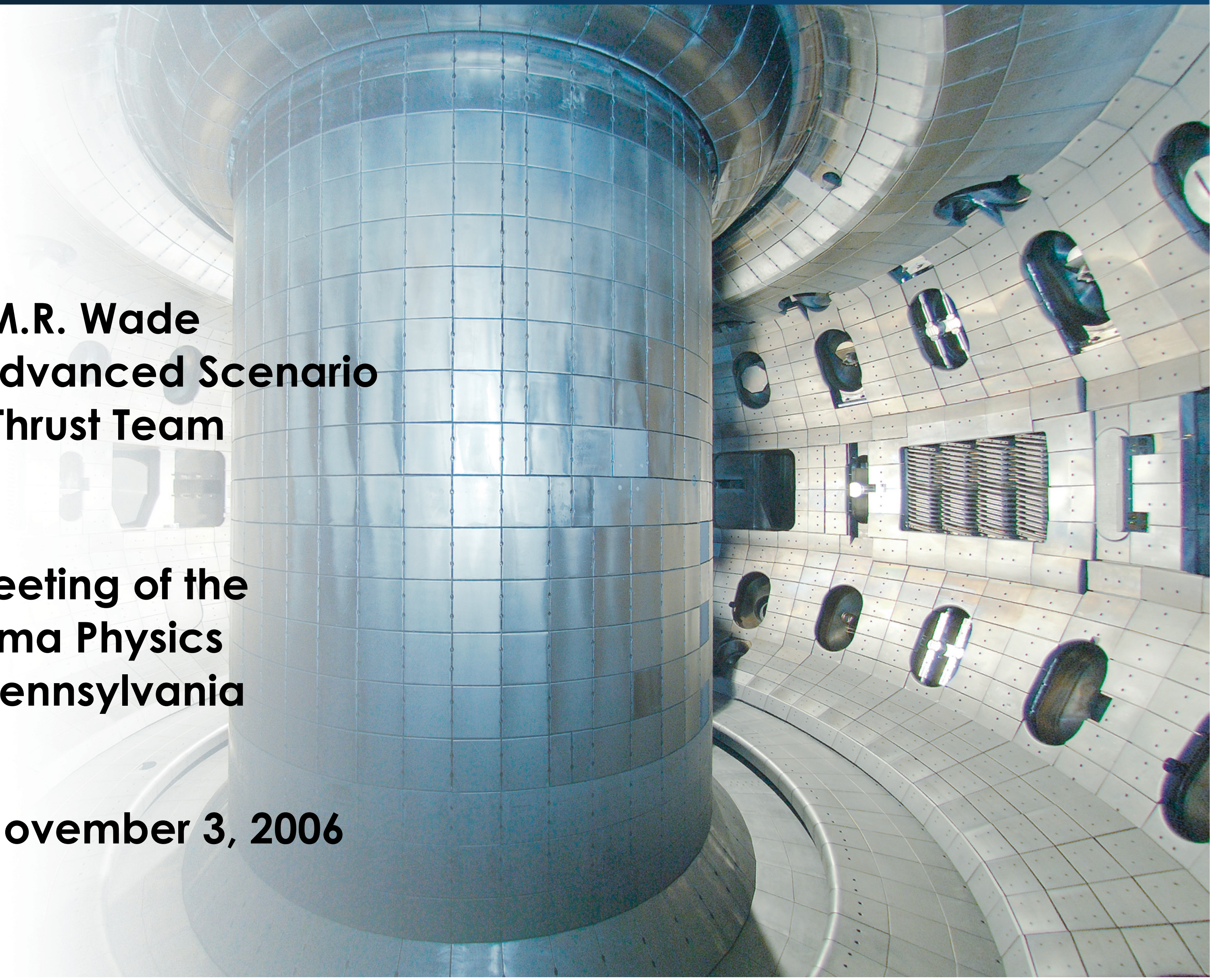
Progress Toward Fully Noninductive, High Performance Conditions in DIII-D



by
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presented by M.R. Wade
for the DIII–D Advanced Scenario
Development Thrust Team

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Advanced Tokamak (AT) Research on DIII–D

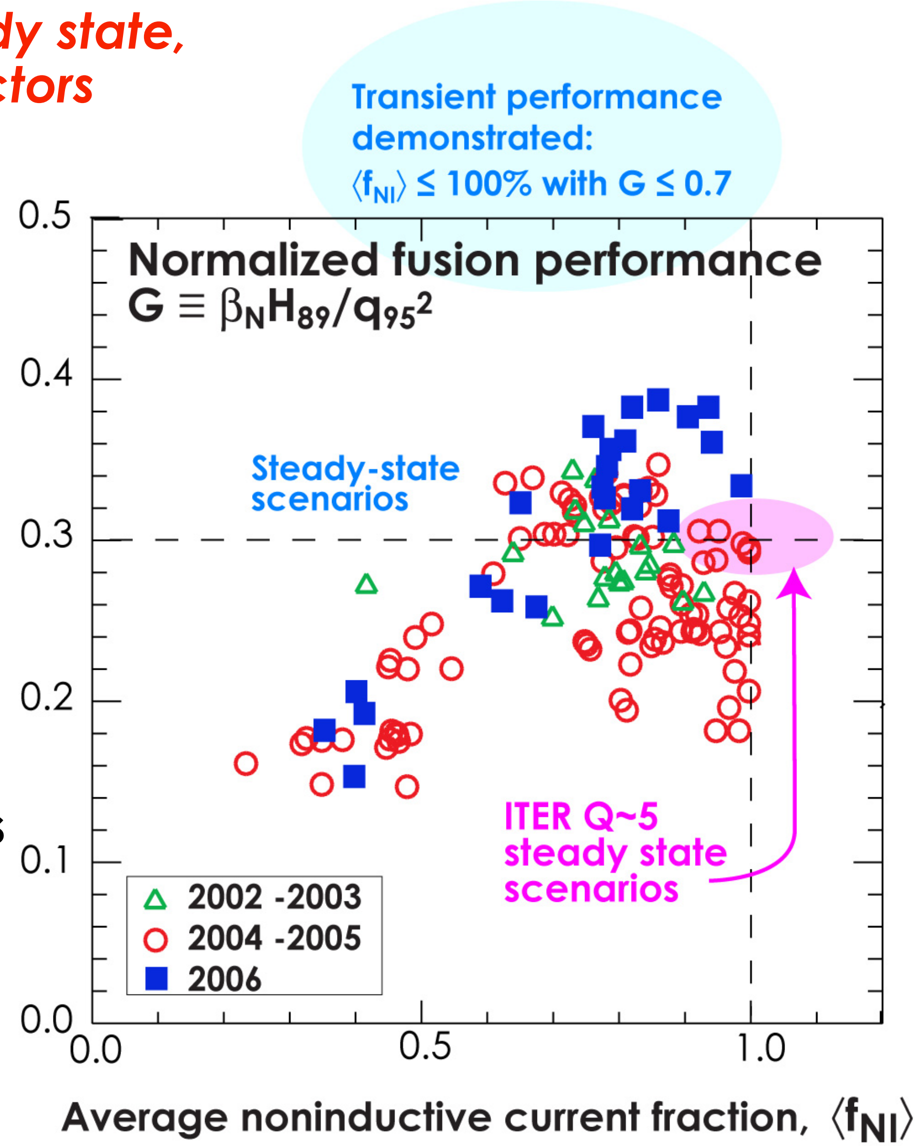
Realizing the Ultimate Potential of the Tokamak

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

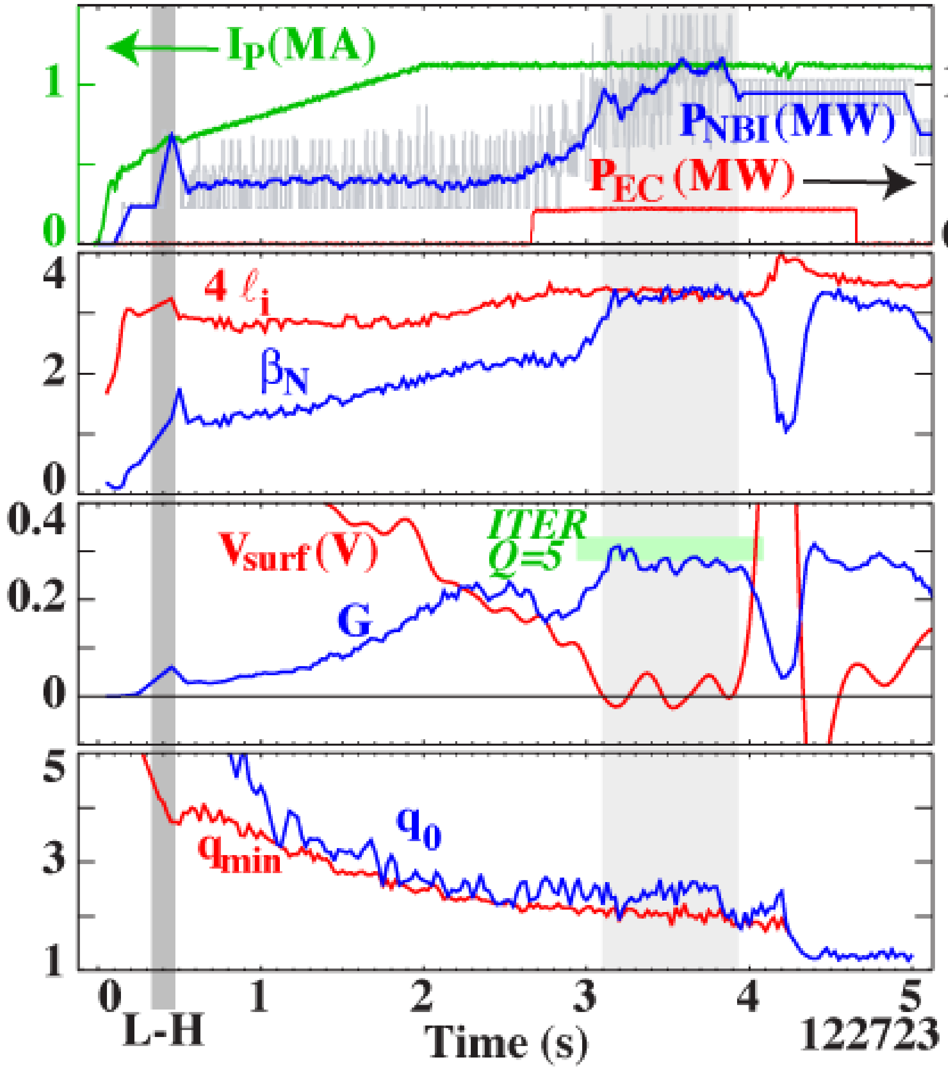
  ⇒ High normalized fusion performance G
- **A growing number of DIII–D discharges have demonstrated f_{NI} ≈ 100% and exceeded G ≈ 0.3**
  - Performance required for the ITER steady-state scenario has been demonstrated

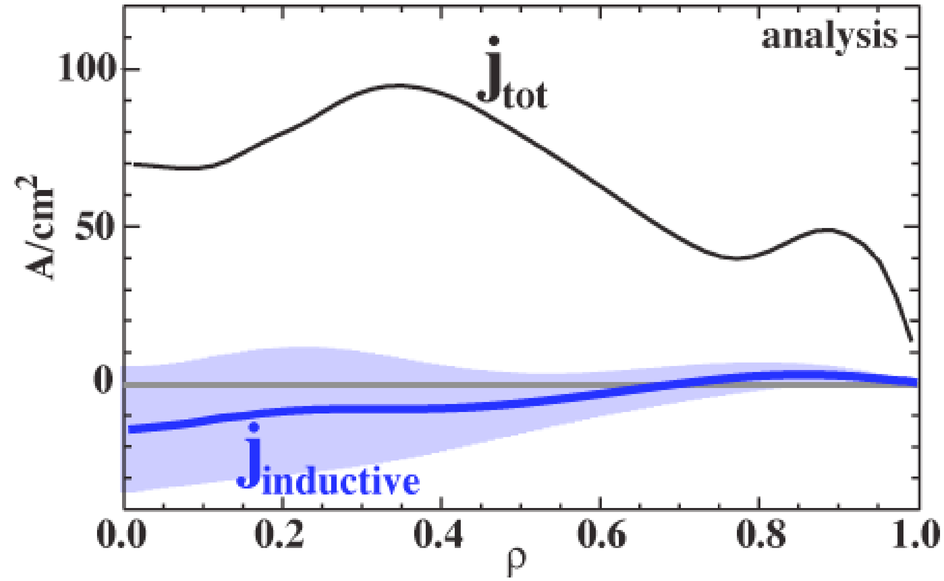


Recent Focus of DIII–D Advanced Tokamak (AT) Research is Optimization for High β Operation

- **Starting point: Experiments with weakly negative central magnetic shear (NCS) achieve performance necessary for ITER Q = 5 steady-state scenarios: $\beta_N \lesssim 3.5$ with $G \lesssim 0.3$ and $f_{NI} \approx 100\%$**
- **Shape optimization allows access to higher performance in weak-NCS scenario, extending stationary operational space to $\beta_N \lesssim 4$ and $G \lesssim 0.4$.**
  - Single- vs. double-null divertor operation
  - Effect of plasma squareness
- **Integrated modeling extrapolates to successful fully noninductive operation of ITER at $Q \geq 5$**

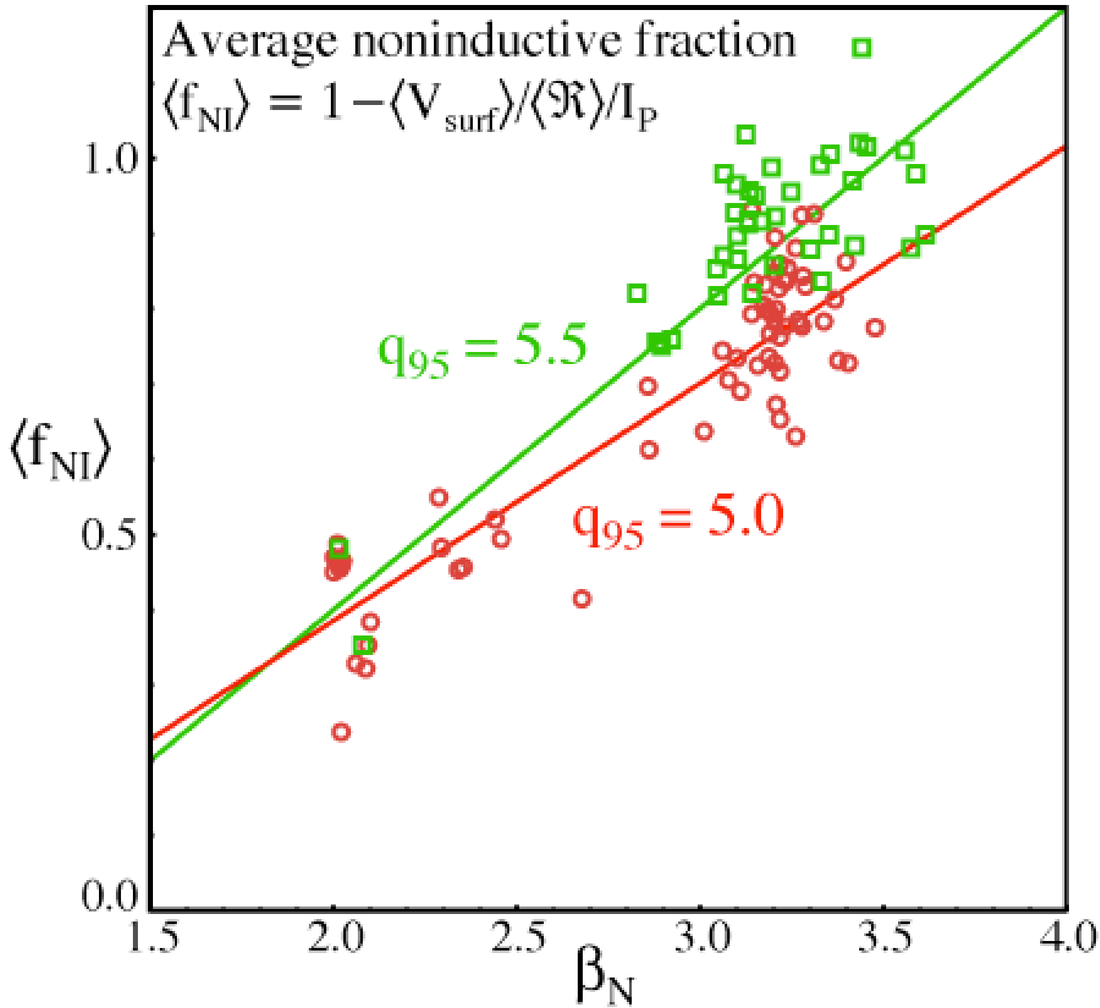
Starting Point: Fully Noninductive AT Discharges With $\beta_N \approx 3.5$



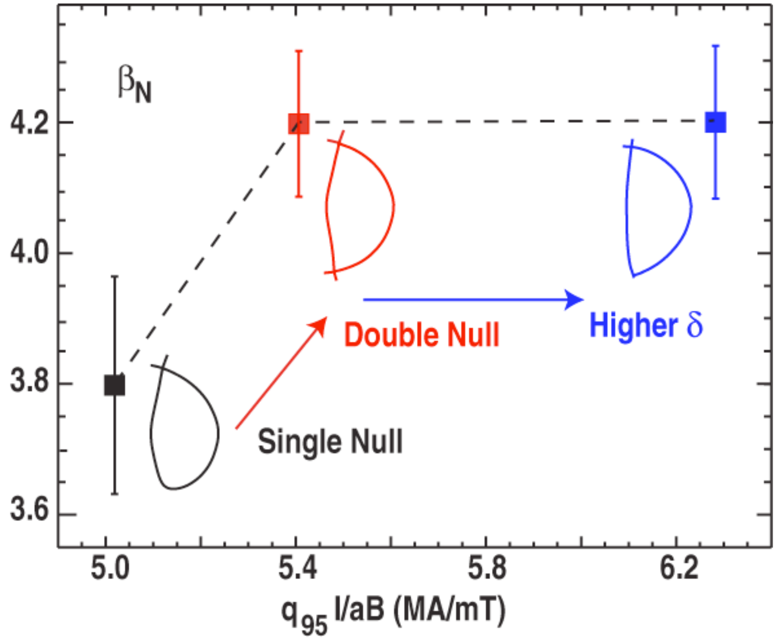


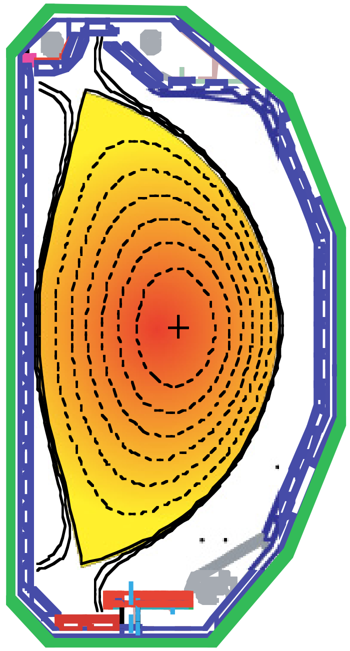
- **Achieved at $\beta_N \approx 3.5$:**
  $f_{NI} \approx 100\%$ for up to $0.5\tau_R$
  $f_{NI} \lesssim 95\%$ for up to τ_R
- **Typical current sources:**
  $f_{BS} \approx 50\text{-}65\%$, $f_{NB} \approx 20\text{-}35\%$, $f_{EC} \approx 5\text{-}10\%$)

AT Optimization Focuses on Increasing β_N at Moderate q_{95}



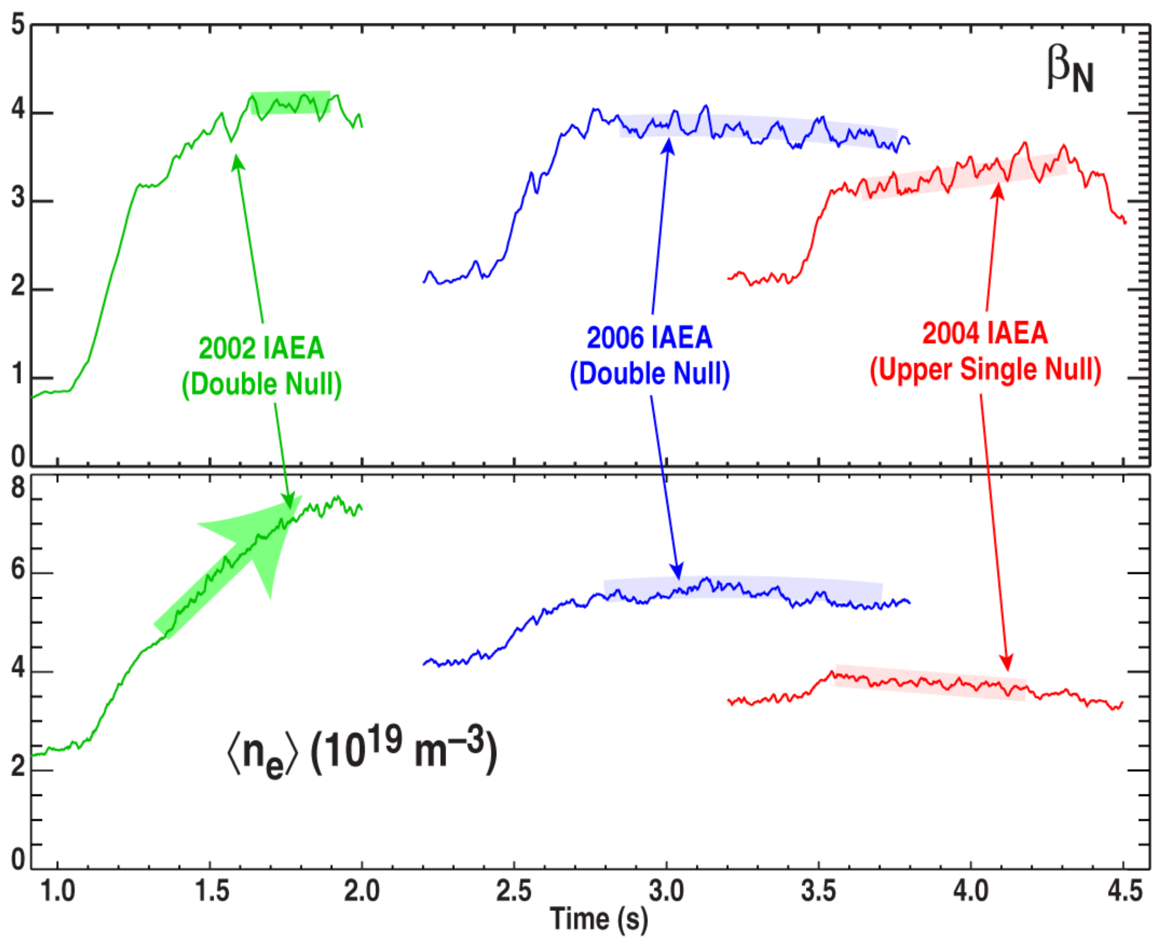
New Lower Divertor Cryopump Allows Operation at Higher Beta With Density Control

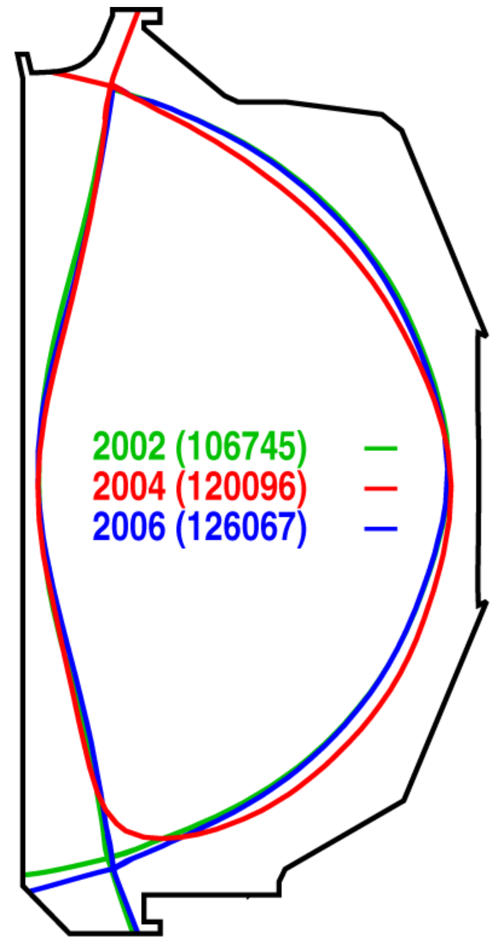




- **Double-null geometry known to increase β limit**
  - However: AT operation requires effective density control
- **New cryopump allows density control in single- and double-null**
- **Research goals:**
  - Quantify benefits of double-null operation
  - Exploit higher β limits to optimize AT performance

Density Control Demonstrated in High β Double-null Plasmas

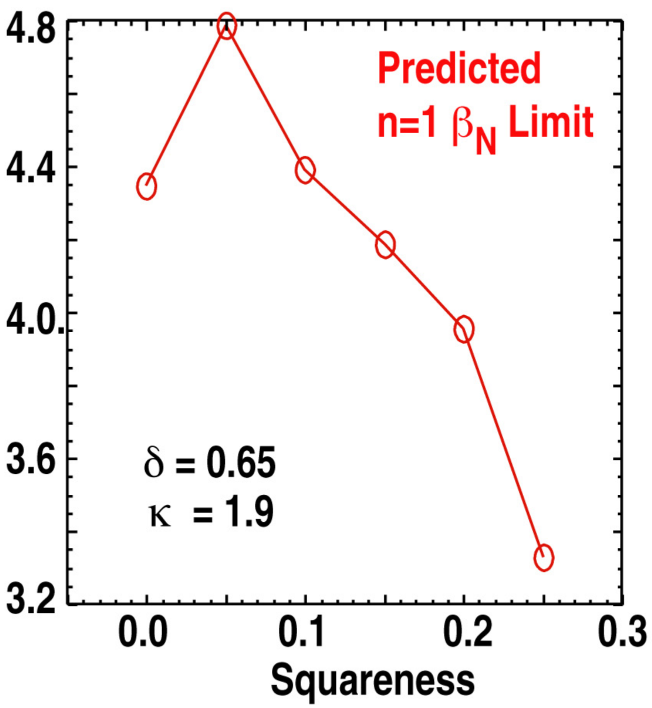


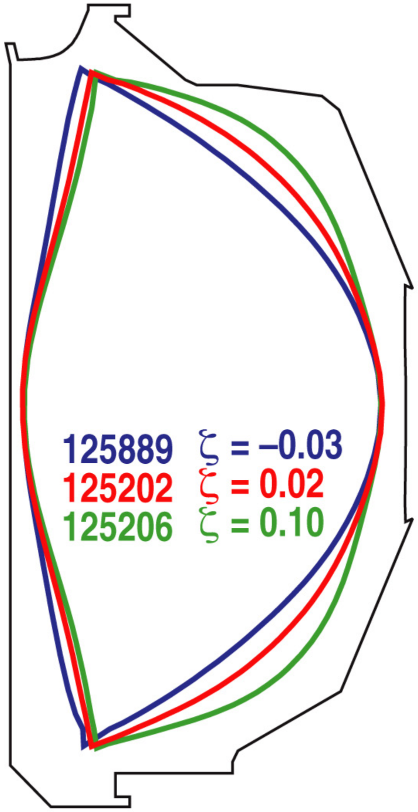


- **Further improvements to density control anticipated with continued optimization**

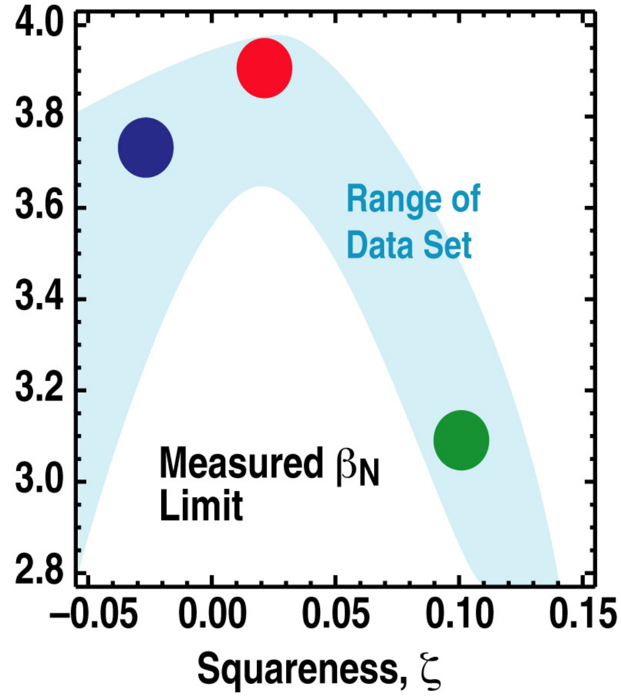
Plasma Performance Shown to be Sensitive to Details of the Plasma Shape

- **Stability analysis indicates n=1 stability limit has a narrow optimum in plasma "squareness"**

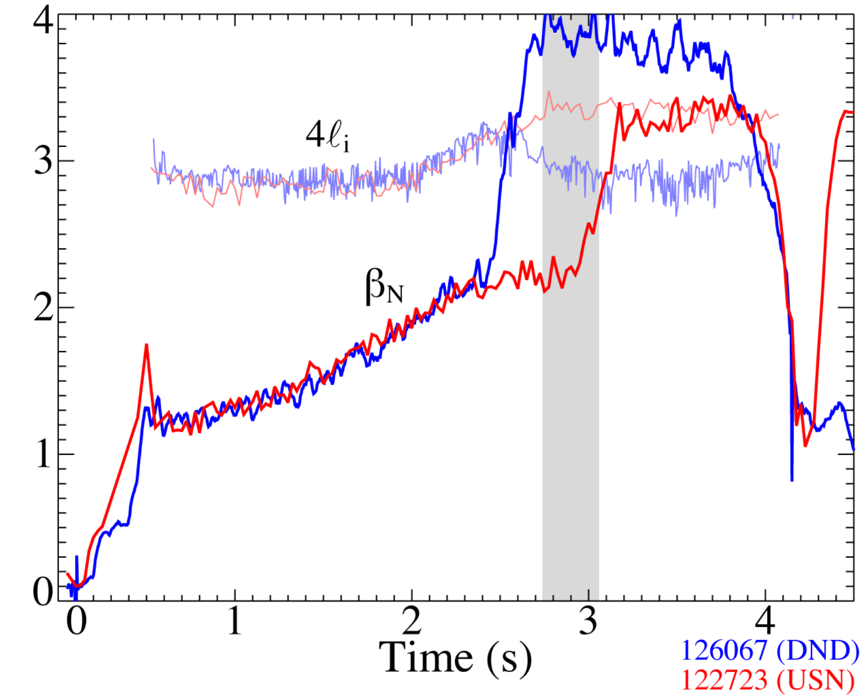


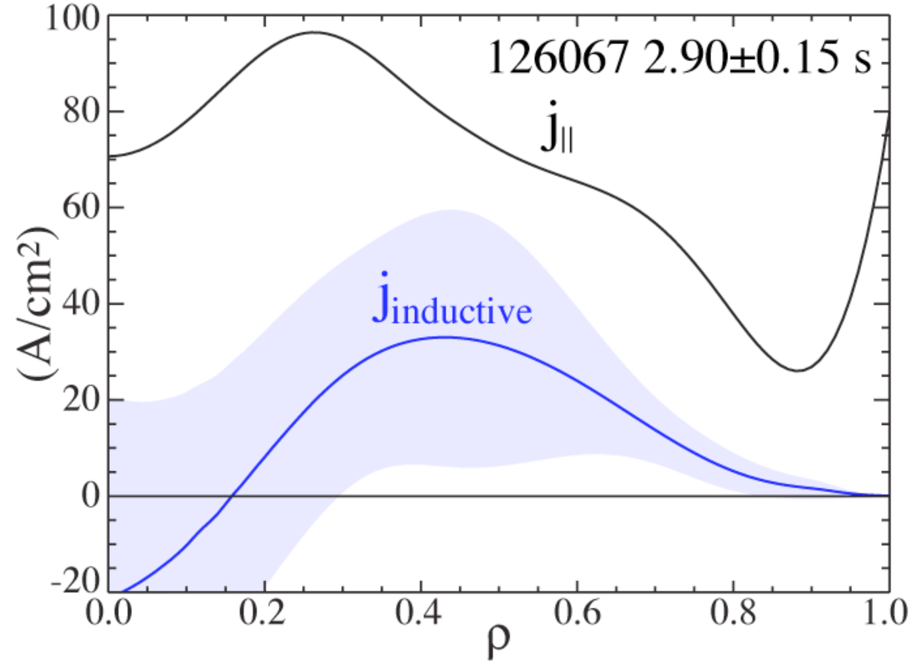


- **Measured long pulse β limit shows similar dependence**



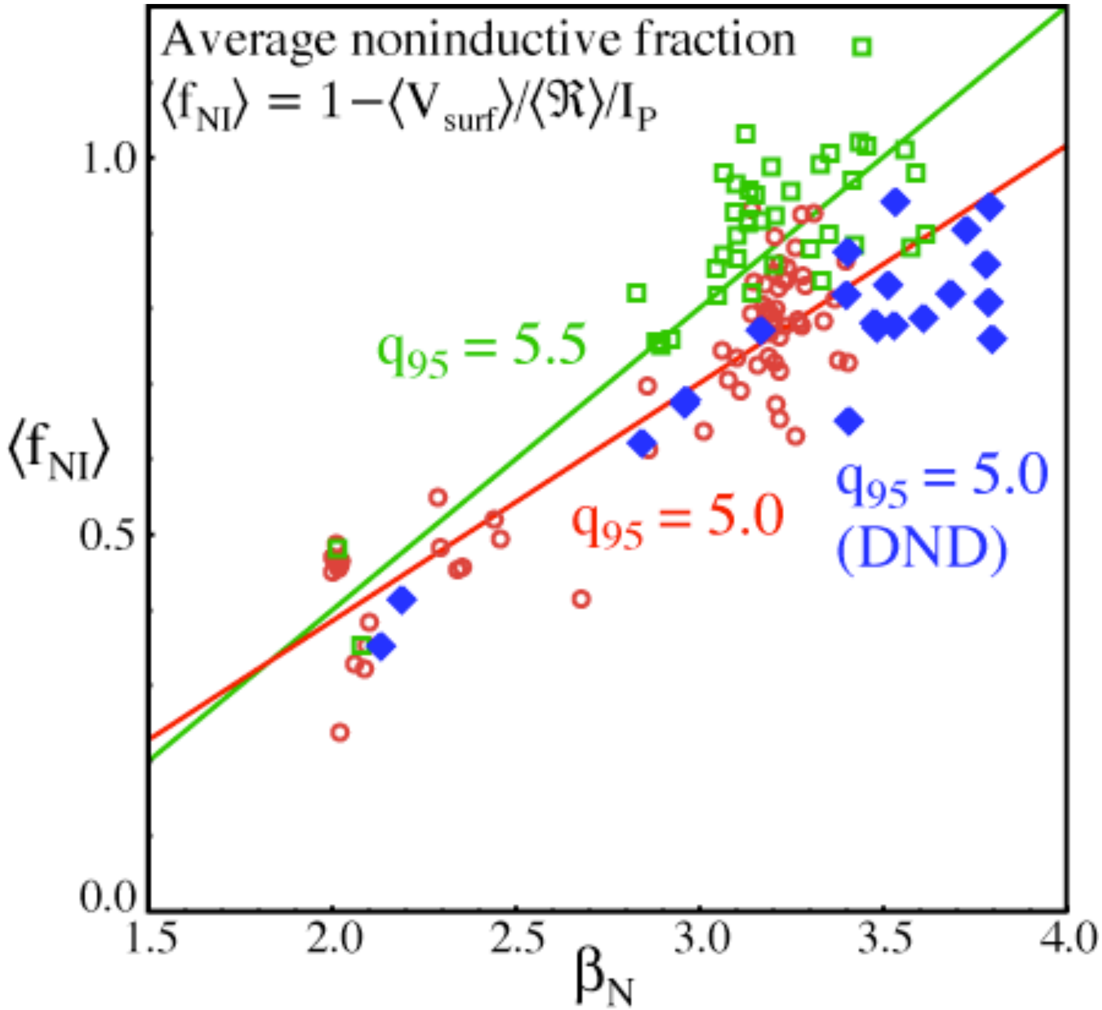
Initial Experiments With Double-null Configurations Demonstrate Increased Performance



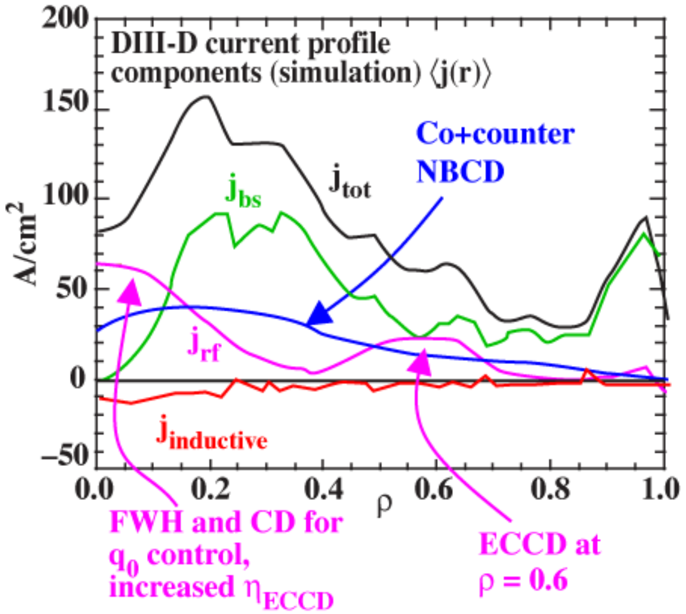


- **Double-null divertor experiments achieve:**
  - $\beta_N \lesssim 4$
  - $G \lesssim 0.4$ (ITER Q = 5 steady-state scenario requires G = 0.3)
- **Current profile analysis indicates additional off-axis current drive required to reach fully noninductive conditions**
  - Additional ECCD available in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

AT Optimization Focuses on Increasing β_N at Moderate q_{95}

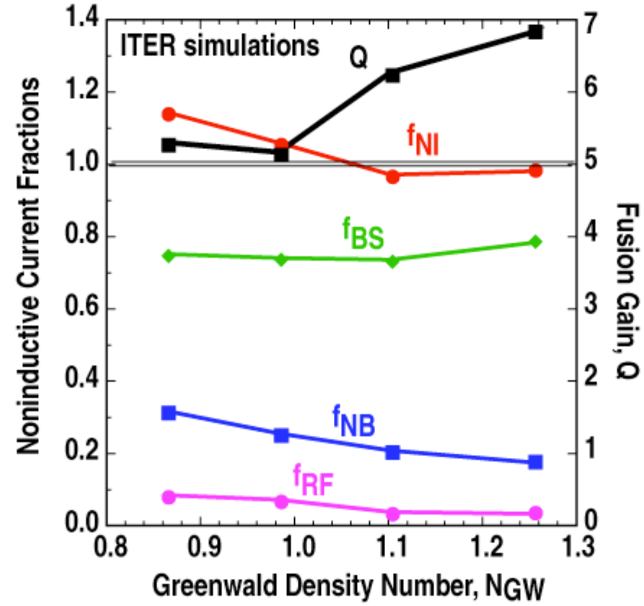


DIII–D Results Extrapolate to Successful Achievement of Steady-state Scenarios with Q ≥ 5 in ITER



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

DIII-D NATIONAL FUSION FACILITY

Performance in DIII–D AT Experiments Meets or Exceeds Requirements for ITER Q=5 Steady-state Scenario

- **$\beta_N \lesssim 4$ and G $\lesssim 0.4$ achieved through shape optimization in plasmas compatible with steady-state operation**
  - Shaping flexibility important for optimization
- **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