Progress Towards Long-Pulse, High-Performance Advanced Tokamak Plasmas on the DIII–D Tokamak

by
M.R. Wade*

*Oak Ridge National Laboratory

Presented at
the American Physical Society
Division of Plasma Physics Meeting
Quebec City, Canada

October 23–27, 2000

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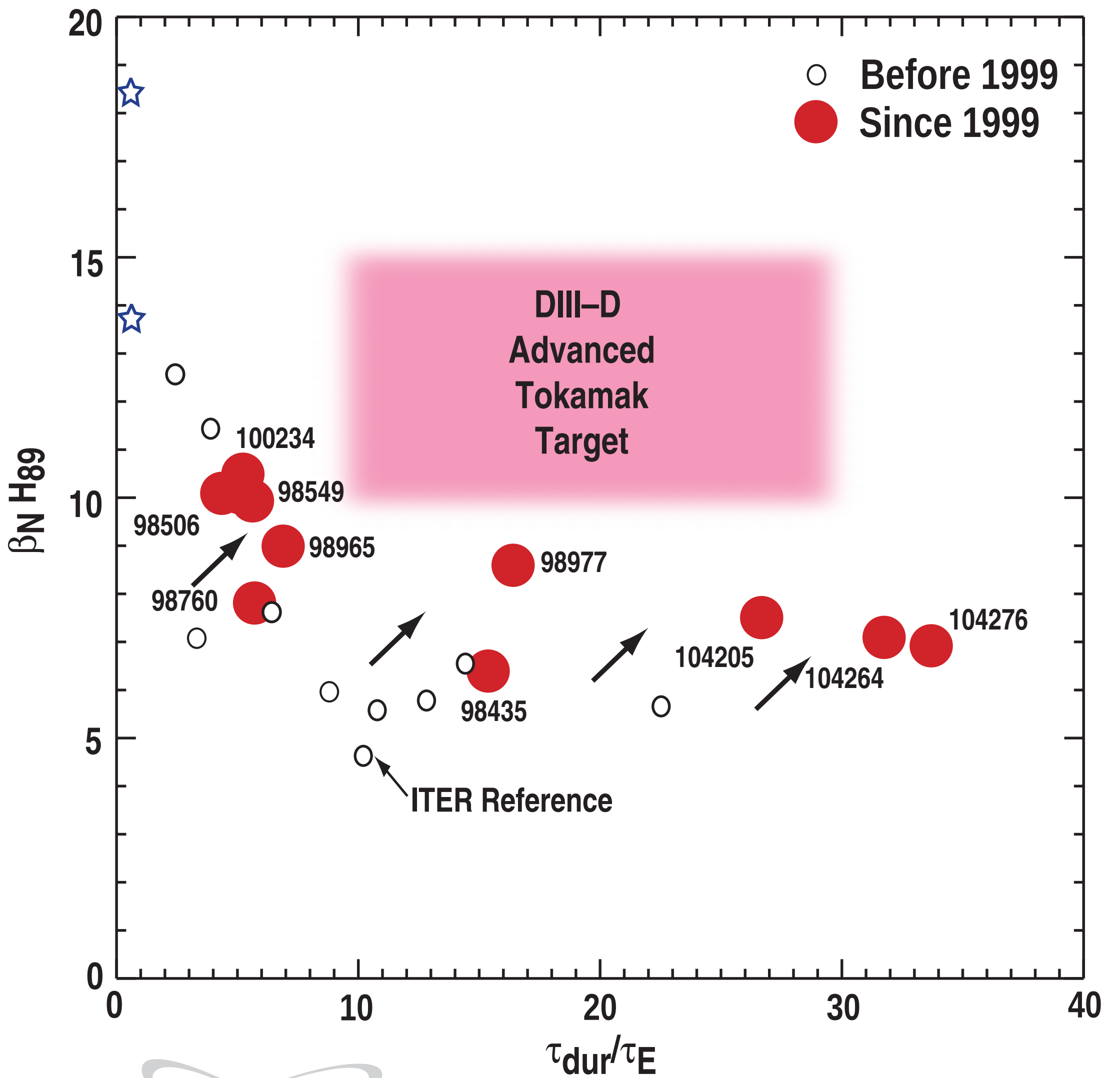

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THE GOAL OF THE DIII–D ADVANCED TOKAMAK PROGRAM IS TO DEVELOP THE BASIS FOR A STEADY-STATE, HIGH PERFOMANCE TOKAMAK

- Simultaneously require:
  - — High fusion power density $\Rightarrow$ High plasma pressure (high β)
  - — High fusion gain $\Rightarrow$ Good energy confinement (high τ_E)
  - — Non-inductive current sustainment $\Rightarrow$ High bootstrap fraction (high β_P)

- Gain and bootstrap current have conflicting scalings
  - — Fusion gain: $\beta\tau_E \propto (\beta_N/q)\ (H_{89}/q^{\alpha})$
  - — Bootstrap current: $f_{BS} \propto \beta_p \propto q\ \beta_N$

$\Rightarrow$ Self-consistent scenarios require β_N and H_{89} above conventional tokamak values

Definitions: $\beta_N = \beta/(I/aB)$ $\quad H_{89} = \tau_E / \tau_{E,ITER89P}$

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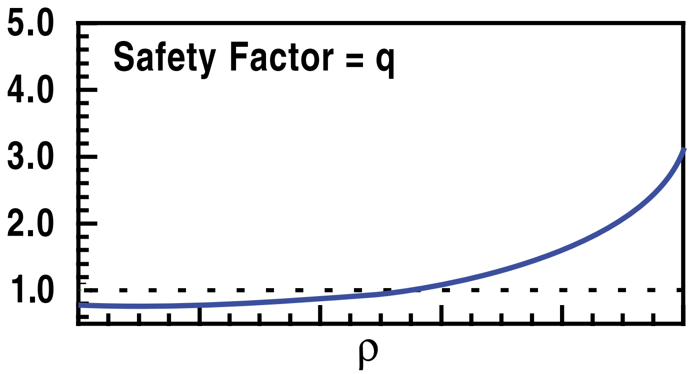
COMPARISON OF CONVENTIONAL AND ADVANCED TOKAMAK FEATURES

Conventional



Features of Monotonic q Profile:

High gain

Moderate turbulence

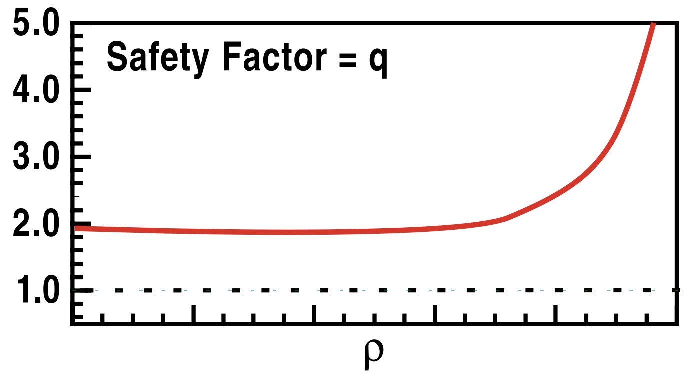
Resistive modes limit β

$f_{BS} < 30$ %; $H_{89P} < 2.0$; $\beta_N < 2.5$

↓

Pulsed

Advanced



Features of High q_{min} and Low Shear:

High f_{BS}

Reduced turbulence

Ideal modes limit β

$f_{BS} > 50$ %; $H_{89P} > 2.5$; $\beta_N > 3.5$

↓

Potential for Steady-State

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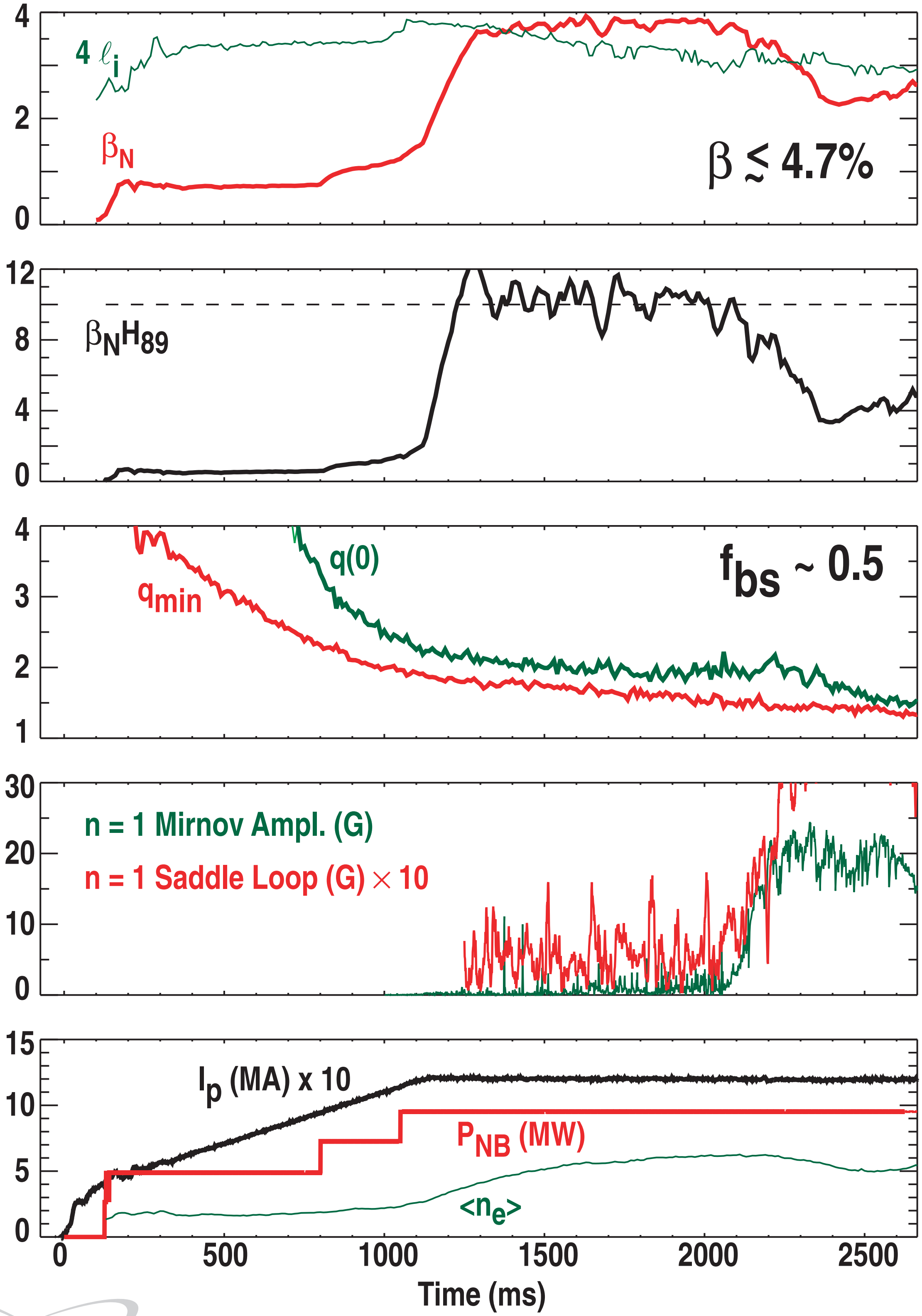
HIGH NORMALIZED PERFORMANCE (~10) SUSTAINED FOR 5 τ_E



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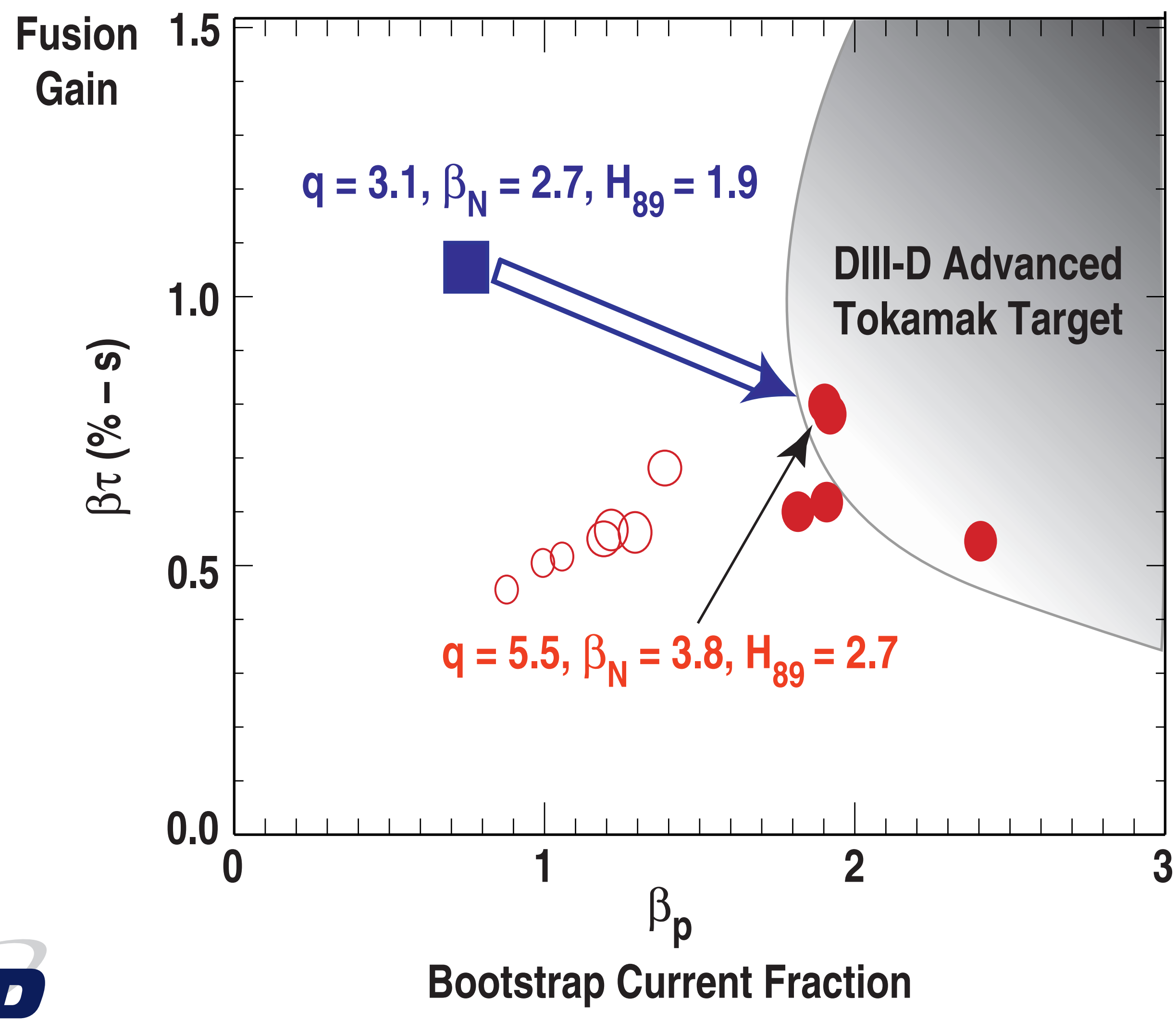
POTENTIAL FOR STEADY-STATE OPERATION IS ACHIEVED FOR MODERATE REDUCTION IN FUSION GAIN



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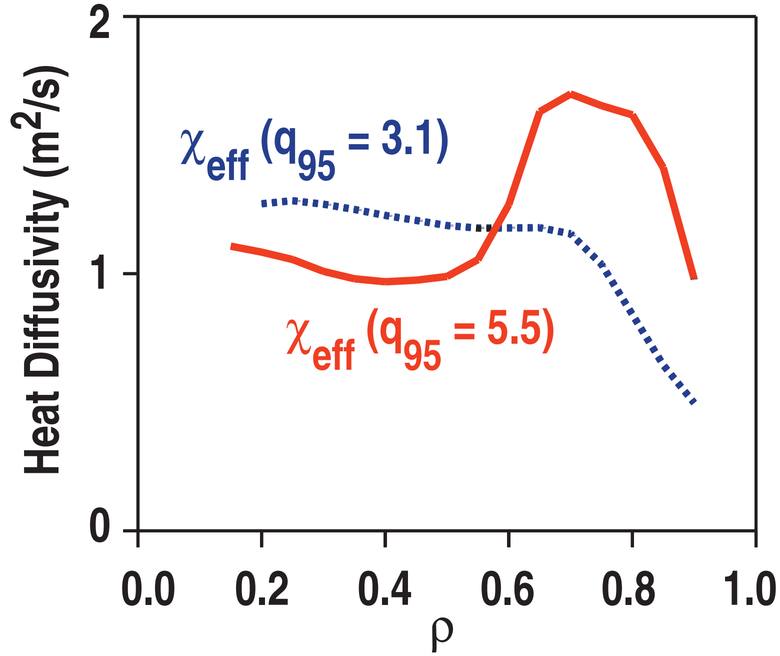
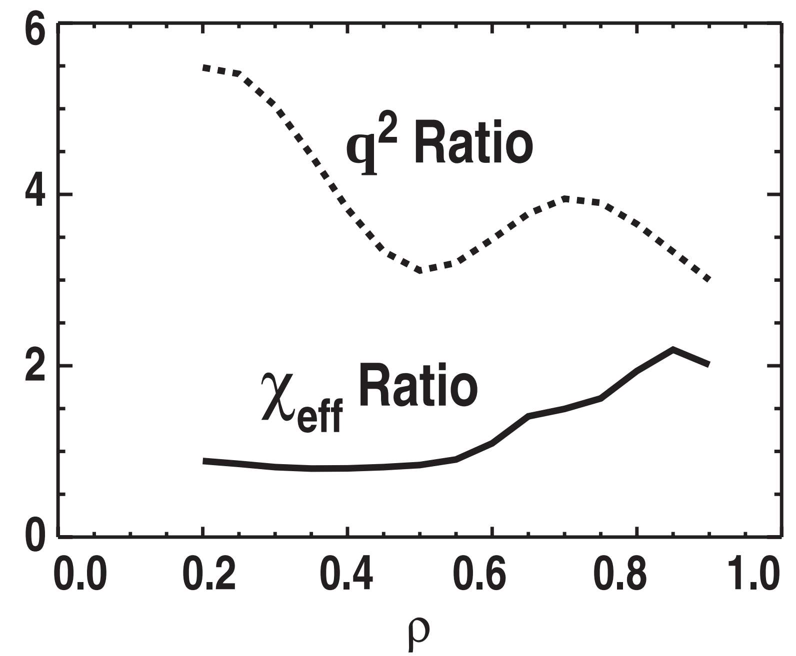
ENERGY TRANSPORT IS NOT SUBSTANTIALLY ALTERED BY THE CHANGE IN q PROFILE

- Neoclassical and empirical scalings predict $\chi \propto q^2$





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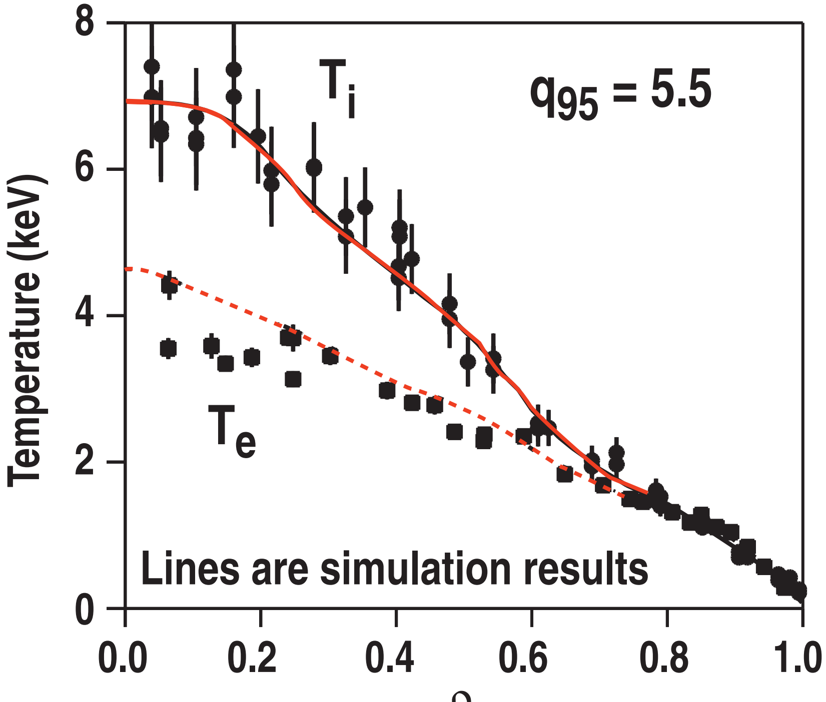
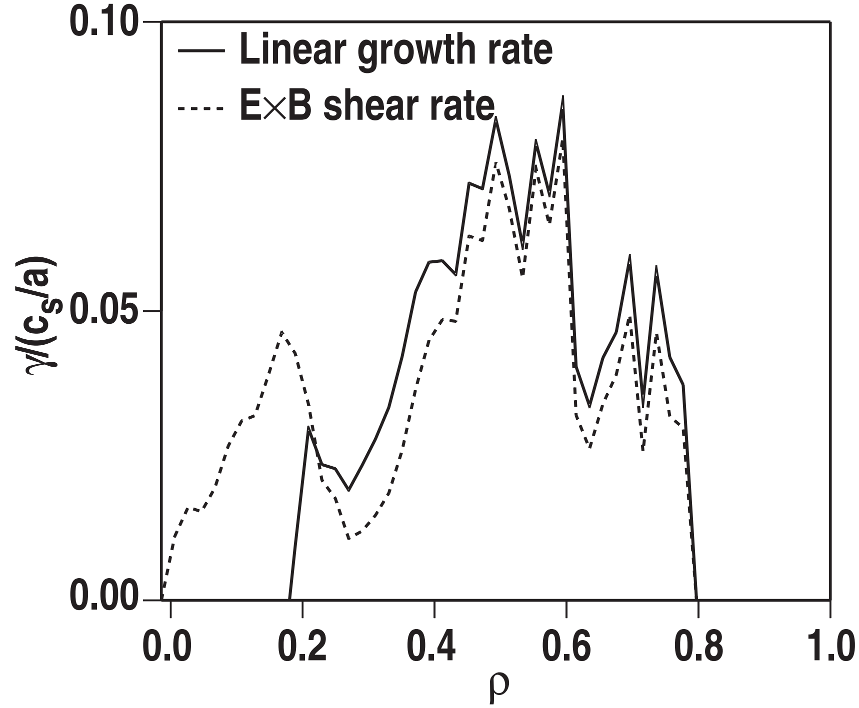
IMPROVED CONFINEMENT IS CONSISTENT WITH DRIFT-WAVE SIMULATION WITH ExB SHEAR

- GLF23 model* contains ITG, TEM, and ETG with effects of E×B shear
- Self-consistent simulation shows reduction but not suppression of turbulence, consistent with measured $\chi_i > \chi_{i,\,neo}$





*Waltz et al, Phys. Plasmas 5 1695 (1998)

Politzer GP1.114

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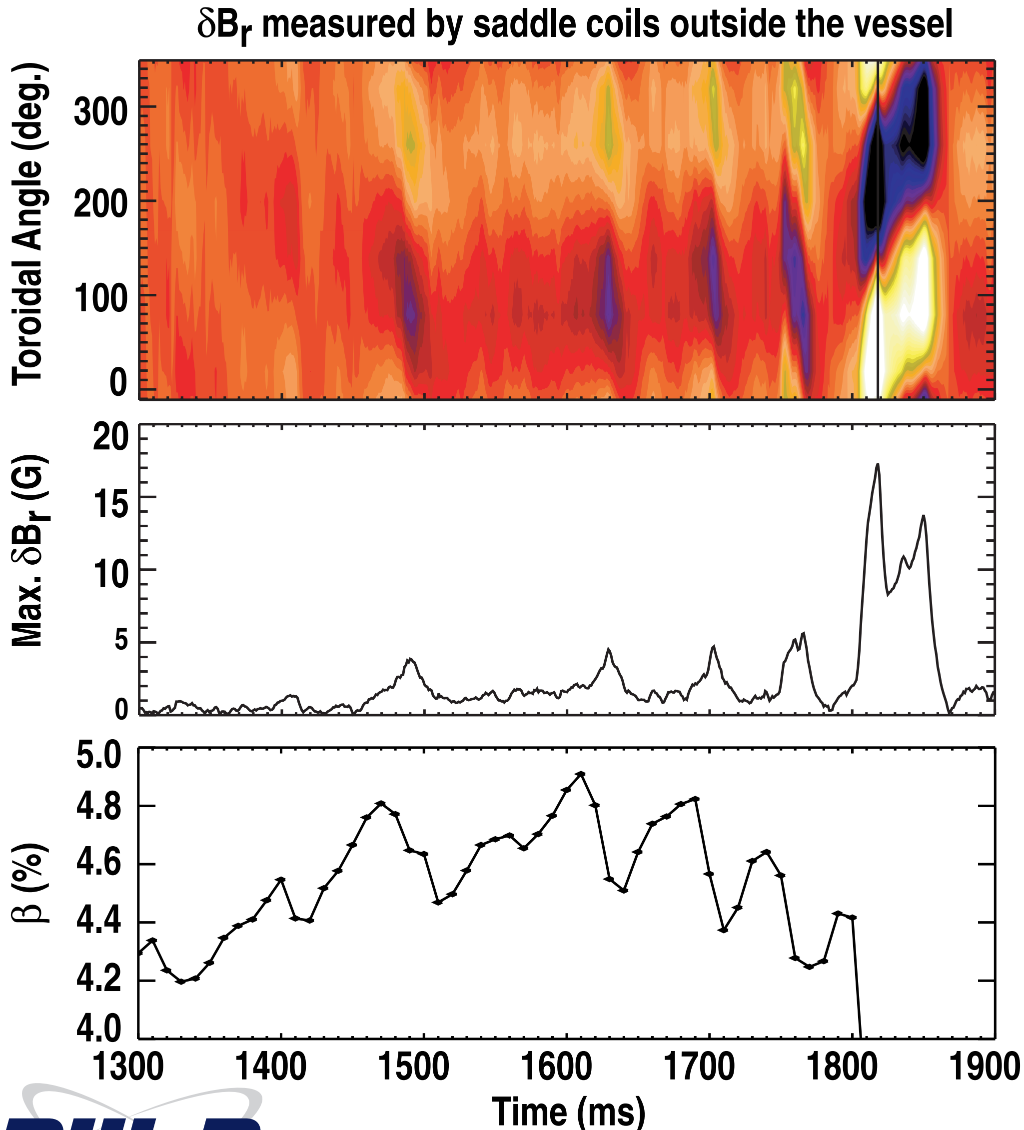
MAXIMUM β IS LIMITED BY RESISTIVE WALL MODES



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
- Proof of principle experiments on feedback control of the resistive wall mode indicate the possibility of raising the β limit

See M. Okabayashi GI1.5
Garofalo M01.004

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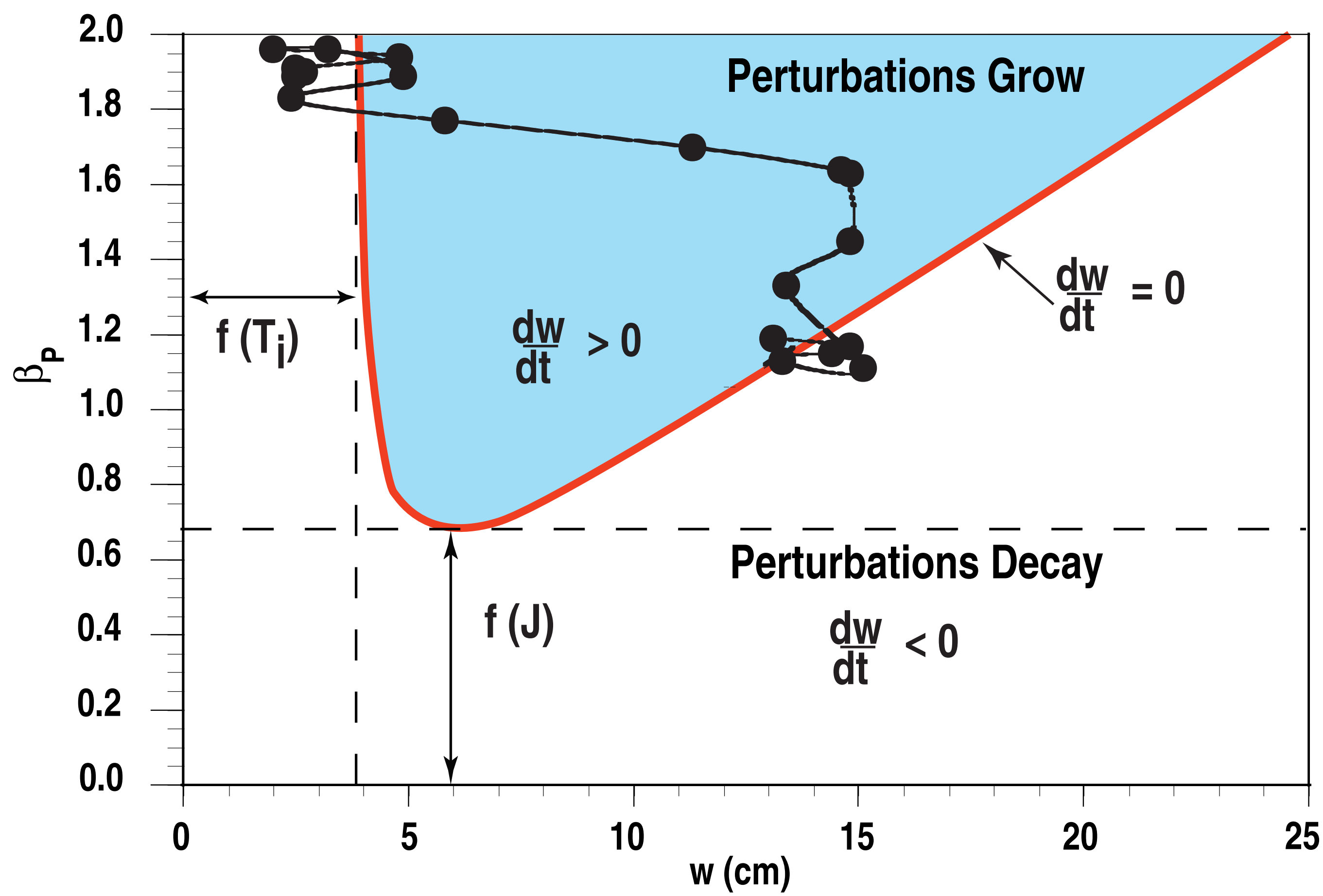
TEARING MODE BEHAVIOR AGREES WITH NEOCLASSICAL TEARING MODE MODEL



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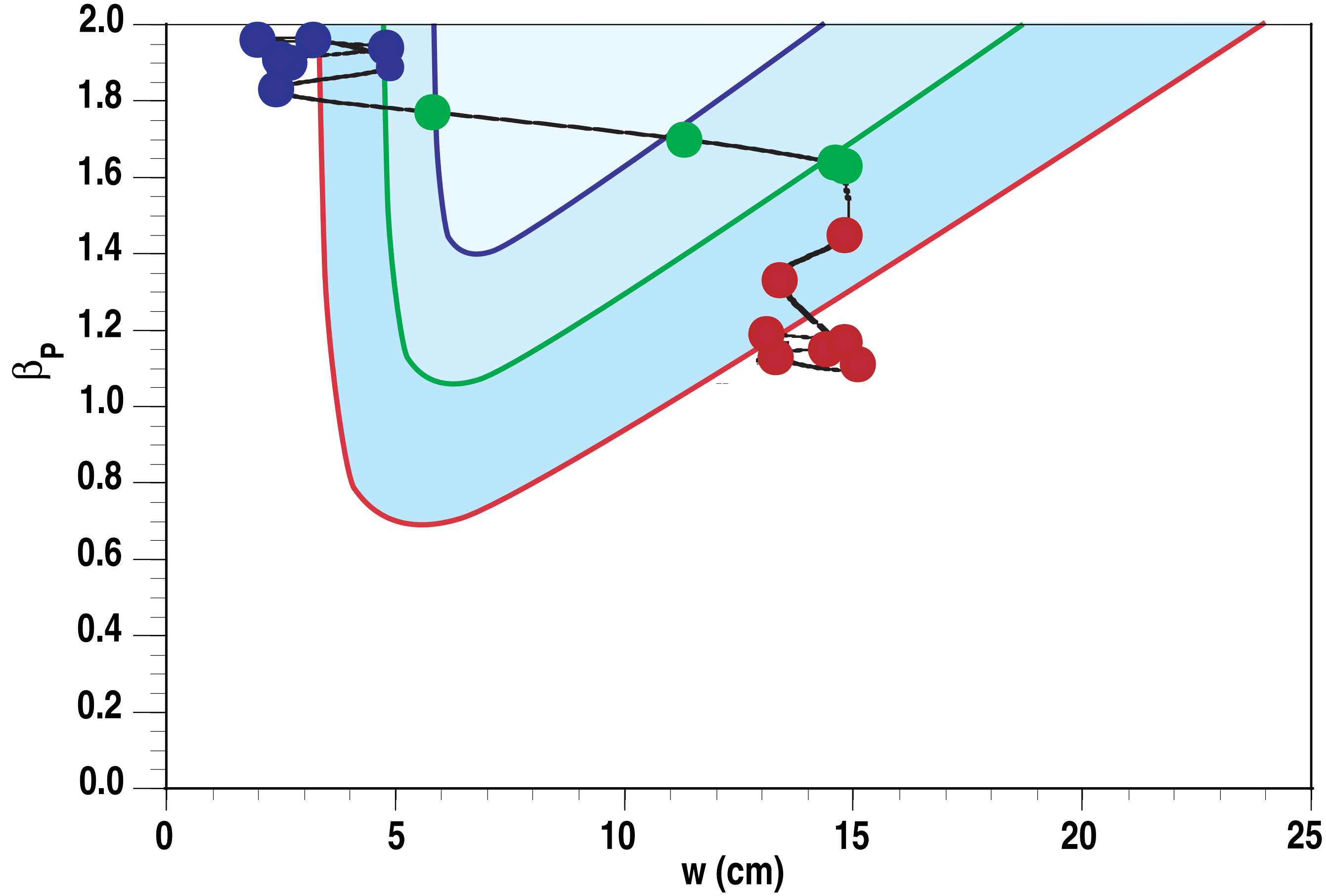
TEARING INSTABILITY MAY OCCUR DUE TO LACK OF CURRENT SUSTAINMENT AND DENSITY CONTROL



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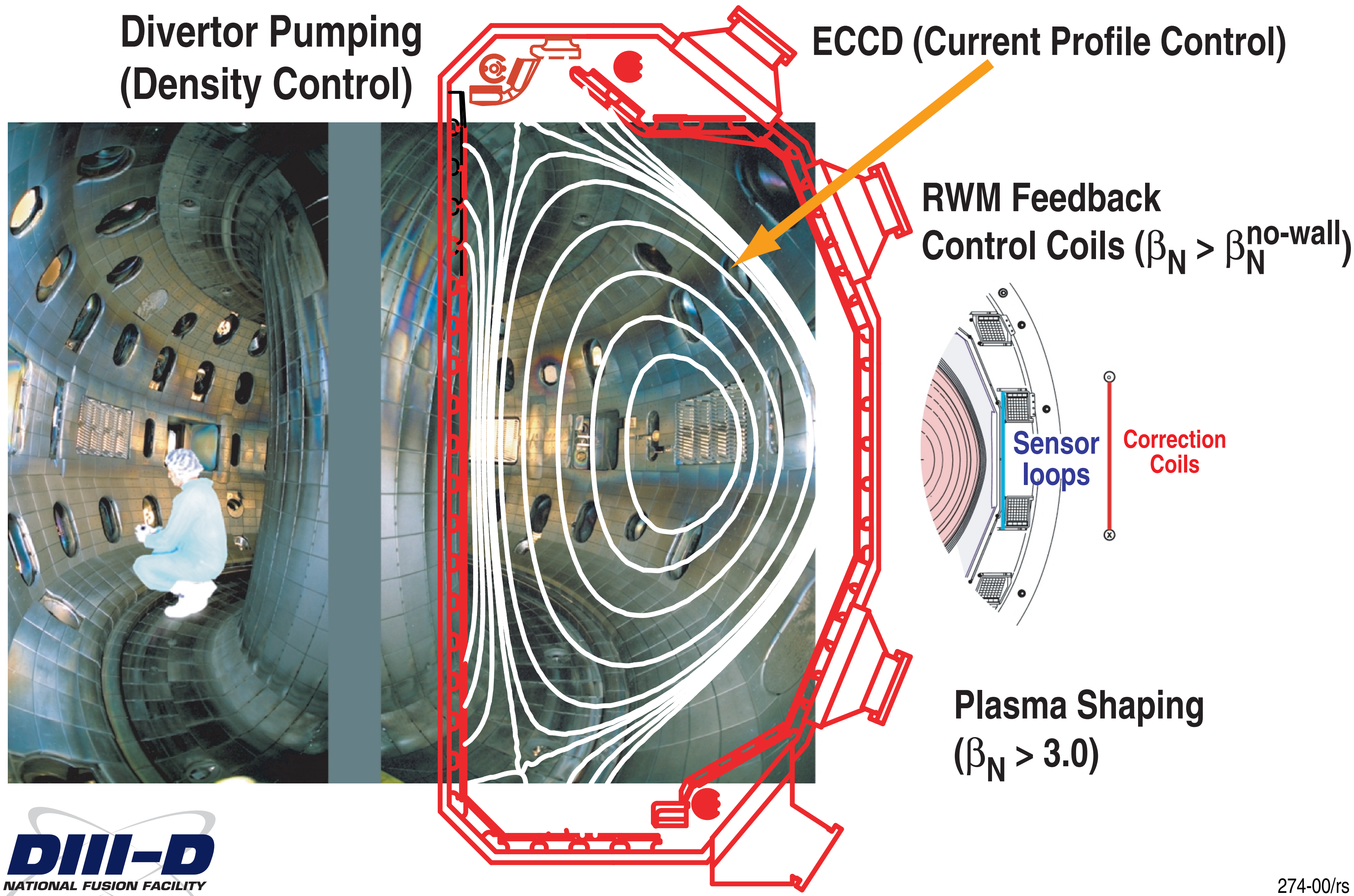
DEVELOPMENT OF CONTROL TOOLS IS NECESSARY TO EXPLOIT THE PHYSICS OF ADVANCED TOKAMAKS



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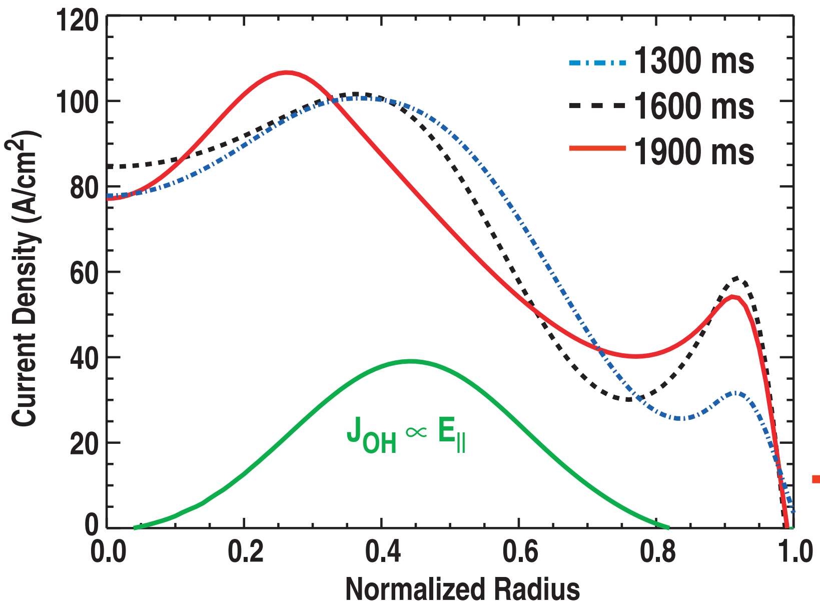
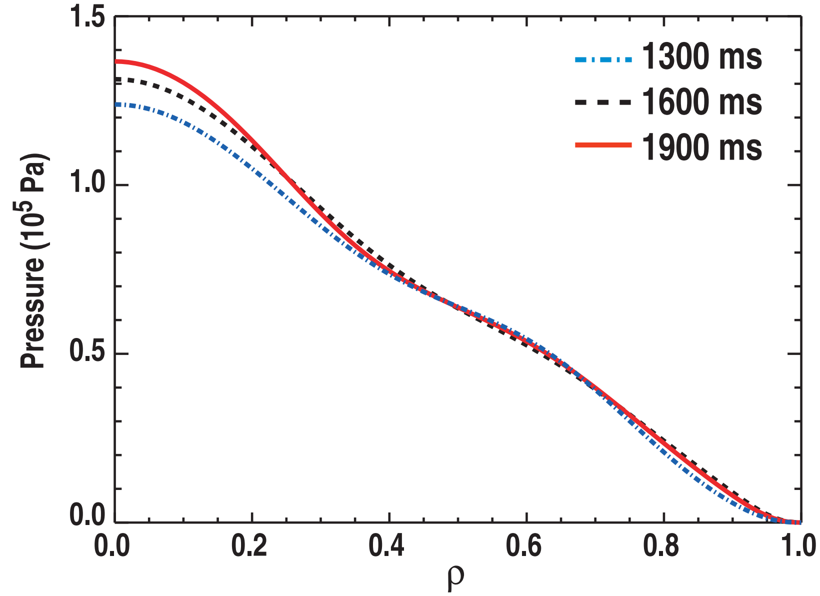
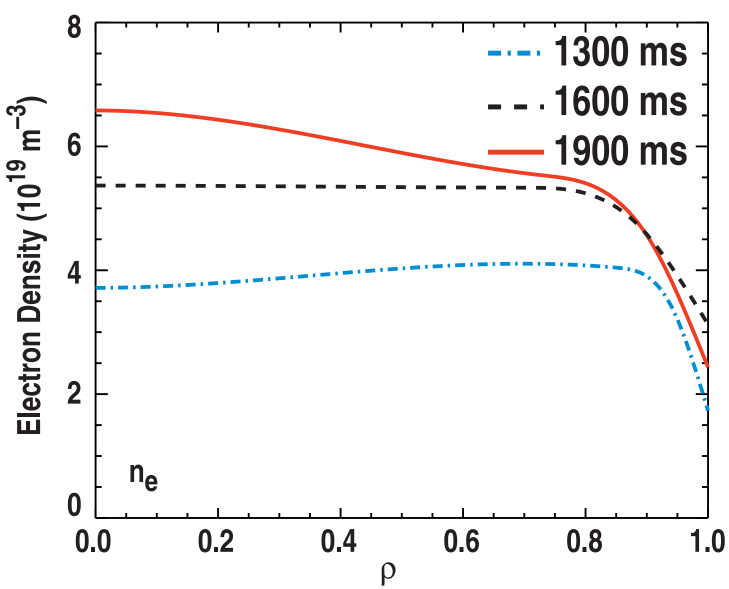
CURRENT PROFILE EVOLVES THROUGHOUT THE HIGH PERFORMANCE PHASE AT CONSTANT PRESSURE



Off-axis ECCD Required





⟹ Density control is required

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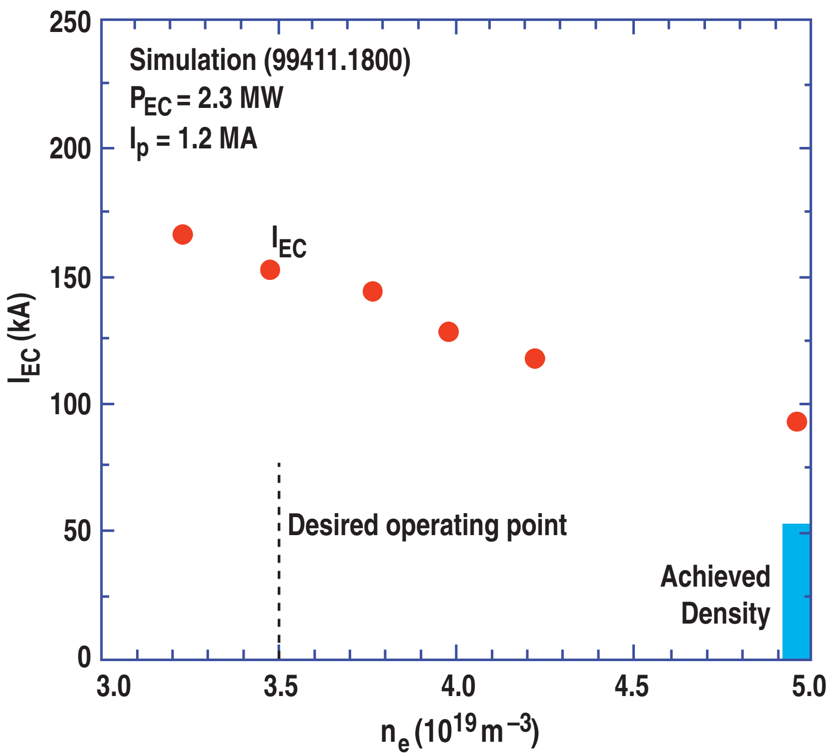
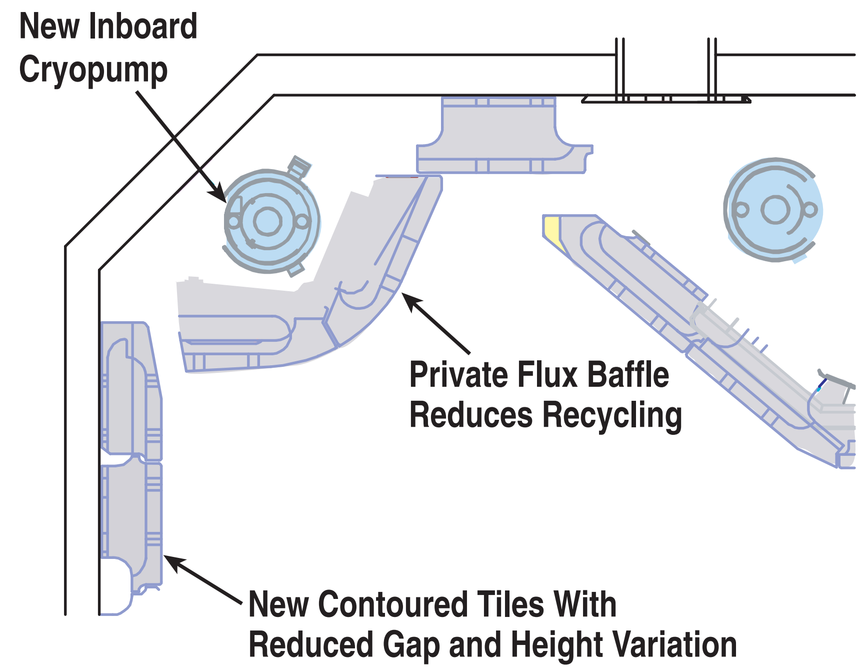
DENSITY CONTROL WILL MAXIMIZE THE EFFECTIVENESS OF OFF-AXIS ECCD

$$I_{EC} \propto \frac{T_e}{n_e} \frac{1}{(Z_{eff} + 5)} \Rightarrow I_{EC} \propto \frac{1}{n^2} \text{ at constant } \beta$$





- New divertor allows pumping in high triangularity shape

Watkins GP1.138

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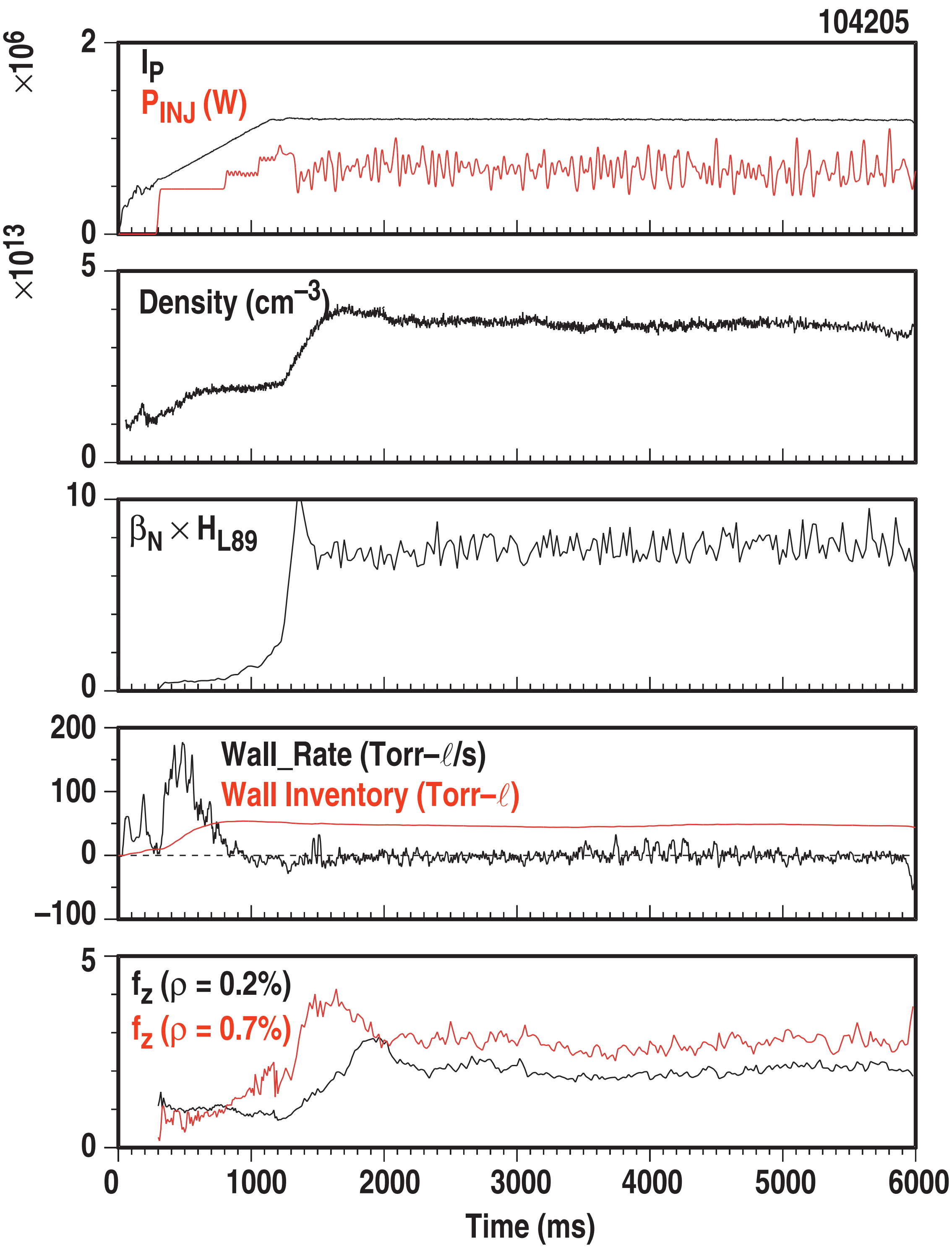
DENSITY AND IMPURITY CONTROL HAS BEEN DEMONSTRATED IN LONG-PULSE ELMING H–MODE DISCHARGES WITH β_N H_{89P} ~ 7.5 FOR OVER 25 τ_E



West GP1.121

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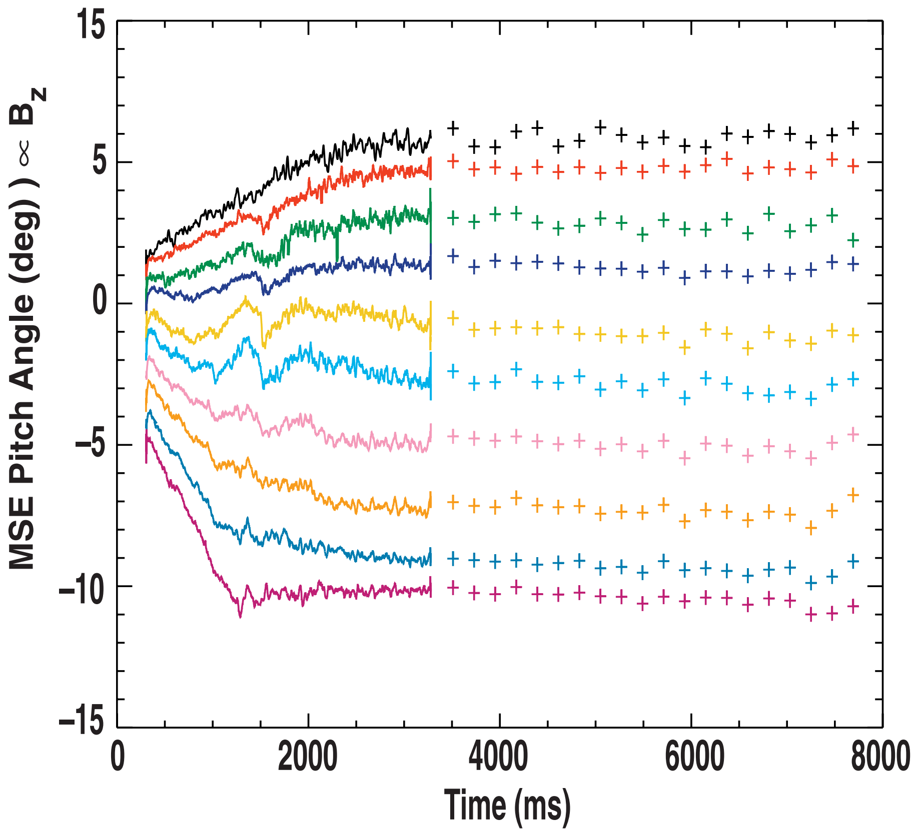
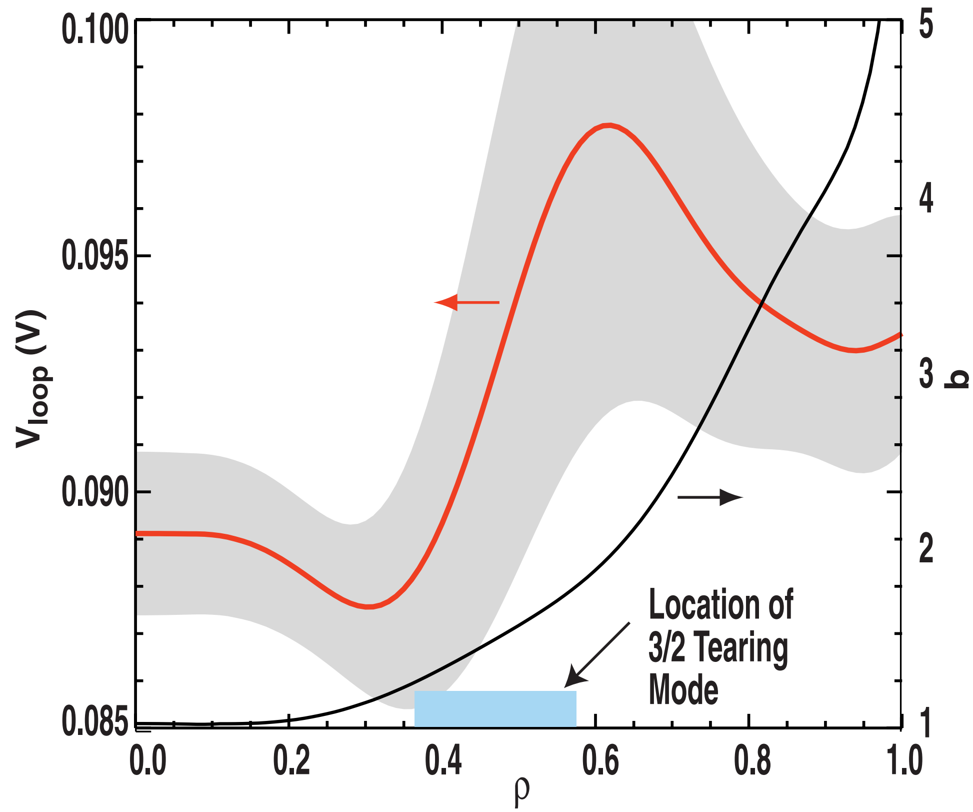
INTERNAL MAGNETIC MEASUREMENTS INDICATE THAT THE CURRENT PROFILE IS NOT EVOLVING





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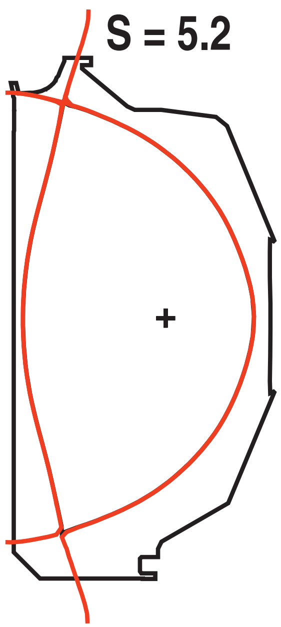
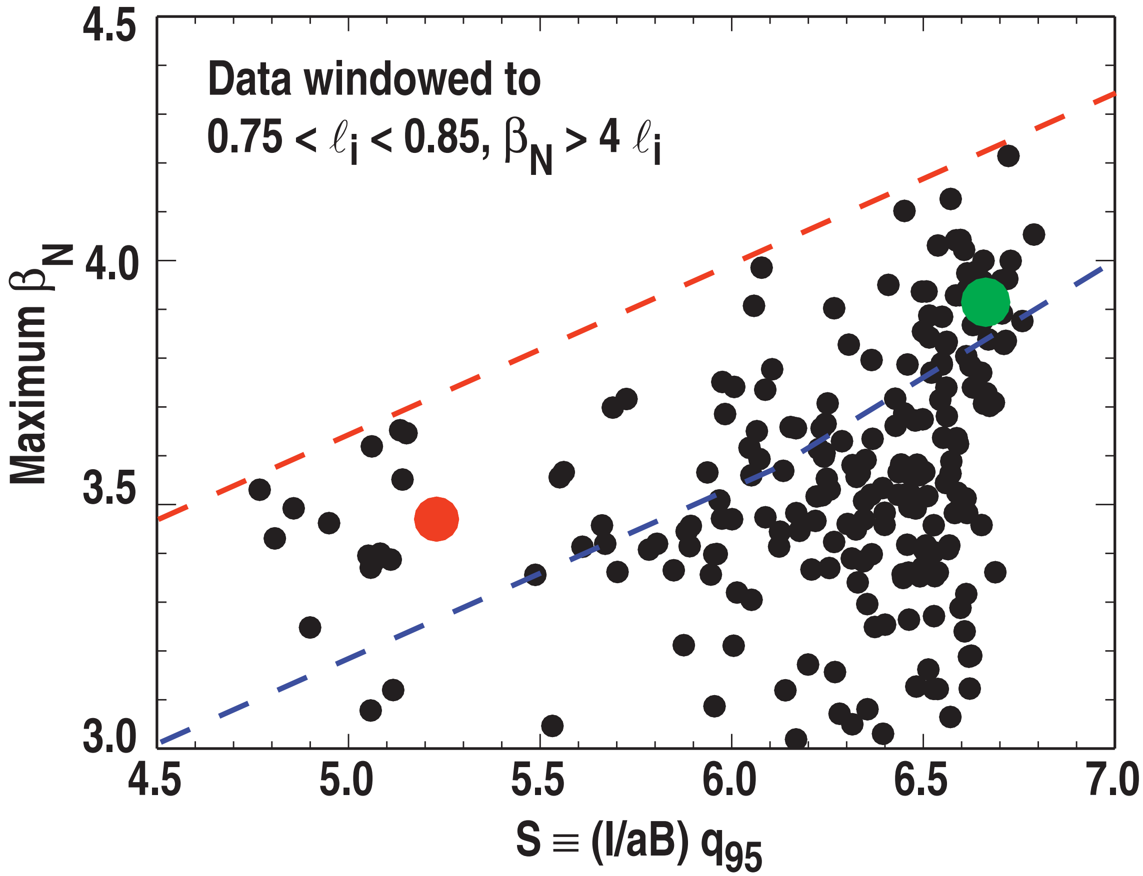
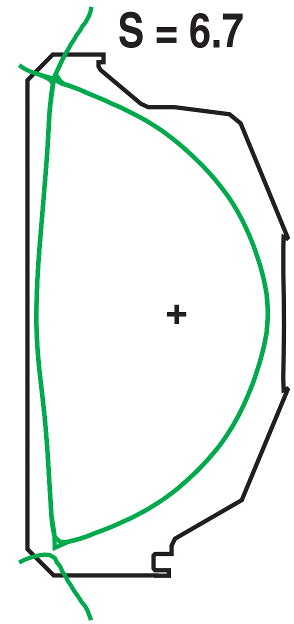
RWM β LIMIT HAS A SIGNIFICANT DEPENDENCE ON PLASMA SHAPE



Pumping Shape

κ = 1.8; δ = 0.6





Optimized Shape

κ = 2.0; δ = 0.9

- Experimental scans at constant I/aB
- Stability calculations at constant q

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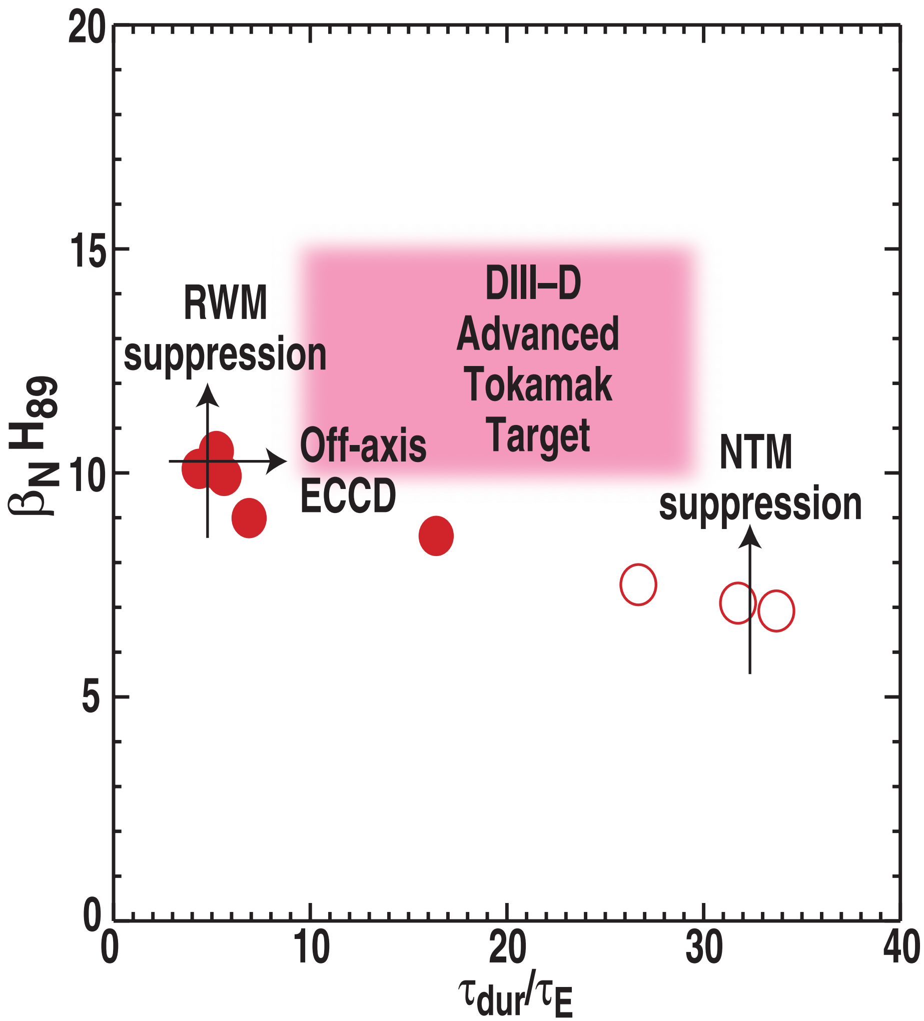
SUMMARY

- Substantial progress has been made in the development of long-pulse advanced tokamak scenarios
  - $\beta_N H_{89} \sim 10$ 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

EXTENSION OF HIGH PERFORMANCE RESULTS RELY ON MITIGATION OF RESISTIVE MHD MODES (RWMs and NTMs)



High Bootstrap Fraction Discharges

- β_N limited by resistive wall modes (RWMs)

  $\Rightarrow$ Need feedback stabilization

- Duration limited by current evolution

  $\Rightarrow$ Need off-axis ECCD

Long-Pulse, High-Performance Discharges

- β_N limited by neoclassical tearing modes

  $\Rightarrow$ Need NTM stabilization