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 ⇒ High plasma pressure (high β)
  - High fusion gain ⇒ Good energy confinement (high τ_E)
  - Non-inductive current sustainment ⇒ High bootstrap fraction (high β_P)

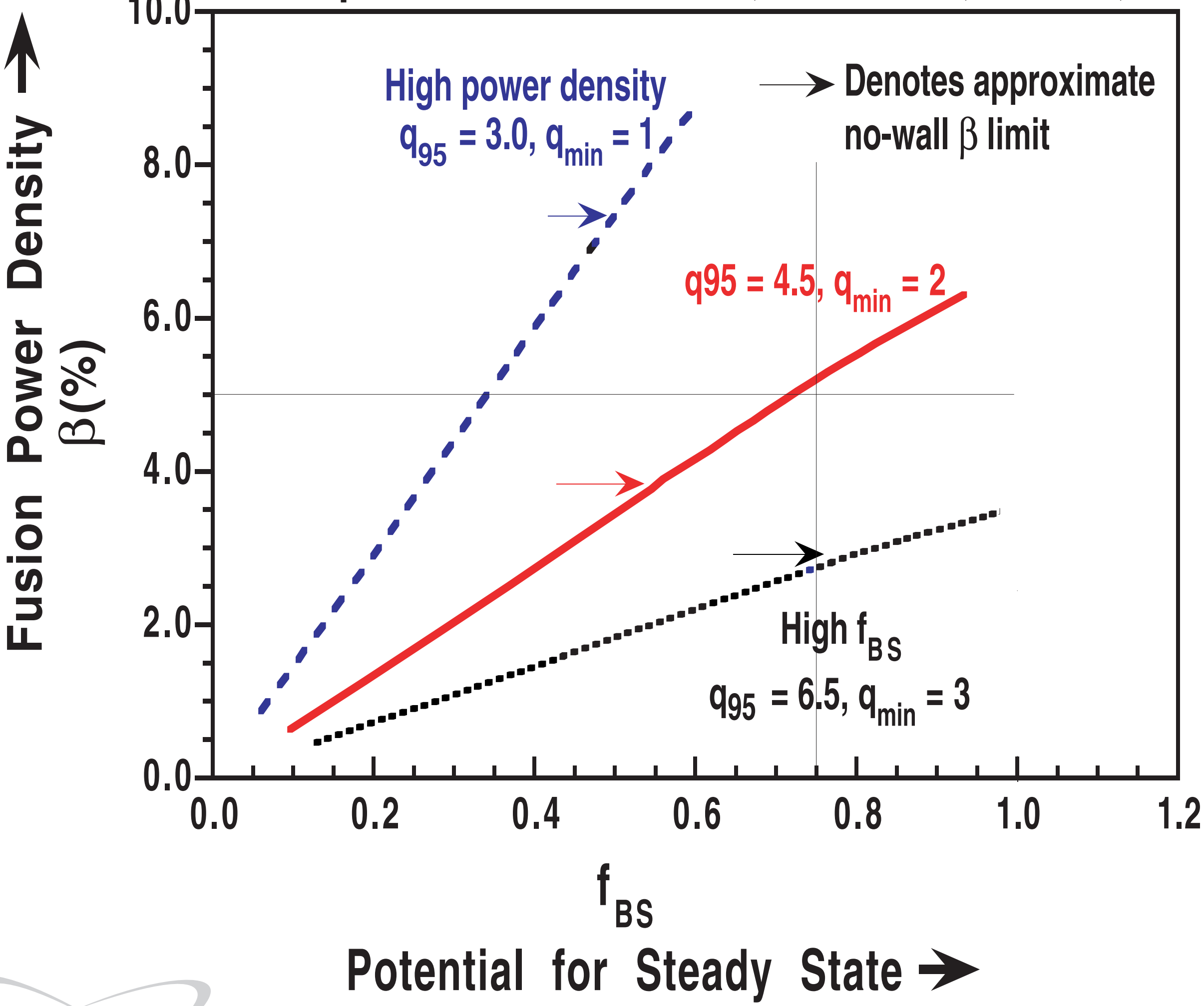
- Gain and bootstrap current have conflicting scaling
  - Fusion gain: $\beta\tau_E \propto (\beta_N/q)\ (H_{89}/q^{\alpha})$
  - Bootstrap current: $f_{BS} \propto \beta_p \propto q\ \beta_N$

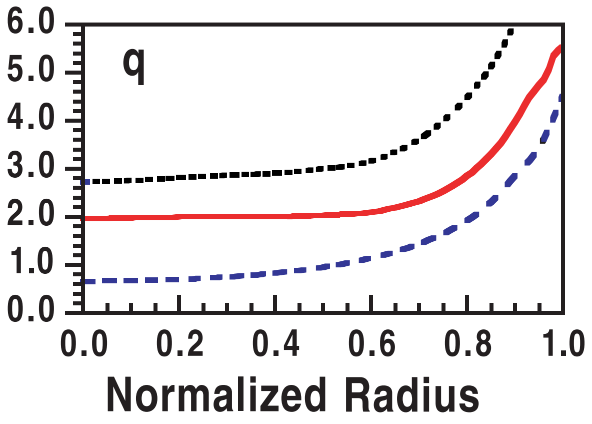
⇒ Self-consistent scenarios require β_N and H_{89} above conventional tokamak values

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

CHOSEN SCENARIO REPRESENTS COMPROMISE BETWEEN ATTAINABLE FUSION POWER DENSITY AND BOOTSTRAP CURRENT FRACTION

TOQ Equilbria with R =1.68 m, a = 0.60 m, κ = 1.8, δ = 0.6





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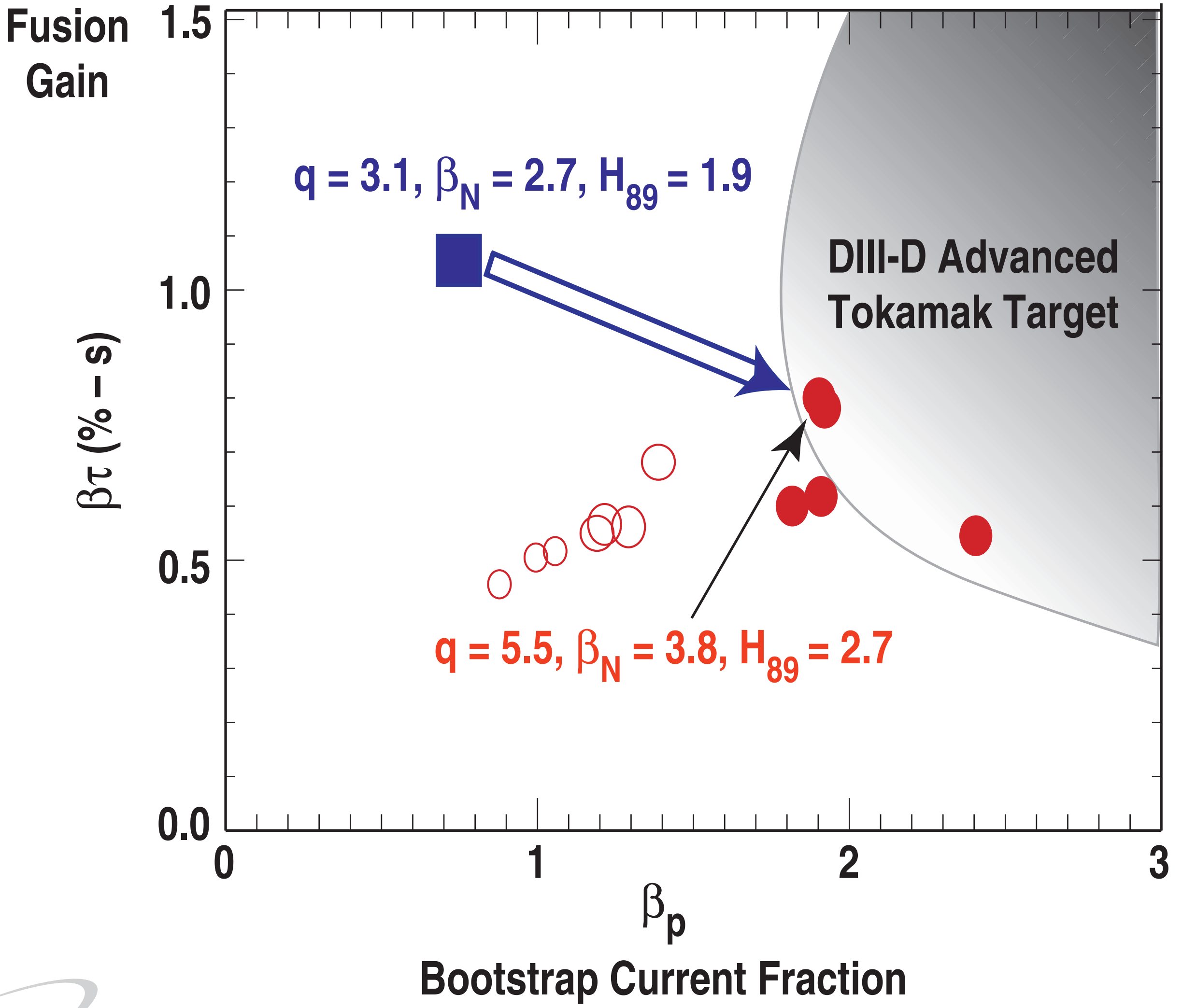
DIII–D STUDIES HAVE SHOWN THAT SIGNIFICANT GAIN IN STEADY-STATE CAPABILITY CAN BE OBTAINED WITH MODERATE COST IN FUSION GAIN



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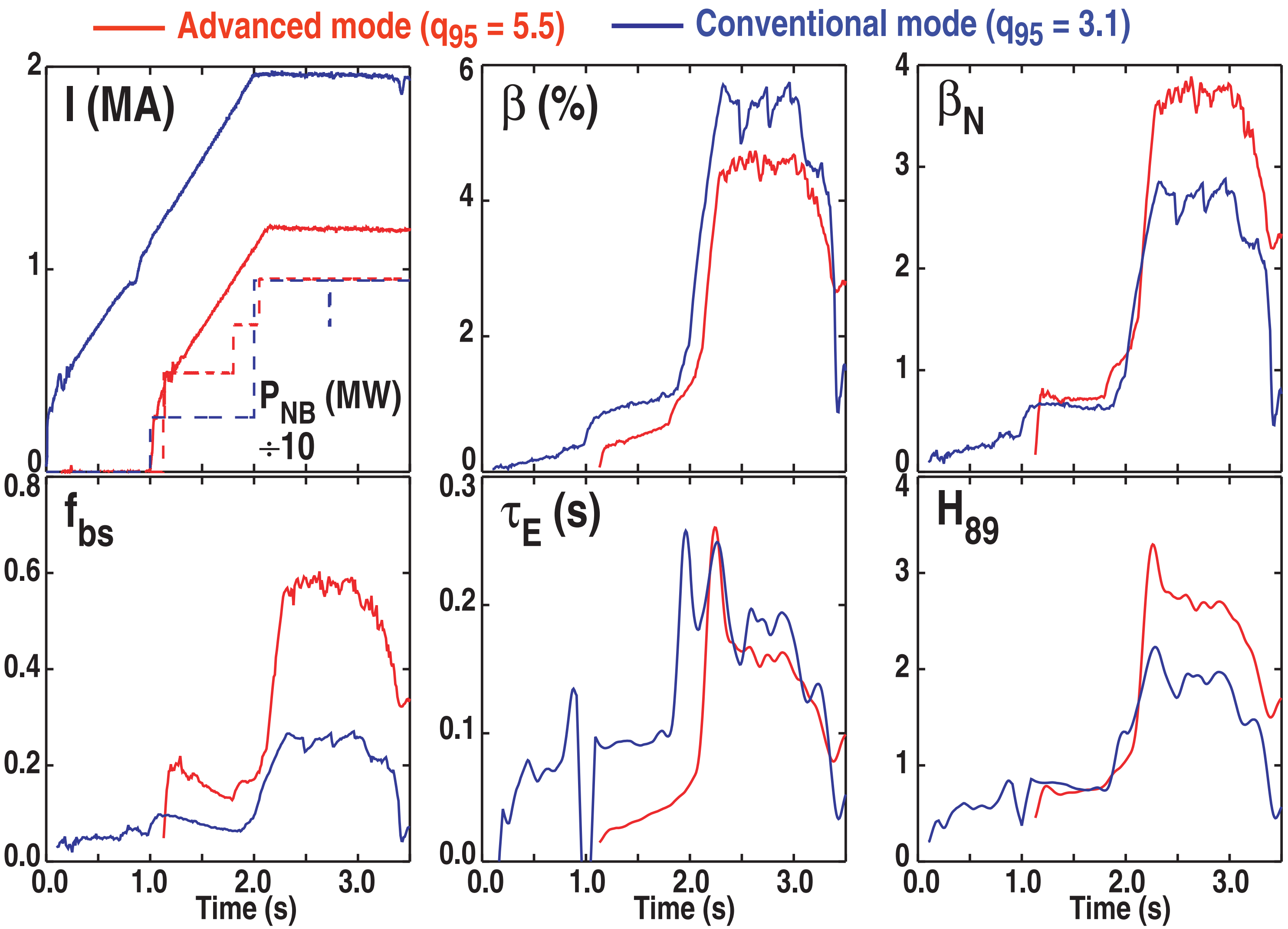
HIGHER f_{BS} WITH SIMILAR $\beta\tau$ IS ACHIEVED IN ADVANCED TOKAMAK SCENARIO AS A RESULT OF HIGHER β_N H



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ACHIEVED β_N IS WELL ABOVE THE CALCULATED n=1 STABILITY LIMIT

$t = 1.8s$

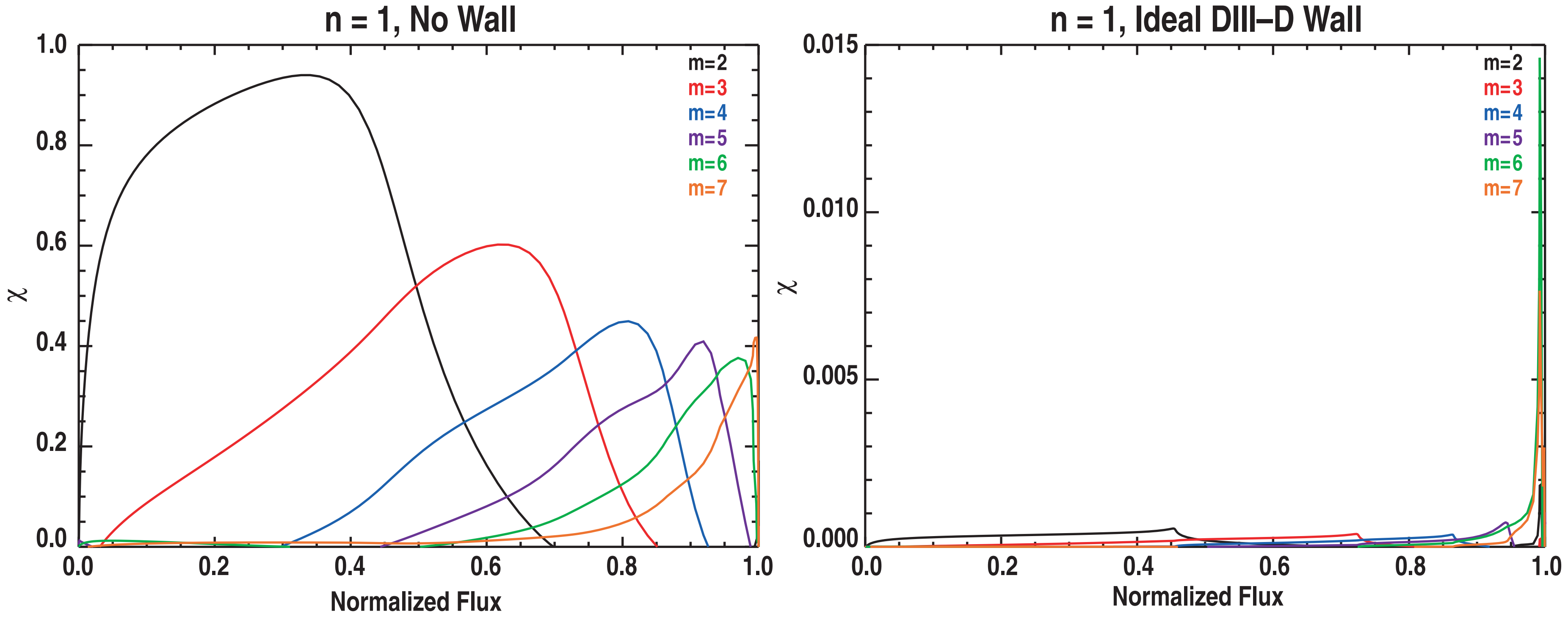
$\beta_N = 4.0$

$\beta_\rho = 1.9$

$q_{min} = 1.5$

$q_0 = 1.88$

$\ell_i = 0.76$



n = 1, No Wall

n = 1, Ideal DIII–D Wall

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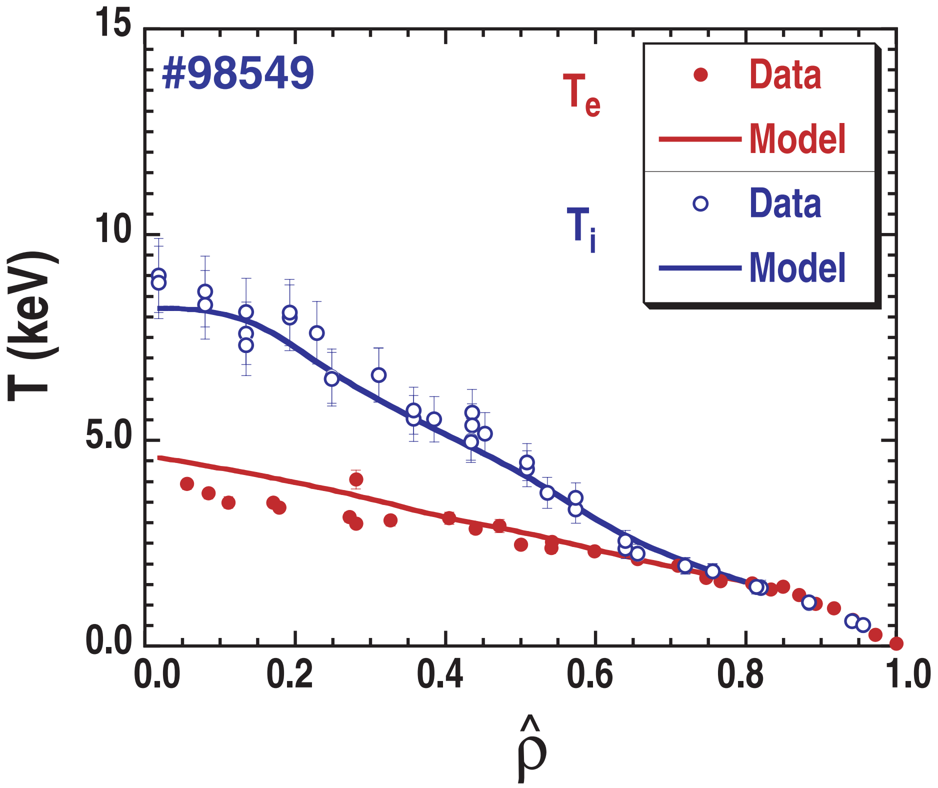
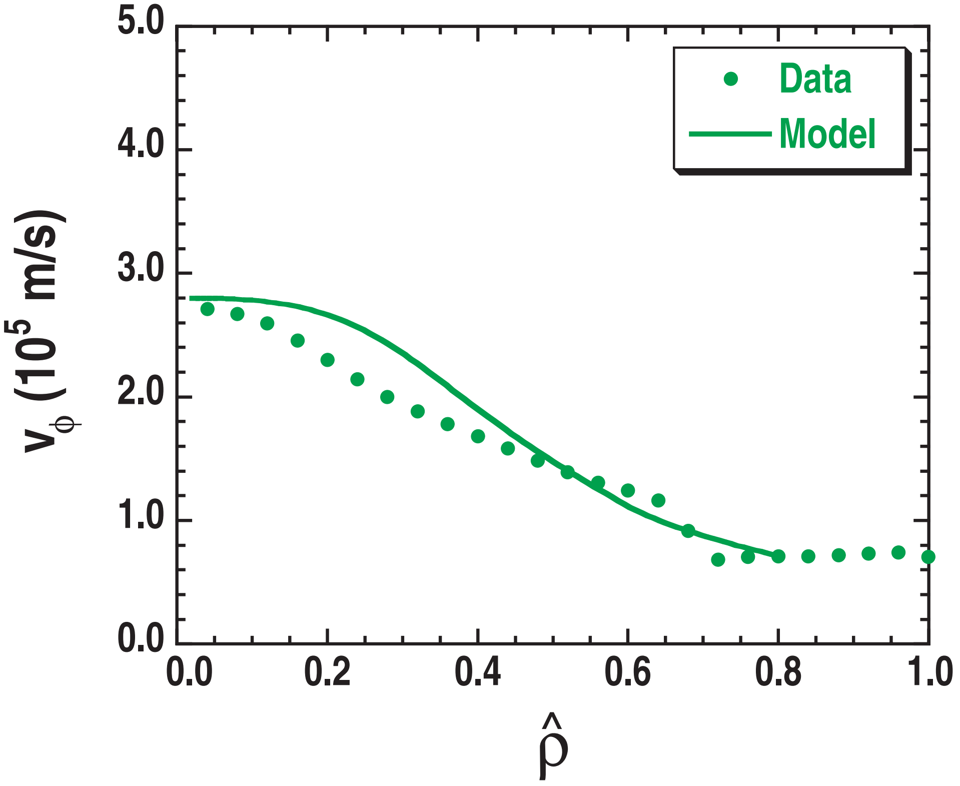
IMPROVED CONFINEMENT IS CONSISTENT WITH DRIFT-WAVE SIMULATION WITH ExB SHEAR

- GLF23 model* self-consistently calculates n_e, T_e, T_i, and v_{tor} resulting from input source profiles and calculated turbulence driven by ITG, TEM, and ETG with effects of E×B shear
- Model predictions are consistent with measured profiles

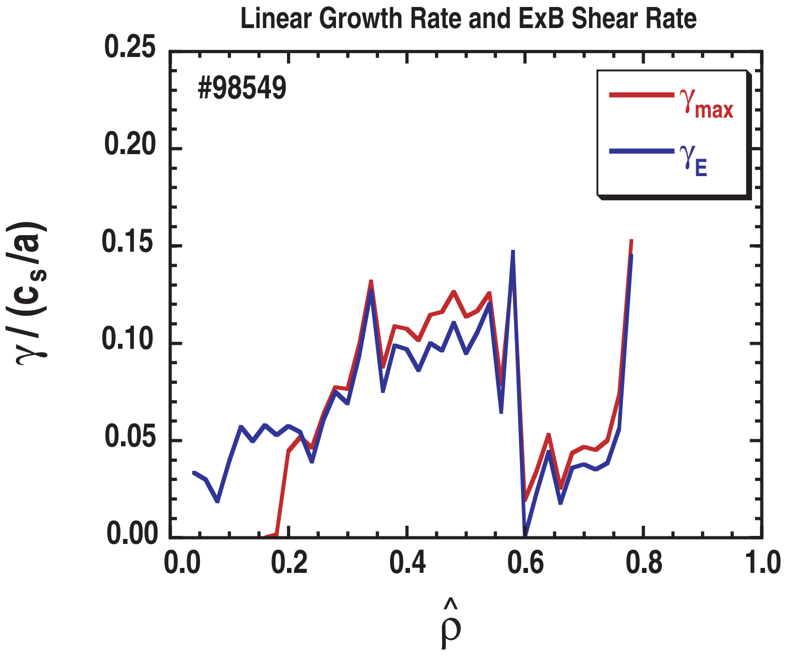


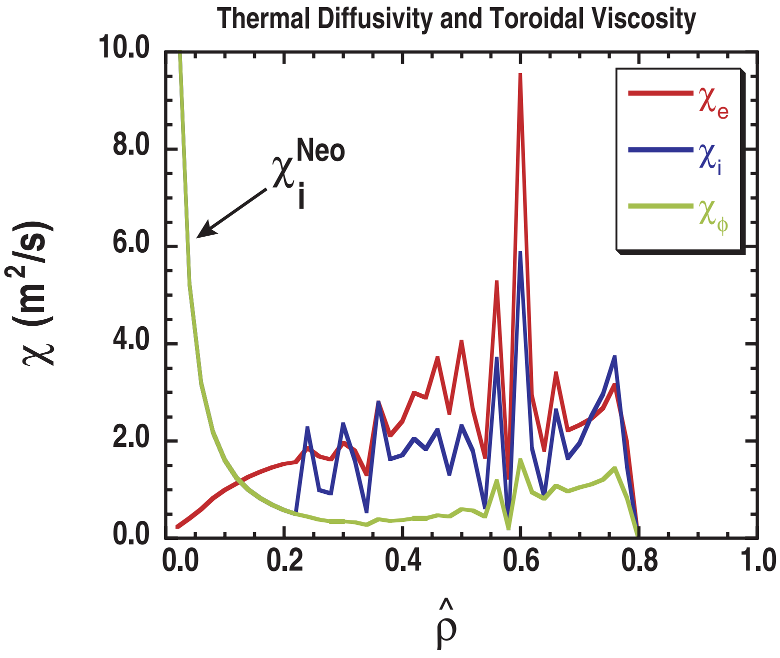


*Waltz et al., Phys. Plasmas 5 1695 (1998)

MODEL SUGGESTS THAT ExB SHEAR REDUCES BUT DOES NOT ELIMINATE TURBULENT TRANSPORT

- Enhanced confinement due to suppressed turbulent transport across most of the plasma radius
- Toroidal viscosity predicted by GLF23 model is approximately a factor of 2 lower than the ion thermal diffusivity





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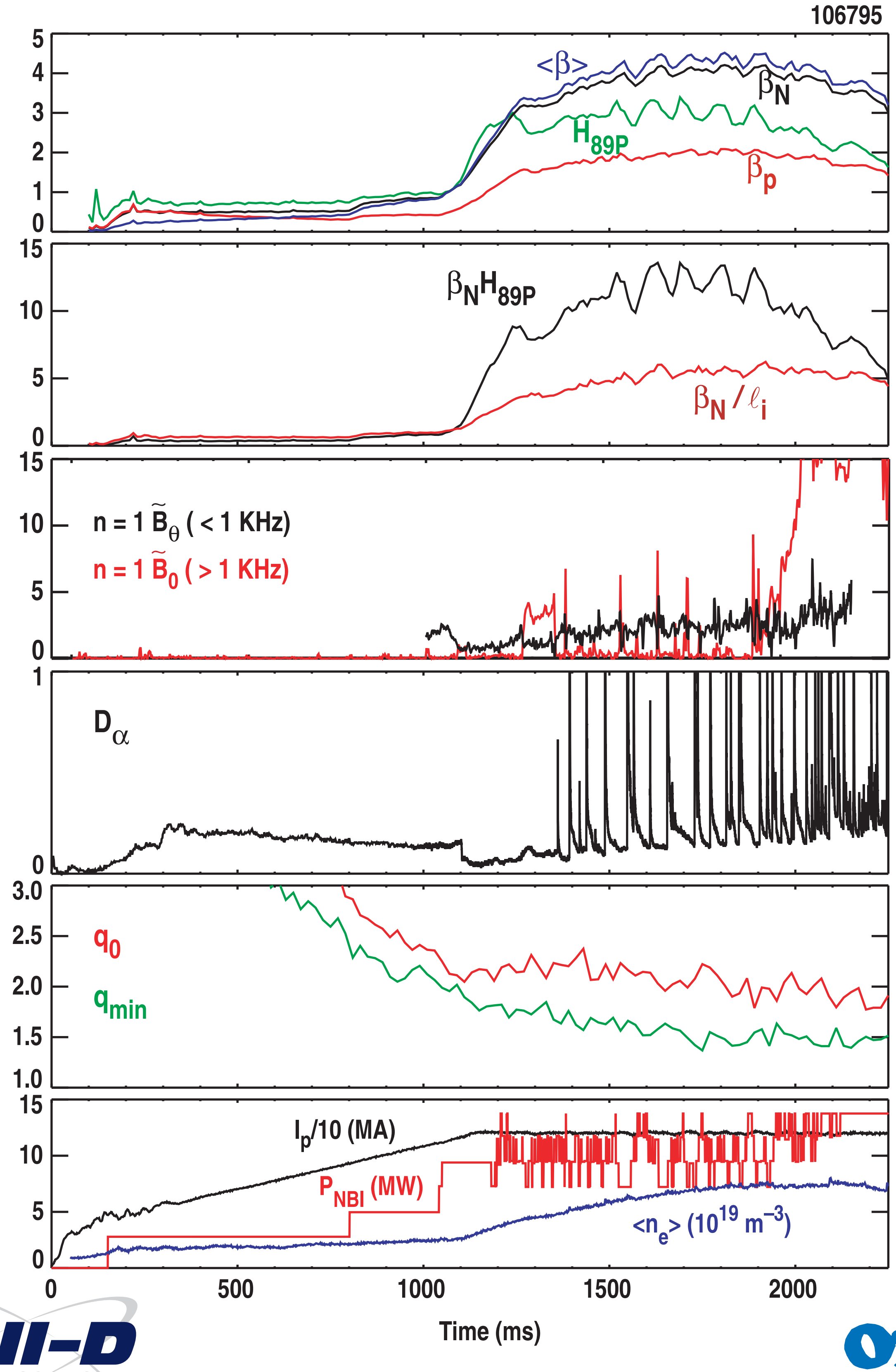
CONDITIONS CONDUCIVE TO HIGH f_{BS} AND HIGH $\beta\tau$ (β_N = 4, H_{89} = 3 WITH q_{min} > 1.5) SUSTAINED FOR $5\tau_E$



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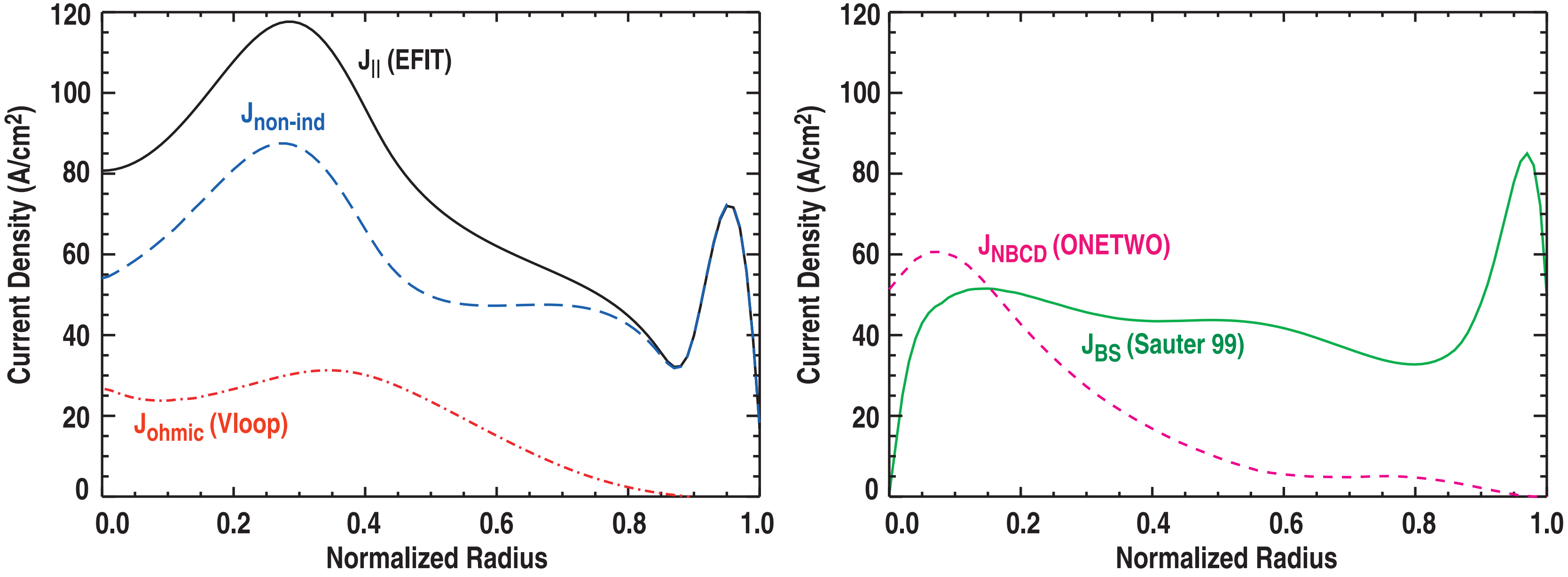
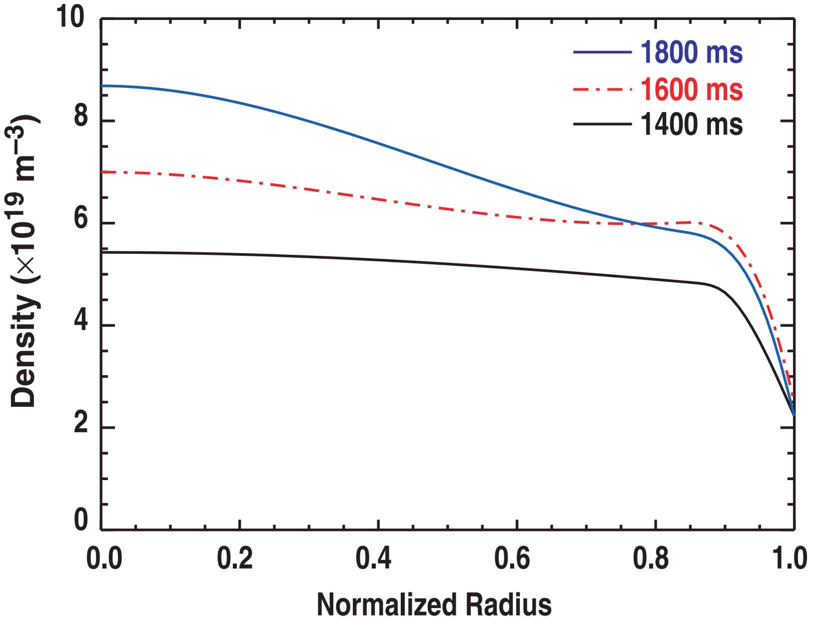
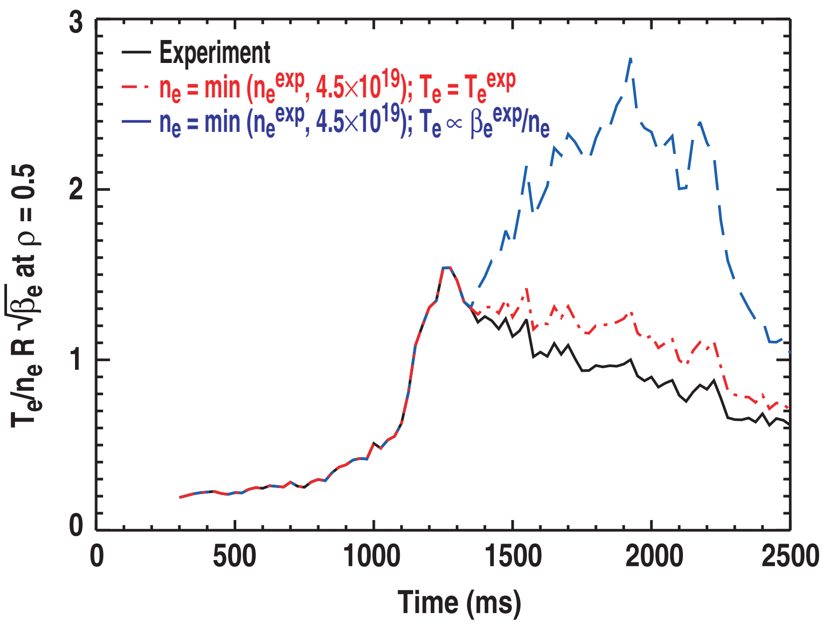
LARGE FRACTION OF CURRENT (f_{BS} ~ 65% AND f_{NI} ~ 80%) IS DRIVEN NON-INDUCTIVELY - REMAINING OHMIC CURRENT PEAKED OFF-AXIS



- Ohmic current at this time has penetrated to core. Replacing Ohmic Current at mid-radius with localized ECCD earlier in evolution should help maintain favorable q profile

UNFORTUNATELY, DENSITY INCREASES UNCONTROLLABLY IN THIS DISCHARGE, LIMITING EFFECTIVENESS OF ECCD -> DENSITY CONTROL IS REQUIRED



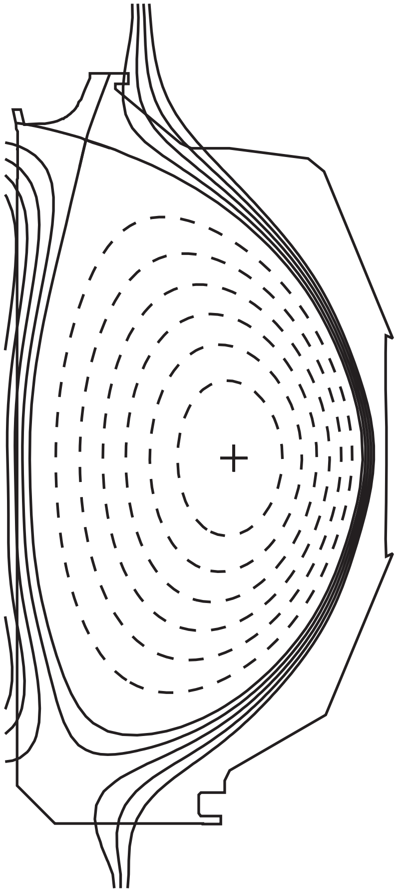


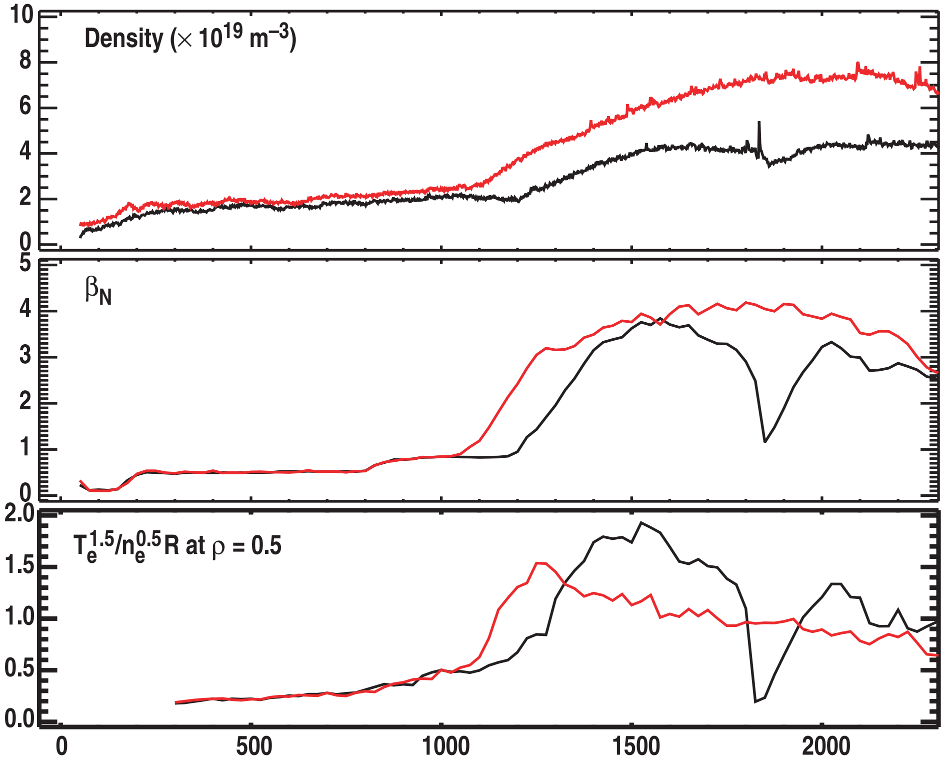
- Density control using the new upper divertor has been demonstrated with slightly unbalanced DN plasma shape - necessary to obtain adequate particle flux to upper divertor (DRSEP > 0.5 cm)

DENSITY CONTROL REQUIREMENTS COME AT A COST AS β LIMIT IS REDUCED IN PUMPING GEOMETRY

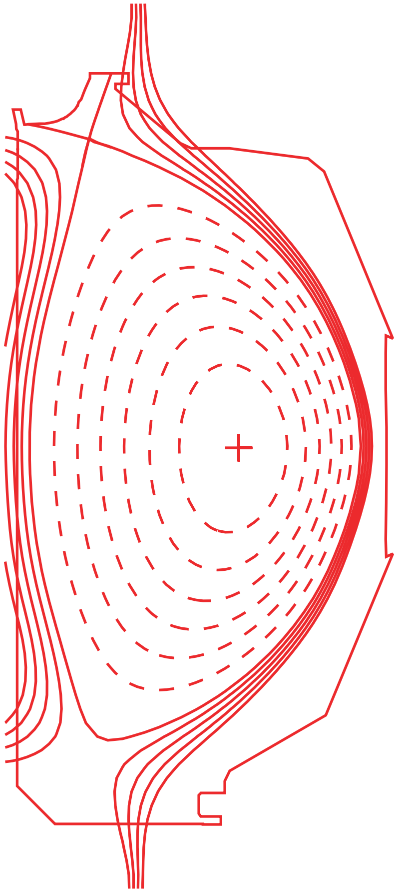
- Primary difference is magnetic balance – DRSEP ~ 1 cm required to obtain adequate particle flux to upper divertor

Pumped Shape





Unpumped Shape



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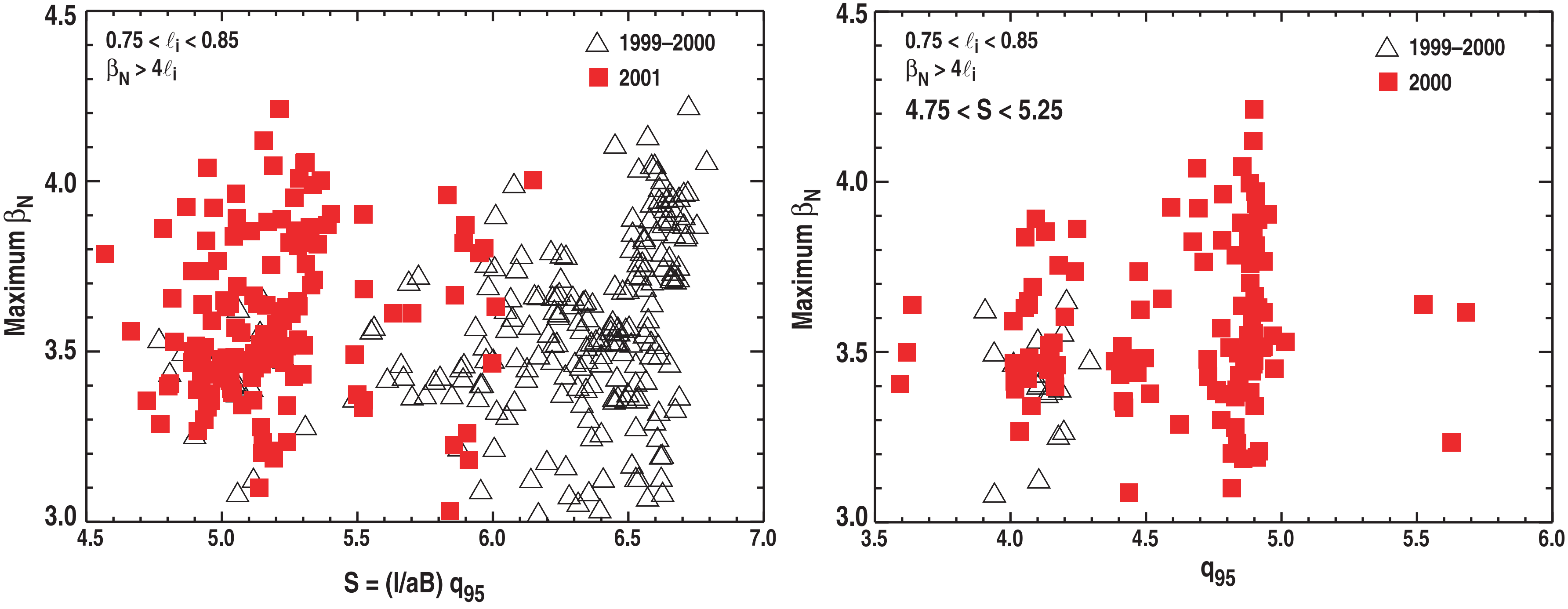
RECENT SHAPE STUDIES INDICATE STRONGEST DEPENDENCE IS ON q_{95}

- Increasing DRSEP causes a drop in the shape parameter $S = (I/aB)\, q_{95}$ and q_{95} itself
- 1999-2000 studies indicated variation of RWM β limit with shape parameter and q_{95}



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ECCD SCOPING STUDIES HAVE BEEN CARRIED OUT AT SOMEWHAT REDUCED PLASMA PARAMETERS

- To date, attempts to obtain high performance at densities compatible with high efficiency ECCD operation have not been successful
- In order to validate predictive models of ECCD efficiency in AT-like conditions, studies have been conducted at slightly reduced plasma parameters optimized for maximizing the effect of ECCD for diagnostic purposes..
  - $I_p = 1.1$ MA, $B_T = 1.7$ T
  - $\beta_N = 3.3$, $H_{89} = 2.5$
  - $n_e = 4.0 \times 10^{19}$ m^{-3}
  - EC Power = 2 MW directed for co-current drive at $\rho = 0.3$

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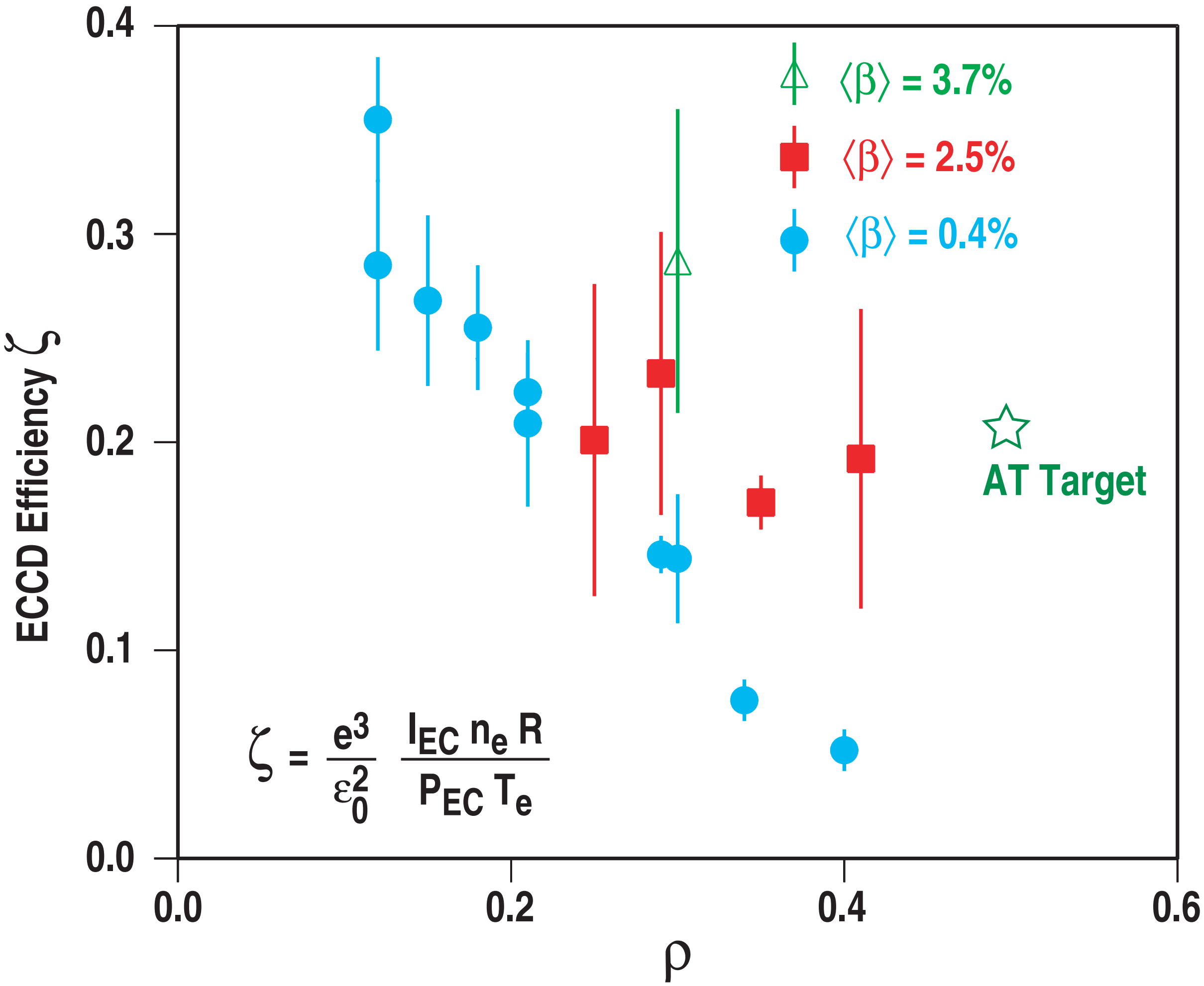
MEASURED ECCD EFFICIENCY IS CONSISTENT WITH EFFICIENCY REQUIRED IN AT TARGET SCENARIO



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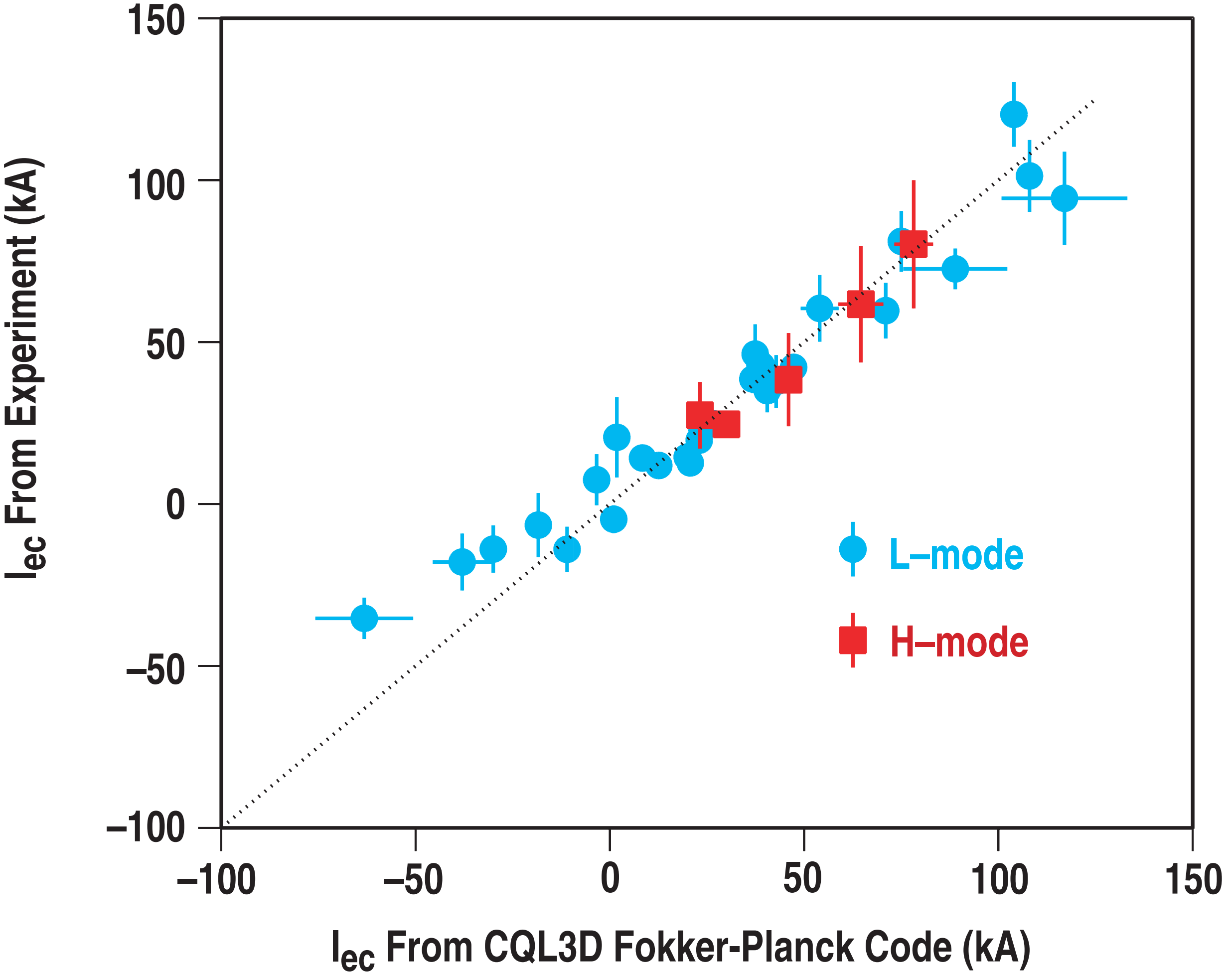
MORE IMPORTANTLY, MEASURED ECCD EFFICIENCY IS CONSISTENT WITH FOKKER-PLANCK PREDICTIONS OVER A WIDE RANGE OF PLASMA CONDITIONS



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SUMMARY

- **The major elements required in achieving integrated, long-pulse, advanced tokamak operation have been demonstrated on DIII-D.**
  - $\beta \sim 4.2\%$, $\beta_p \sim 2$, $\beta_N H_{89} \sim 12$, $f_{BS} \sim 65\%$, $f_{NI} \sim 80\%$ sustained for 5 τ_E
  - Density control ($n_e < 5\times10^{19}$ m^{-3}) at $\beta_N \sim 4$
  - ECCD efficiencies consistent with theory and future AT needs
- **Several issues involving the integration of these elements remain. Of particular importance are:**
  - Obtaining adequate density control at high β
  - Successful implementation of RWM feedback to allow $\beta_N > 4\ell_i$
  - Understanding effect of density/rotation on RWM and NTM limits
- **Physics understanding of stability, confinement, ECCD, and particle control in high performance plasmas has been advanced**
  - **Stability**
    - ★ Error field amplification by RWMs observed and mitigated by improved error field correction techniques (see L. Johnson, P4.008)
    - ★ Onset of m=2/n=1 NTM correlated with q_{min} -> 1.5 - consistent with NTM theory which predicts increase in Δ' as q_{min} -> 1.5 (see D. Brennan P3.004)
  - **Confinement**
    - ★ GLF23 modeling indicates that E×B shear acts to reduce (but not eliminate) turbulence-driven transport, consistent with measured $\chi_i > \chi_{i,\,neo}$
  - **ECCD**
    - ★ Measured ECCD efficiency improves with increasing β_e, consistent with theoretical predictions (see C. Petty P3.062)
  - **Particle Control**
    - ★ Slightly unbalanced magnetic configuration (DRSEP = 1.0 cm) is adequate for sufficient particle exhaust in these high performance plasmas.

ACKNOWLEDGMENT

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