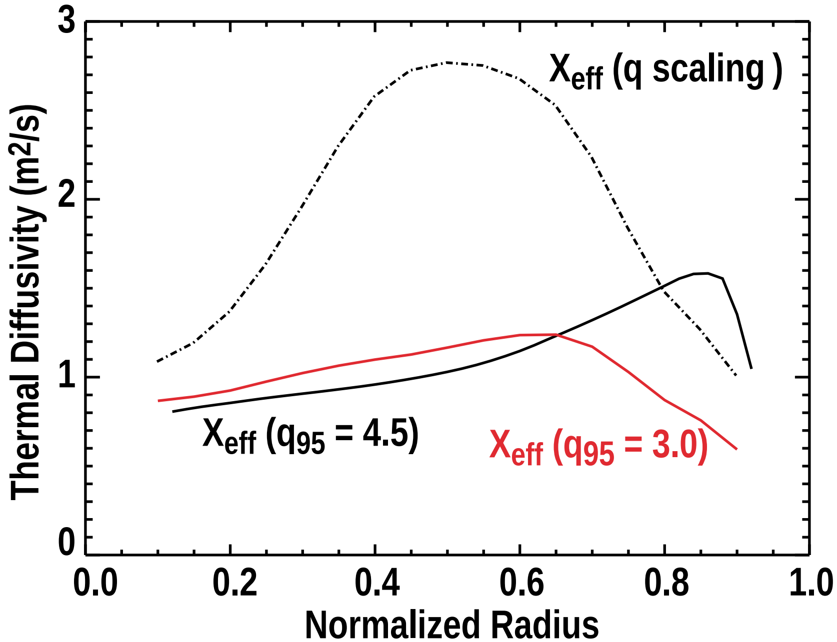

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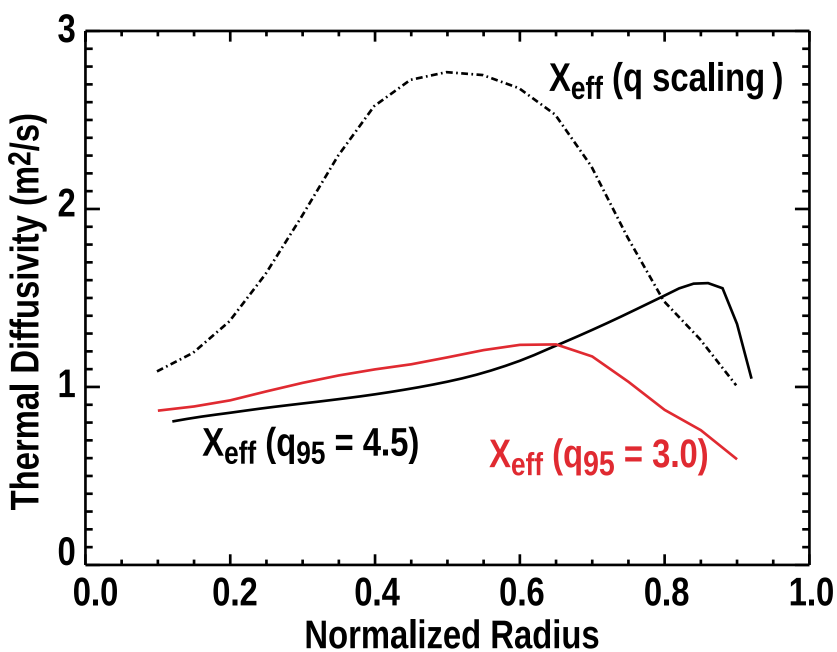
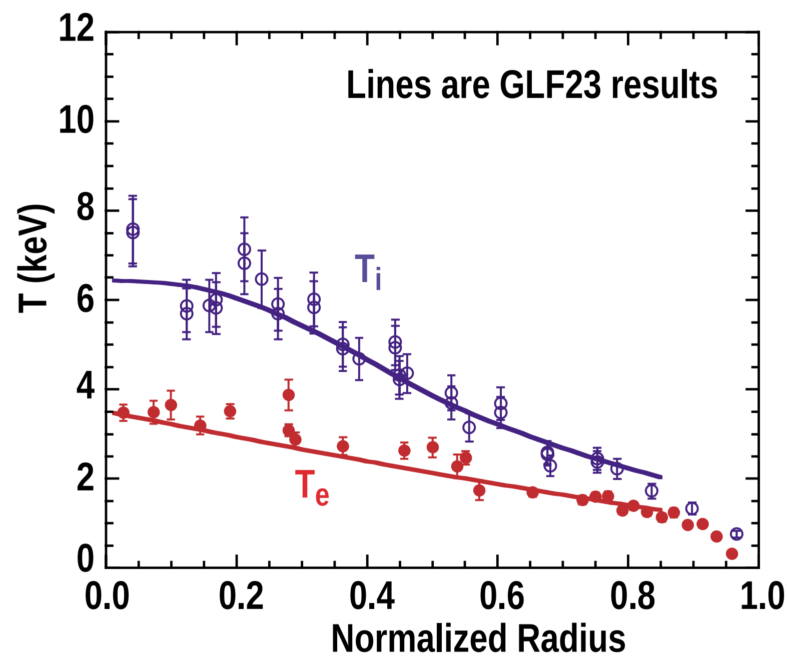
- GLF23 drift-wave model gives good agreement with measured profiles
- Model contains ITG, TEM, and ETG with effects of ExB





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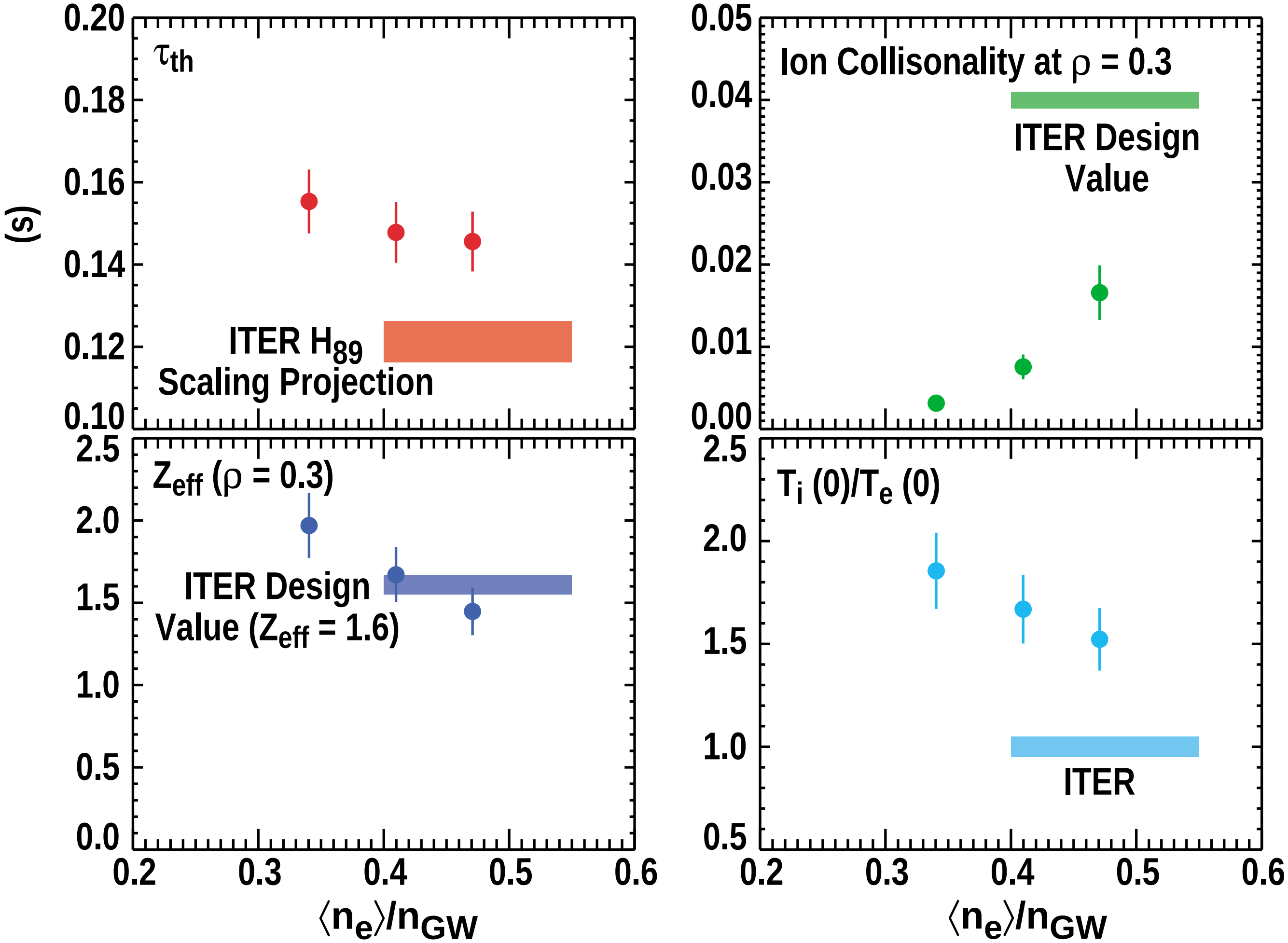
MODEST RANGE IN DENSITY DEMONSTRATED (n_e/n_{GW} ~ 0.5) WITHOUT SIGNIFICANT LOSS IN CONFINEMENT

- Z_{eff}, ion collisionality near ITER design parameters
- T_i/T_e ~ 1.5 even in highest density cases



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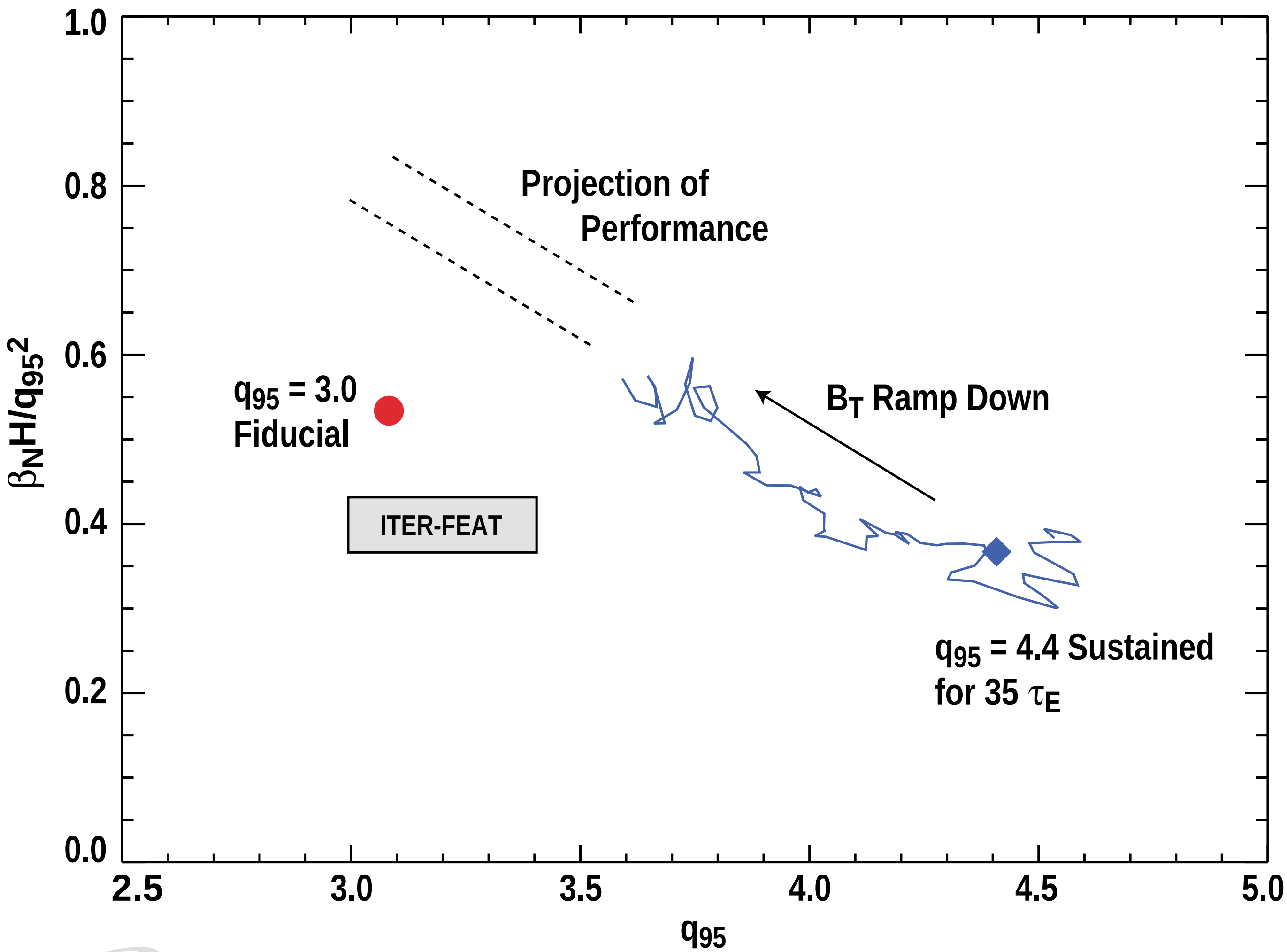
IMPROVED PERFORMANCE MAINTAINED AT $q_{95} < 4.0$

- Scan accomplished by B_T ramp down while maintaining β_p constant
- Trend projects to 50% higher $\beta_N H/q_{95}^2$ at q_{95} = 3.0 than fiducial



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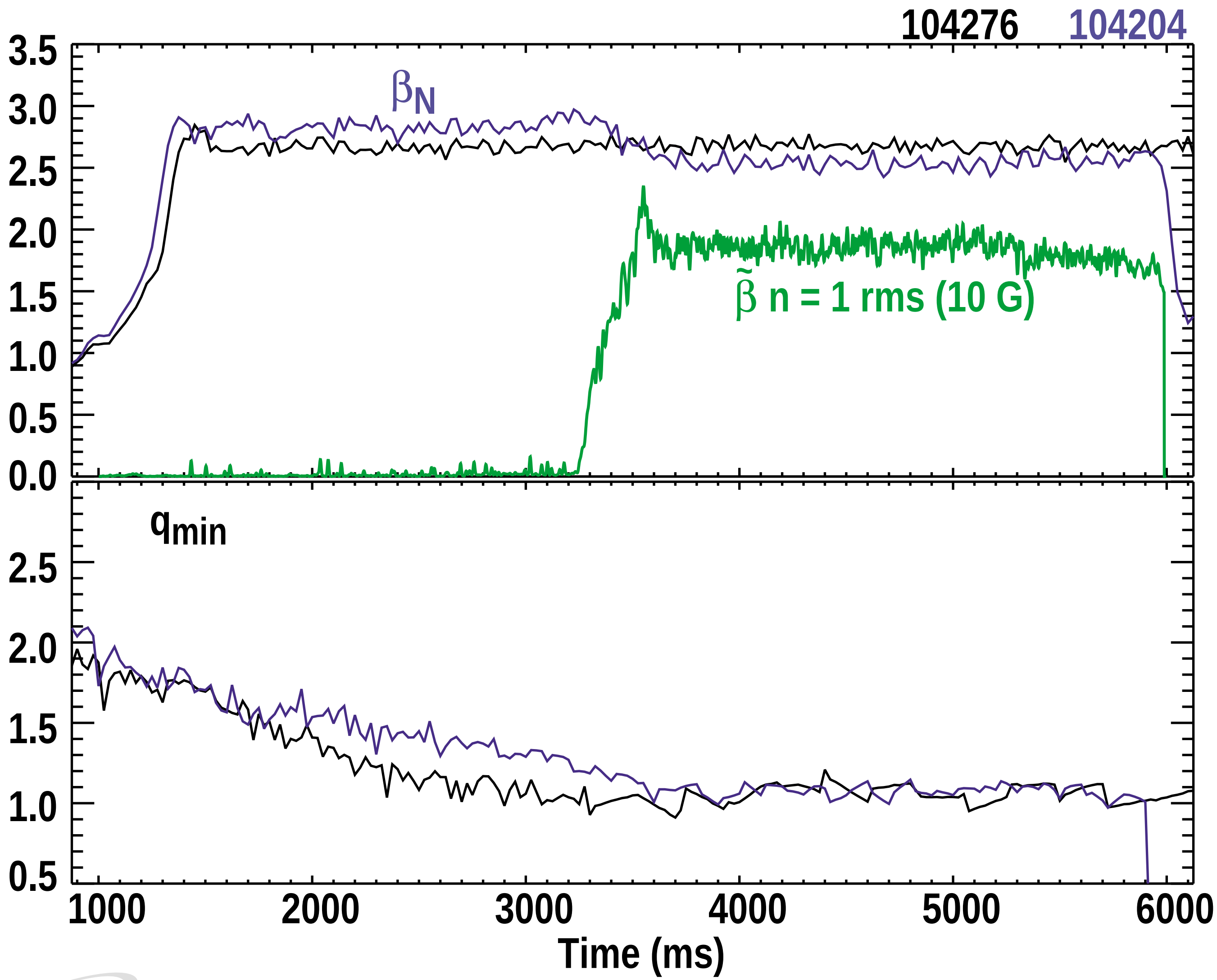
PRESENT OPERATIONAL LIMIT ON PERFORMANCE IS ONSET OF m = 2/n = 1 NTM

- Requesting higher β early almost always results in NTM at ~ 3.0 s



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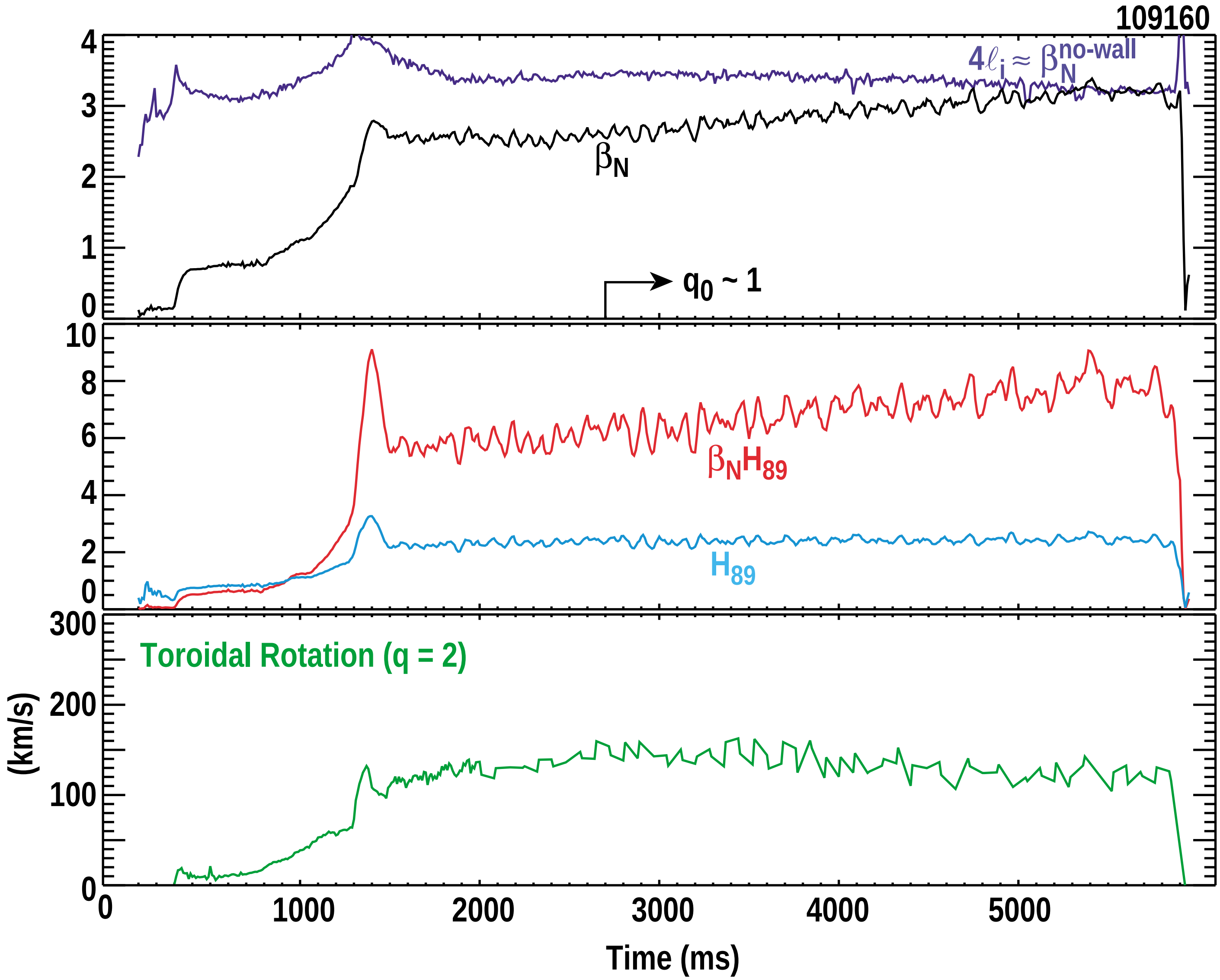
β CAN BE INCREASED TO NO-WALL β LIMIT AFTER q_0 REACHES 1 WITH NO SIGN OF CONFINEMENT DEGRADATION



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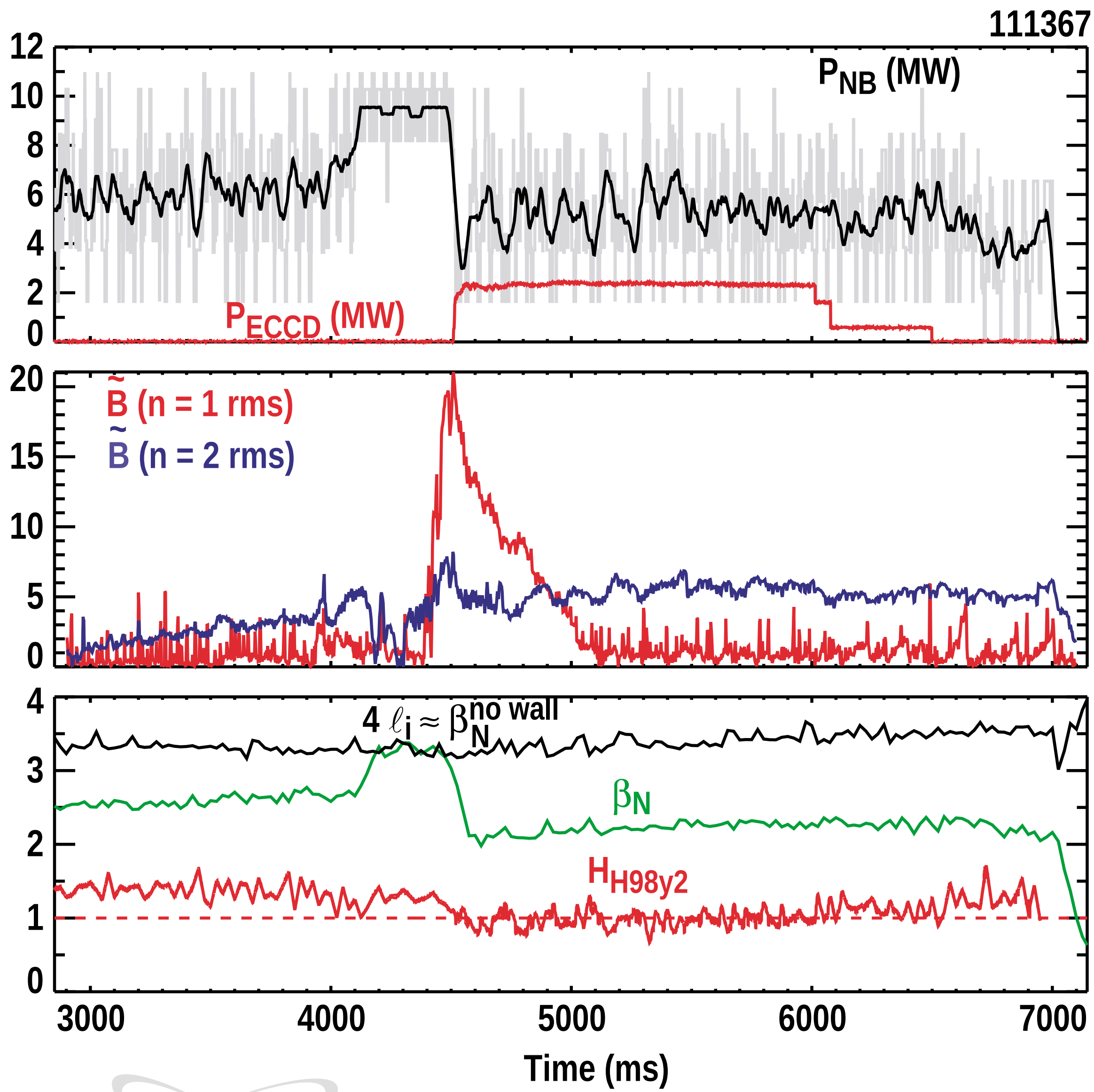
RECENT EXPERIMENTS HAVE DEMONSTRATED CAPABILITY OF STABILIZING m = 2/ n = 1 TEARING MODE VIA ECCD



- NBI power increased at 4.0 s to induce 2/1 mode
- Mode suppressed and stabilized by ECCD starting at 4.5 s
- Moderate degradation in confinement with ECCD

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SUMMARY

- Stationary discharges with $\beta_N H/q_{95}^2$ commensurate with the ITER design have been demonstrated on DII-D
  - $\beta_N H \sim 7$ for $35\tau_E$
  - $\beta_N H \sim 8.5$ for $4\tau_E$

  } at $q_{95} = 4.4$ (duration limited by hardware constraints)
- Discharges are stationary on the thermal, resistive, and wall equilibrium time scales
- Improved performance results from improved stability and transport properties
  - χ_{eff} comparable to $q_{95} = 3.0$ reference case, much lower than expected from q scaling of transport
  - Lack of sawteeth, fishbones allow access to higher β_N
- Limiting factor on performance is m = 2 / n = 1 NTM
  - $\beta_N \sim \beta_N^{no\text{-}wall}$ have been obtained without 2/1 NTM
  - Recent experiments indicate ECCD can be used to stabilize 2/1 NTM

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