Progress Toward High Performance Steady-State Operation in DIII–D

by

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for

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GENERAL ATOMICS

274-06/CMG

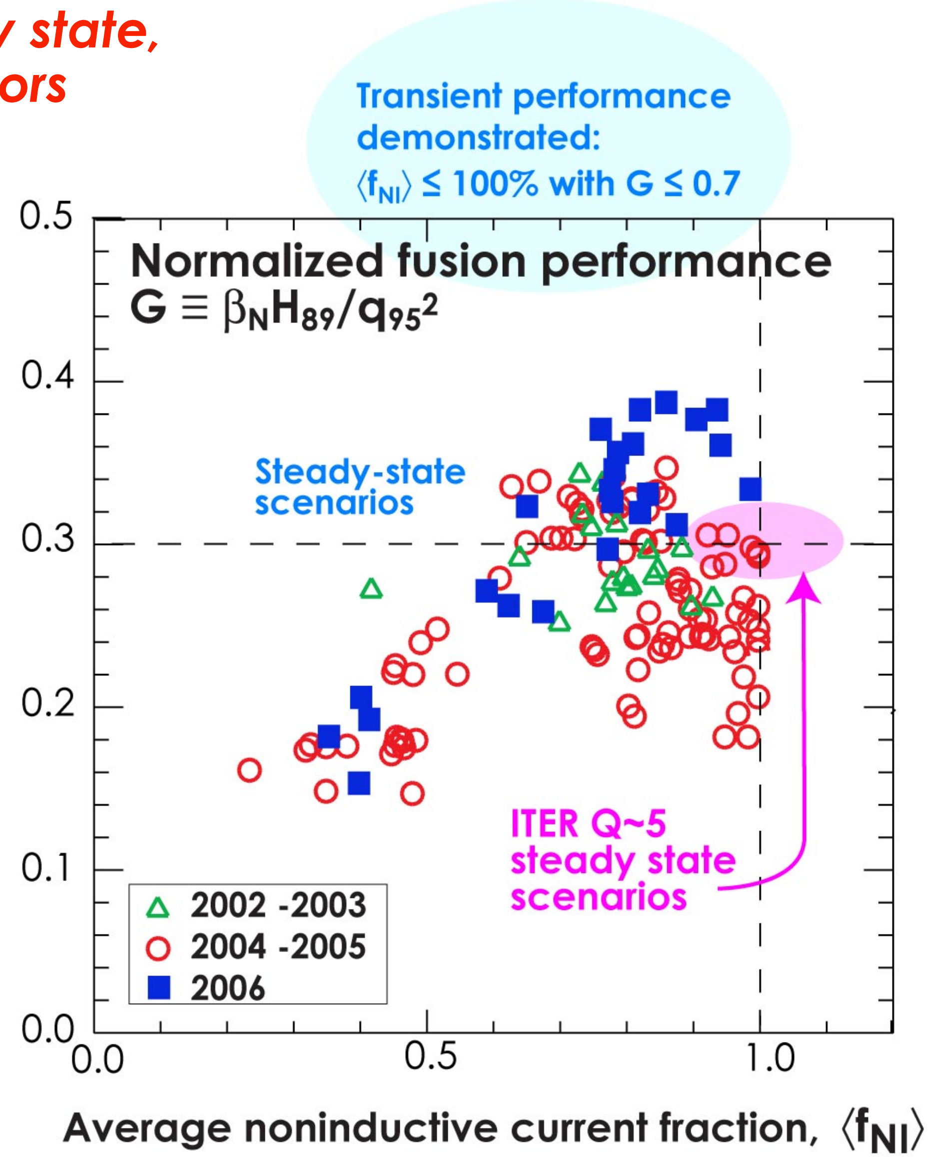
ADVANCED TOKAMAK RESEARCH ON DIII–D

Realizing the Ultimate Potential of the Tokamak

Goal: Develop the scientific basis for steady state, high performance operation of fusion reactors

This requires:

- **Steady state ⇒ f_{NI} ≈ 100%**
  - Large, well aligned self-generated bootstrap current ⇒ high β_P
  - Current drive + profile control
- **High power density and fusion gain**
  - High β_T
  - High τ_E
  - ⇒ High normalized fusion performance G
- **A growing number of DIII–D discharges have demonstrated f_{NI} ≈ 100% and exceeded G ≈ 0.3**
  - Performance required for the ITER steady-state scenario has been demonstrated



Fusion performance needed for ITER Q=5 scenario has been demonstrated in two separate lines of research

- **Recent focus of DIII–D Advanced Tokamak (AT) research is optimization for high β operation**
  - Discharges with high q_{min} and internal transport barriers (ITB) achieve very high performance using continuous ramps in I_P and B_T
    - $\beta_N \approx 6\ell_i \approx 4$ sustained for 2 seconds with $G \equiv \beta_N H_{89}/q_{95}^2 \leq 0.7$
  - Experiments with weakly negative central magnetic shear (NCS) use tools compatible with steady-state
    - $\beta_N \lesssim 3.5$ with $G \lesssim 0.3$ and $f_{NI} \approx 100\%$
  - Shape optimization allows access to higher performance in weak-NCS scenario
    - Stationary operational space expanded to $\beta_N \lesssim 4$
- **Integrated modeling extrapolates to successful fully noninductive operation of ITER at $Q \geq 5$**

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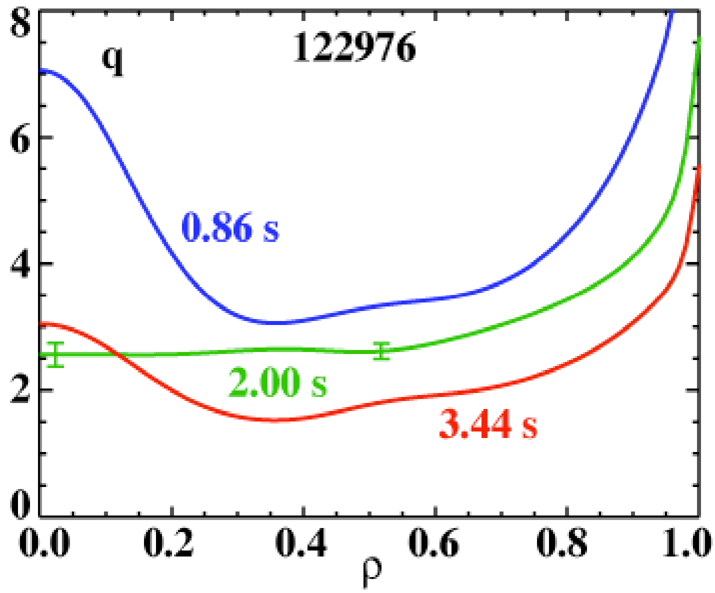
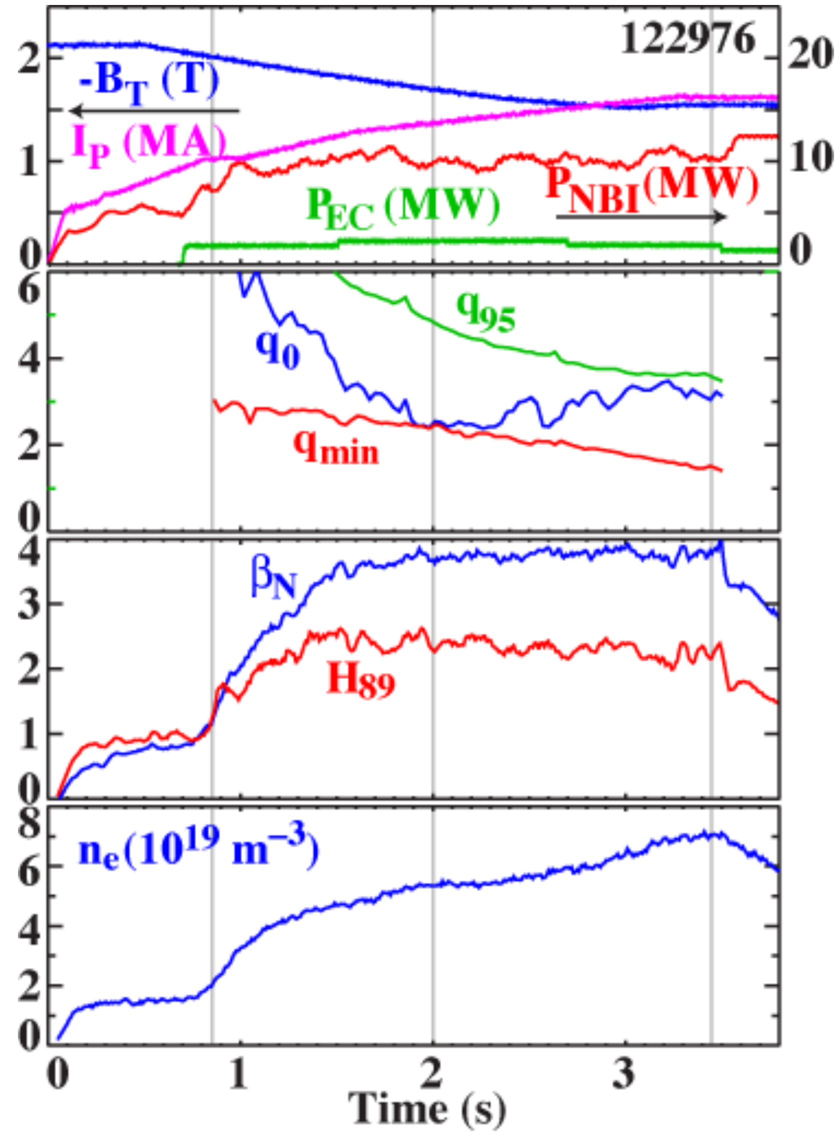
High fusion performance obtained with early beam heating and I_P and B_T ramps

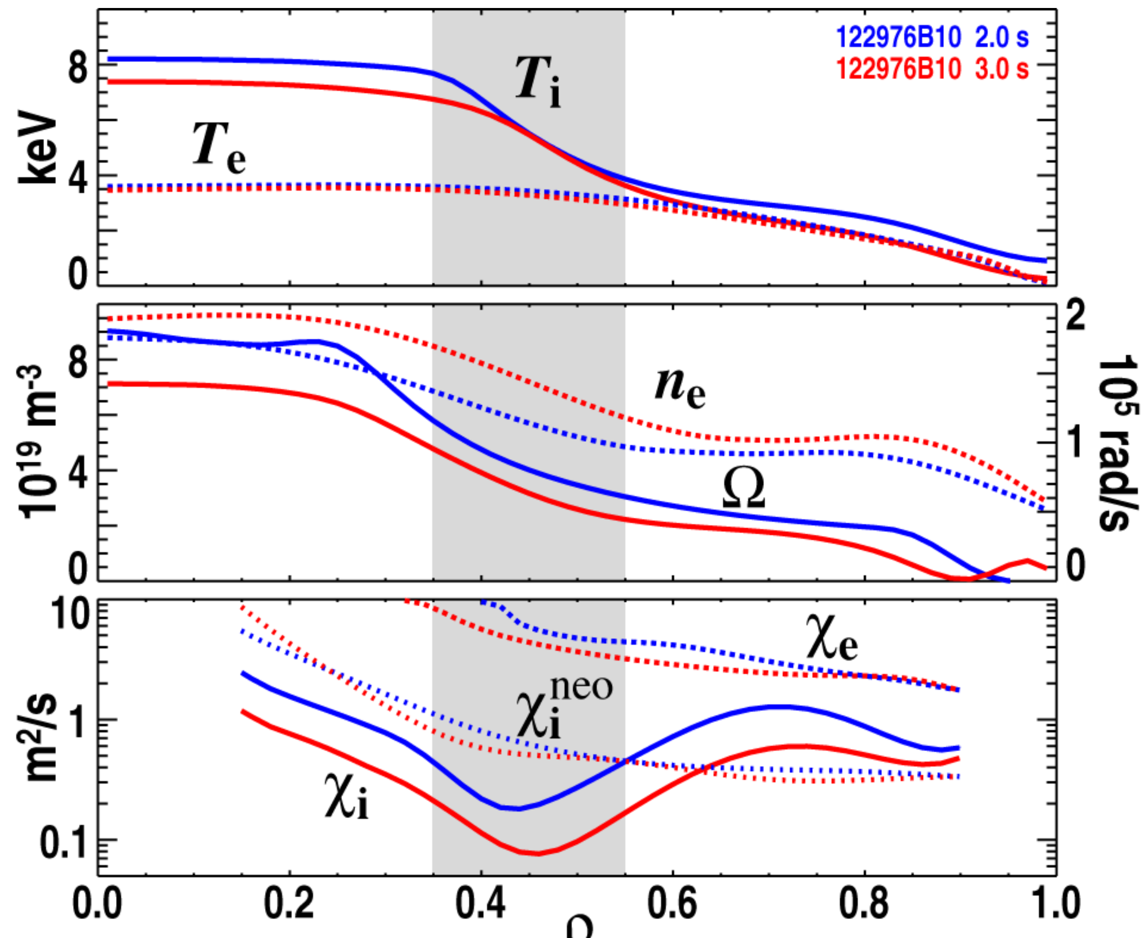




- **β_N ≈ 4 obtained and sustained for 2 s with:**
  - Early heating ⇒ Elevated *q*
  - Off-axis ECCD and B_T ramp ⇒ Broad current profiles
  - Internal transport barriers
- **Transient tools ⇒ transient performance**
  - May suggest new approaches to steady-state

These discharges exhibit an ion thermal internal transport barrier (ITB)

- **Existence proof: ITB does not preclude high β operation**
  - Contrasts with previous experience: Low β limits with peaked profiles in ITB discharges
- **No barrier in electron channel**



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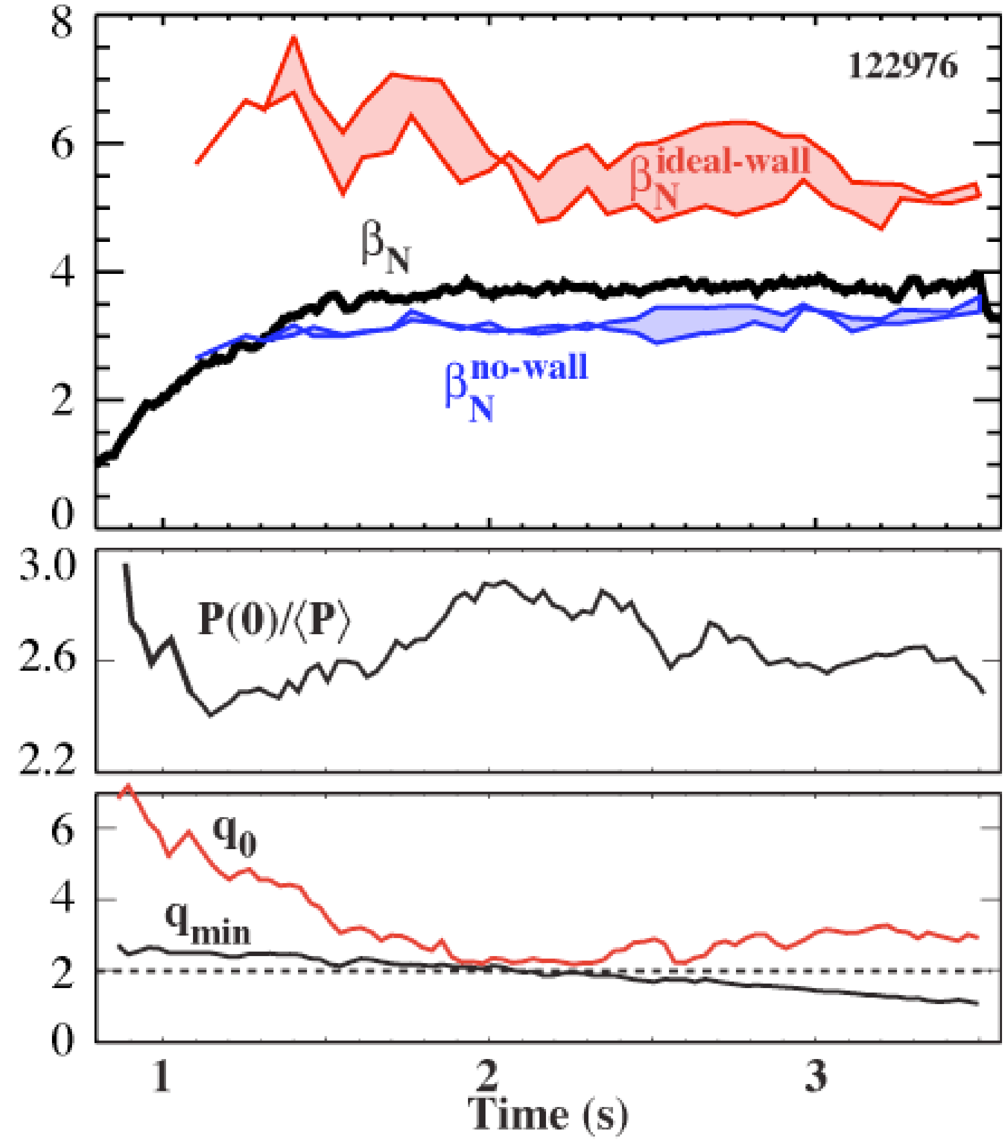
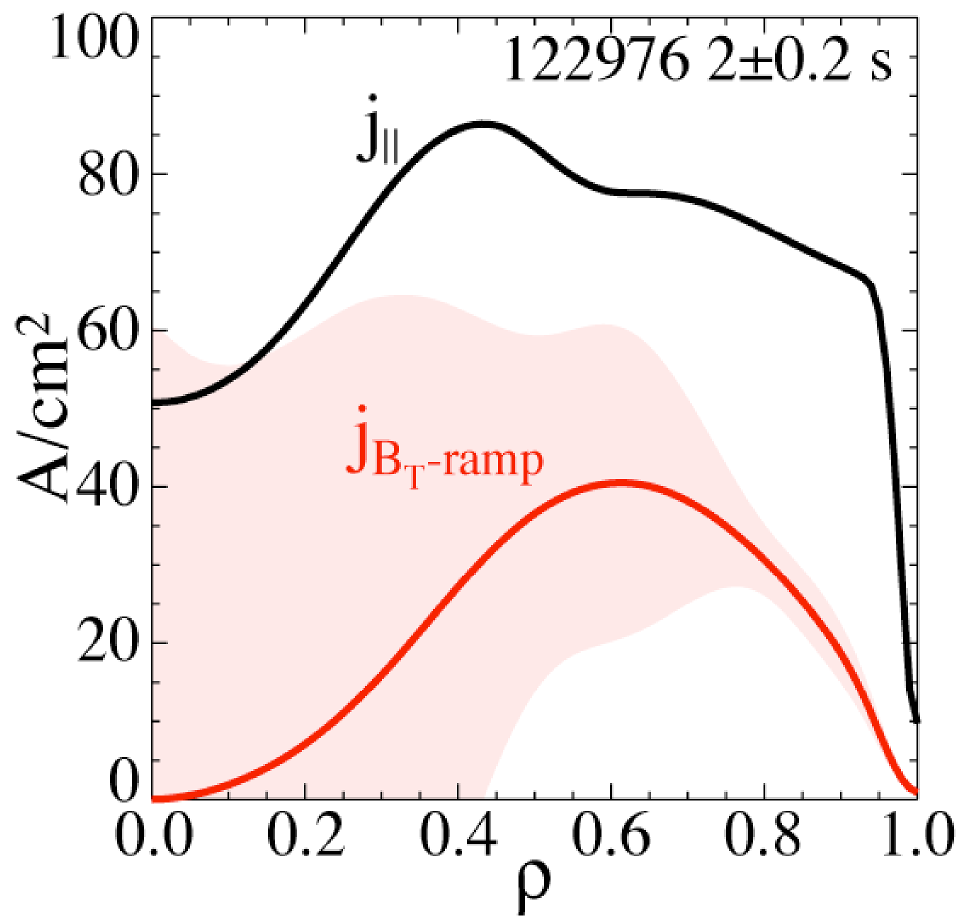
β_N is significantly above the no-wall limit to the n=1 kink mode

- **Large separation between no-wall and ideal-wall limits enabled by broad current profile and wall stabilization**
  - Access to this region requires active control of error fields and Resistive Wall Modes [Garofalo EX/7–1Ra, Friday morning]
- **Relatively insensitive to pressure peaking**
  - Explains compatibility with ITB



B_T ramp broadens the current profile

- **Continuous B_T ramp drives large off-axis current**
  - Negative inductive current near axis, driven by back-EMF, amplifies effect
- **Stability calculations indicate increasing $j_{BT\text{-ramp}}$ results in increasingly large separation between no-wall and ideal-wall limits**
  - Similar effect should be seen using other off-axis current drive tools



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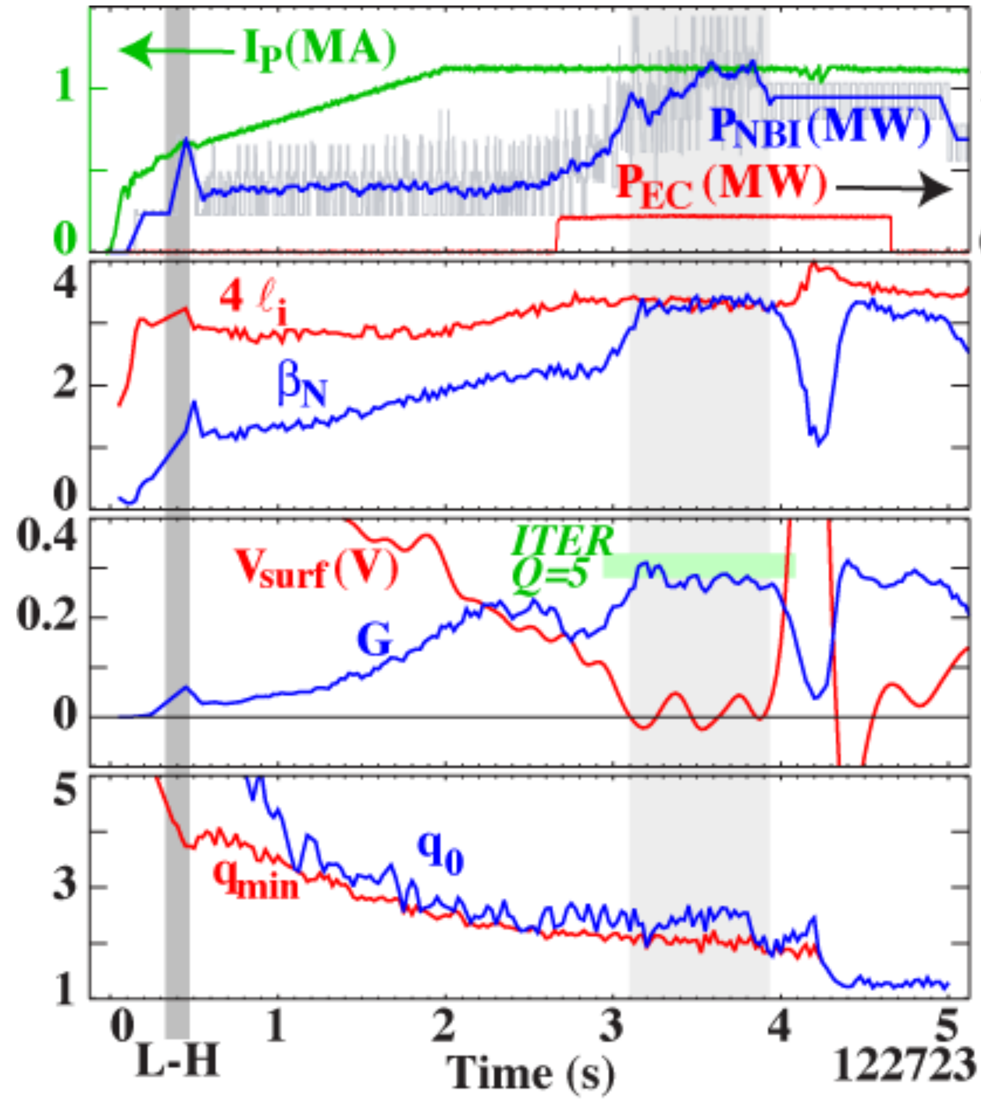
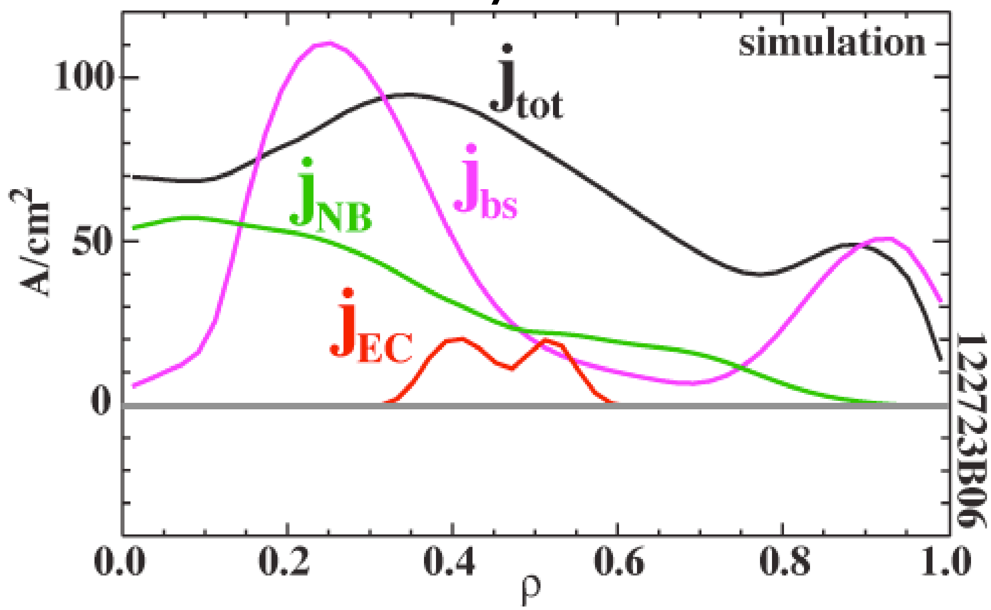
DIII–D AT discharges demonstrate the performance needed for the ITER Q = 5 steady-state scenario

- **Target condition: Broad, weakly reversed shear *q* profile with q_{min} ≈ 2 and q_0 - q_{min} ≲ 0.5**
  - Early H–mode
  - Feedback control during current ramp (β or q) [Ferron EX/P1-4, Tuesday afternoon]

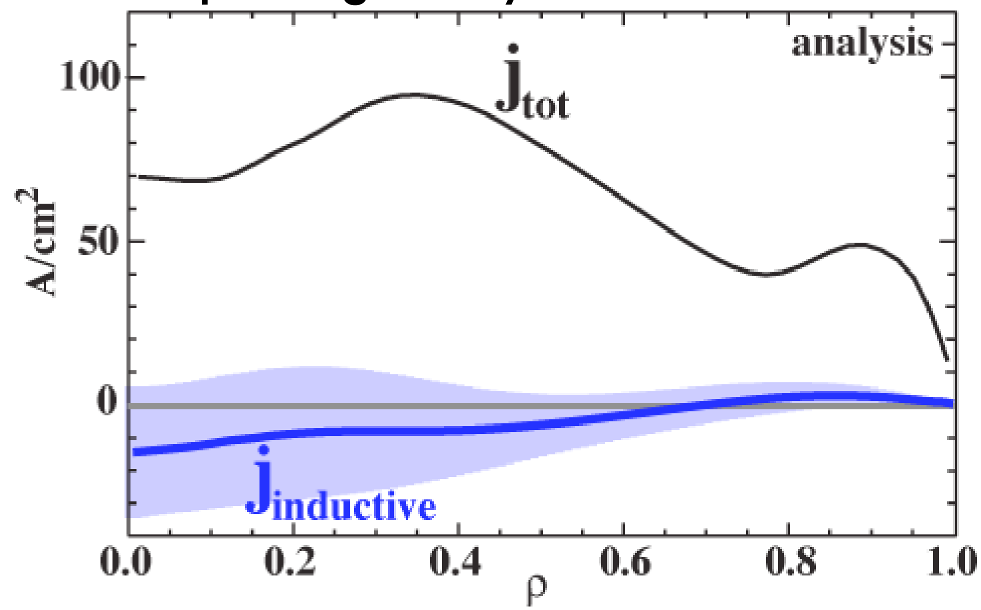


100% noninductive condition achieved both globally and locally across the plasma

TRANSP with theory based CD models



Loop voltage analysis



- **Achieved at $\beta_N \approx 3.5$:**
  $f_{NI} \approx 100\%$ for up to $0.5\tau_R$
  $f_{NI} \lesssim 95\%$ for up to τ_R
- **Typical current sources:**
  $f_{BS} \approx 50\text{-}65\%$, $f_{NB} \approx 20\text{-}35\%$, $f_{EC} \approx 5\text{-}10\%$)

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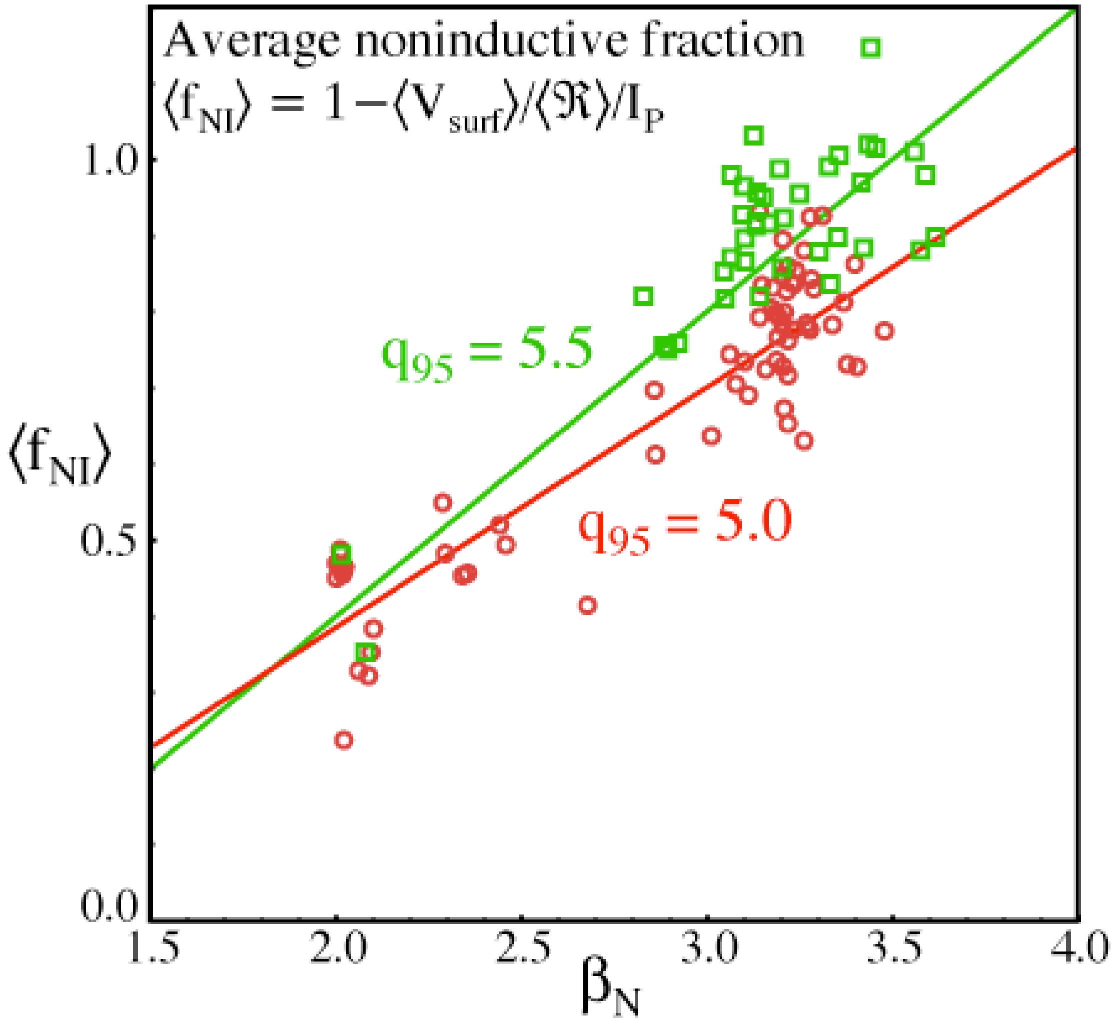
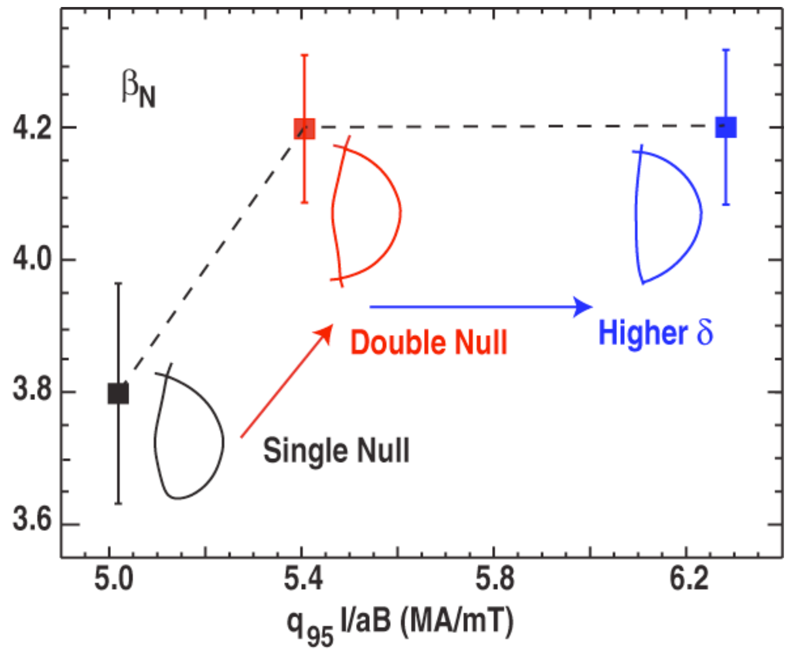
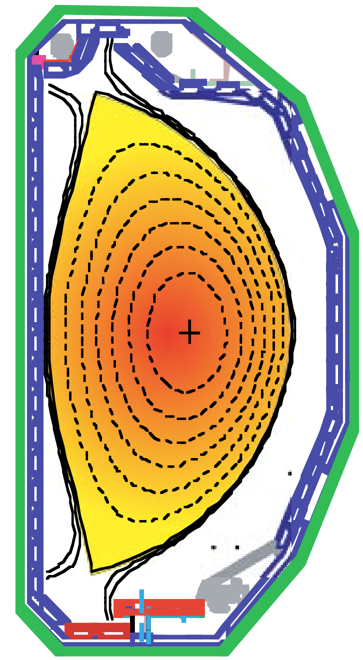
AT optimization focuses on increasing β_N at moderate q_{95}



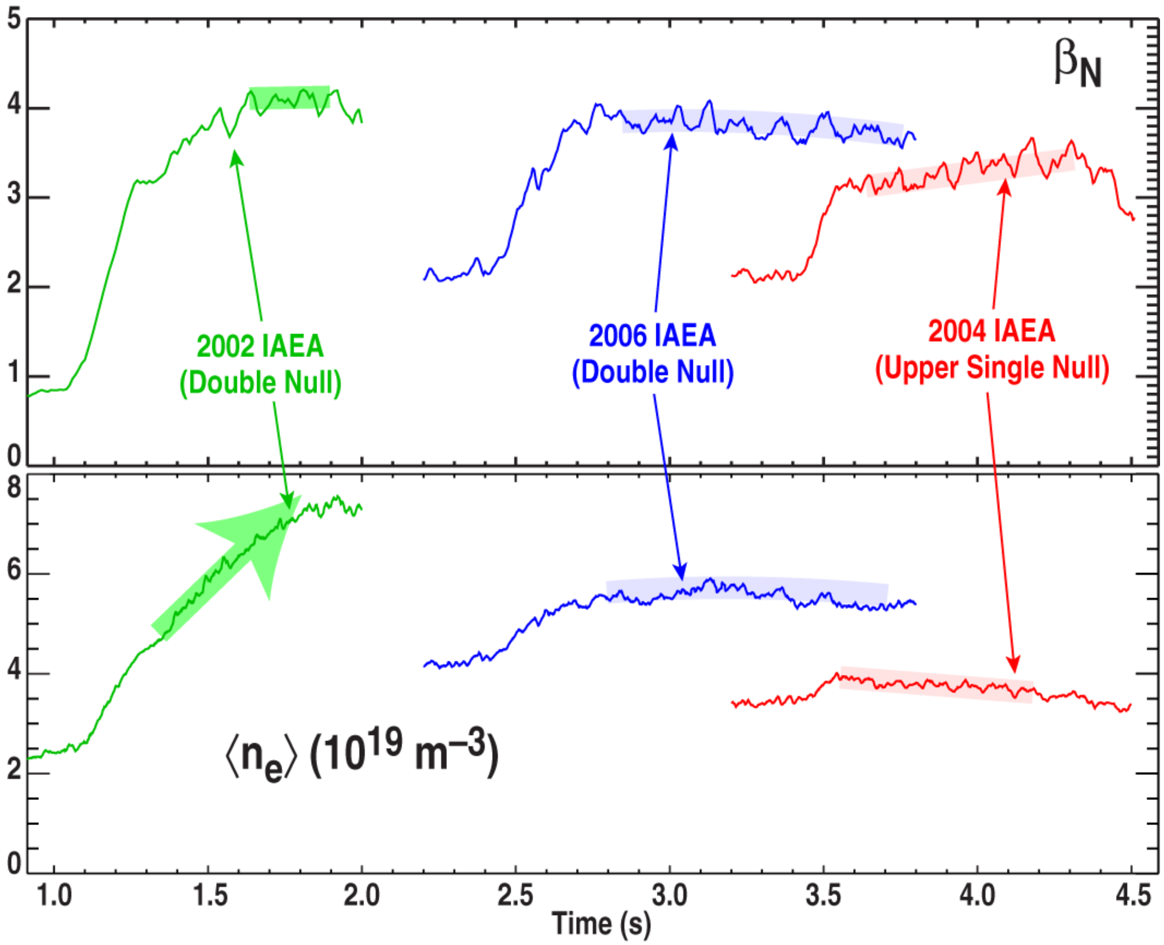
New lower divertor cryopump allows operation at higher beta with density control

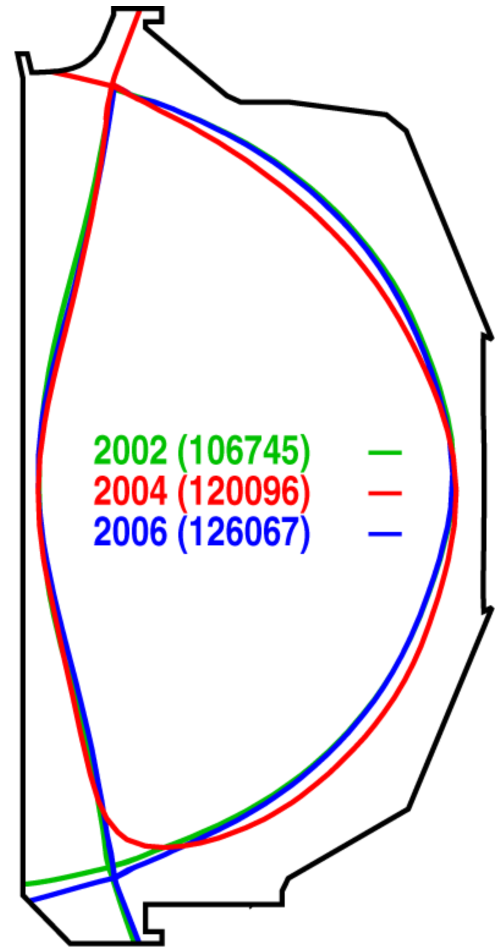




- **Double-null geometry known to increase β limit**
  - However: AT operation requires effective density control
- **New cryopump allows density control in single- and double-null [Petrie EX/P1-16, Tuesday afternoon]**
  - Built in collaboration with ASIPP
- **Research goals:**
  - Quantify benefits of double-null operation
  - Exploit higher β limits to optimize AT performance

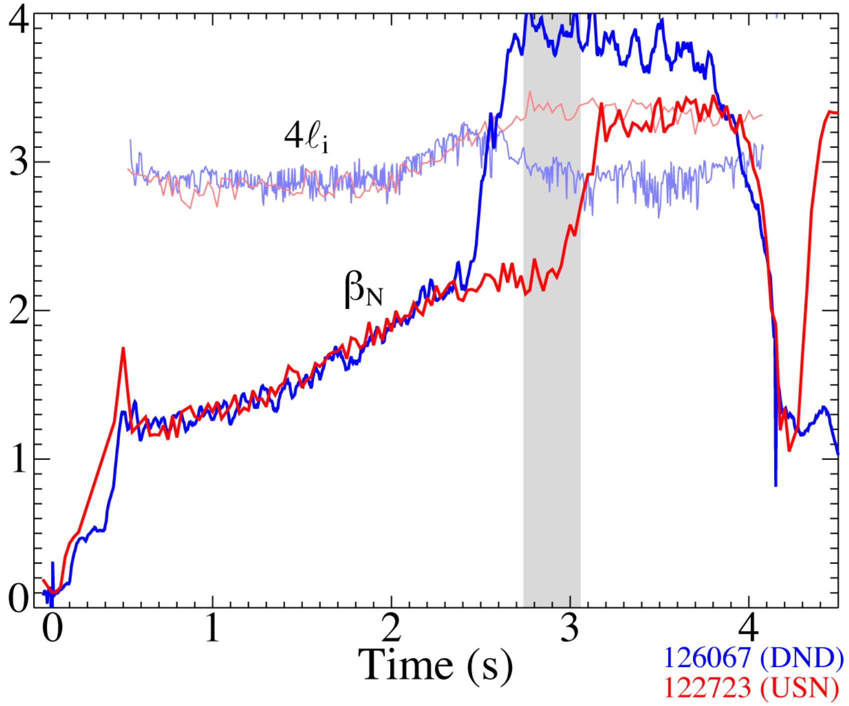
Density control demonstrated in high β double-null plasmas

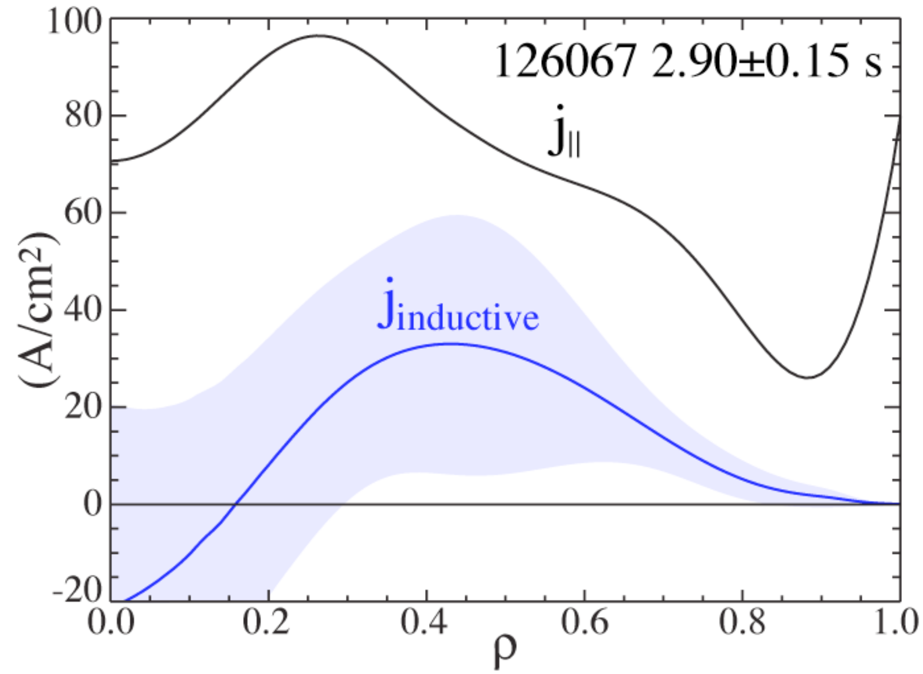




- **Further improvements to density control anticipated with continued optimization**

Initial experiments with double-null configurations demonstrate increased performance





- **Double-null divertor experiments achieve:**
  - $\beta_N \lesssim 4$
  - $G \lesssim 0.4$ (ITER Q = 5 steady-state scenario requires G = 0.3)
- **Current profile analysis indicates additional off-axis current drive required to reach fully noninductive conditions**
  - Additional ECCD available in upcoming campaign

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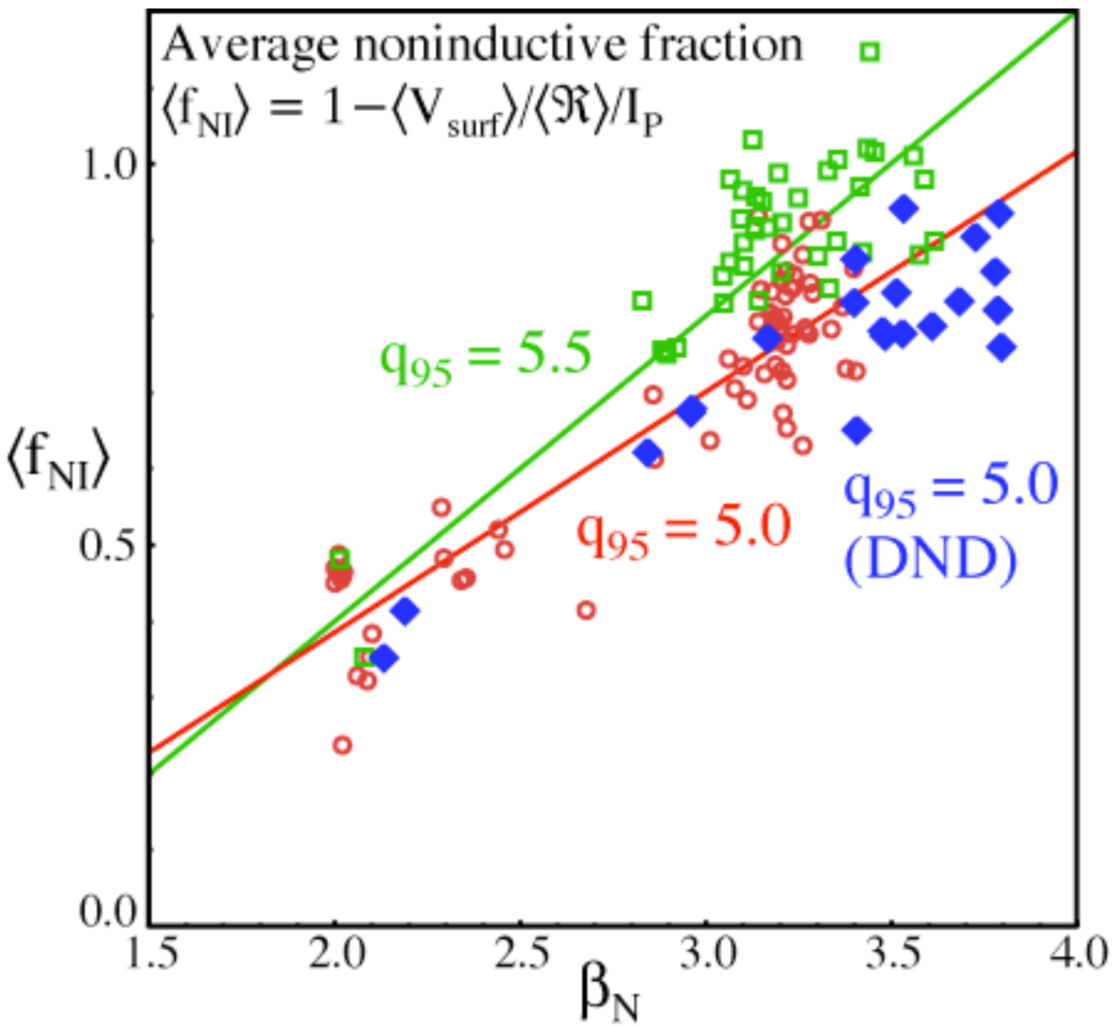
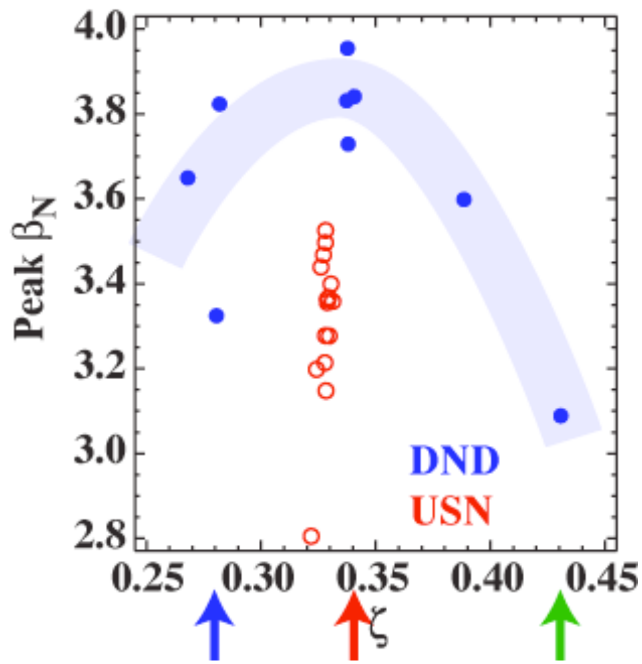
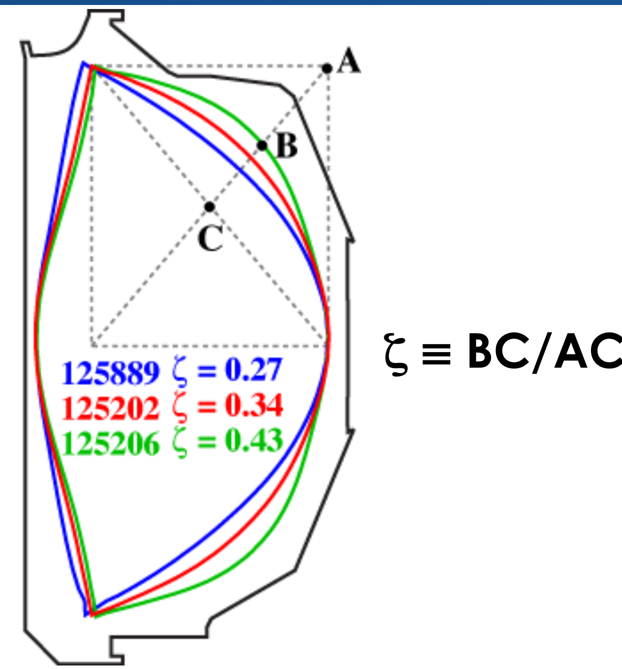


Optimum squareness for access to high β_N





- ***β*** **limits and confinement known to be sensitive to shape**
  - Elongation κ and triangularity δ constrained by vessel geometry
- **Squareness ζ also calculated to have significant impact on *β* limits**
  - ζ can be varied without impacting coupling to divertors
  - Difficult to predict exact dependence due to sensitivities to profile details… need to do experiment
- **Maximum *β* found at ζ ≈ 0.33**
  - Indicates importance of shaping flexibility

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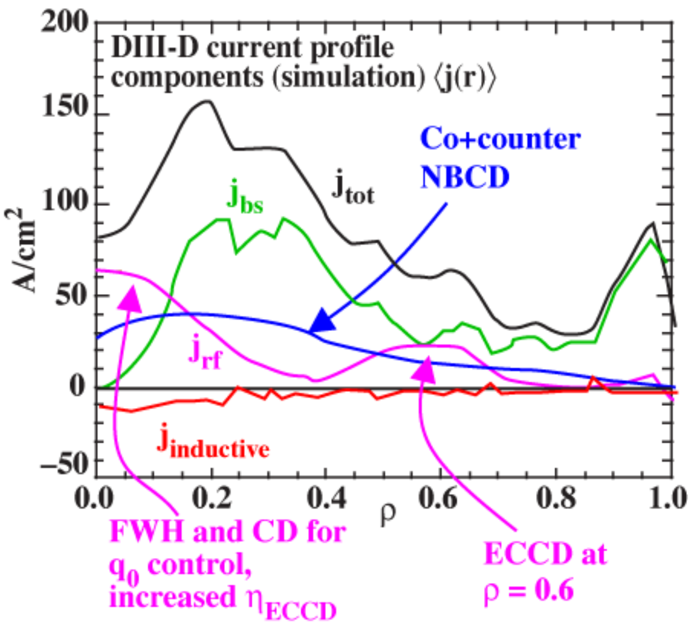
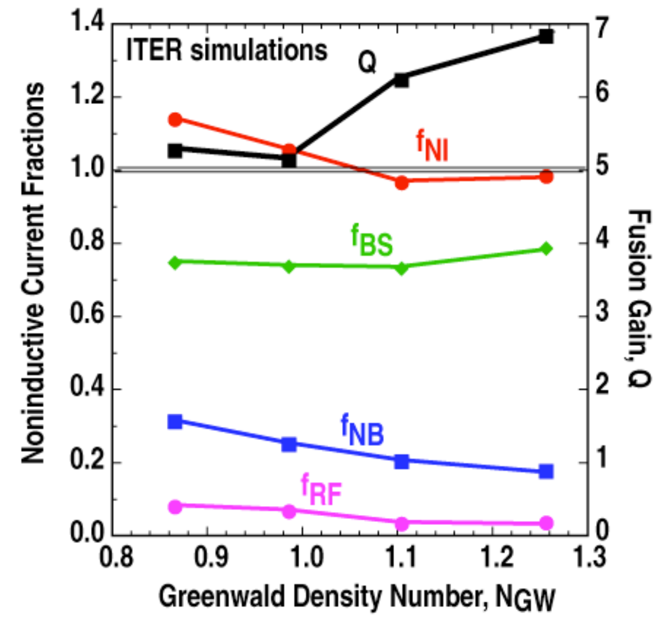
DIII–D results extrapolate to successful achievement of steady-state scenarios with $Q \geq 5$ in ITER



Simulation parameters

	DIII–D	ITER
B_T (T)	1.86	5.3
I_P (MA)	1.19	9
q_{95}	5	5
P_{NB} (MW)	6.8	33
P_{EC} (MW)	4.5	20
P_{IC} (MW)	3.5	20
β	4.1%	2.5%
β_N	3.8	2.7



- **Integrated modeling predicts continued progress in future DIII–D AT experiments with improved heating and current drive capabilities**
  - ONETWO/GLF23
- **Same models and techniques used to predict behavior in ITER**
  - Q increases with density while f_{NI} decreases slowly

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Performance in DIII–D AT experiments meets or exceeds requirements for ITER Q=5 steady-state scenario

- **$\beta_N \approx 6\ell_i \approx 4$ for 2 seconds with G ≤ 0.7 in discharges with B_T ramp**
  - Broad current profile ⇒ $\beta_N^{ideal\text{-}wall} >> \beta_N^{no\text{-}wall}$
  - Active instability control allows us to operate in this range
- **$\beta_N \approx 3.5$ and G ≈ 0.3 with $f_{NI} \approx 100\%$ using tools compatible with steady-state operation**
  - Shaping flexibility important for optimization
  - Plasmas with optimized double-null geometry reach $\beta_N \approx 4$ and G ≈ 0.4
- **Integrated modeling extrapolates results to successful achievement of ITER Q=5 steady-state scenario**
- **Future work in DIII–D: Apply current drive tools to operate at $\beta_N \gtrsim 4$ and $f_{NI} \approx 100\%$**
  - 6 MW (source) of ECCD and 4 MW (source) FWCD will allow increased flexibility in scenario exploration and support fully noninductive operation at high β_N

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