# Overview of Recent Experimental Results from the DIII–D Advanced Tokamak Program


*S.L. Allen*

*for the*

*DIII–D Team*


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# Overview of Recent Experimental Results from the DIII–D Advanced Tokamak Program

**DIII-D "*AT*" research goals are to optimize Tokamak Operation:**

• ***We have made progress since the last IAEA in:***

***Performance*** $\beta_N H_{89P}$ ~ 9 for 16 $\tau_E$, limited by RWM
~ 7 for 3 $\tau_R$, limited by hardware

***Development of AT control tools***

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# Overview of Recent Experimental Results from the DIII–D Advanced Tokamak Program

DIII-D "*AT*" research goals are to optimize Tokamak Operation:

- ***Plasma Pressure*** $\beta$ (Control of plasma shape and MHD)
  - Resistive Wall Mode (RWM) - coils
  - Neoclassical Tearing Mode (NTM)- ECCD
  - Feedback of NBI heating power to control $\beta$
- ***Plasma Confinement*** $H_{89P}$ ( ITB Control tools)
  - "Counter" NBI, impurities, pellets
  - New Quiescent Double Barrier (QDB) Regime
- ***Power and Particle Control*** (Divertor 2000)
  - Density, impurity, and heat flux control
- ***Non-Inductive Current Sustainment*** (Profile control)
  - ECCD comparison with models

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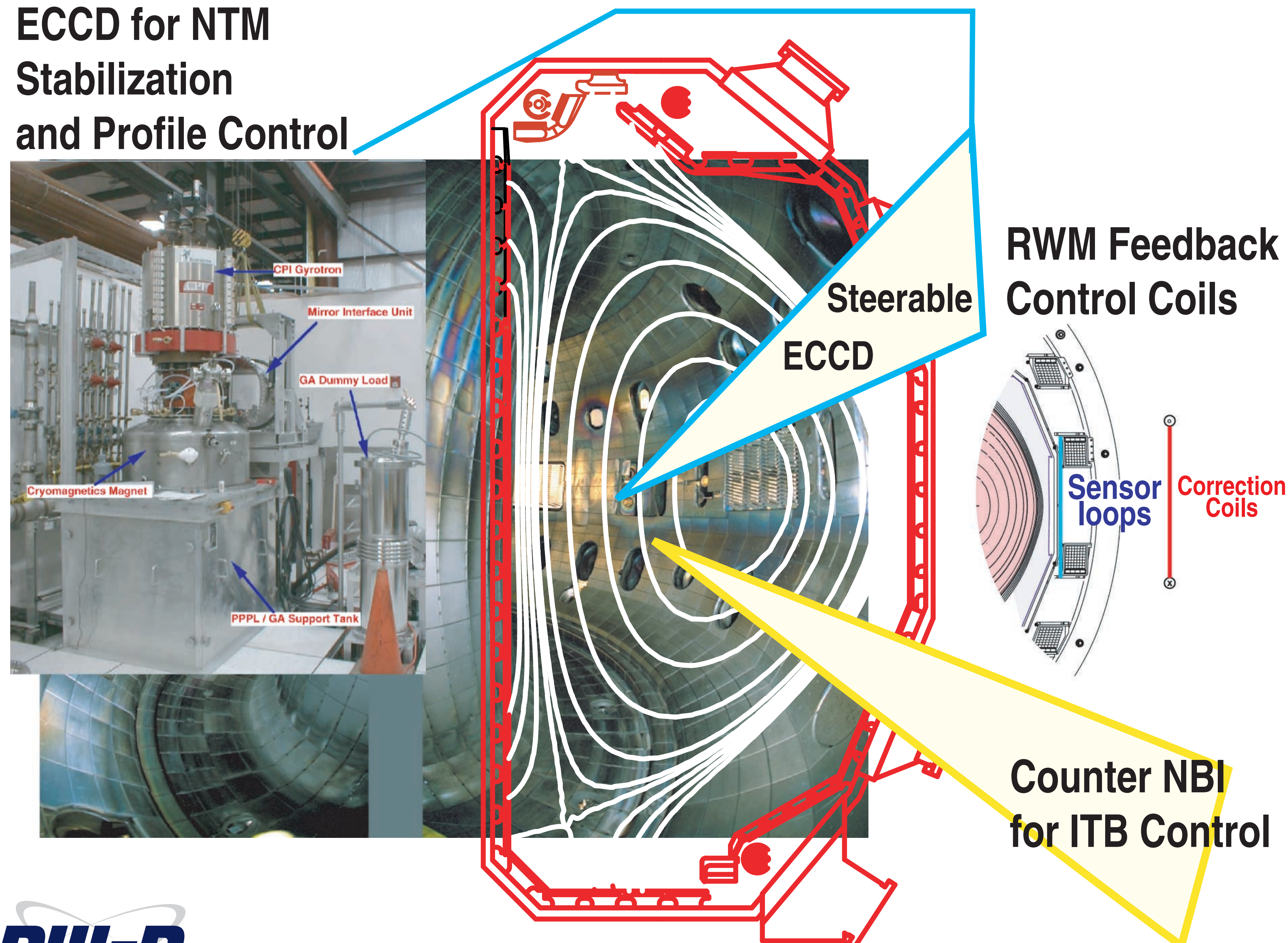


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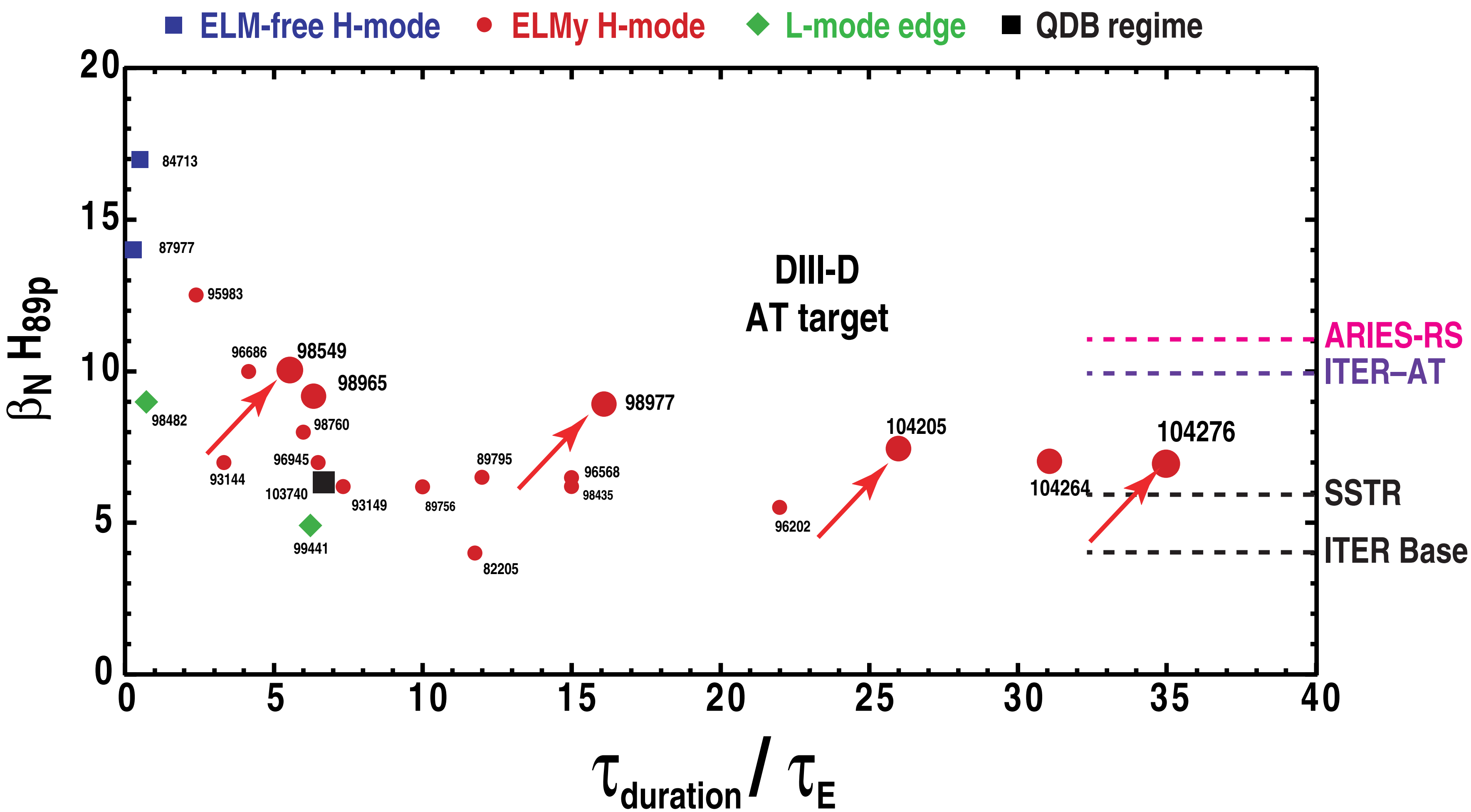
# Significant progress in long-pulse high performance since the '98 IAEA

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# Overview of DIII-D Advanced Tokamak Results

## *1. High Performance ELMing H-mode*

- $\beta_N H_{89} \sim 9$ for 16 $\tau_E$ at $n_e/n_{GW} = 0.6$

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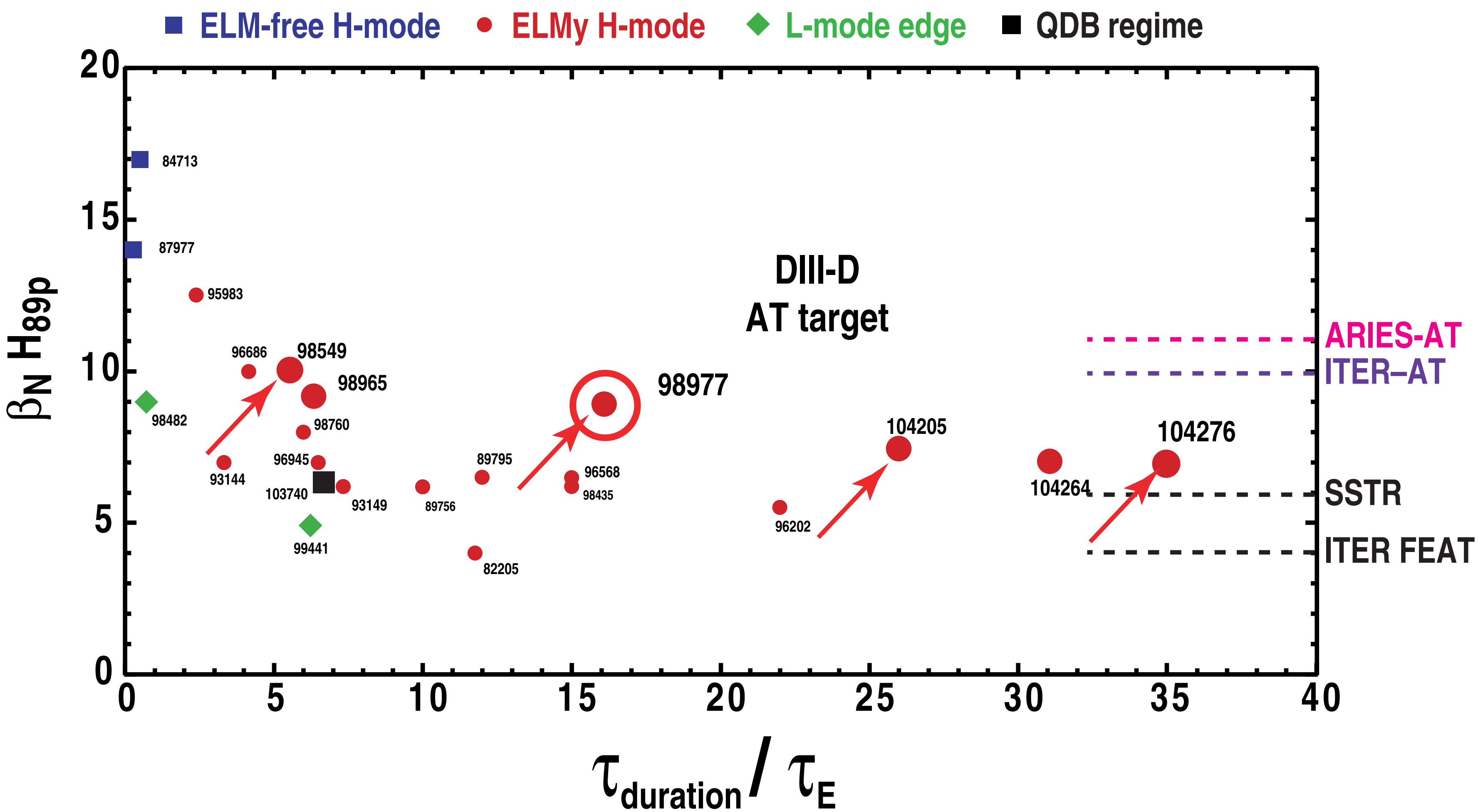


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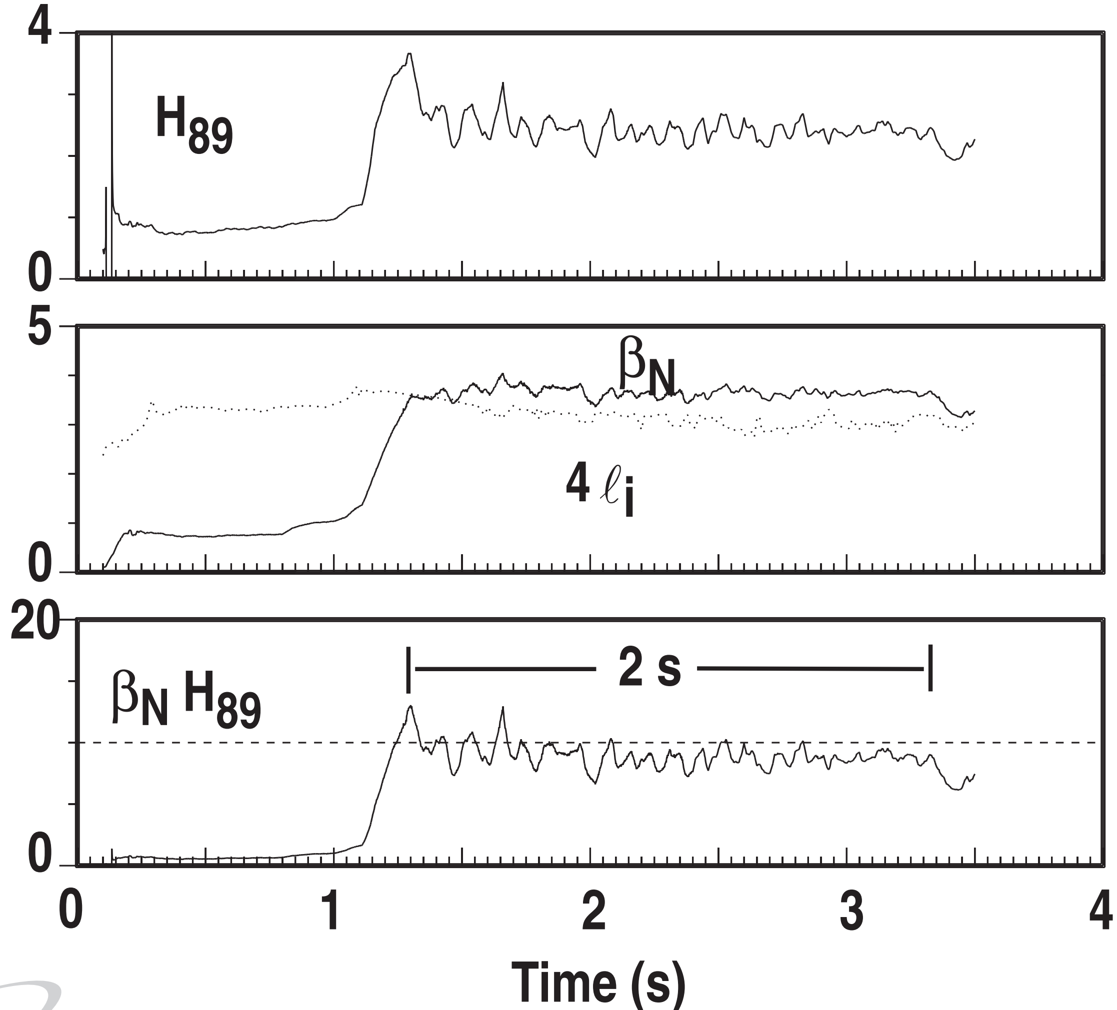
# $\beta_N H = 9$ sustained for 16 $\tau_E$, limited by RWM




- $n_e/n_{GW} = 0.6$
- $f_{BS} \sim 0.5$
- $f_{non\text{-}inductive} \sim 0.75$

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*see LUCE EX 4/3*

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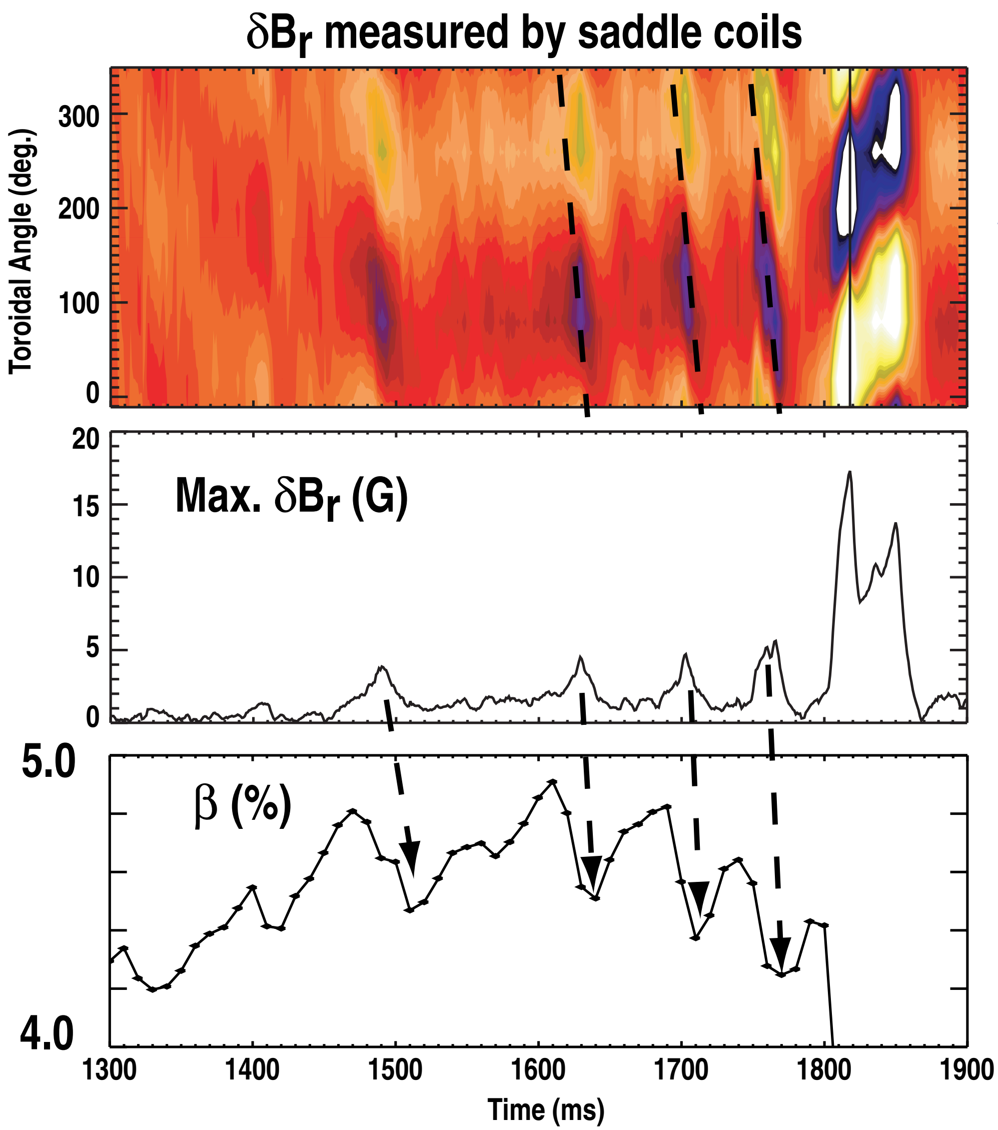
# Beta is limited in magnitude and duration by resistive wall modes




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

***see A. Garofolo EXP 3/01***
***G. Navratil EXP3/4***

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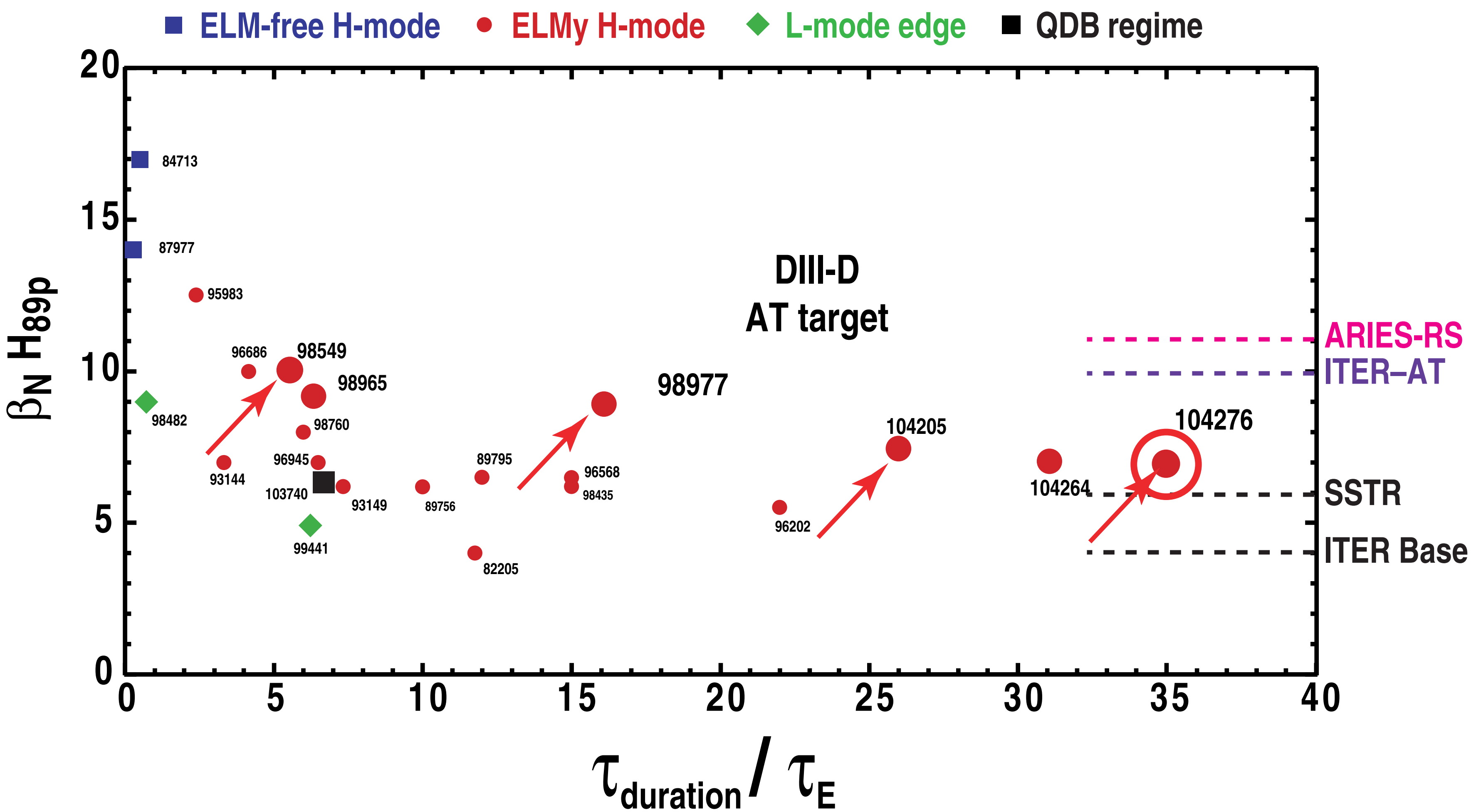
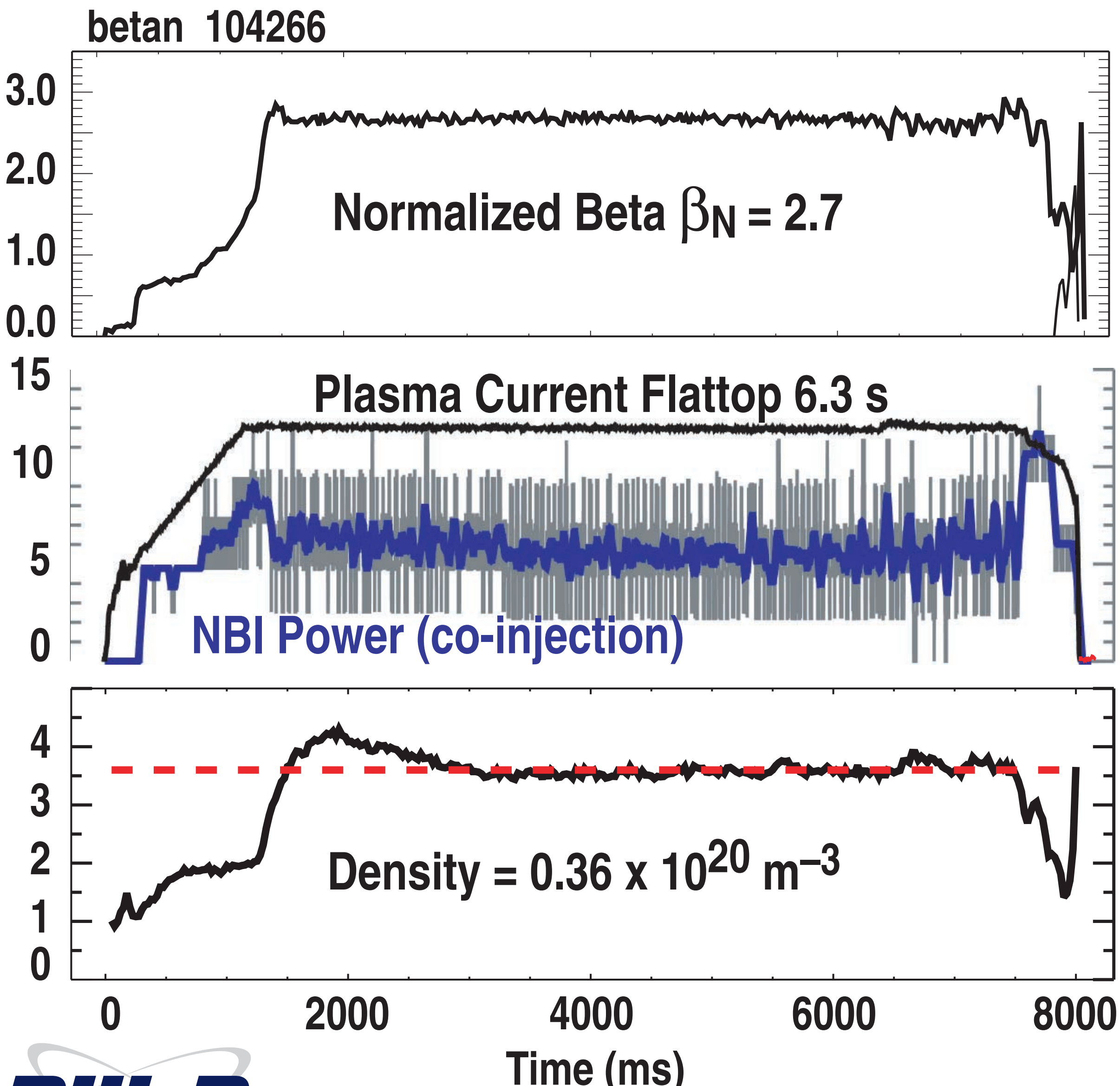


# Long pulse ELMing H–mode achieved by NBI feedback control and divertor pumping




- NBI power is feedback controlled on plasma beta at $\beta_N$ = 2.7
- Density is controlled with divertor pumping
- m = 3, n = 2 NTM present, no sawteeth

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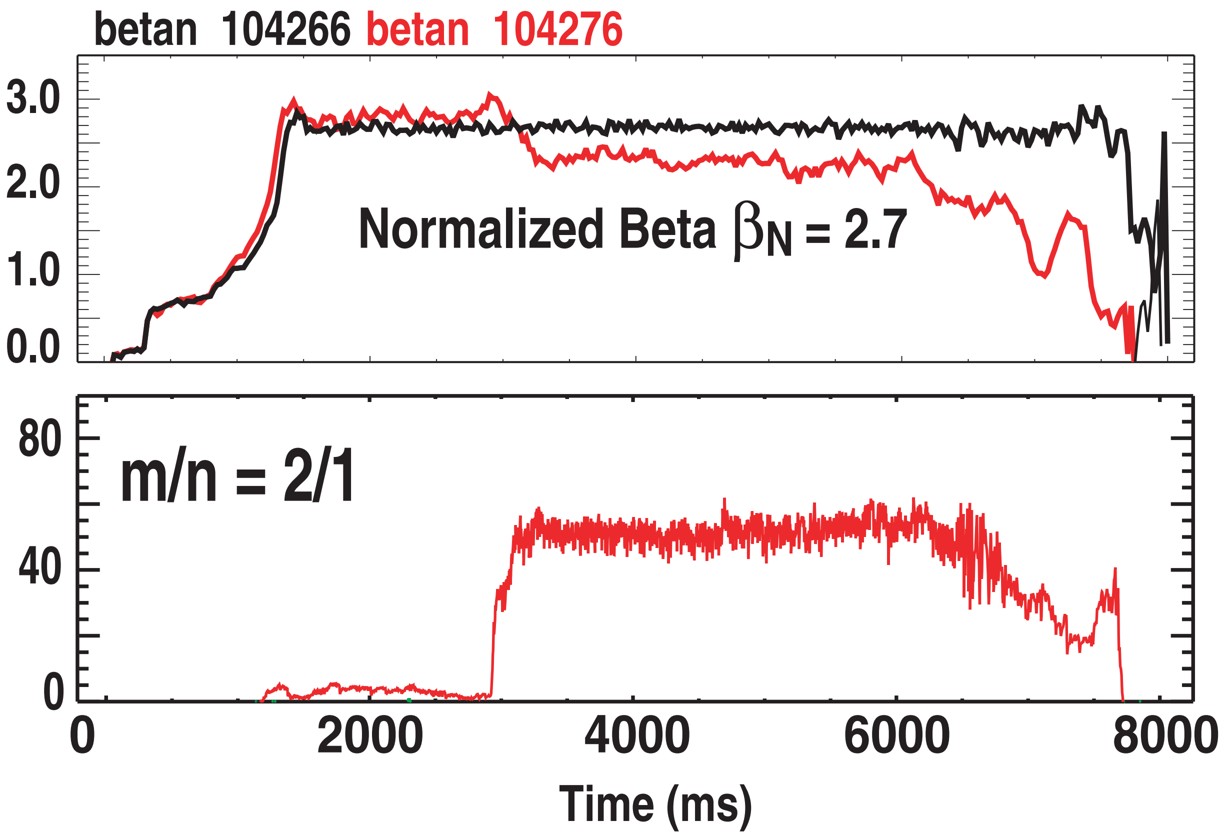


- NBI power is feedback controlled on plasma beta at $\beta_N = 2.7$
- Density is controlled with divertor pumping
- m = 3, n = 2 NTM present, no sawteeth
- Performance limited by m = 2, n = 1 MHD

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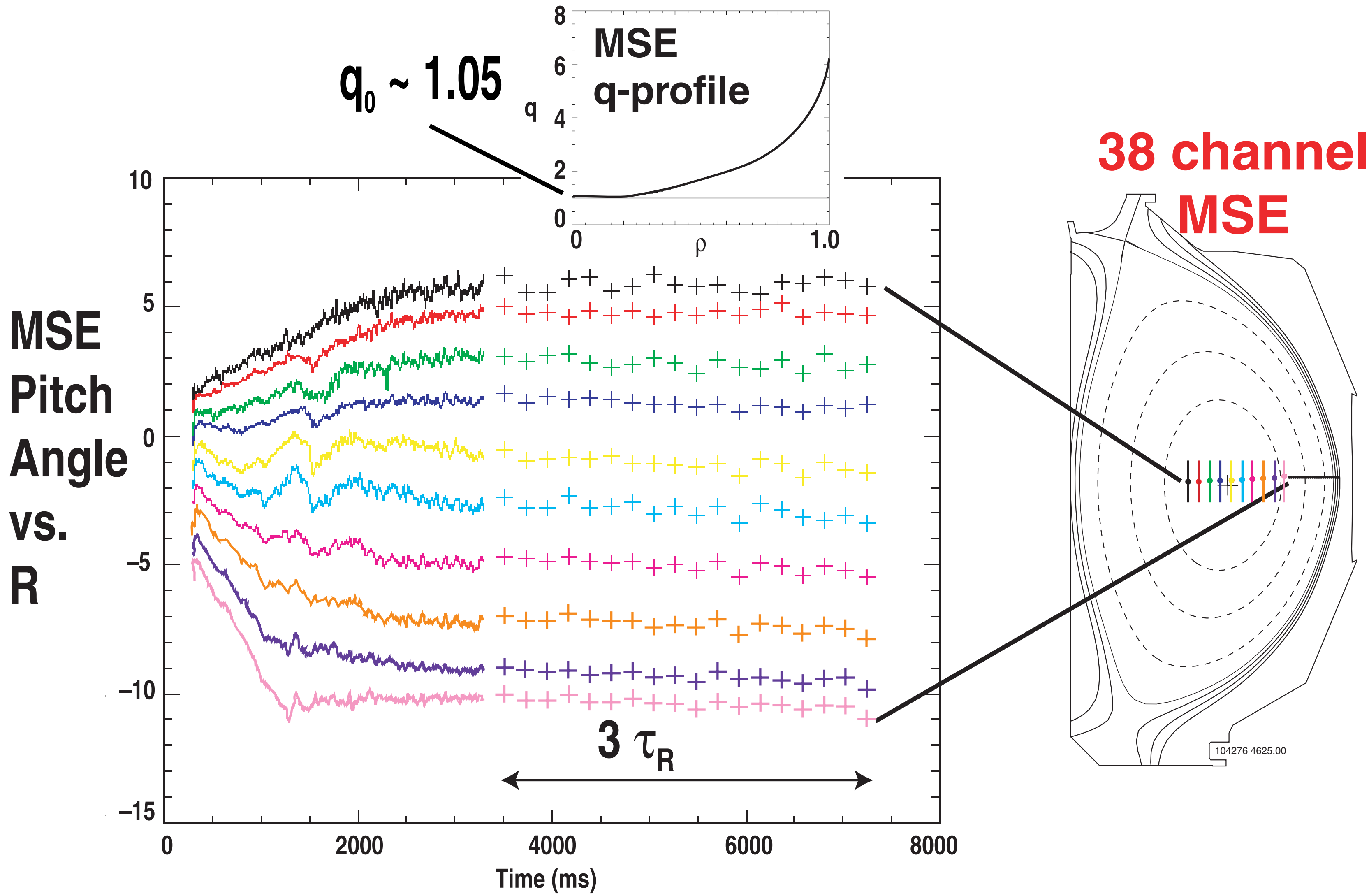
# MSE shows J(r) profile has reached resistive equilibrium with $q_0$ ~1.05

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- Internal transport barrier, $\beta_N H_{89} \sim 7.0$, with density control
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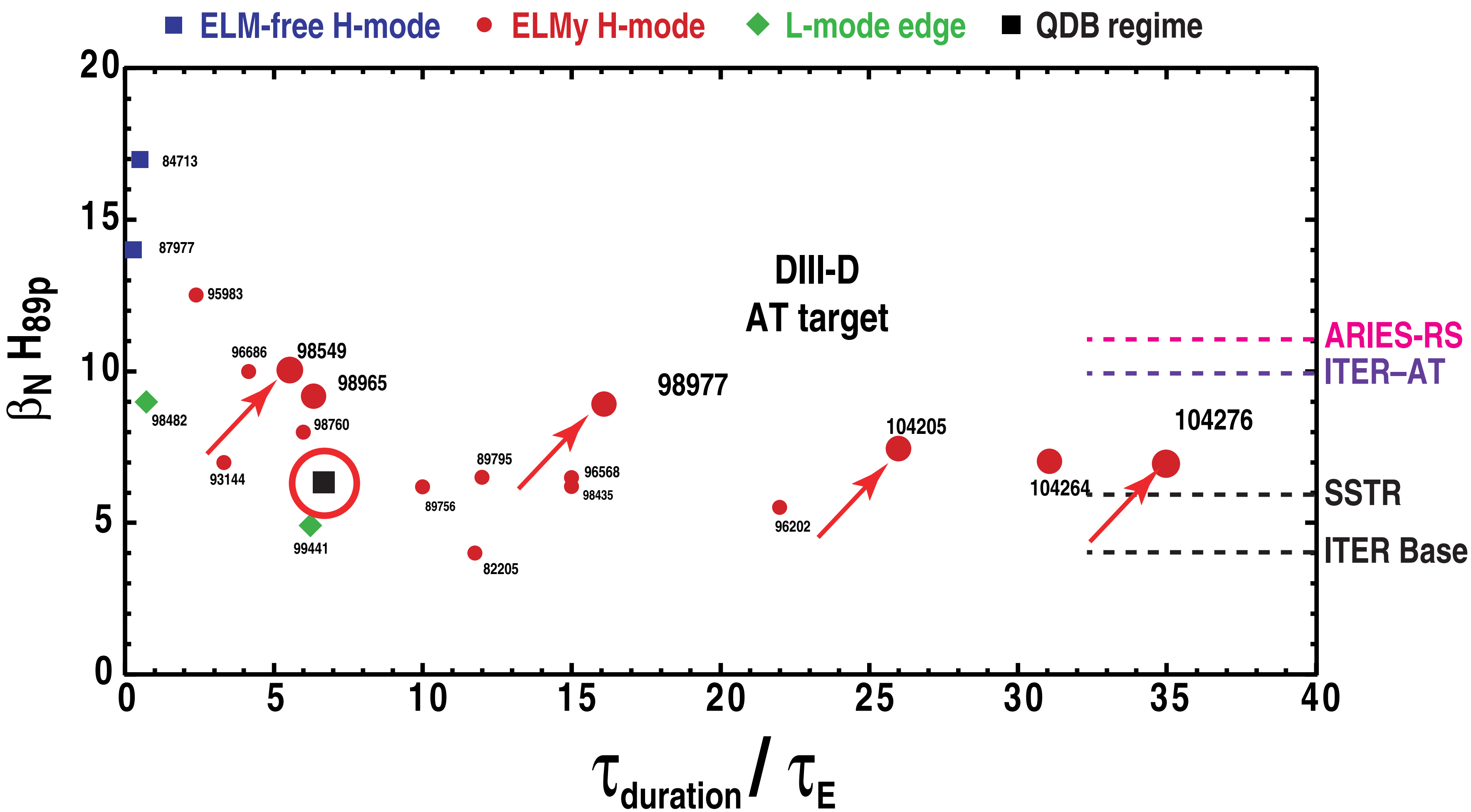
# QDB mode is an ELM-free double barrier mode with good confinment

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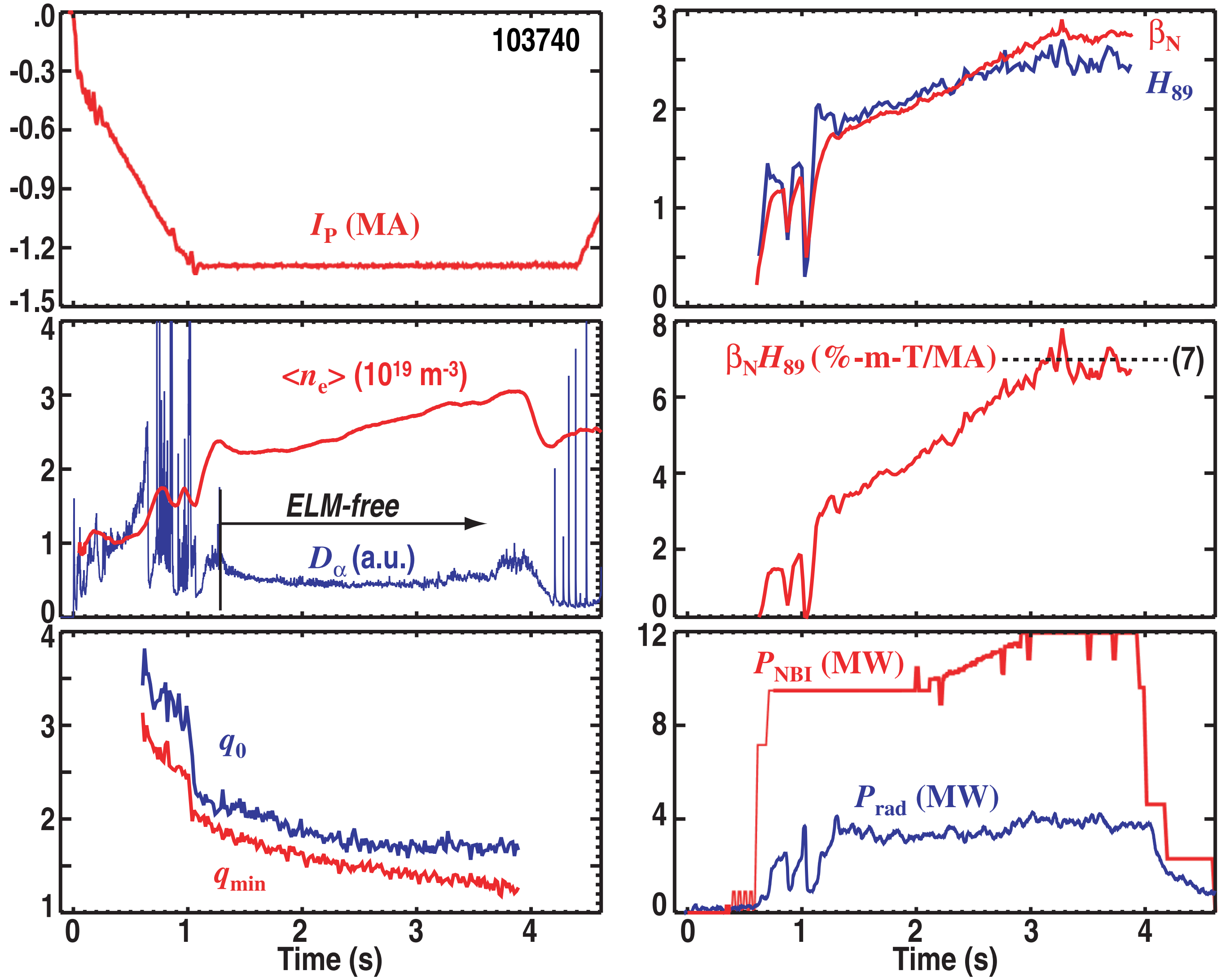
# QDB is a Core ITB with a quiescent QH-Mode edge, no sawteeth

- Reverse $I_p$
- ELM-free
- $q_0 > 1$




$\beta_N H_{89}$ ~ 7,
Not optimized

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see Doyle EX 6/2

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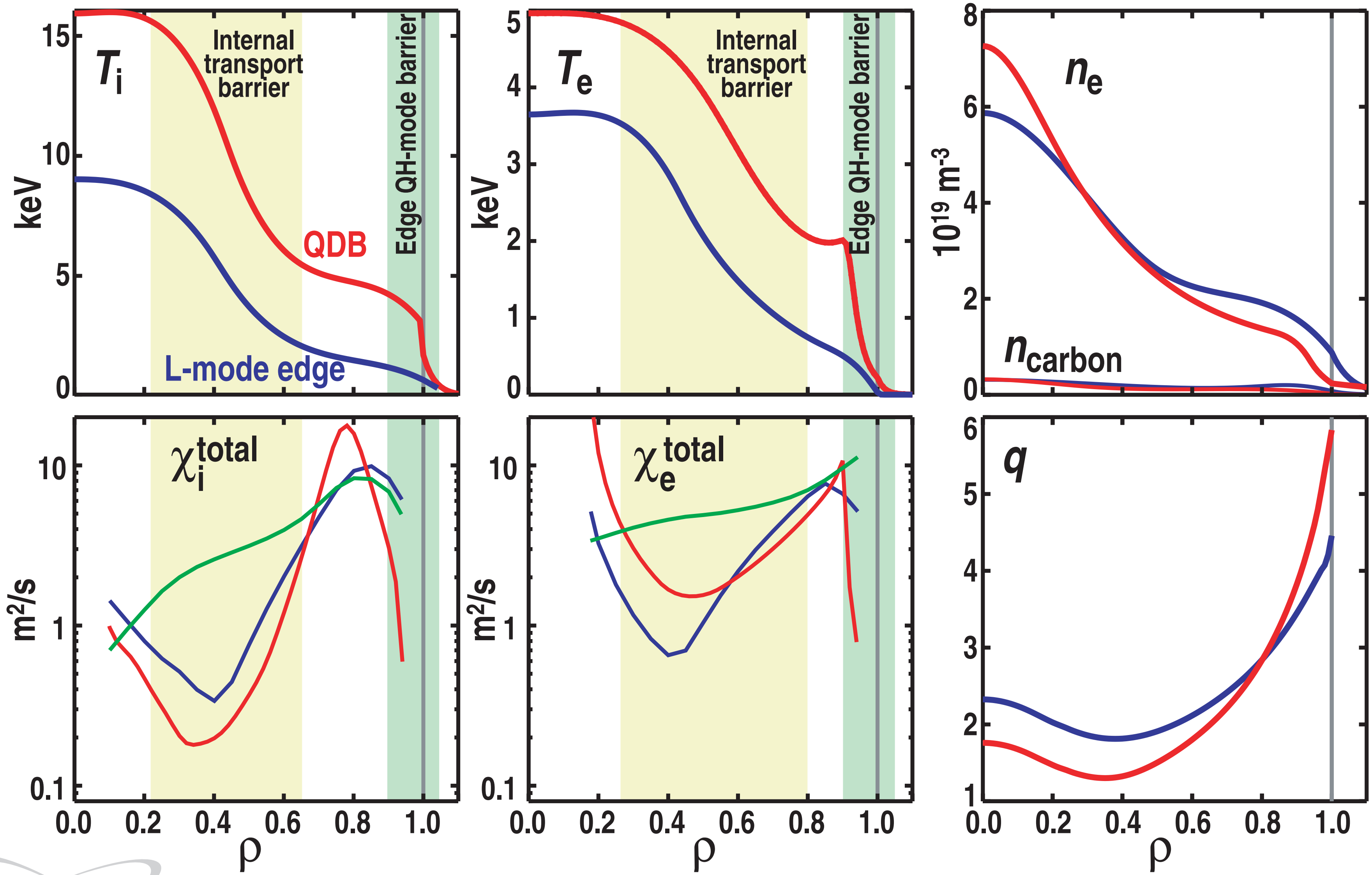
# L–Mode edge has a internal transport barrier — QDB adds edge barrier

L-mode (99852 0.70s) L-mode edge ITB (99849 1.12s) QDB (103740 3.3s)

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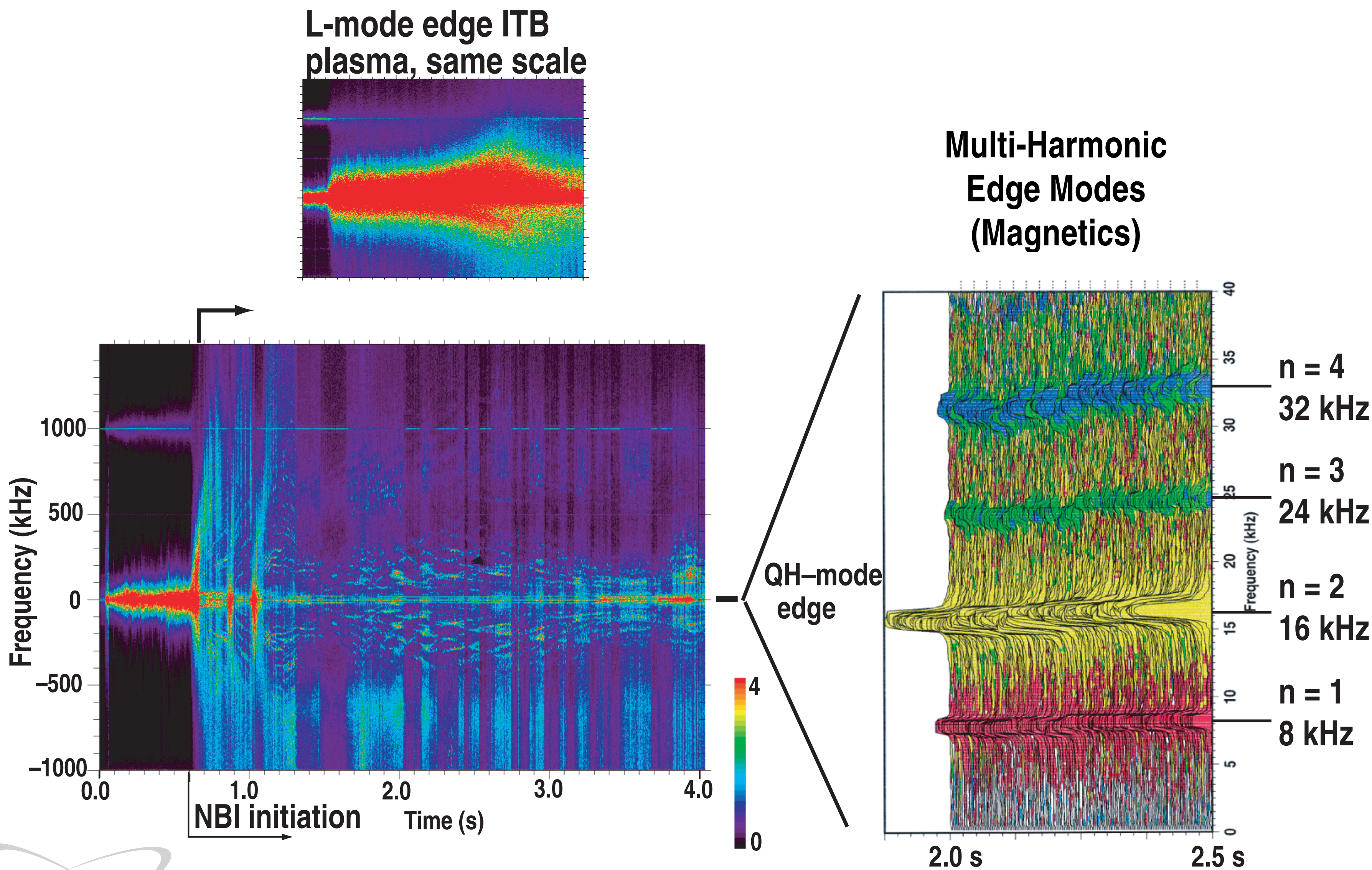
*see E. Doyle, EX5/03*

# Turbulence is reduced to low levels in the QDB regime

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*3. Several new AT control techniques demonstrated*

- Transport barrier control tools

# ITB control depends on an understanding of turbulence supression

| | | | | |
|---|---|---|---|---|
| Turbulence Scale | 0.1 | $k_\Theta \rho_s$ | 1 | 10 |
| | 1 | $k_\Theta (cm^{-1})$ | 10 | 100 |
| Mechanism | ITG | TEM | ETG | |
| Transport Channel | Ion thermal | Electron particle | Electron thermal | |
| Stabilization mechanisms | Reversed magnetic shear | | | |
| | E x B Shear | *Counter NBI* | | |
| | Impurity injection | | | |
| | $\alpha$ (pressure gradient) stabilization | *ECH Heating* | | |

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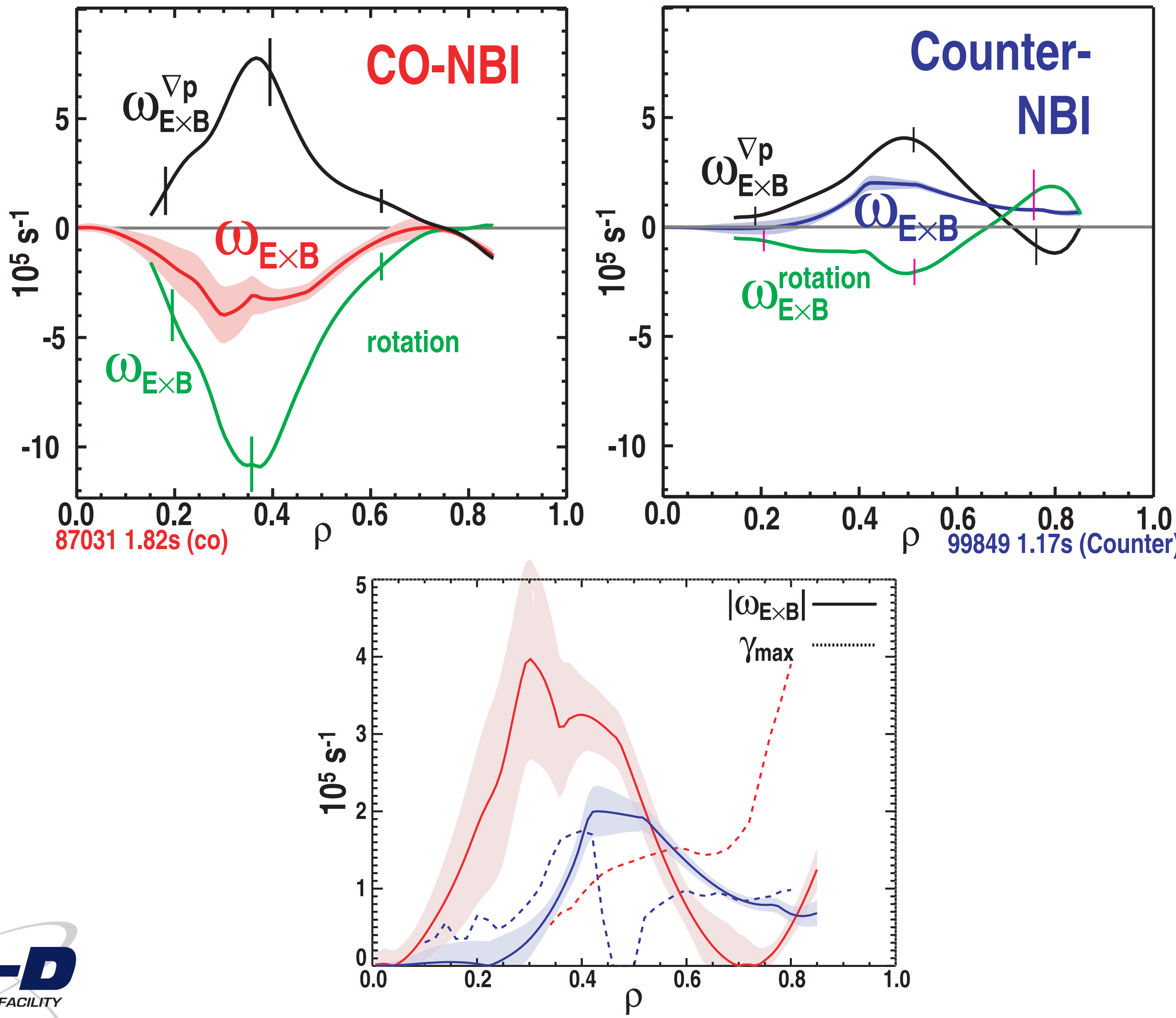
# ITB expansion with counter injection depends on E×B shear profiles

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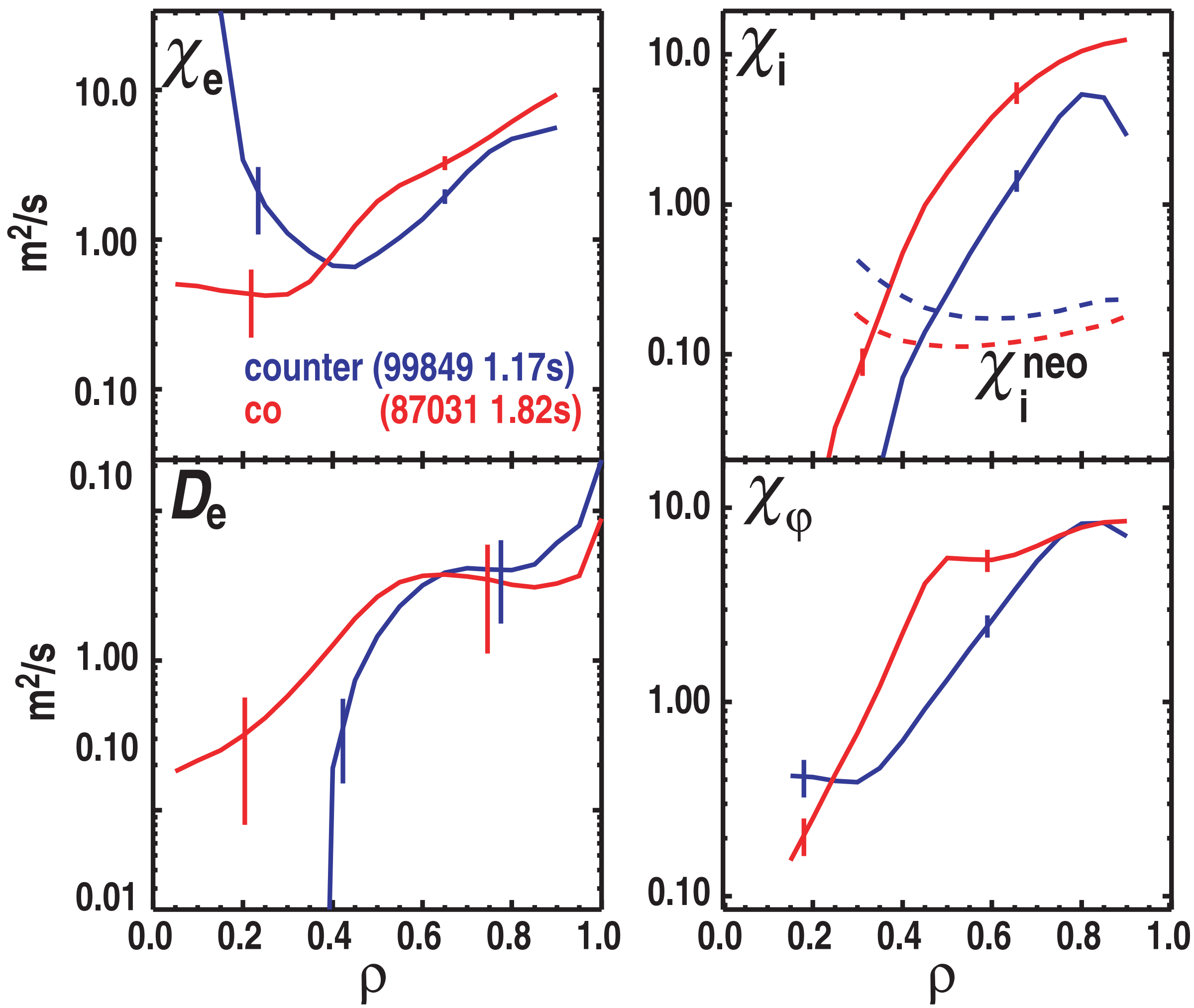
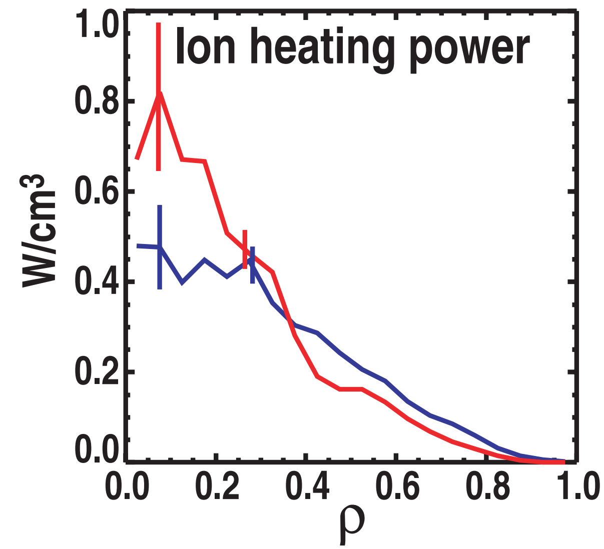
# The reduced transport region is broader in all channels with counter-NBI




- Possible causes of ITB broadening
  - Broader heating profile
  - Enhanced E×B shear

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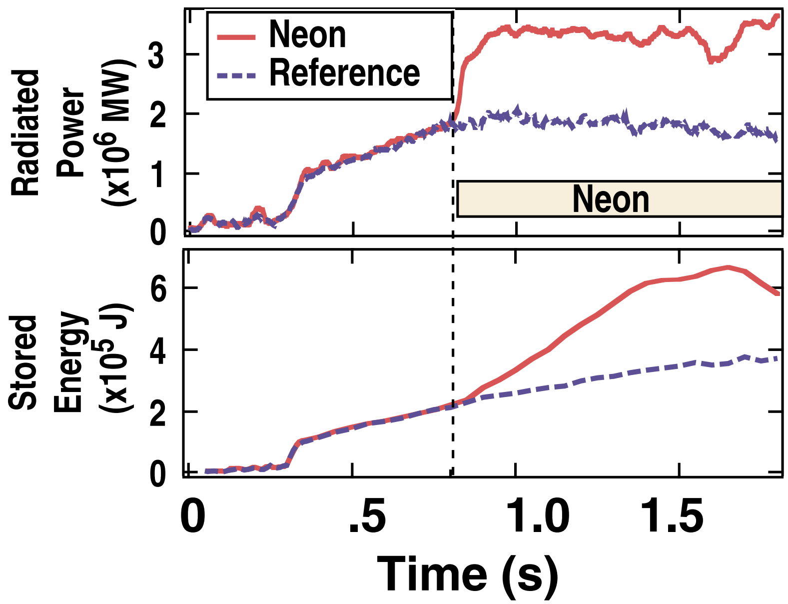
*see E. Doyle, EX5/03*

# Impurity injection reduces ion transport in H–mode plasmas

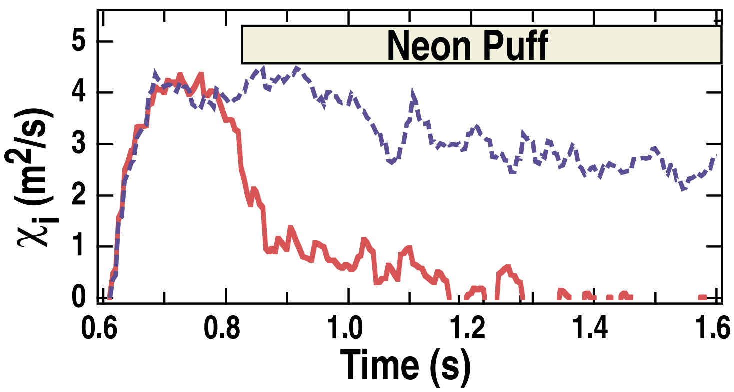
## Neon increases stored energy



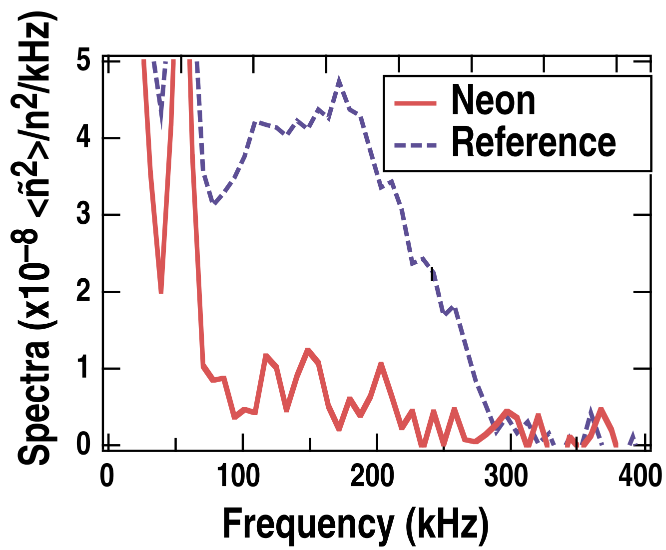

Radiation near 75% of injected power

80% increase in stored energy

## $\chi_i$ is reduced with neon




## BES shows fluctuations reduced

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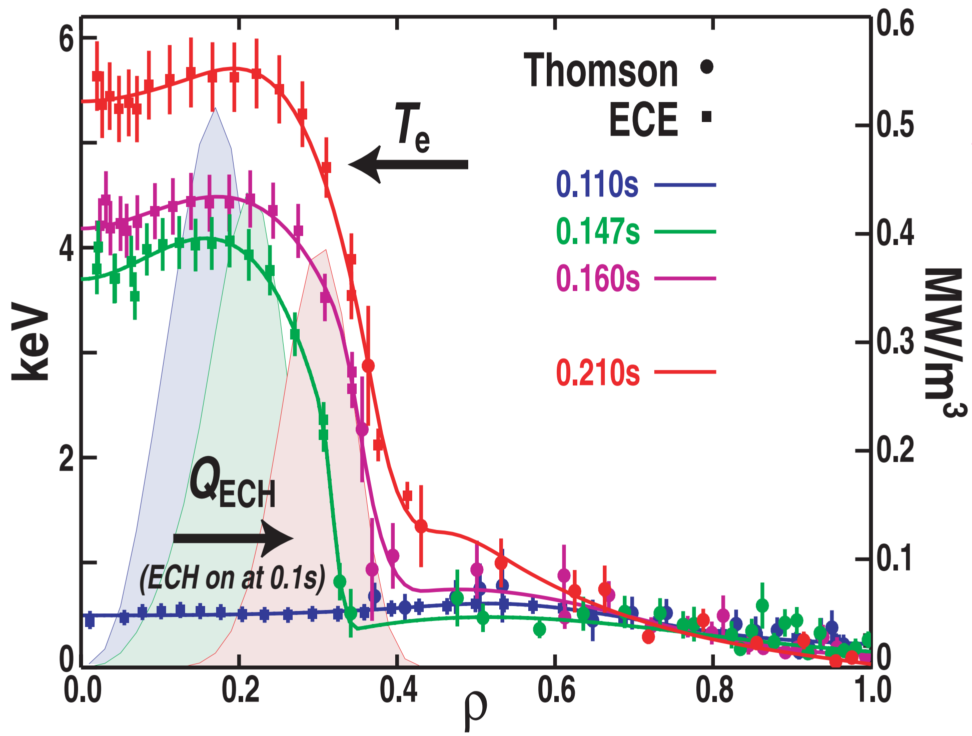
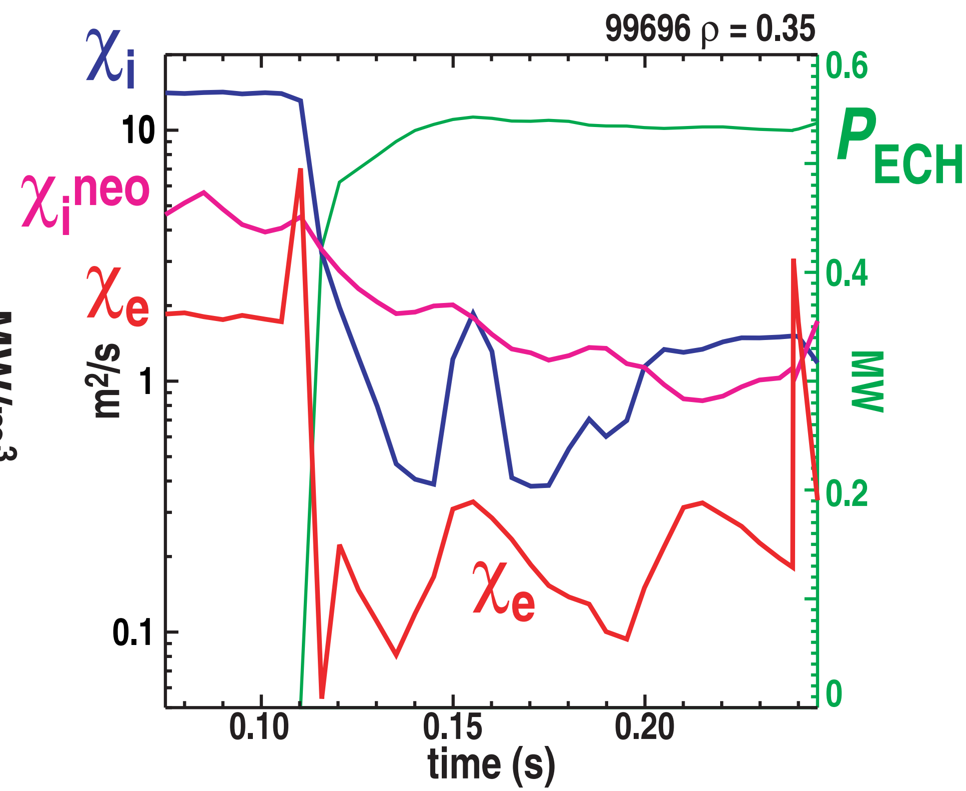
*see M. Murakami, EX5/01*

# Electron transport barrier forms with ECH heating

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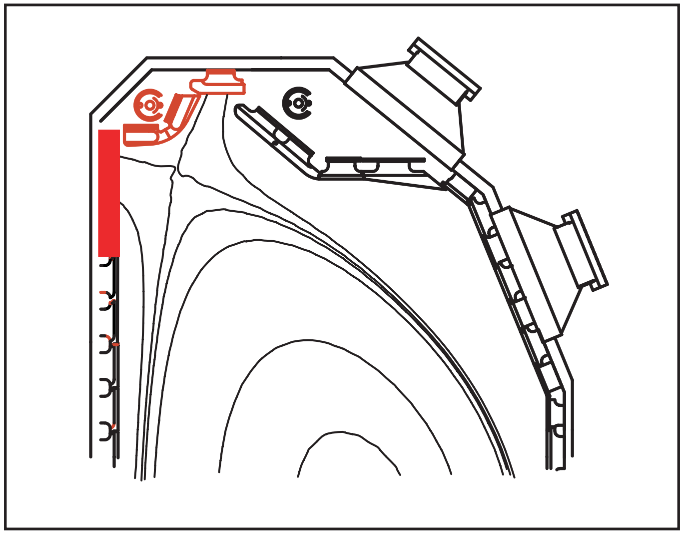
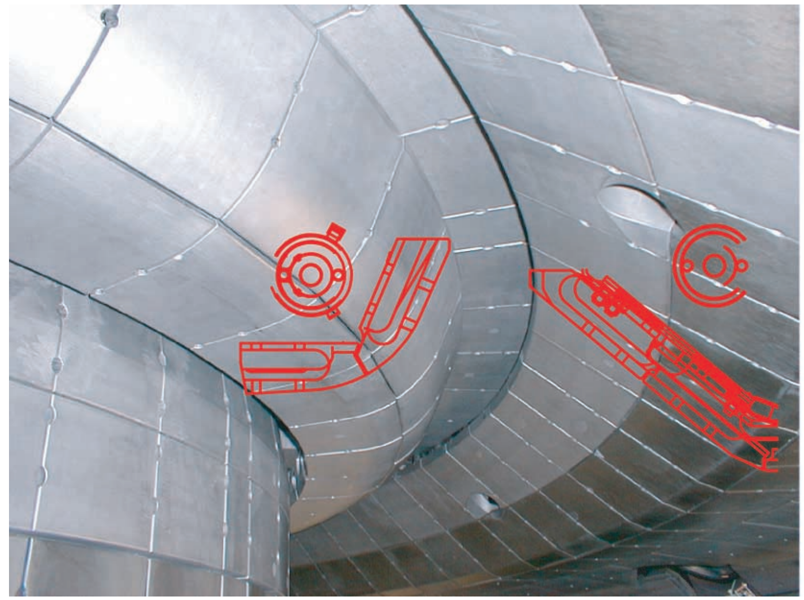
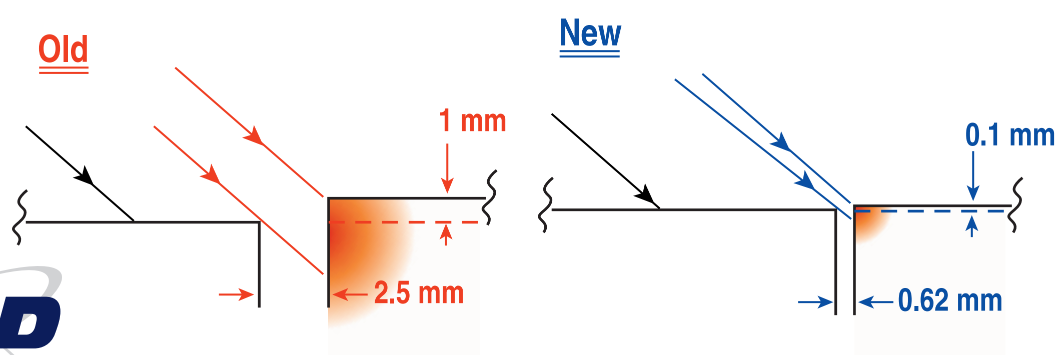
- Density and impurity control with Divertor-2000

# Divertor-2000 achieves AT density and impurity control - 50 MJ input








- Accurate tile alignment prevents hot spots

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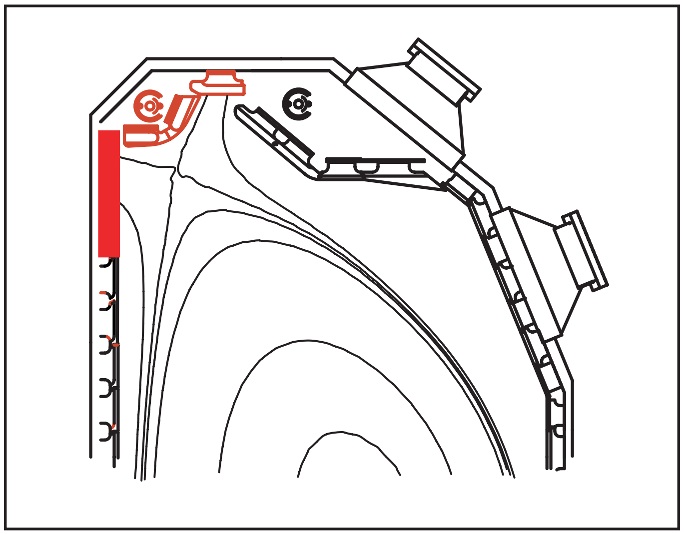
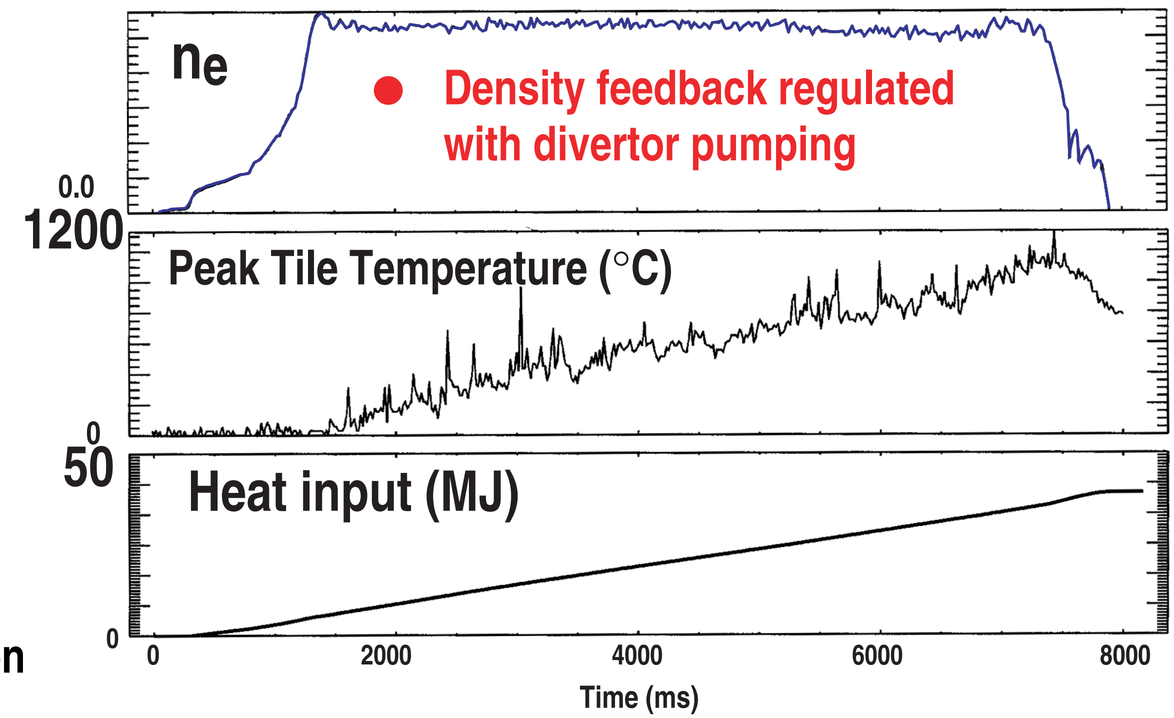
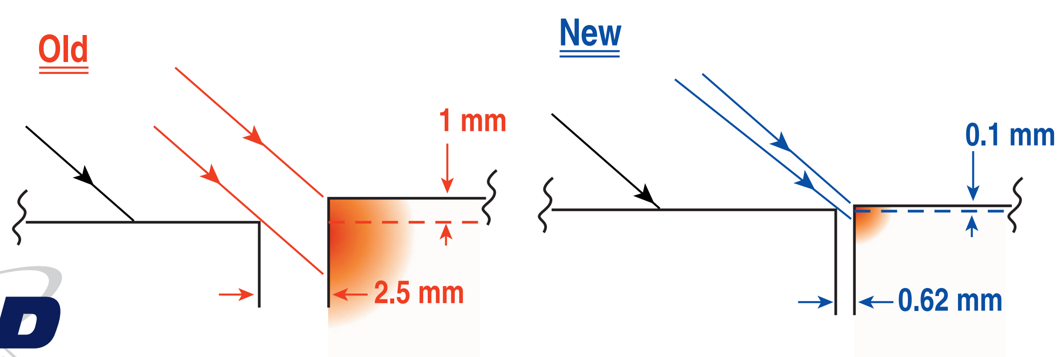





- Density feedback regulated with divertor pumping

Carbon Concentration (%) is
Reduced Compared to Previous Operation

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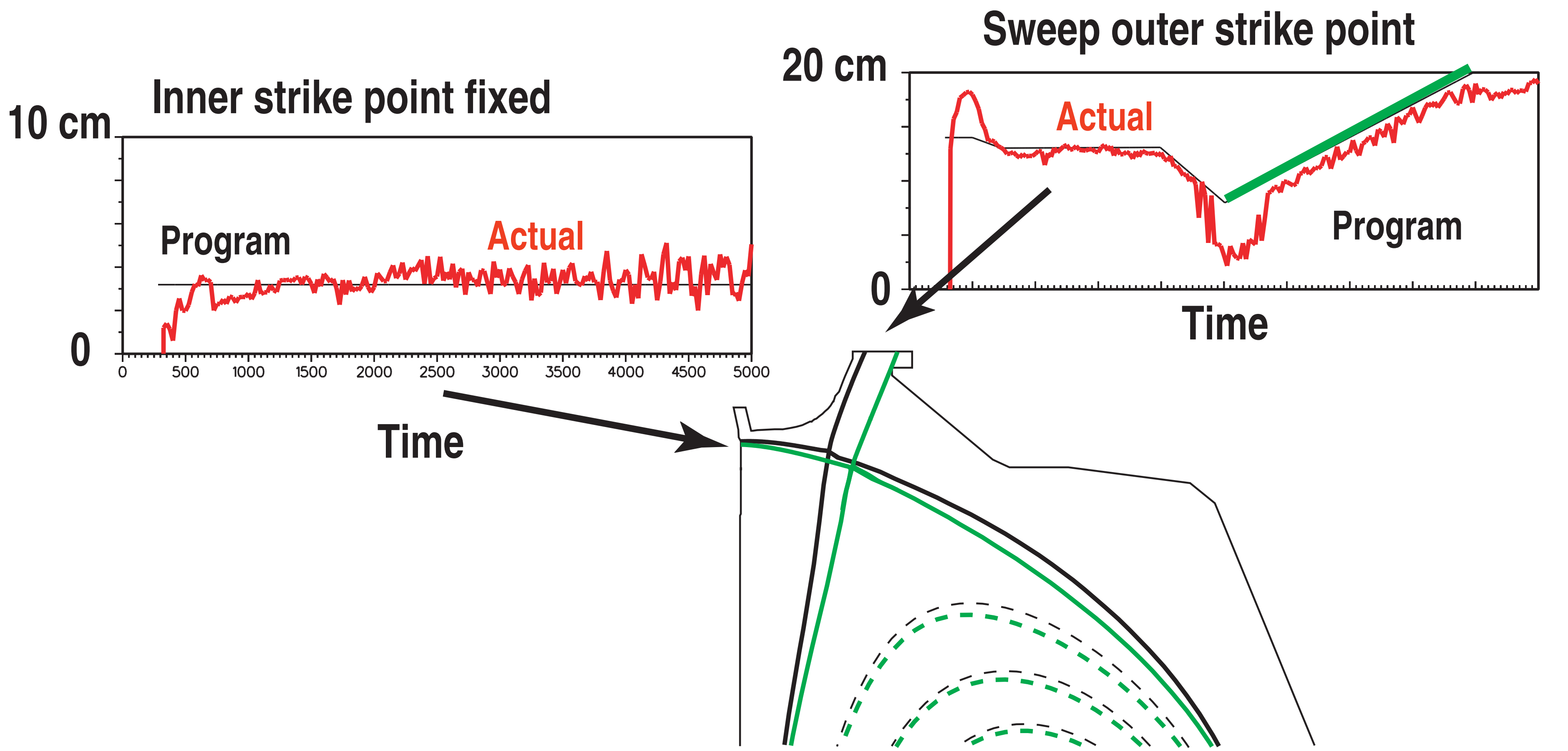
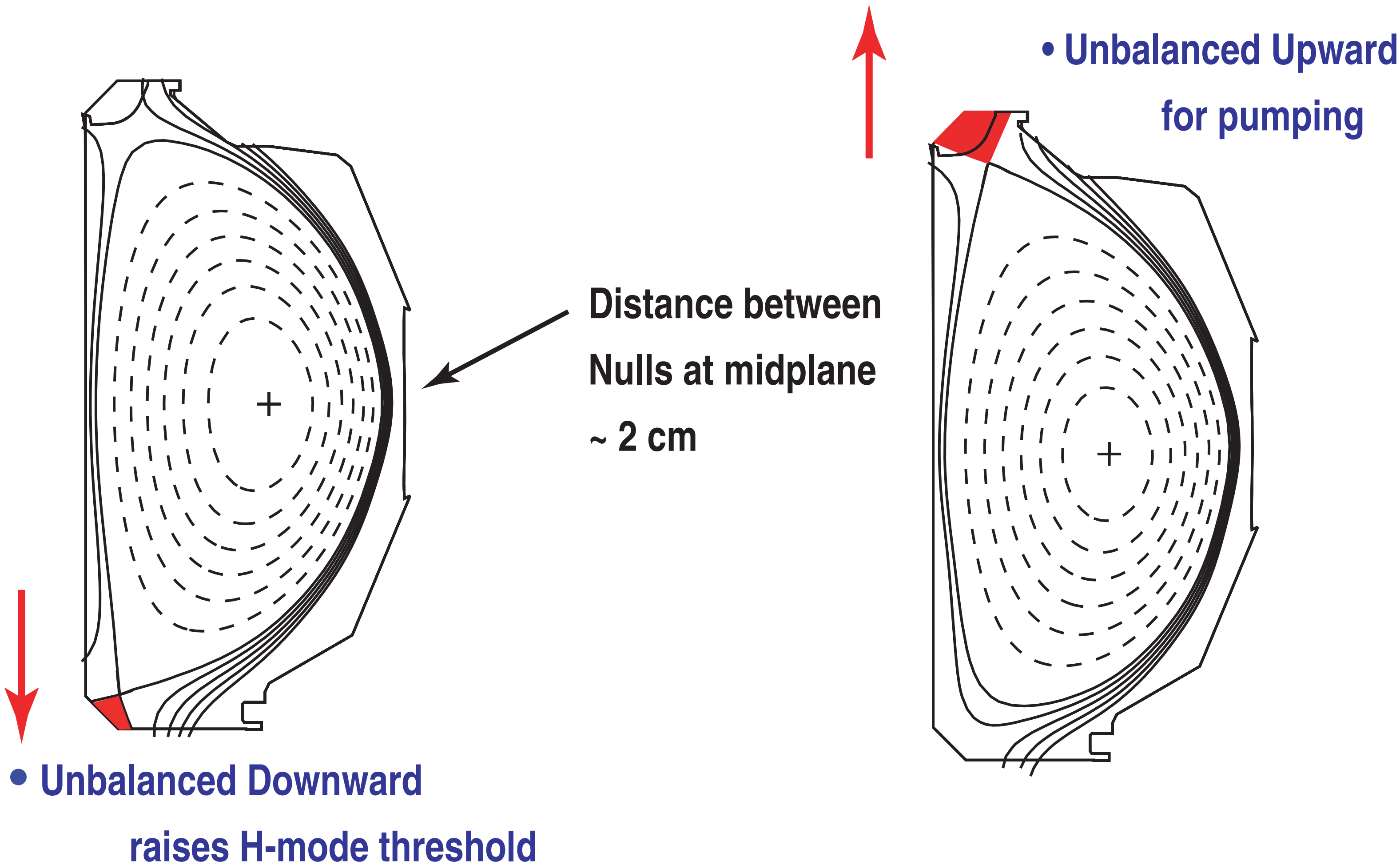
# Real time control of divertor and plasma shape achieved for AT operation

- Outer strike point sweep to control pumping



# DN balance to control H-mode power threshold, pumping

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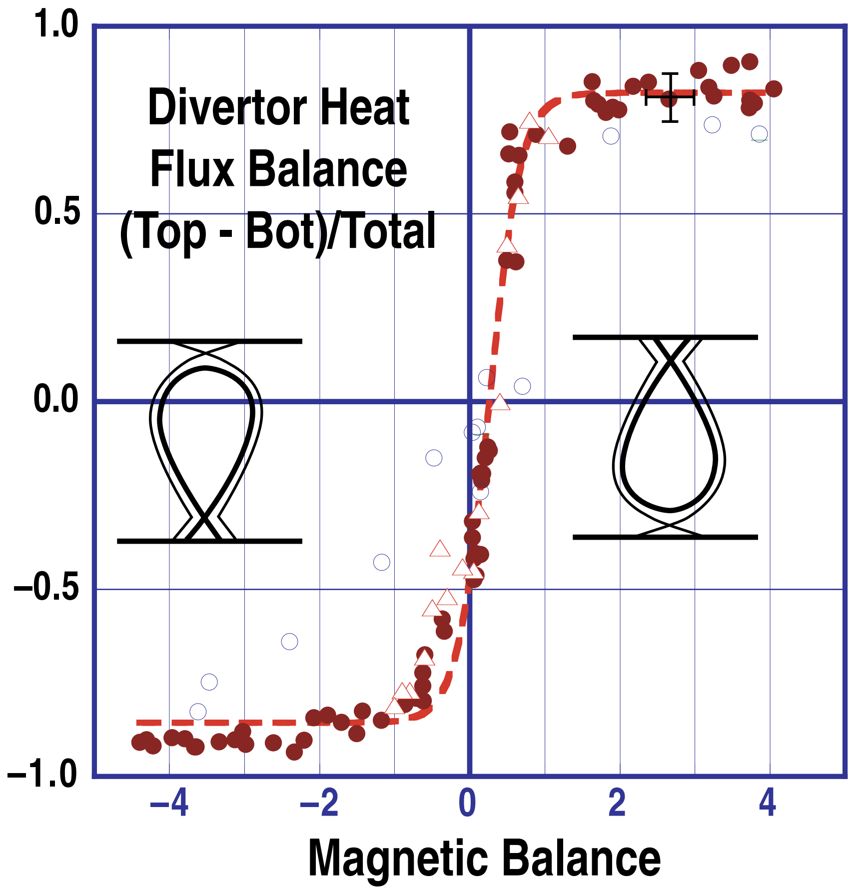
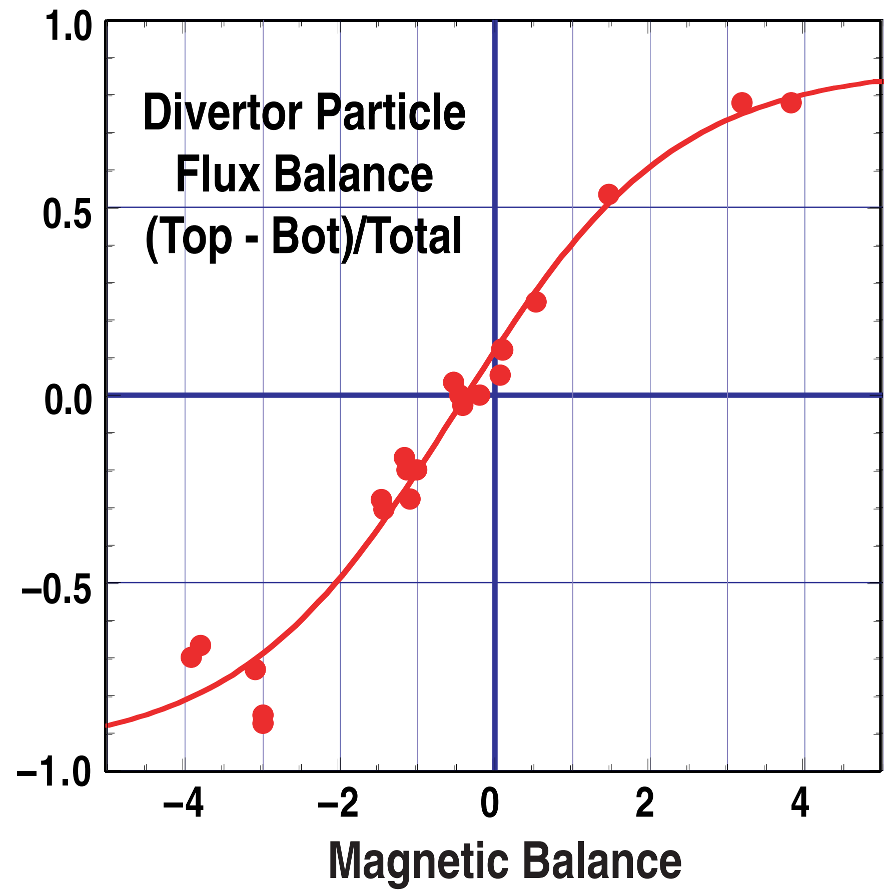
# Magnetic balance can be used for power and particle control

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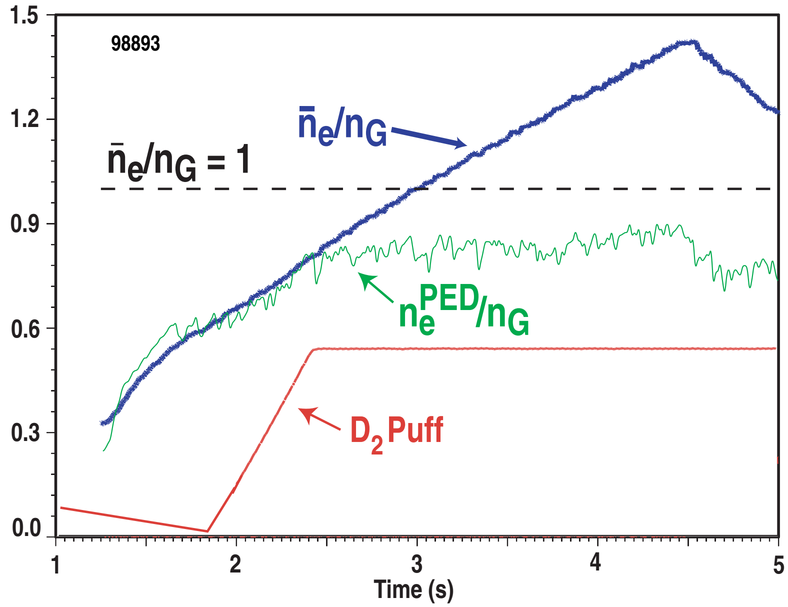
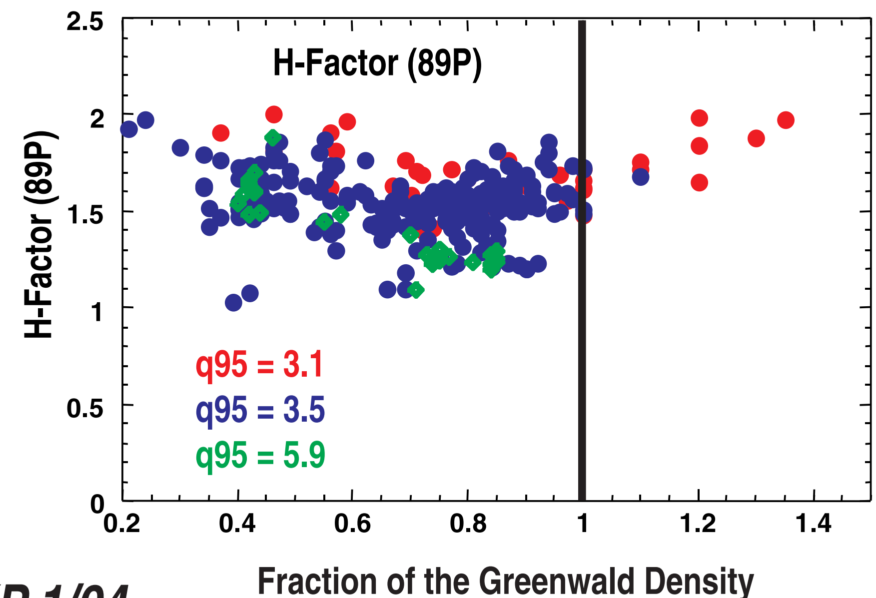
*see M. Fenstermachπer, EX2/4*

# Gas puff fueled H–mode discharges with high energy confinement above the Greenwald density on DIII–D




- High density operation is easier with pumping
- Controlling Pedestal is important

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*see A. Mahdavi, EXP 1/04*

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- Resistive Wall Mode (RWM) feedback control with external loops

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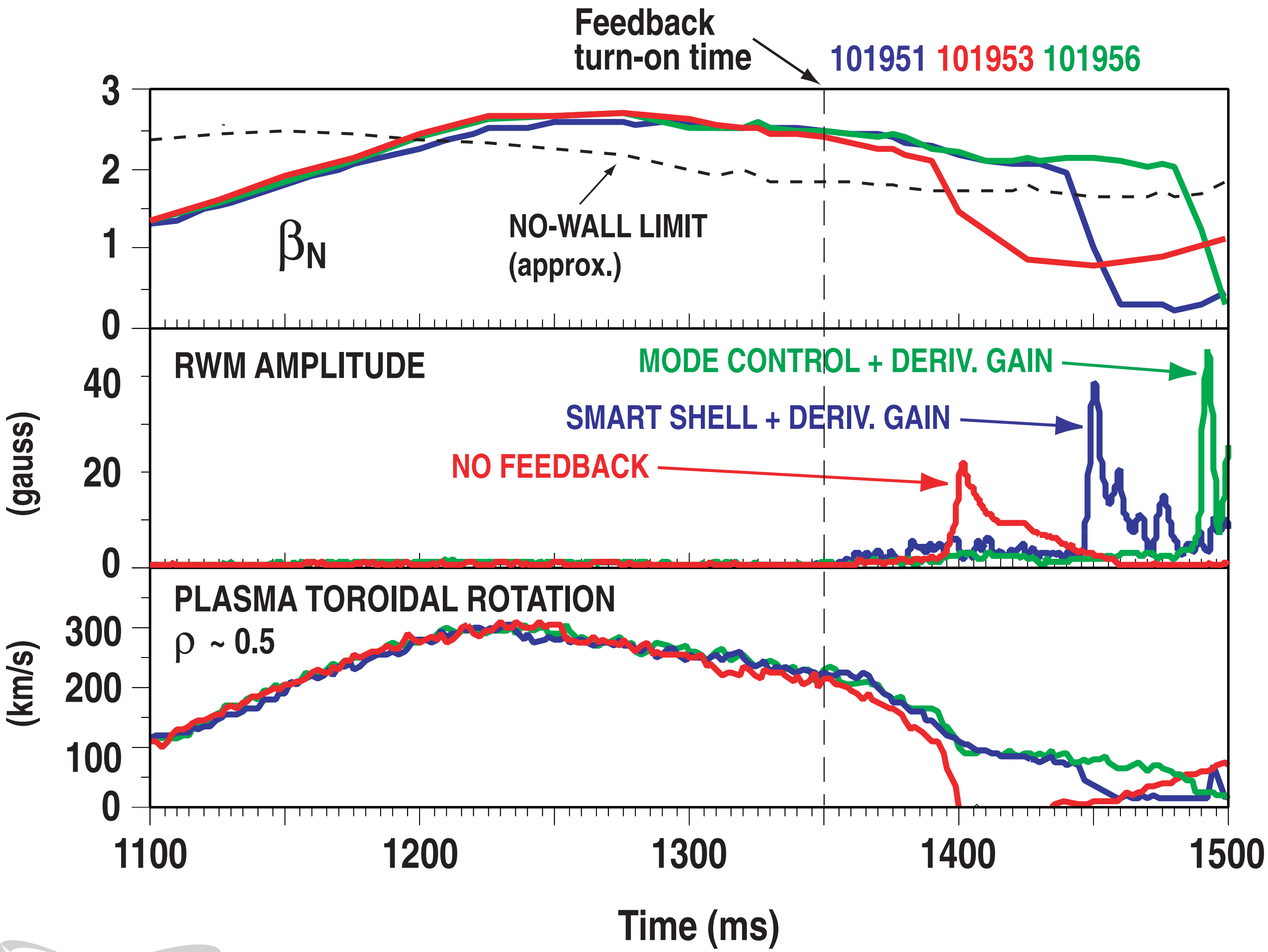
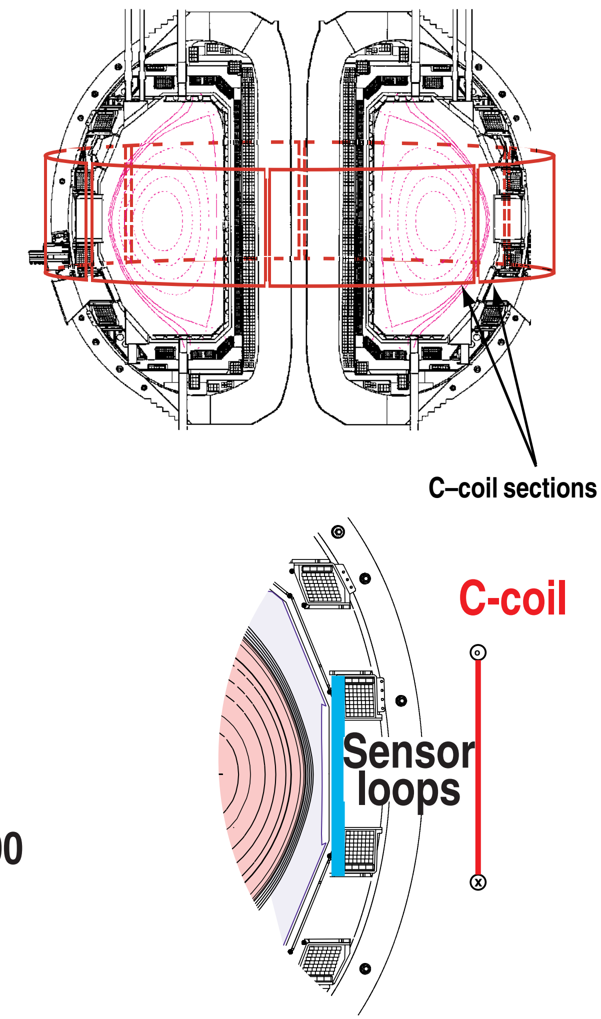
# The n = 1 RWM is controlled by external fields applied in closed loop feedback

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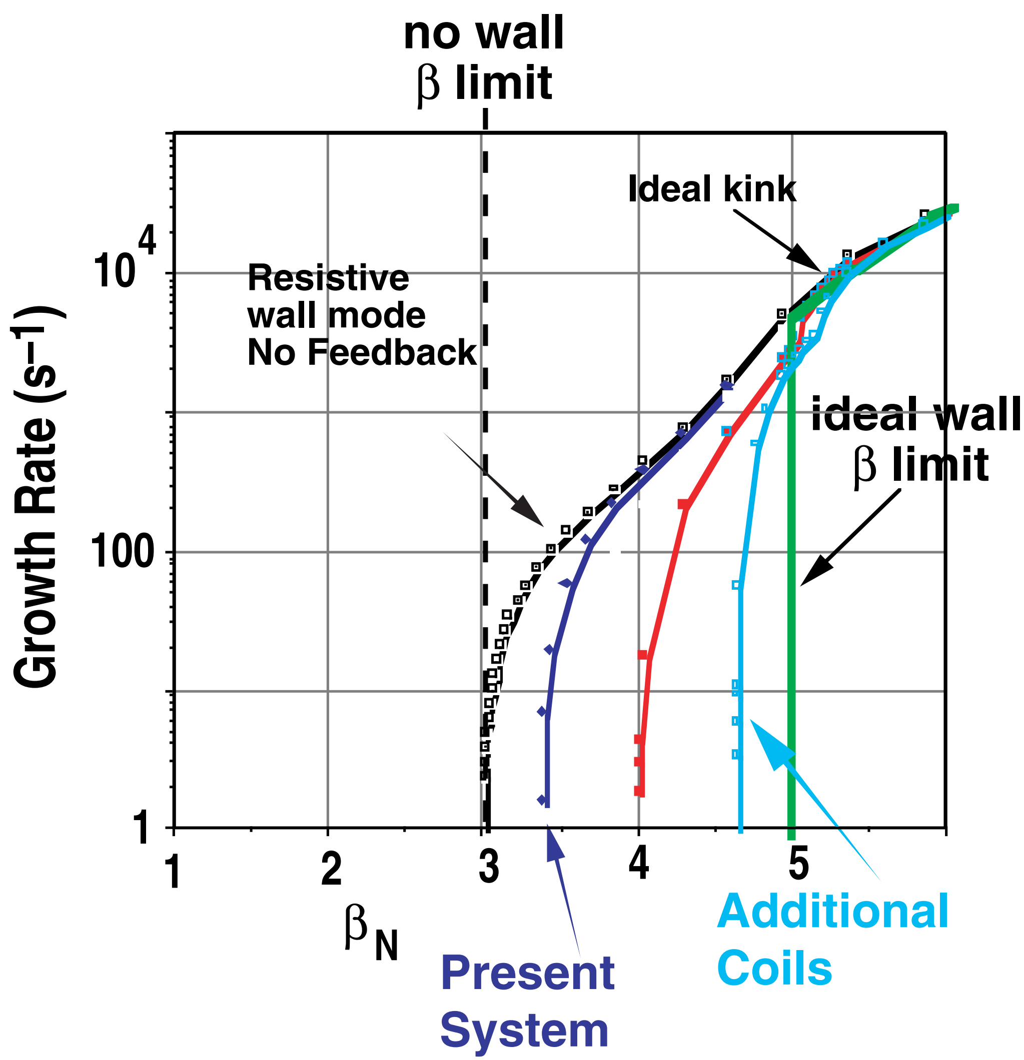
# VALEN model agrees with experiment, predicts RWM stabilization

- Existing 6 coil set can increase RWM stability limit to $\beta_N \sim 3.4$ for basic "smart shell" control algorithm

- Base six-element C-coil can reach 50% towards ideal wall beta using internal Bp sensors

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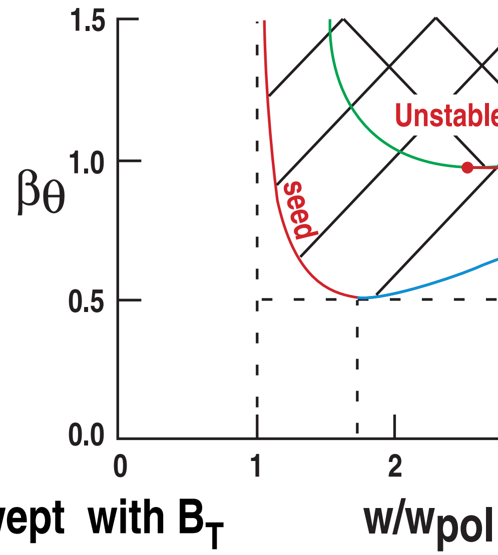
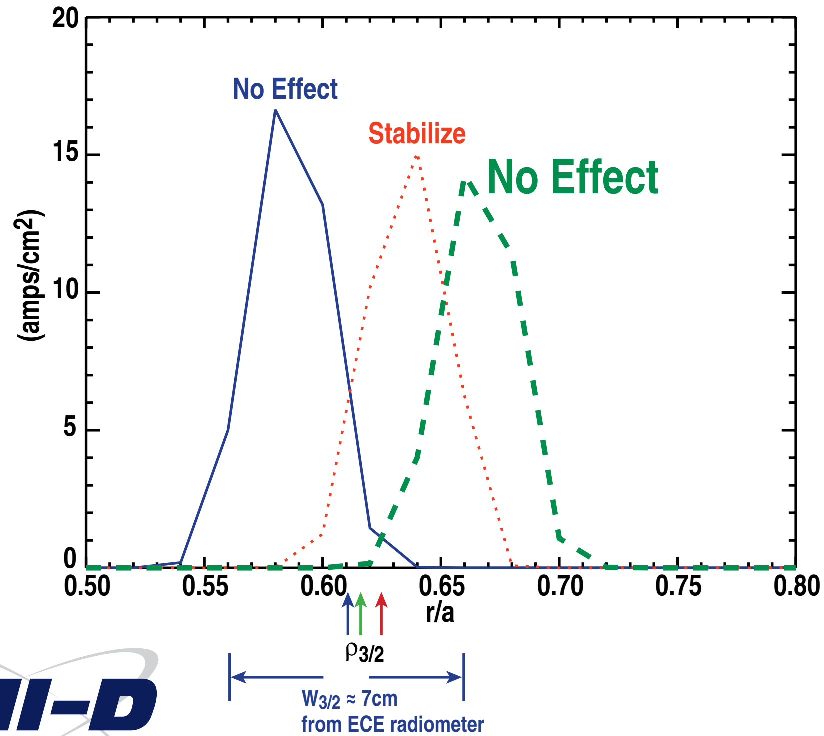
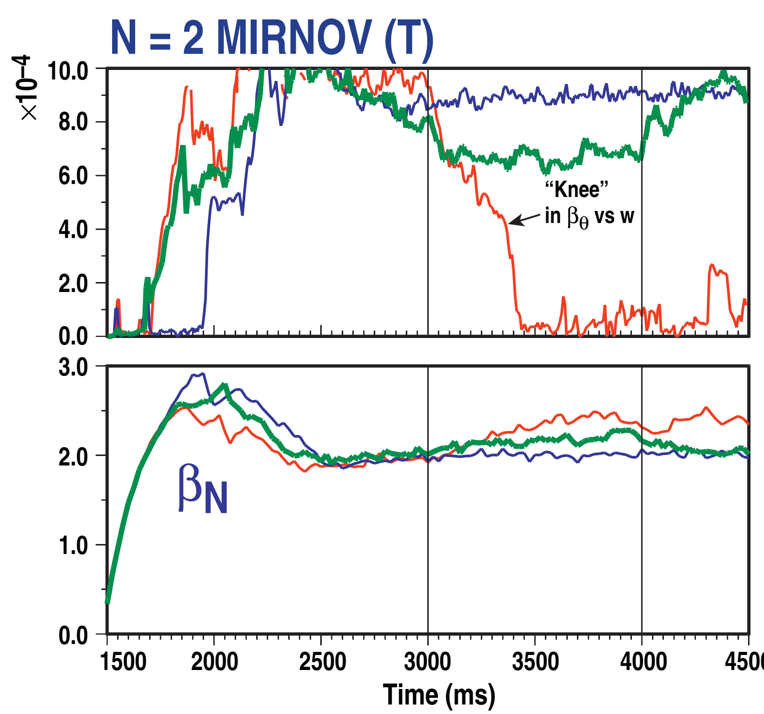
- Resistive Wall Mode (RWM) feedback control with external loops
- Neoclassical Tearing Mode (NTM) suppression with ECCD

# Localized ECCD used to stabilize NTM's




Localized ECCD swept with $B_T$

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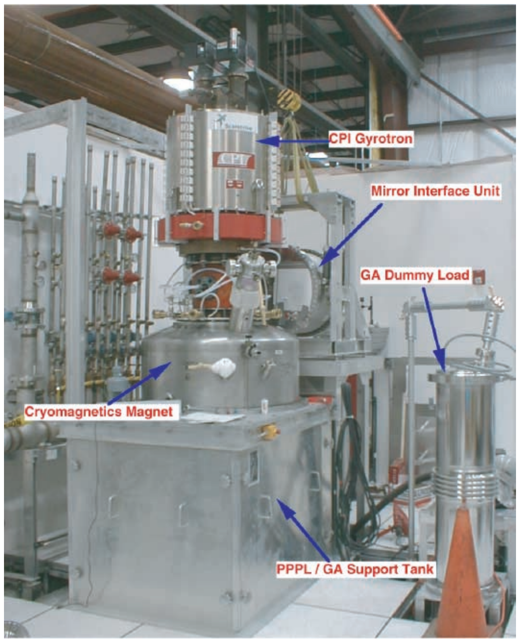
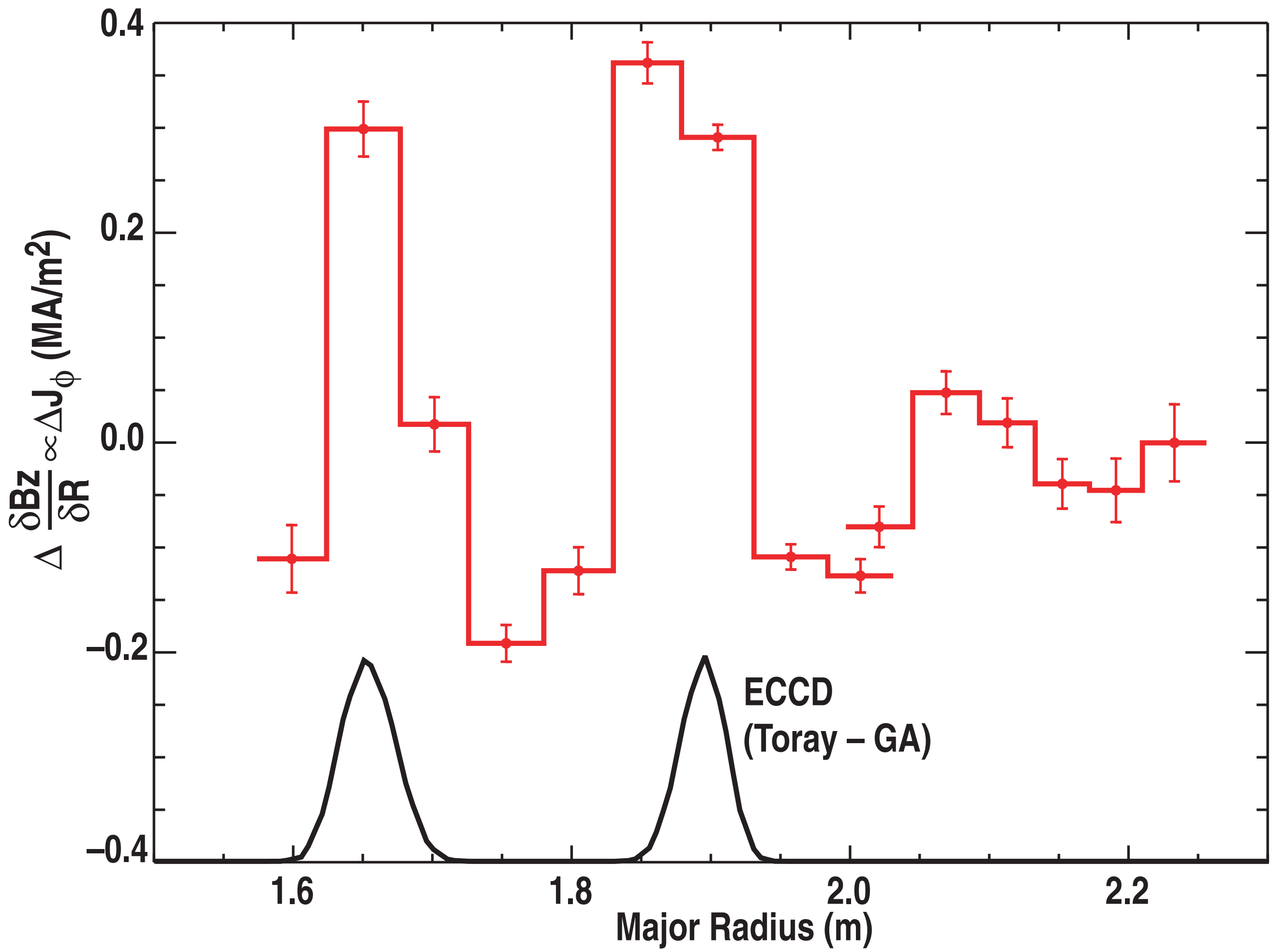
# Localized change in current profile during ECCD is clearly observed in elming H–mode plasmas

Three – 1 MW Class Gyrotrons (2000)

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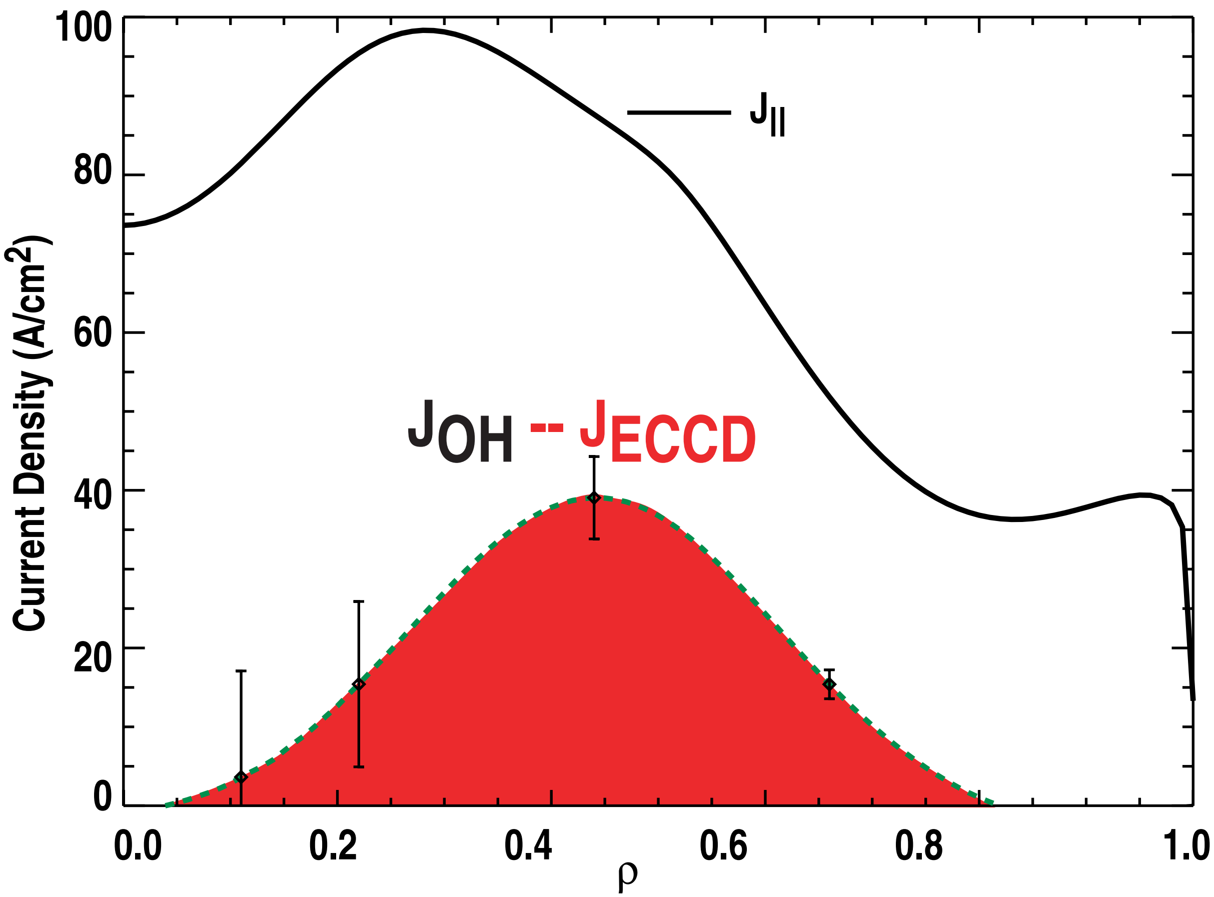
*see Prater EX 8/1*

# 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

**New for 2001:**

**3 - 1 MW, 2s Gyrotrons**
**3 - 1 MW, 10s Gyrotrons**

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000-00/rs

# Overview of Recent Experimental Results from the DIII–D Advanced Tokamak Program

## DIII-D "*AT*" research goals are to optimize Tokamak Operation:

- ***We have made progress since the last IAEA in:***

***Performance*** $\beta_N H_{89P}$ ~ 9 for 16 $\tau_E$,
~ 7 sustained

*New QDB regime with Core ITB, Quiescent edge with density control in Counter NBI*

***Development of AT control tools***

- ***Particle control with Divertor-2000***
- ***RWM feedback control***
- ***ECH stabilized NTM, Core ITB***
- ***Other ITB tools - impurities, pellets***

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