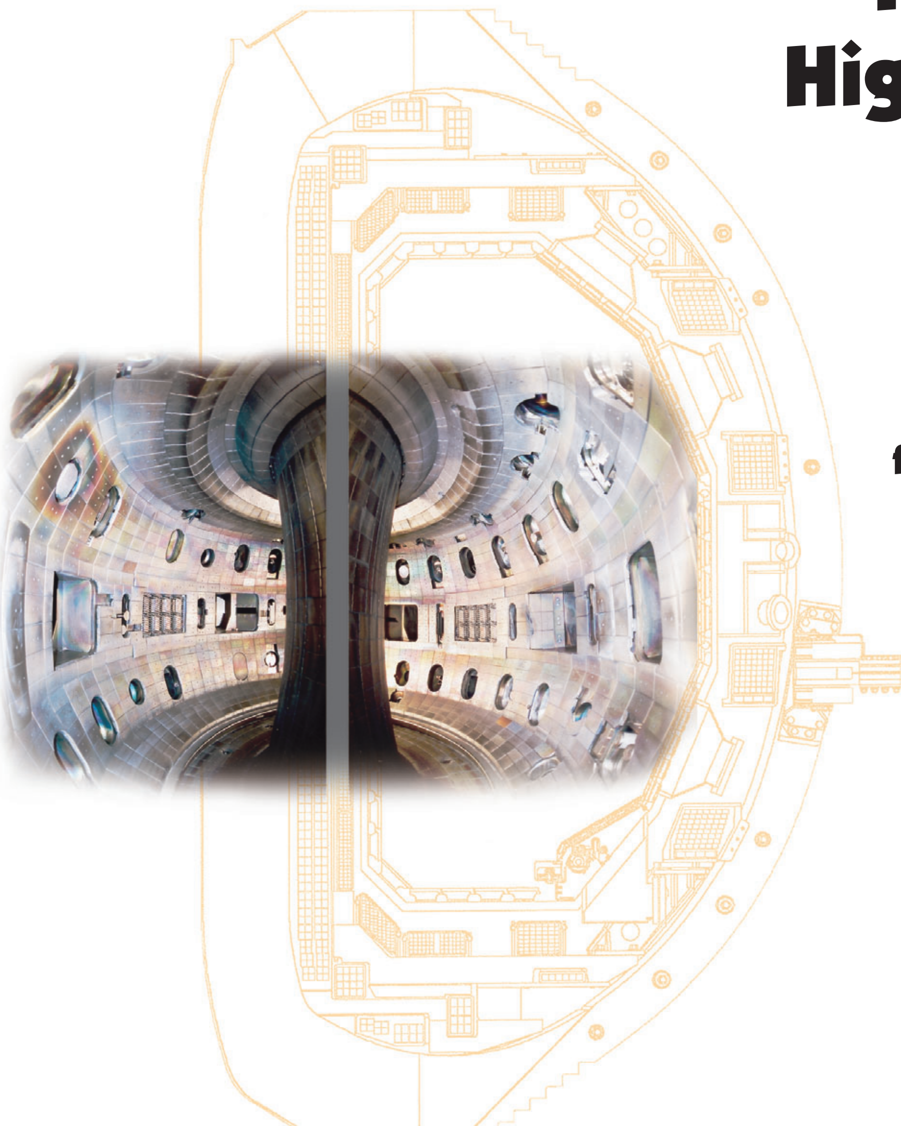

High Bootstrap Fraction, High Performance Plasmas on DIII–D

by
M. R. Wade*

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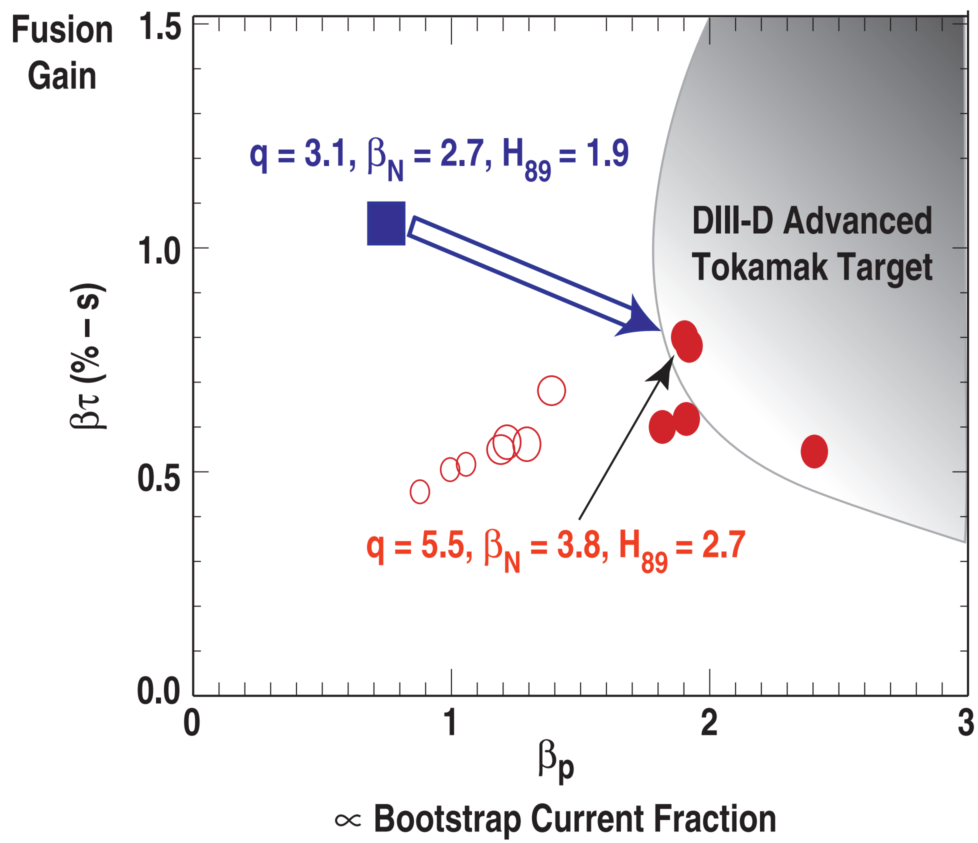
MOTIVATION

- High bootstrap fraction, high performance plasmas offer an alternative to pulsed scenarios based on conventional tokamak physics
  - High $f_{BS} = I_{BS}/I_p$ leading to reduced recirculating power
  - Comparable $\beta\tau$ due to improved stability and confinement limits



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MAJOR ELEMENTS HAVE BEEN DEMONSTRATED — FOCUS NOW IS ON INTEGRATION OF ELEMENTS

- The major elements required in achieving integrated, long-pulse, advanced tokamak operation have been demonstrated

  $\beta = 4.2\%$ $\qquad f_{BS} = 65\%$

  $\beta_p = 2$ $\qquad f_{NI} = 80\%$

  $\beta_N H_{89} \geq 10$ for 600 ms ($\sim 4\ \tau_E$)

  — Density control ($n_e < 5 \times 10^{19}\ m^{-3}$) 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 β_e for ECCD at high β

  — Avoiding NTM at high β

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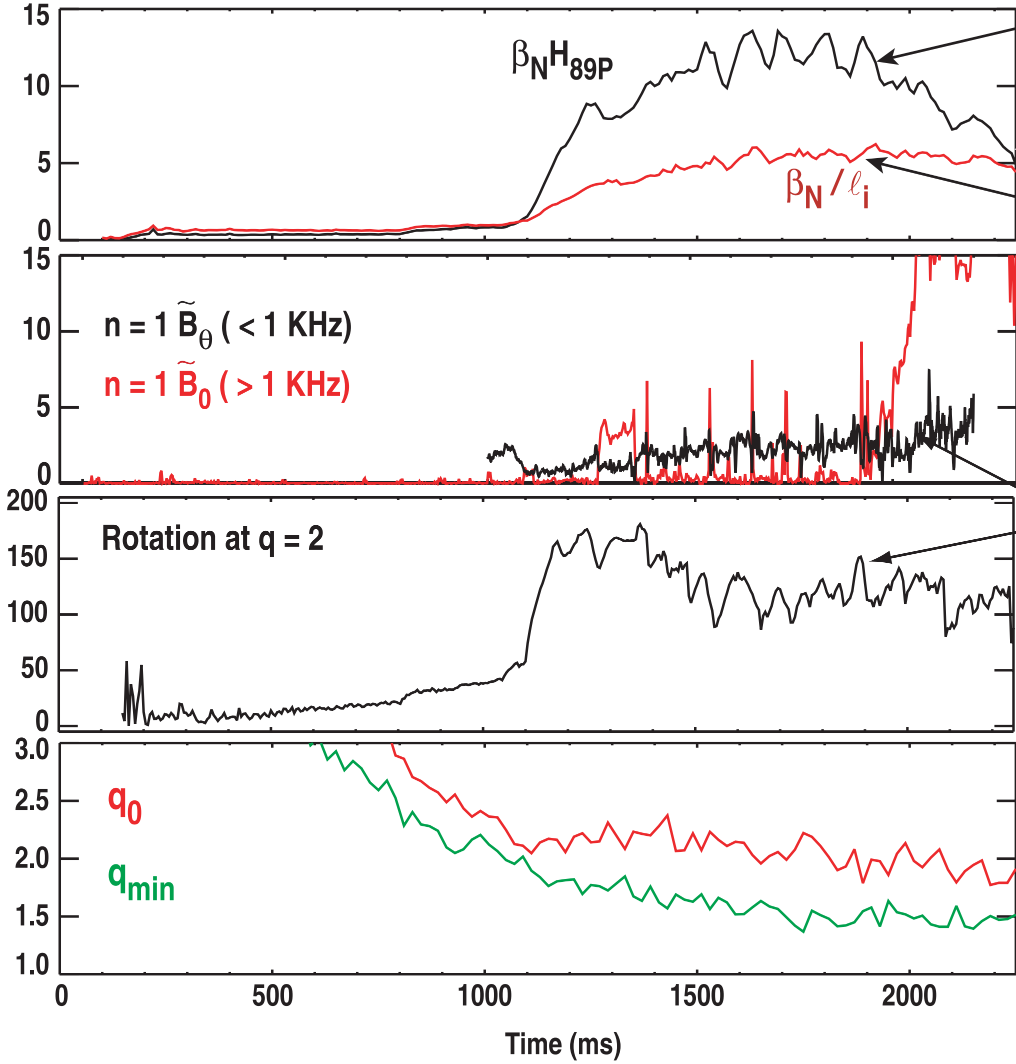
CONDITIONS CONDUCIVE TO HIGH f_{BS} AND HIGH $\beta\tau$ ACHIEVED
($\beta_N \approx 4$, $H_{89} \approx 3$, $\beta_p \approx 2$)



$\beta_N H_{89}$ > 10 sustained for 600 ms (~4τ_E)

β_N/ℓ_i ~6 approached

- Minimal MHD activity during high performance phase

Small RWM amplitude due to sustained plasma rotation (Garafalo BI1.002)

- NTM limits duration as $q_{min} \rightarrow 1.5$

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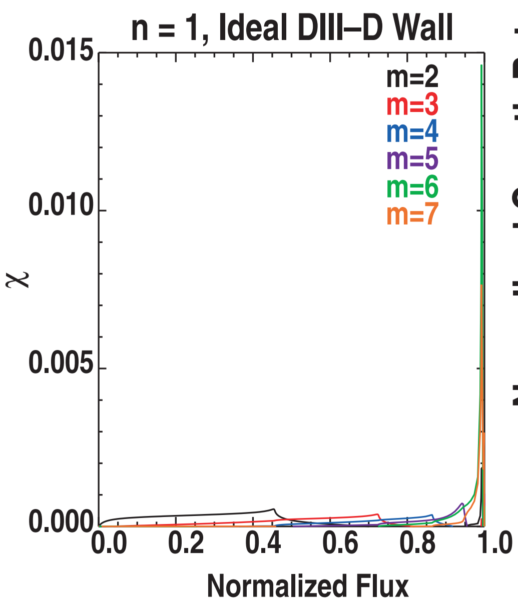
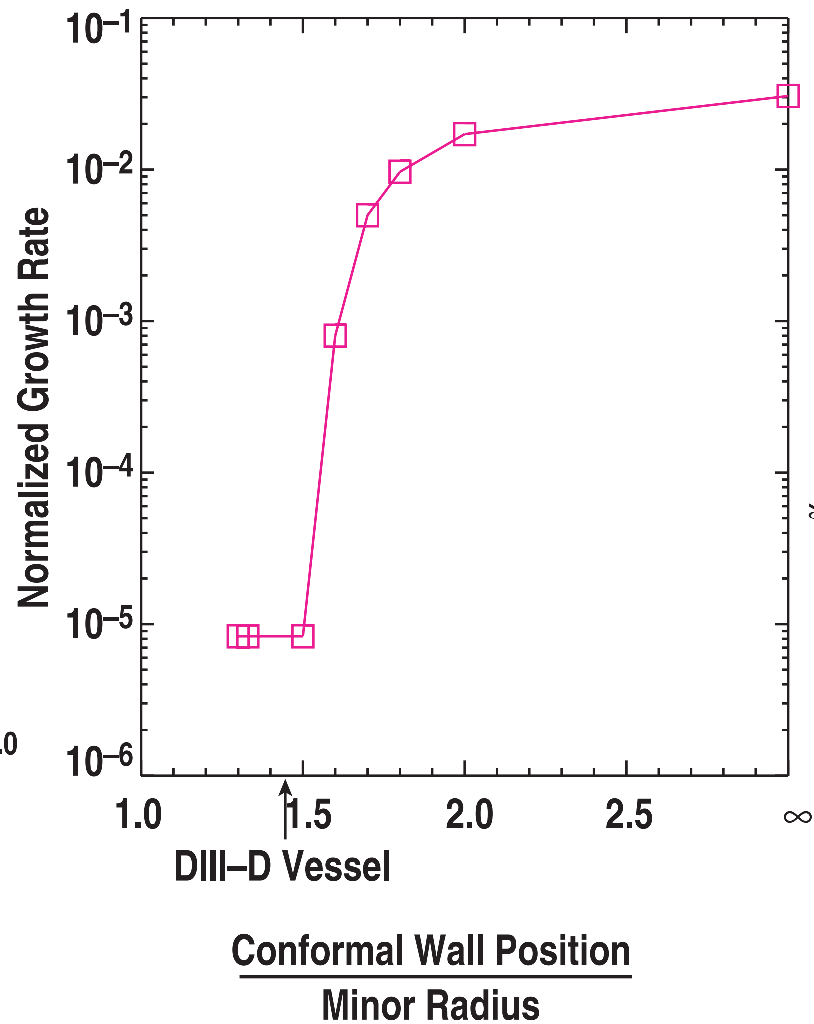
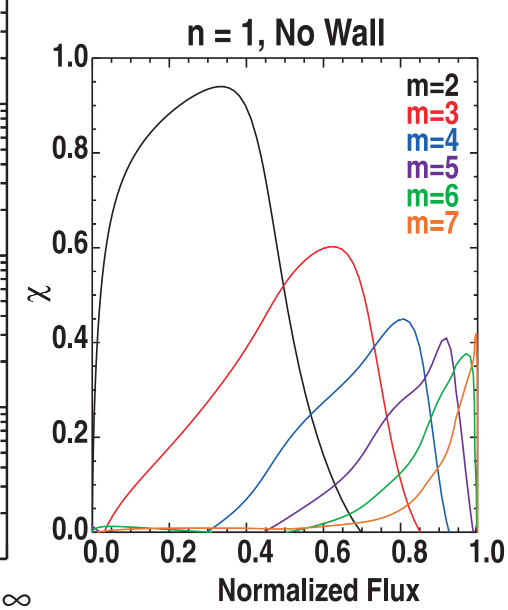
ACHIEVED β IS WELL ABOVE CALCULATED NO–WALL n = 1 IDEAL LIMIT







(Ferron RP1.013)

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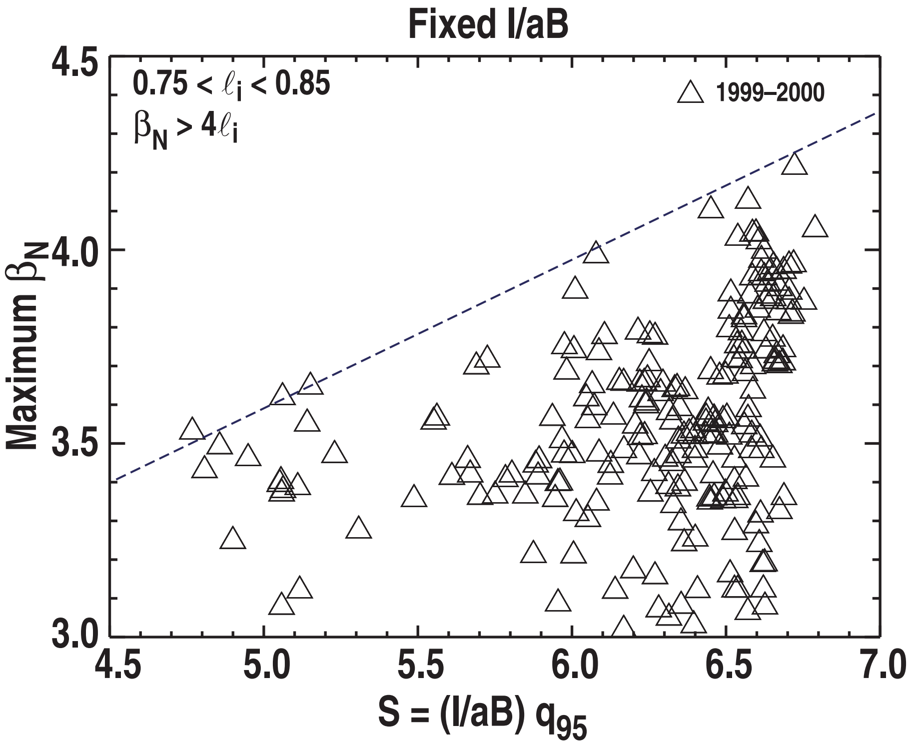
EXPERIMENTAL STUDIES INDICATE β_N INCREASES WITH q_{95}; DEPENDENCE NOT EXPLAINED BY NO-WALL, n = 1 β LIMIT

- 1999-2000 studies indicated variation of RWM β limit with shape parameter and q_{95}



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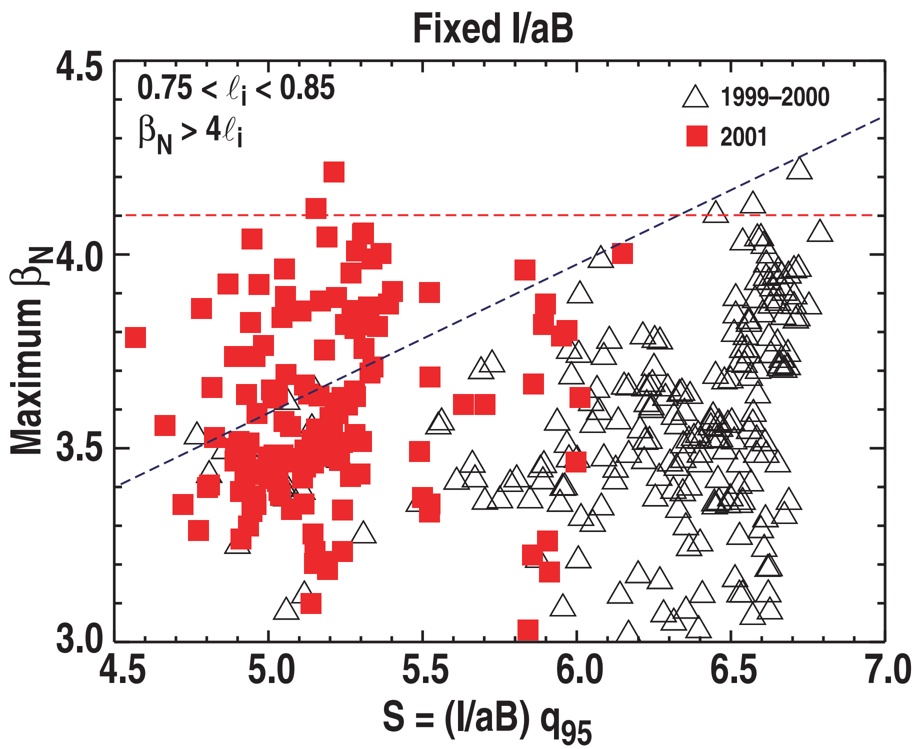

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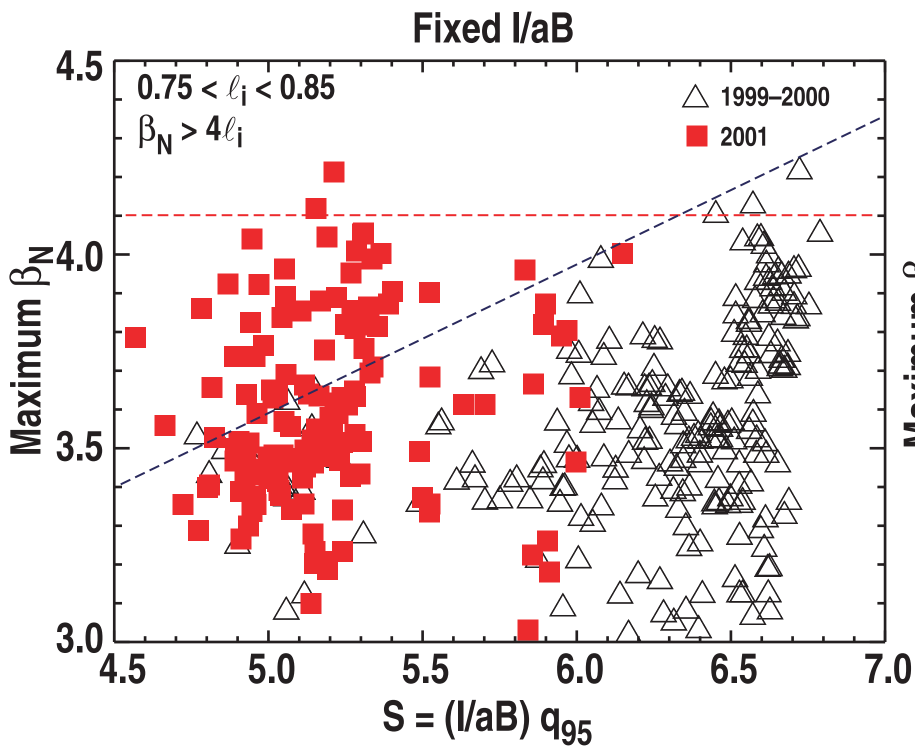

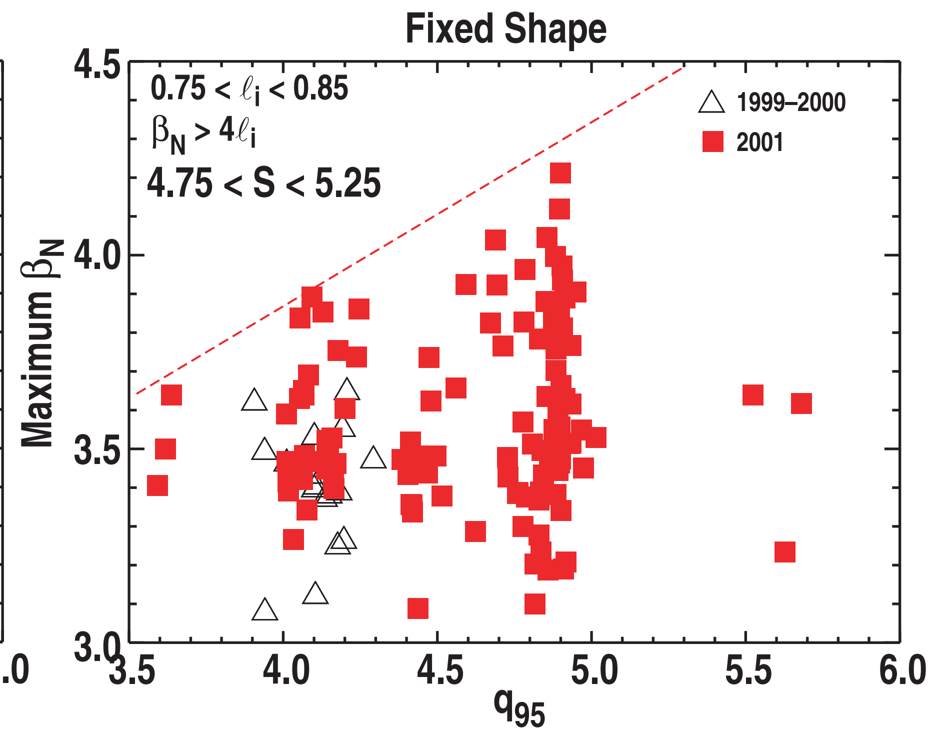

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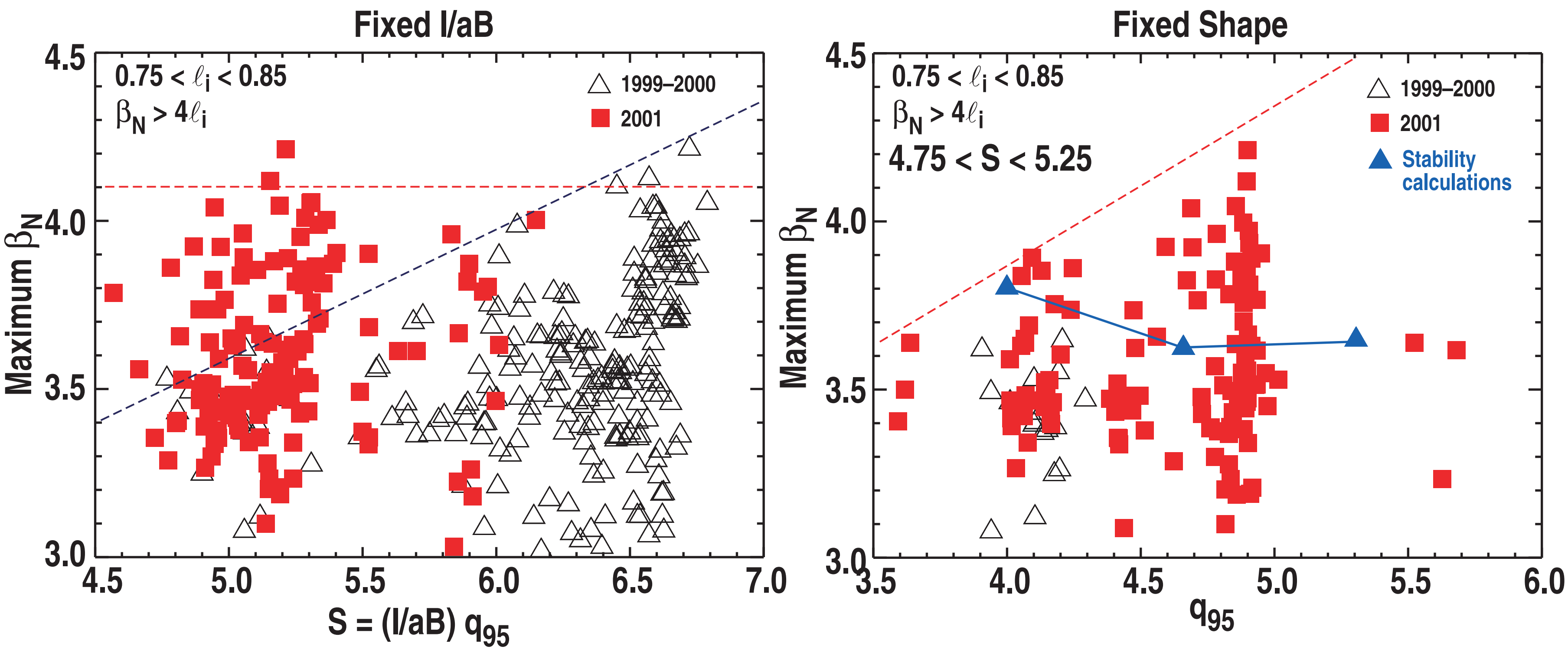

- Discrepancy between experimental and theoretical trends suggests more physics involved than simply no–wall, n=1 stability

(Ferron RP1.013)

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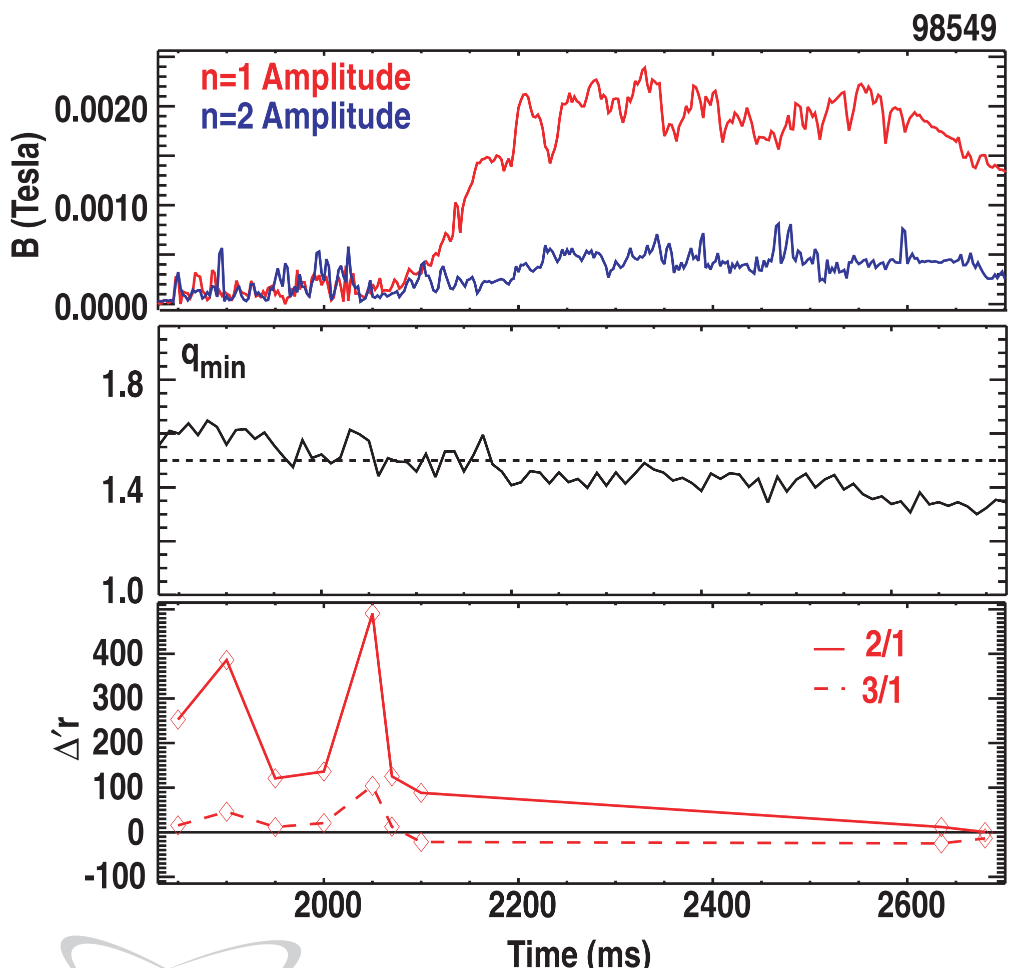
2/1 TEARING MODE DESTABILIZED AS $q_{min} \to 1.5$
THEORY INDICATES CLASSICAL DESTABILIZATION AS $\Delta' > 0$

- Tearing modes generally occur with $\beta_N > \beta_N^{nowall}$ and with q_{min} 1.5 – 1.8



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130-01/jy

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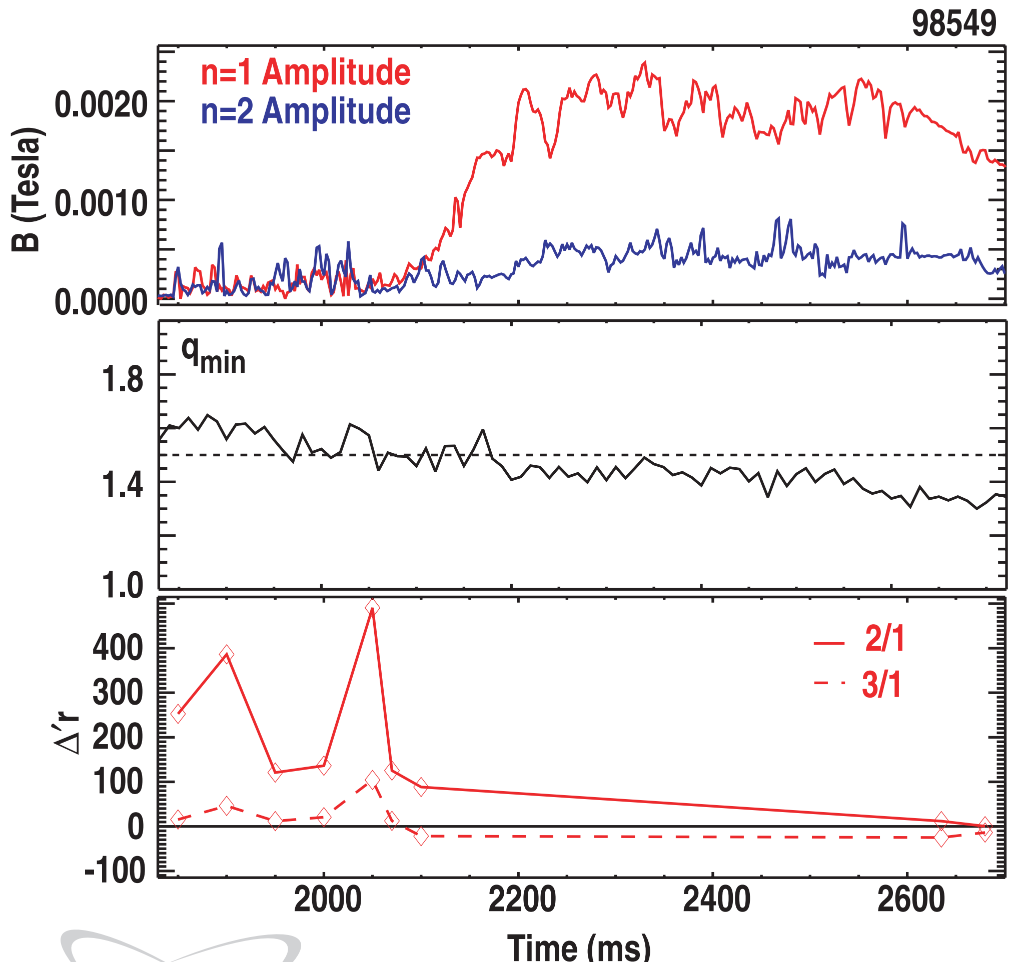

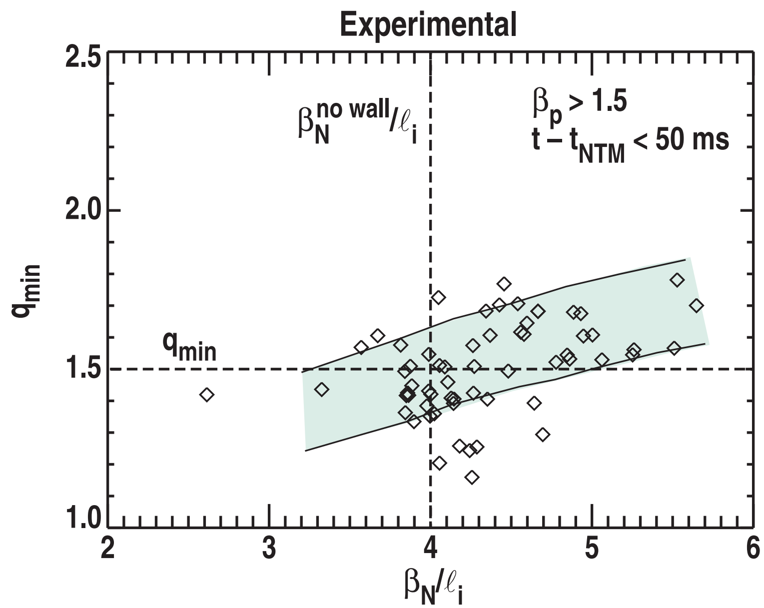

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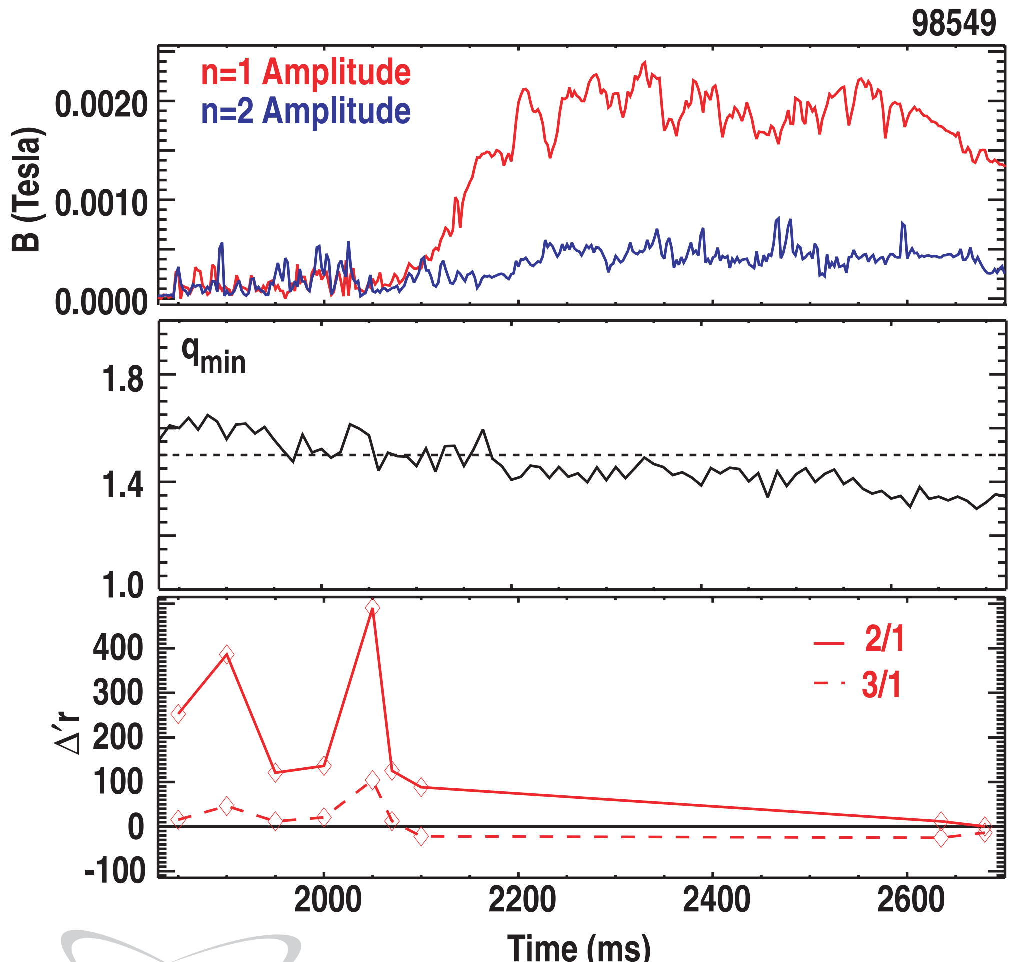
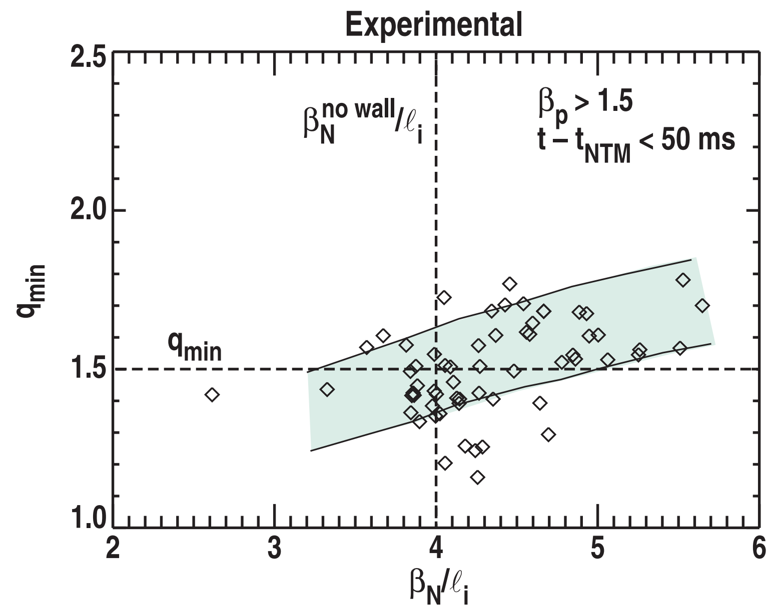
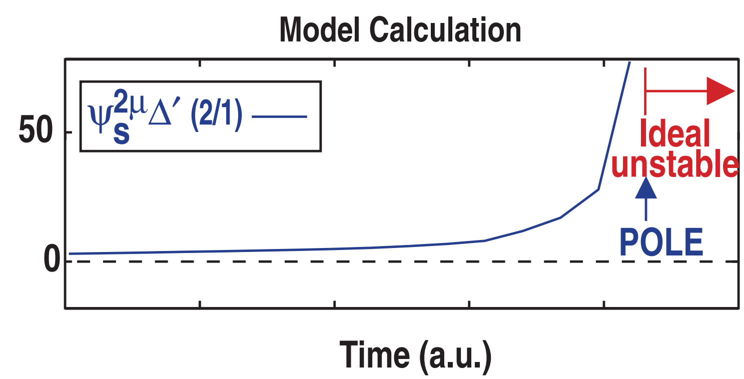
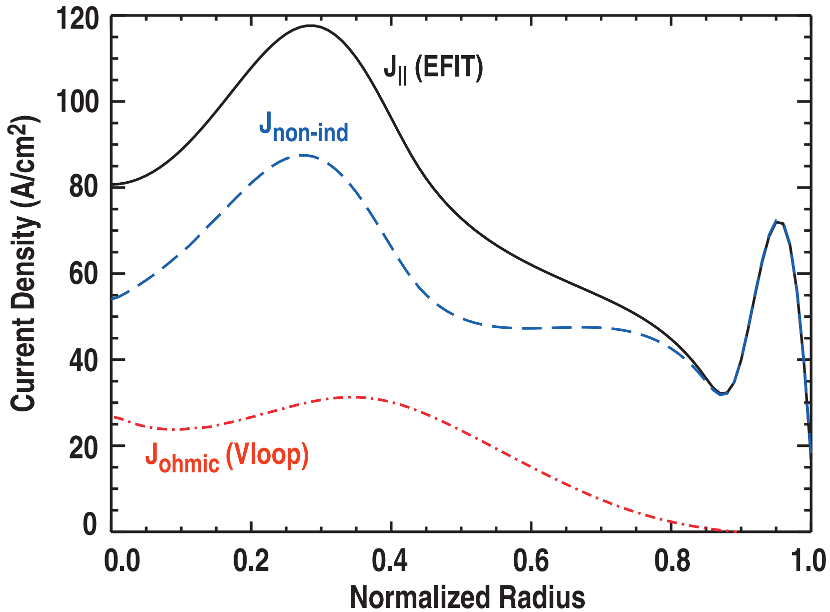


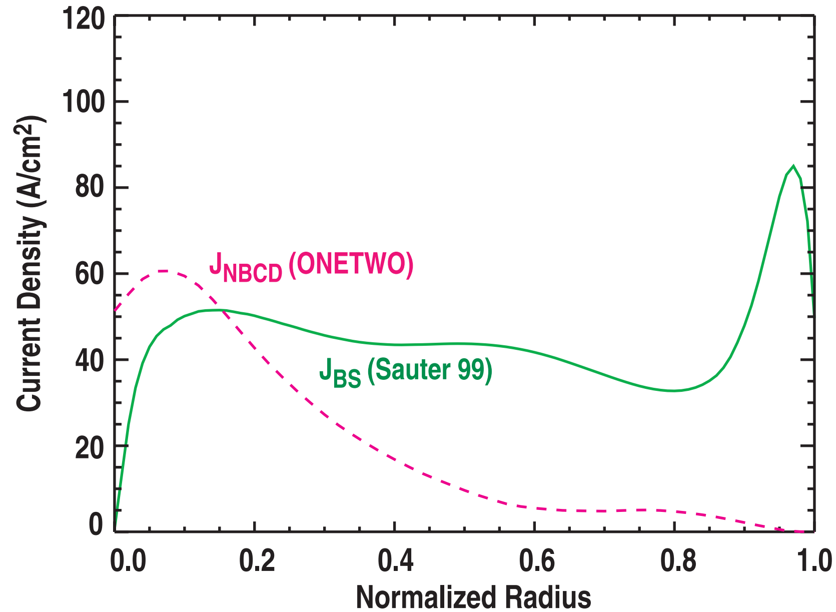




(Brennan F01.007)

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

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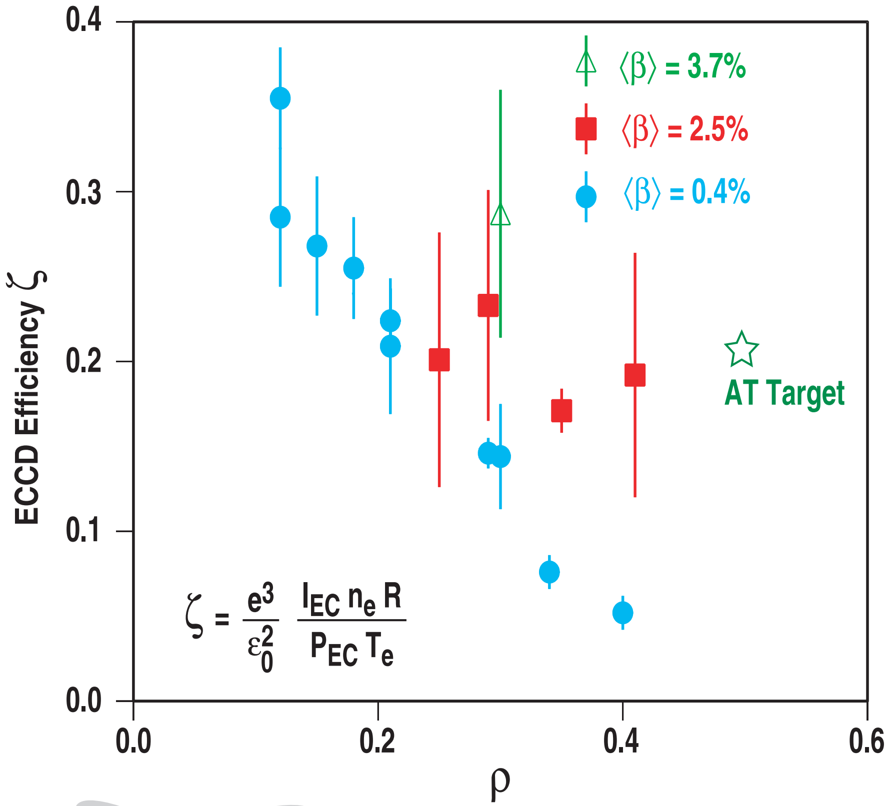
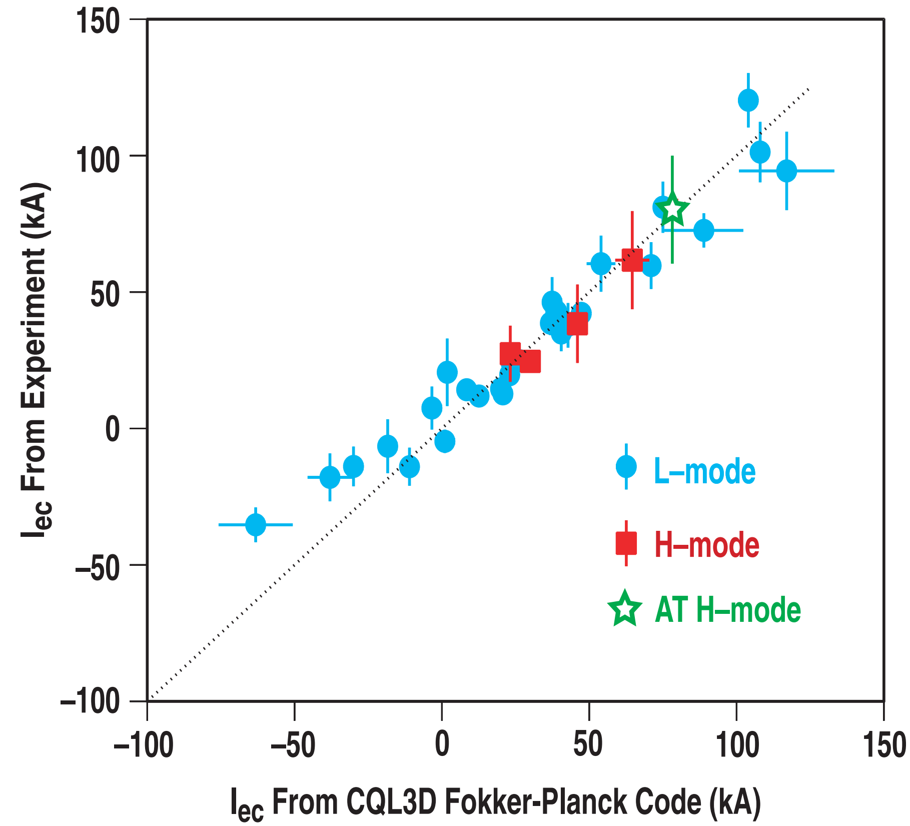
MEASURED ECCD EFFICIENCY IS CONSISTENT WITH THAT REQUIRED FOR AT TARGET SCENARIO AND IS CONSISTENT WITH FOKKER-PLANCK PREDICTIONS

- Dimensionless current drive efficiency defined as:

$$\zeta\,(N_{||}, \theta_{pol}, \rho, \beta_e, \ldots) = \frac{e^3}{\varepsilon^2}\;\frac{I_{EC}\, n_e\, R}{P_{EC}\, T_e}$$





(Petty F01.002))

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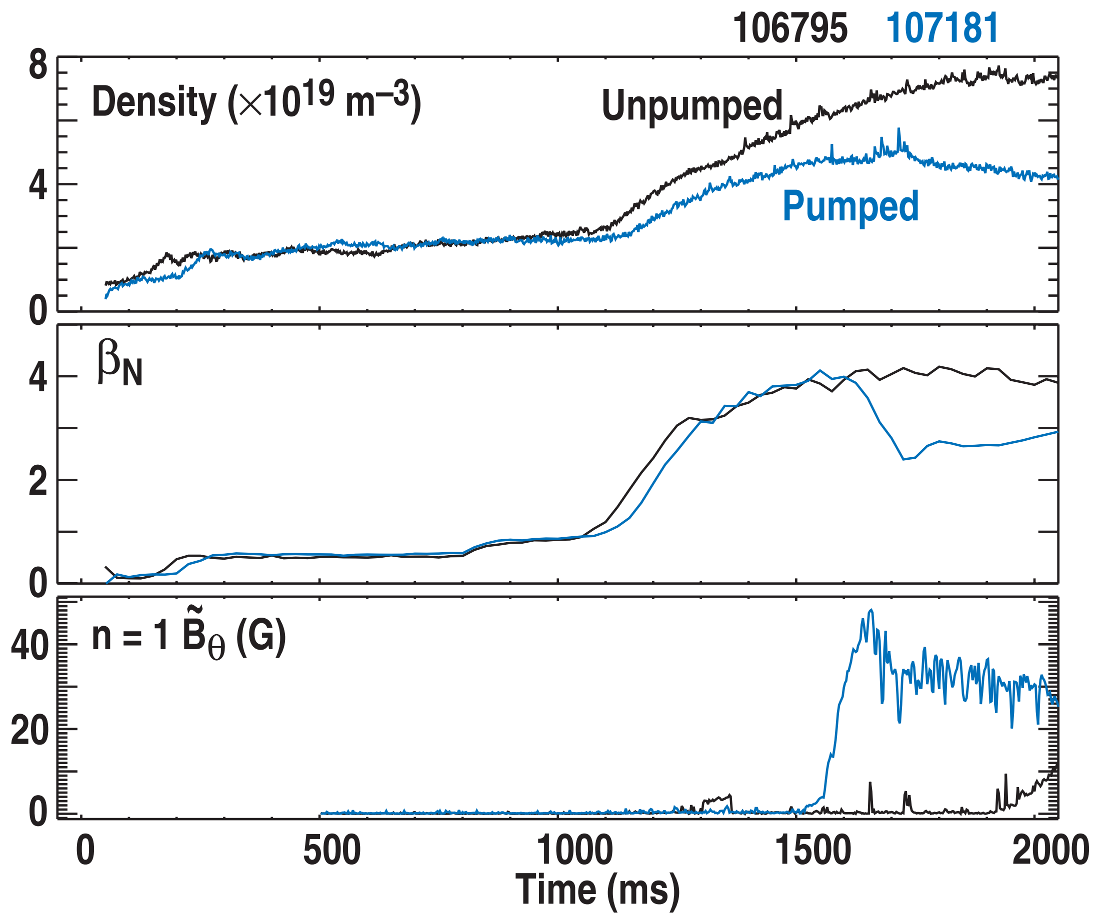
DENSITY CONTROL ($n_e < 5.0 \times 10^{19}$) HAS BEEN ACHIEVED SIMULTANEOUSLY WITH $\beta_N \sim 4$

- Data and simulation shows $\zeta(\beta_e) \propto \beta_e^{1/2} \Rightarrow \eta = \frac{I_{EC}}{P_{EC}} \propto \frac{\beta_e^{3/2}}{n_e^2 R}$



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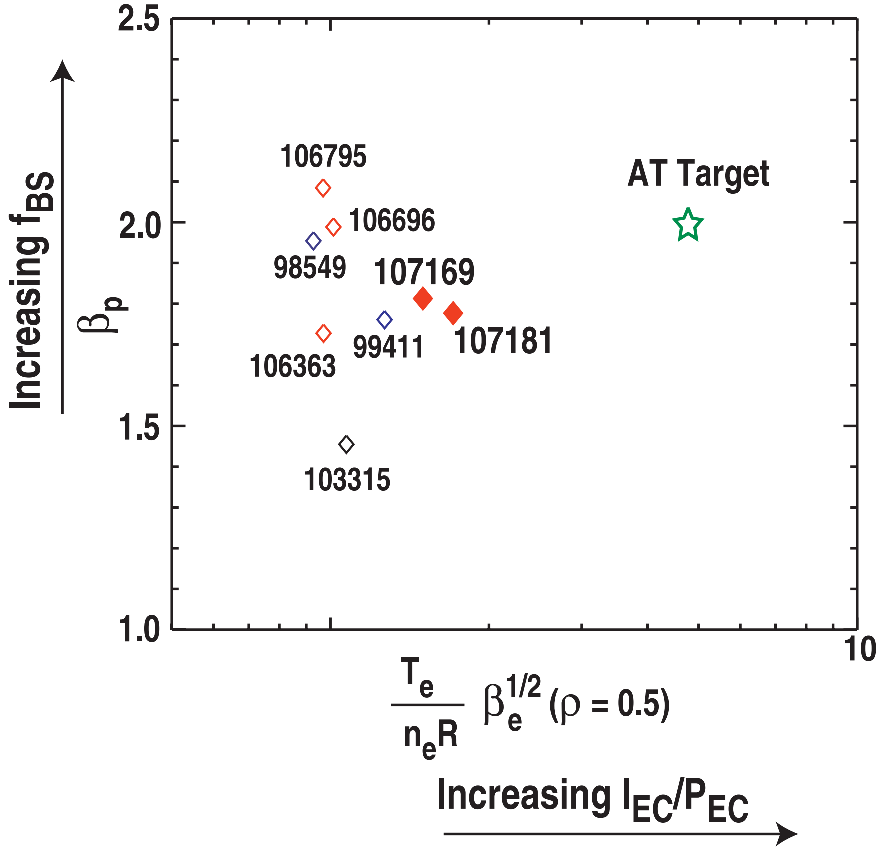
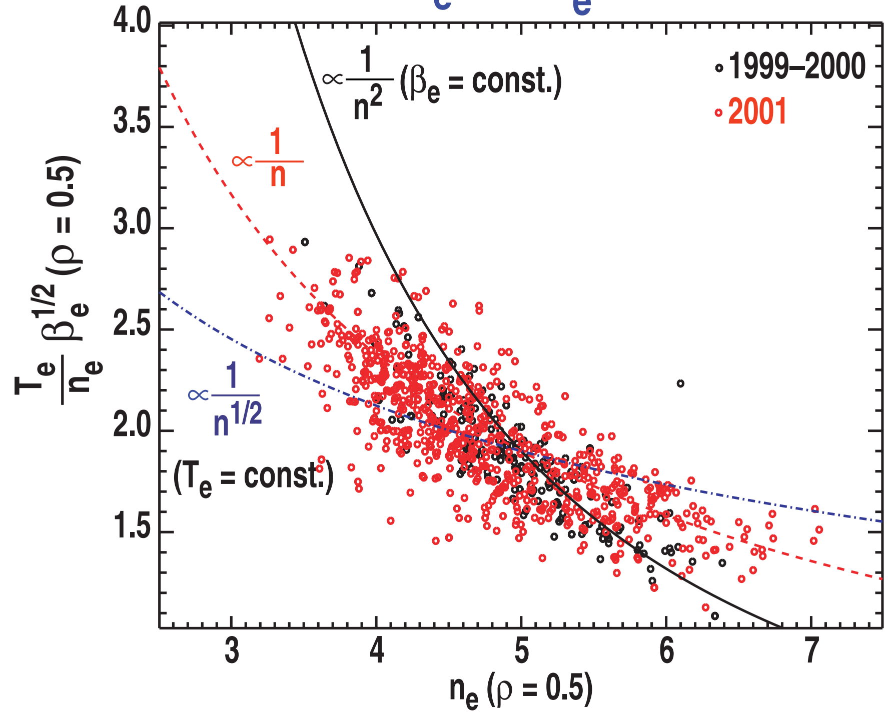
EFFORTS AT OPTIMIZING NON-INDUCTIVE CURRENT DRIVE COMPLICATED BY β_e DEPENDENCE ON DENSITY

- To maximize non-inductive current drive, want to simultaneously optimize f_{BS} and η_{ECCD}

$$\eta \propto \frac{\beta_e}{n_e^2 R} \propto \frac{T_e^{3/2}}{n_e^{1/2} R}$$





- Degradation due to $\beta_e = f(n_e)$

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SUMMARY

- Accomplished
  - β_N H_{89} > 10, f_{BS} = 65% sustained for 4 τ_E
  - Density control ($n_e < 5\times10^{19}$ m^{-3}) achieved simultaneous with $\beta_N \sim 4$
  - ECCD efficiencies found to be consistent with theory and future AT needs
- Key issues for 2002
  - Avoidance of 2/1 NTM onset via q profile control
  - Increasing T_e via density control and scenarios with $T_e \sim T_i$

SUMMARY

- Accomplished
  - $\beta_N H_{89} > 10$, $f_{BS} = 65\%$ sustained for 4 τ_E
  - Density control ($n_e < 5\times10^{19}$ m^{-3}) achieved simultaneous with $\beta_N \sim 4$
  - ECCD efficiencies found to be consistent with theory and future AT needs
- Key issues for 2002
  - Avoidance of 2/1 NTM onset via q profile control
  - Increasing T_e via density control and scenarios with $T_e \sim T_i$
- Current drive
  - $f_{BS} \sim 65\%$, $f_{NI} \sim 80\%$ achieved
  - Current drive capability (I_{EC}/P_{EC}) limited by attainable T_e at current drive location
  - Modeling indicates q profile can be sustained for >> 10 s with 35 mw ECCD (Muratam: F01.003)
- Stability
  - β limit well above no-wall, ideal limit approaching ideal DIII–D wall β limit
  - Experimental β limit does not scale with theoretical n = 1, no wall β limit
  - High β duration limited by classically destabilized tearing mode (Brennan F01.007)
- Confinement
  - GLF23 modeling indicates E×B shear limits turbulent transport but does not completely suppress turbulence (Kinsey Q01.012)

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