LONG-PULSE HIGH-PERFORMANCE DISCHARGES IN THE DIII–D TOKAMAK

by
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in collaboration with

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DIII–D ADVANCED TOKAMAK GOALS

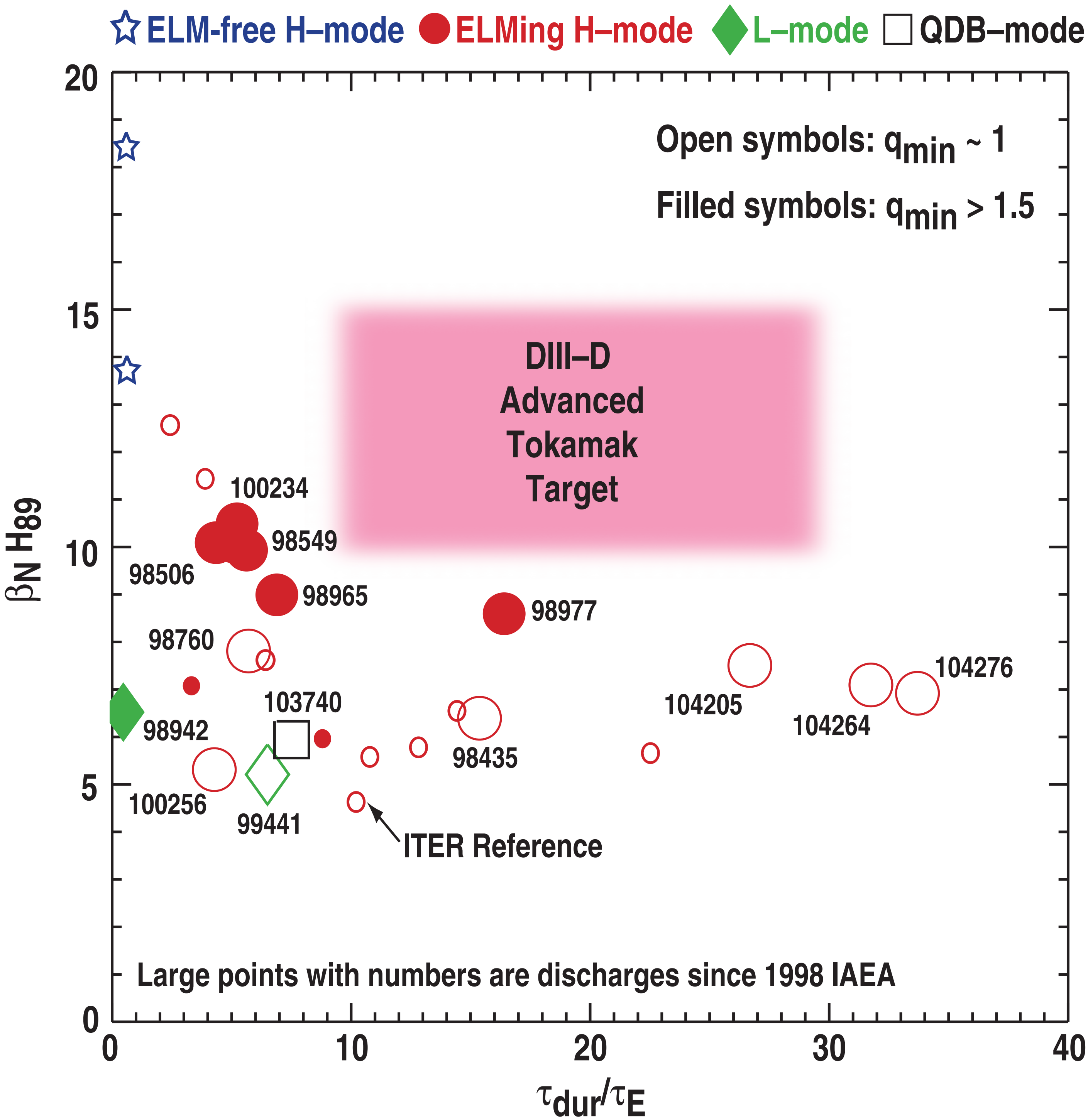
- The DIII–D team is pursuing research to establish the basis for a high fusion gain steady-state tokamak. This requires simultaneously:
  - High fusion power $\propto \beta$
  - High bootstrap fraction $\propto \beta_p$
  - High fusion gain $\propto \beta \tau_E$

- To achieve this on DIII–D at reactor-relevant parameters will require several control tools — density control, pressure control, off-axis non-inductive current drive, and to reach the ultimate performance limits, direct control of MHD instabilities

OUTLINE — HIGHLIGHTS

- Progress in long-pulse advanced tokamak development since the 1998 IAEA meeting
  - $\beta_N H_{89} \sim 10$ for 5 τ_E
  - $\beta_N H_{89} \sim 9$ for 16 τ_E
- Stability
  - Resistive wall modes are the β limiting instability in most discharges with $q_{min} \geq 1.5$
  - Neoclassical tearing modes limit β in discharges with $q_{min} \sim 1$ and sometimes limit the duration of higher q_{min} discharges
- Confinement
  - Local heat diffusivity on high q_{min} plasmas similar to that found on conventional sawtoothing H–mode plasmas
  - Electron and ion temperature profiles are well simulated by an ITG model including $E \times B$ shear
- Current evolution
  - Non-inductive current fraction is 60%–75% in high q_{min} discharges
  - Remaining inductive current is peaked off-axis
- Control tools
  - Density and β control demonstrated by operating at $\beta_N H_{89} \sim 7$ for 6.3 s with β at >90% of the 2/1 tearing mode limit

SIGNIFICANT PROGRESS HAS BEEN MADE IN LONG-PULSE HIGH PERFORMANCE



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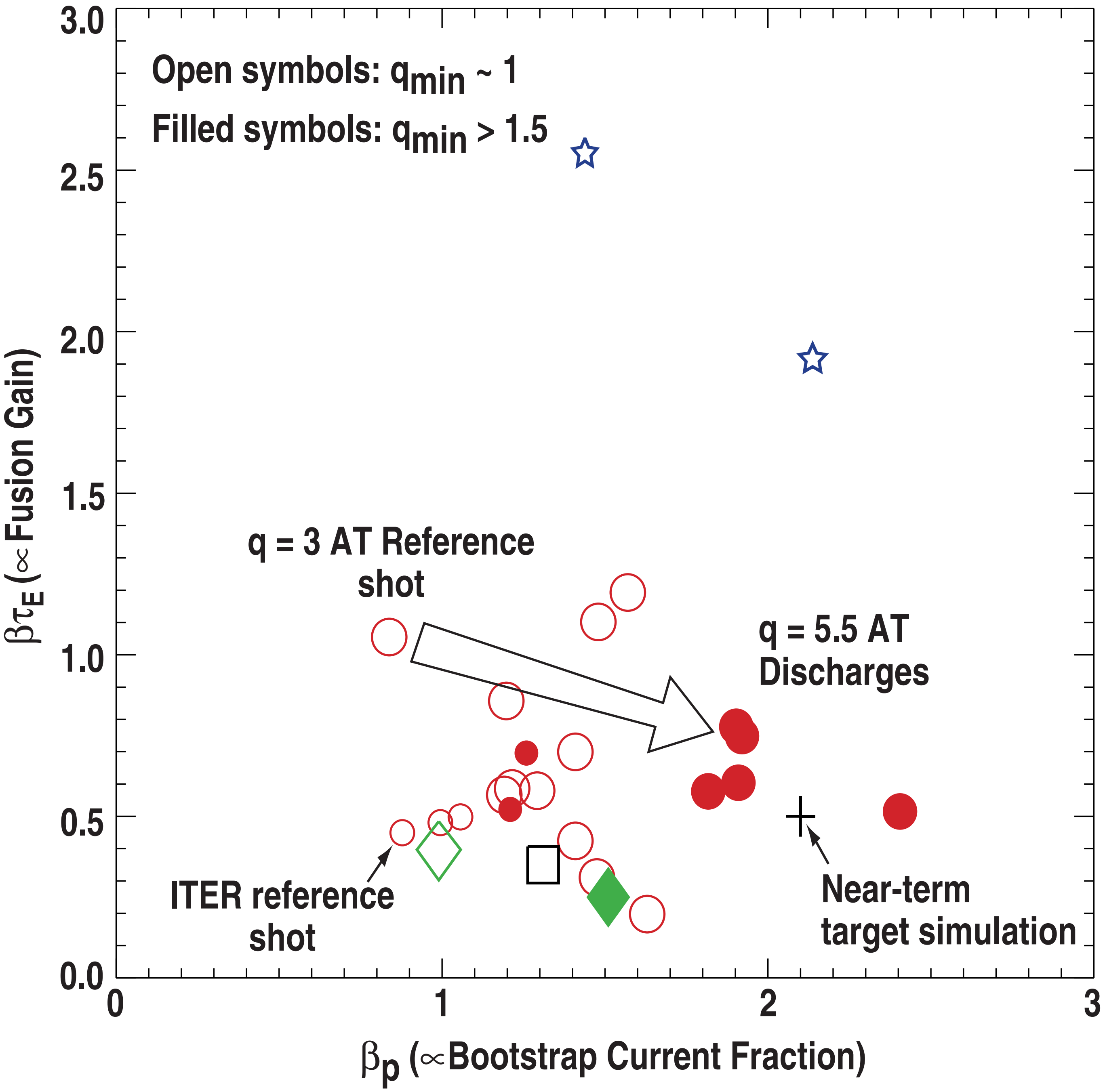
ADVANCED TOKAMAK DISCHARGES SEEK TO MAXIMIZE FUSION GAIN AND BOOTSTRAP FRACTION SIMULTANEOUSLY



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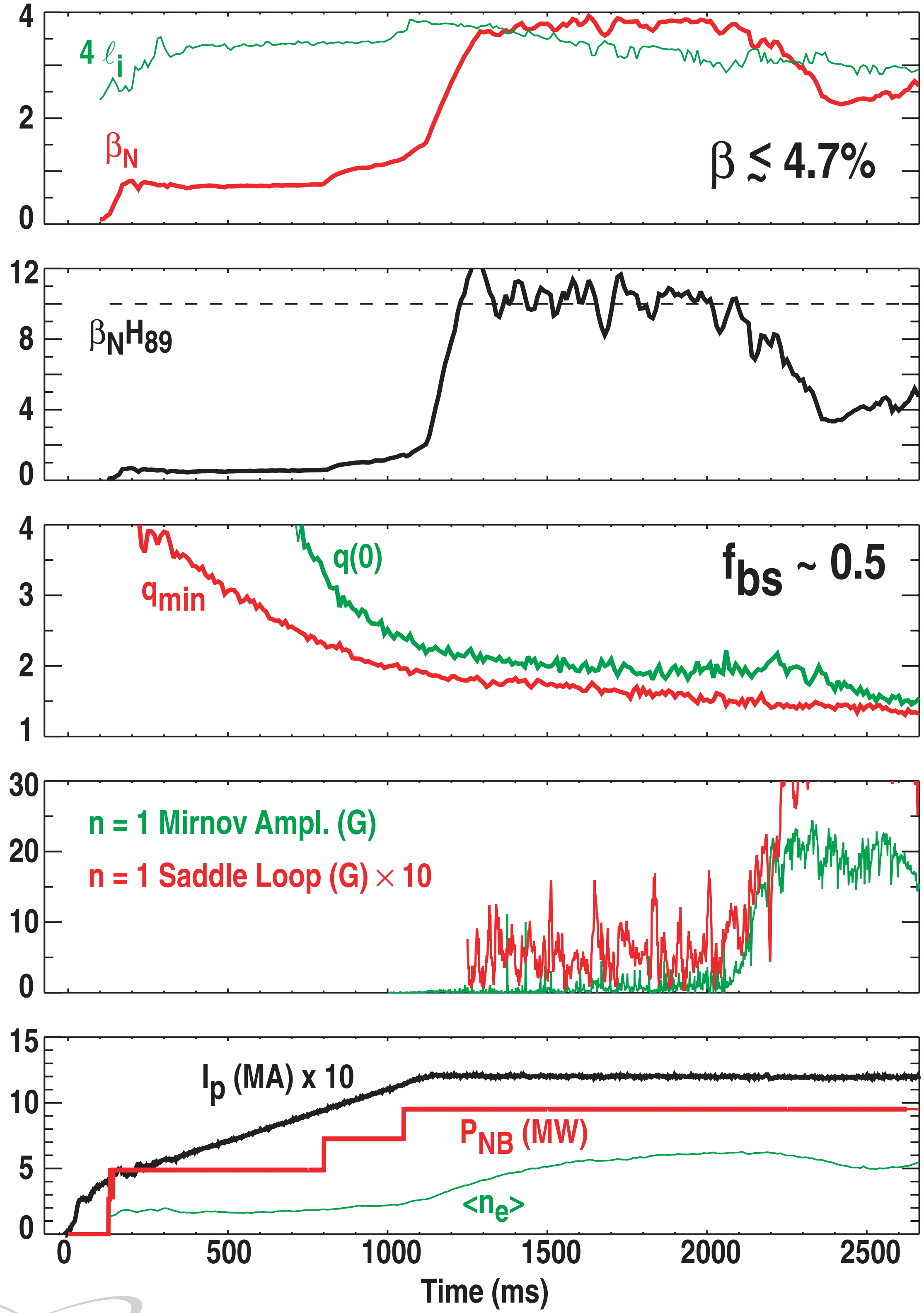
HIGH NORMALIZED PERFORMANCE (~10) SUSTAINED FOR 5 τ_E



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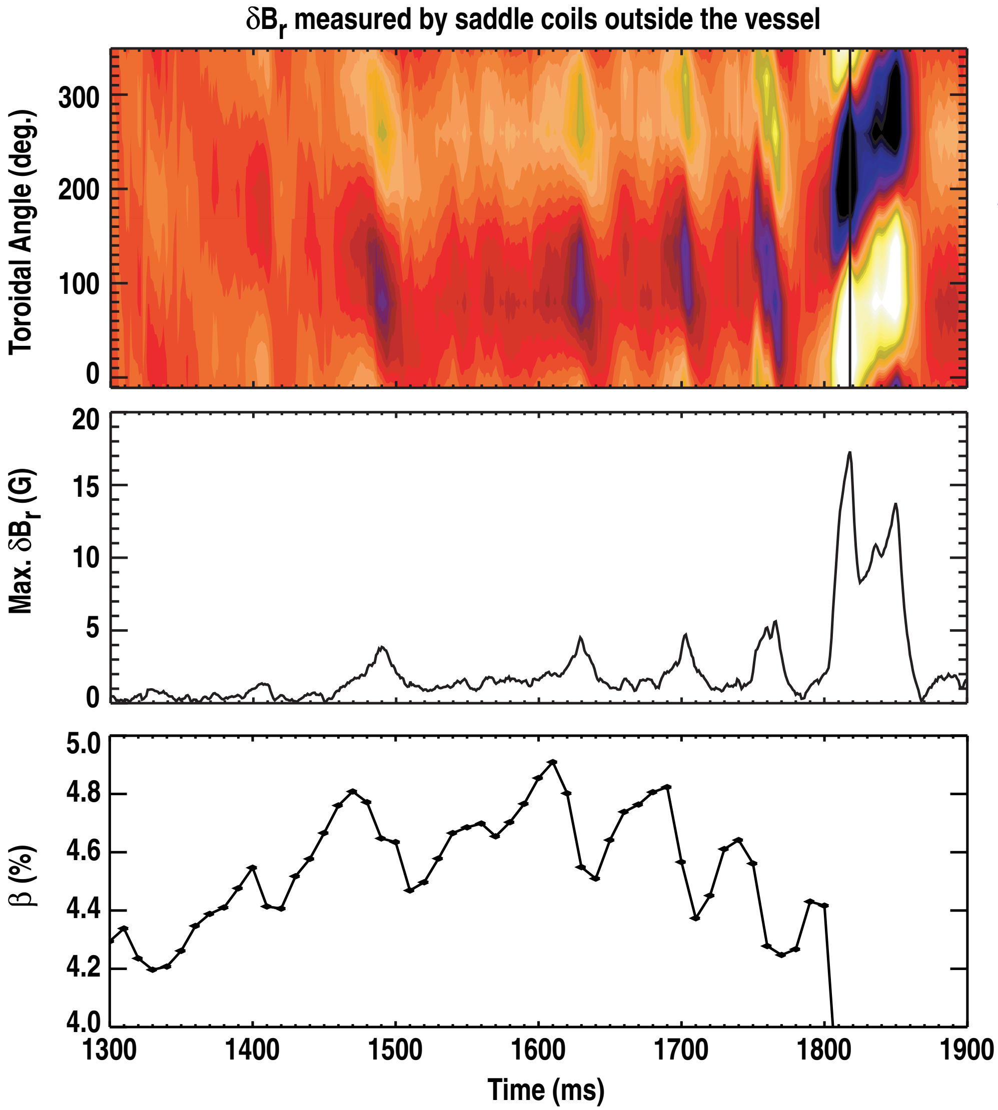
β IS LIMITED IN MAGNITUDE BY RESISTIVE WALL MODES



Limiting modes have the characteristics of resistive wall modes:

- Onset is at or above the no-wall ideal limit ($\beta_N \gtrsim 4\ell_i$)
- Growth rate consistent with characteristic wall time
- Real frequency (<100 Hz) consistent with wall time, not fluid rotation

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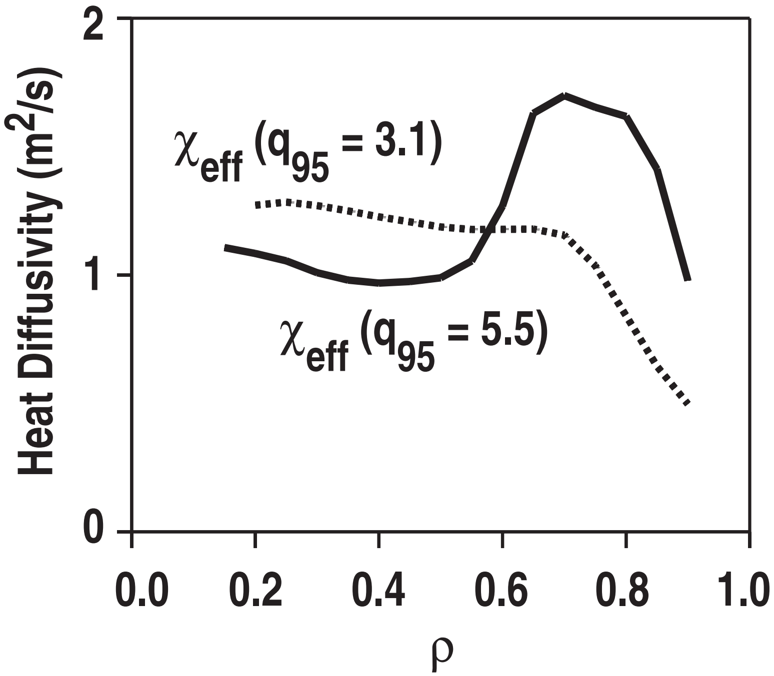
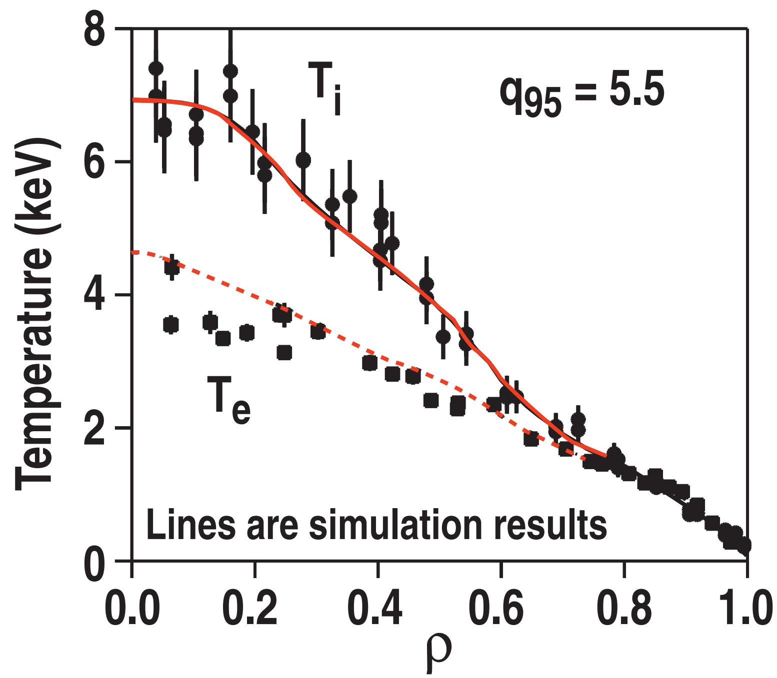
CONFINEMENT REMAINS GOOD AT HIGHER q

- Neoclassical theory and empirical measurements predict q^2 scaling
- One-fluid diffusivity is nearly the same in low q and high q discharges



- Drift-wave model simulation gives good agreement with measured profiles
- Model contains ITG, TEM, and ETG with effects of E×B shear



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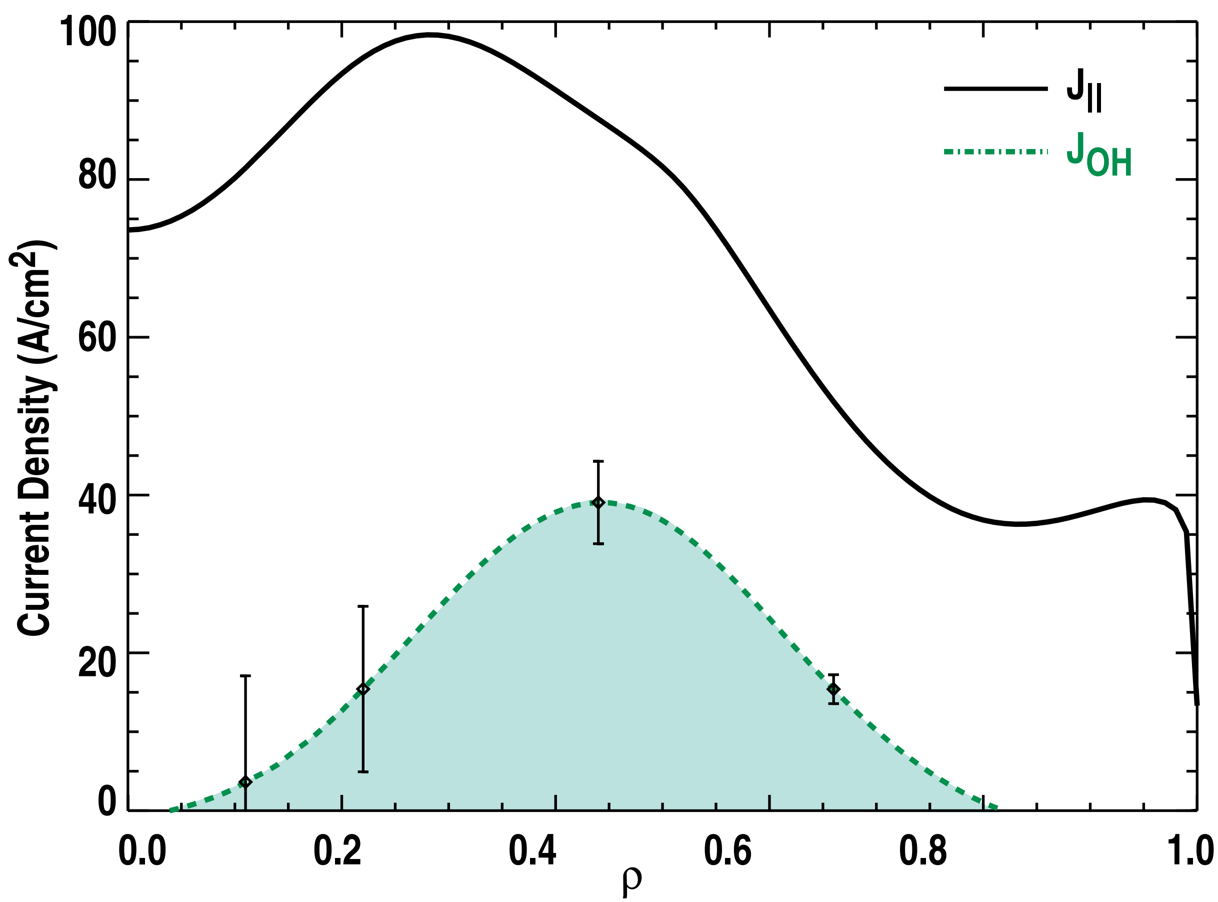
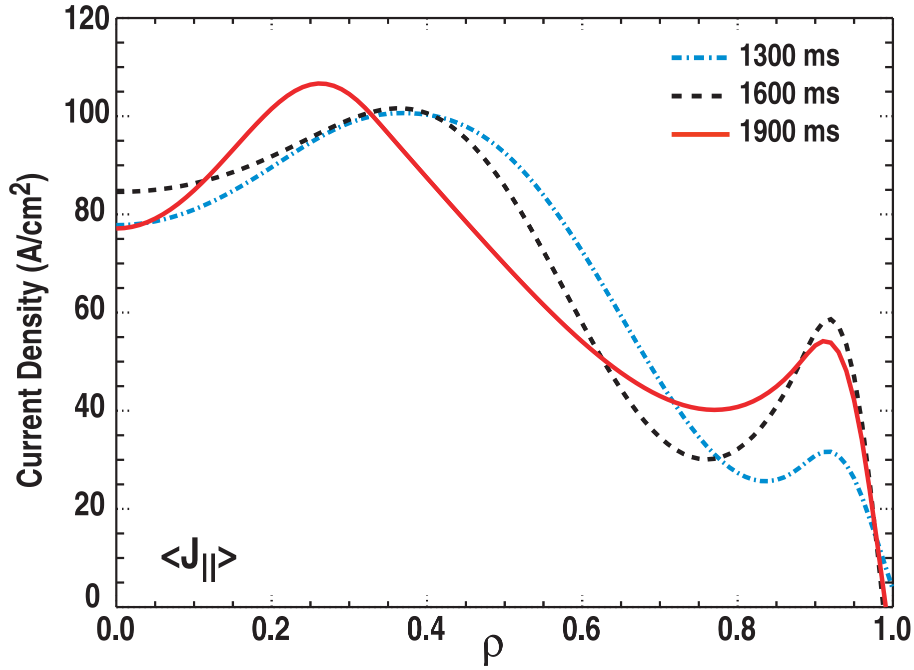
NON-INDUCTIVE CURRENT NEEDS TO BE SUPPLIED AT THE HALF RADIUS FOR STEADY STATE



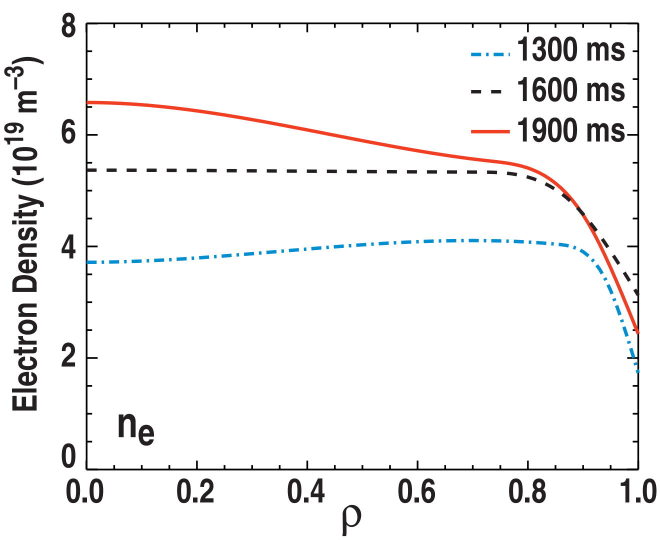
- $E_{||}$ measured; with assumption of neoclassical conductivity, gives J_{OH}
- Edge current drive consistent with bootstrap current calculations
- Central current drive consistent with bootstrap and neutral beam current drive calculations
- ECCD at the half radius will be required for steady-state

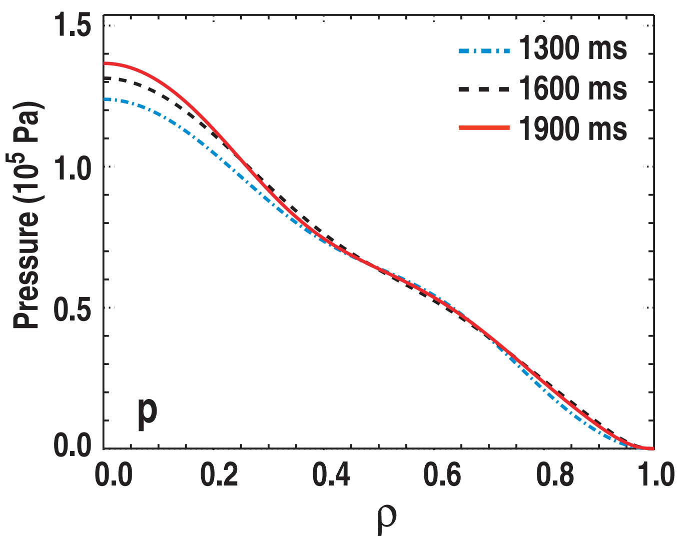
FULLY NON-INDUCTIVE OPERATION REQUIRES DENSITY CONTROL AND OFF-AXIS CURRENT DRIVE

- Current evolves to unstable profile at constant pressure



- Density rises steadily at constant pressure without pumping





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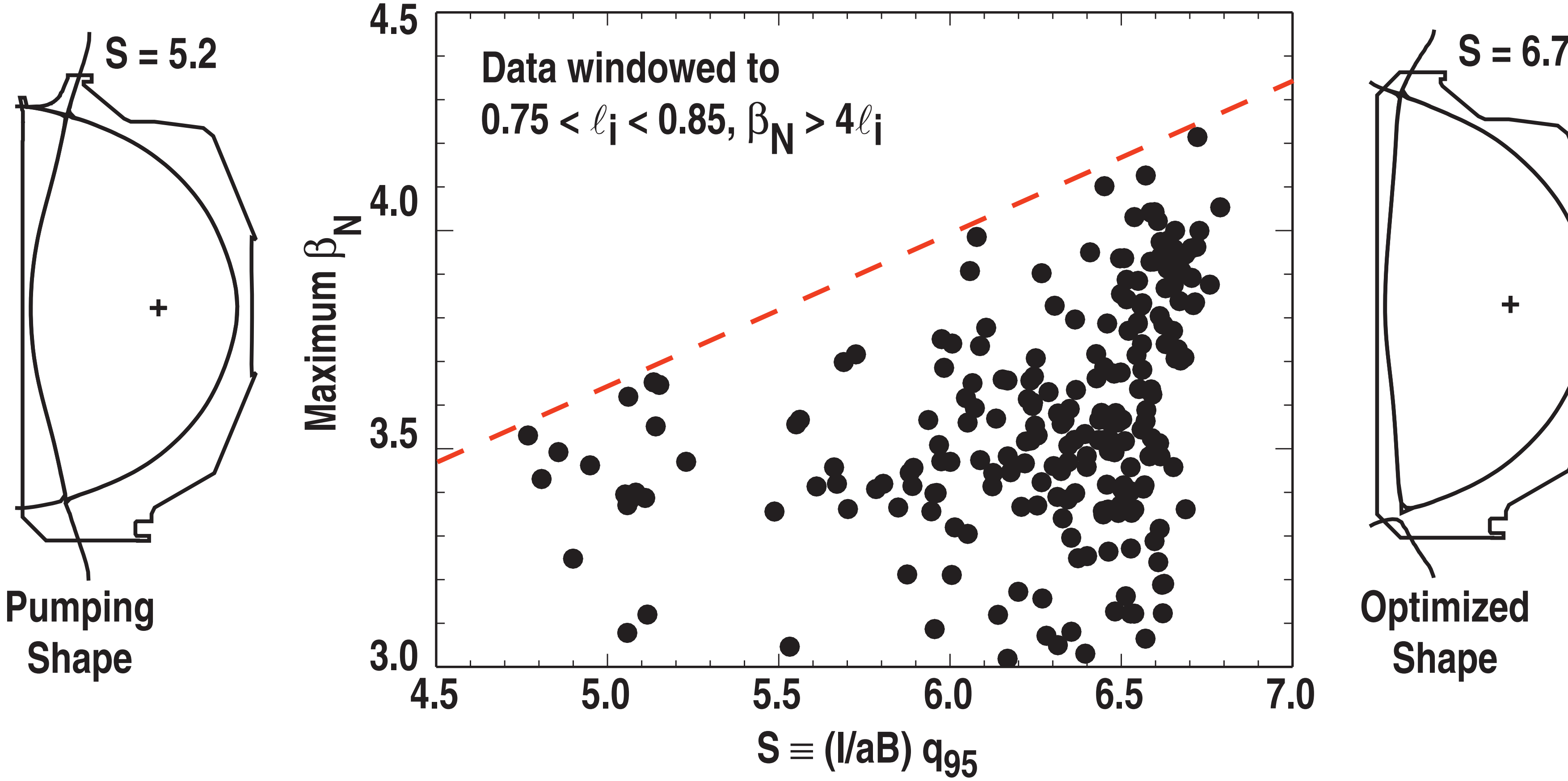
SHAPE STRONGLY AFFECTS STABILITY LIMIT



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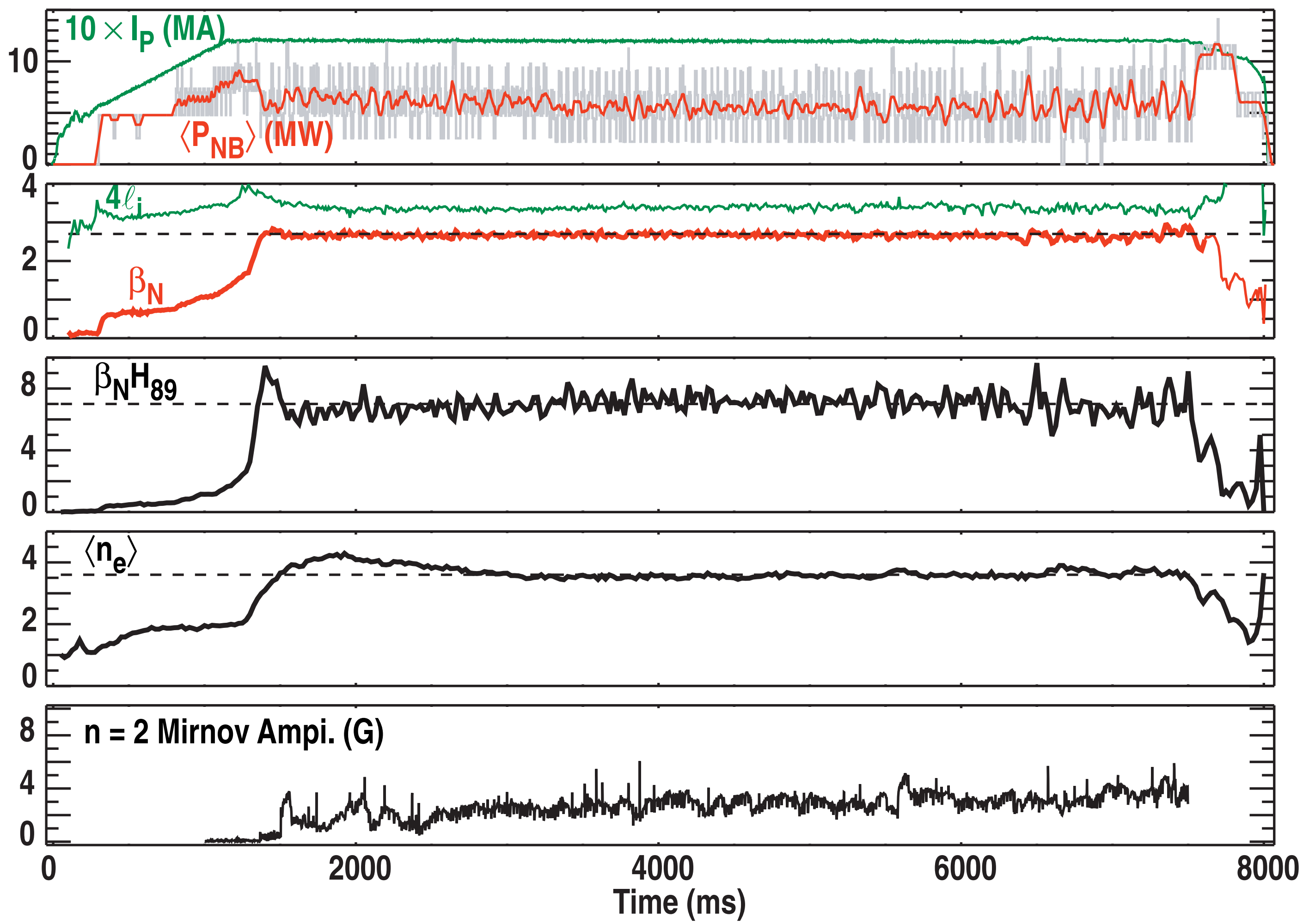
DENSITY AND β FEEDBACK CONTROL DEMONSTRATED IN ELMING H–MODE



- β control by real-time control of NB power
- β >90% of 2/1 tearing mode limit
- $\beta_N H_{89}$ ~7 for $34\tau_E$, 3.4 τ_R
- Density regulation by pumping and gas puffing
- q_{min} >1

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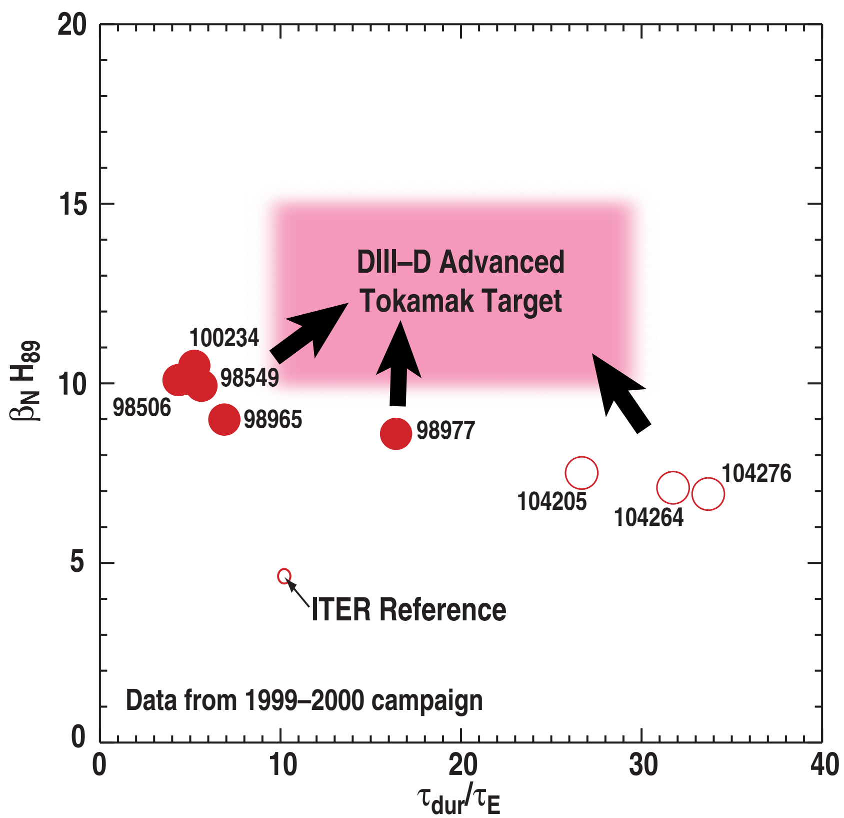
FUTURE PROSPECTS



- To extend the duration of present high performance discharges and reach fully non-inductive operation requires:
  - Understanding stability dependence on shape and q Turnbull TH3/6
  - Density control
  - Current profile of sustainment by off-axis ECCD Prater EX8/1
- To reach higher levels of performance requires:
  - Active control of resistive wall modes

    Garofalo EXP3/01

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