Advanced Tokamak Development in DIII–D

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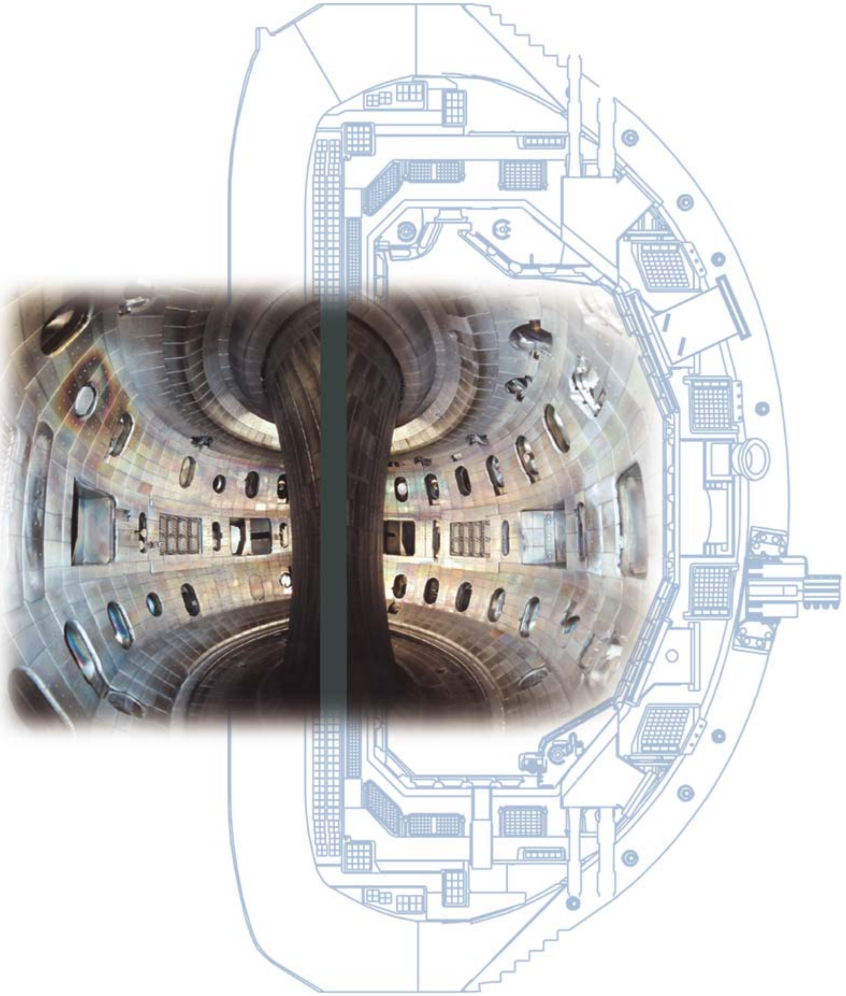

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212-05

DIII–D Advanced Tokamak experiments have demonstrated the performance required for the ITER Q=5 steady-state scenario

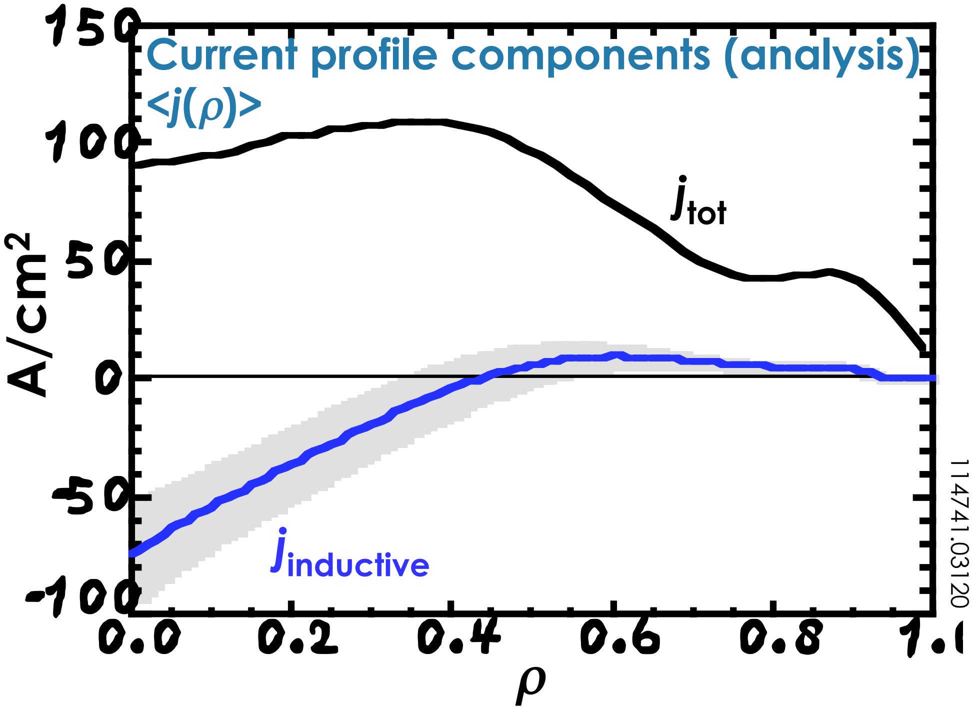
- **Experiments in the high bootstrap negative central shear regime emphasize stationary, in-principle steady-state, operation [Murakami UI2.05, Friday morning]**
  - With $\beta_N \approx 3.5$:
    - $f_{NI} \approx 100\%$ for 0.5 – 1.0 s (inductive current ⇒ 0 both globally and locally)
    - $f_{NI} \leq 95\%$ for 2 s, limited by hardware pulse length

- **Internal transport barriers (ITB) with broad current profiles can maintain very high performance under nonstationary conditions [Garofalo UI2.03, Friday morning]**
  - $\beta_N \approx 4$ for 2 s with elevated q profile

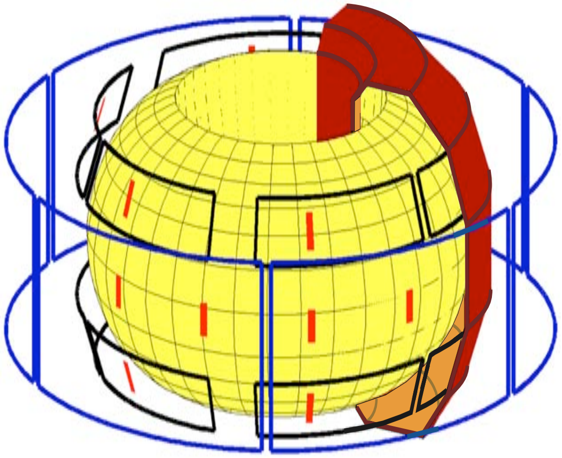
Progress in tool development is discussed elsewhere

Where we were:
100% noninductive current achieved, but not fully relaxed

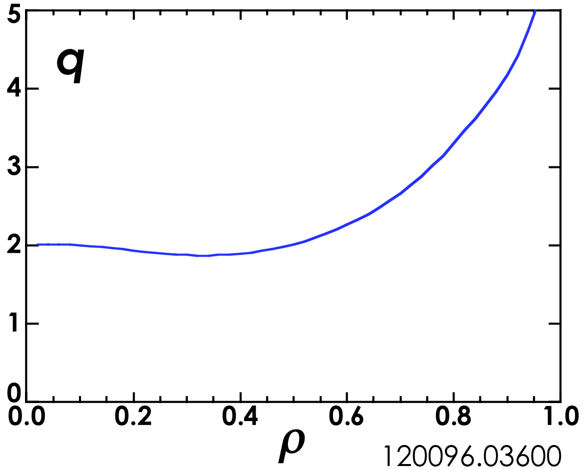
- **Advanced tokamak goals call for:**
  - For steady-state: **$j_{inductive}(\rho,t) = 0$**
  - For fusion performance and high bootstrap current: **high β**
- **Achieved: Net $f_{NI} \approx 100\%$ with $\beta_N \approx 3.5$ and $\beta_T \approx 3.6\%$, but…**
  - Locally non-zero inductive current
    - Neutral beam current overdrive near axis
  - "Reduced" confinement ($H_{89} \leq 1.9$)
  - Current profile not stationary



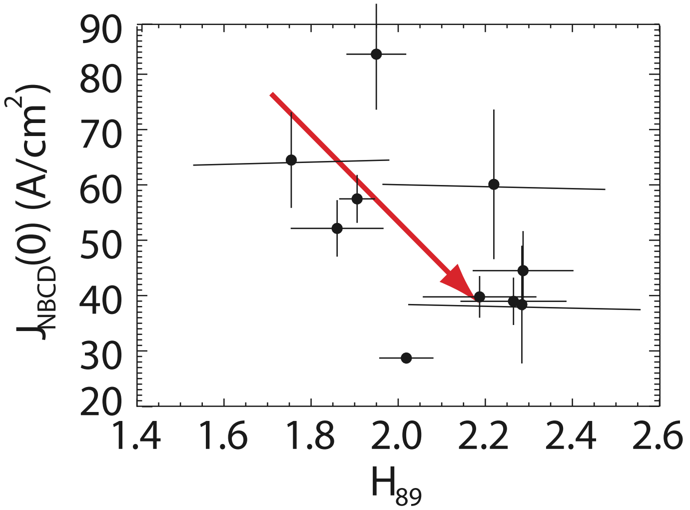
Development of control techniques results in improved AT performance



- **Improved error field and RWM control**
  - Both internal and external coils



- **Early β feedback control (during current ramp)**
  - ⇒Finer control of target *q* profile
    - Best performance found with slightly negative central shear

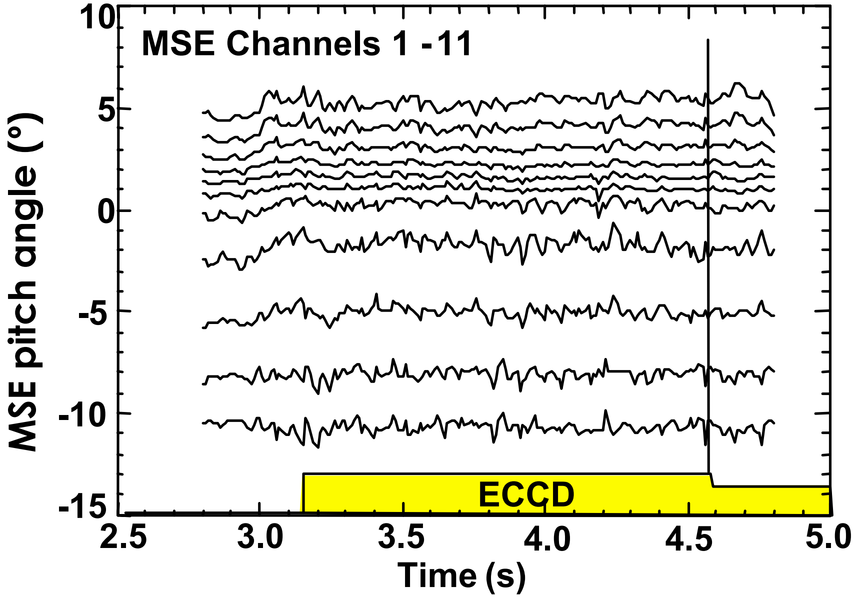


⇒**Improved stability and confinement**

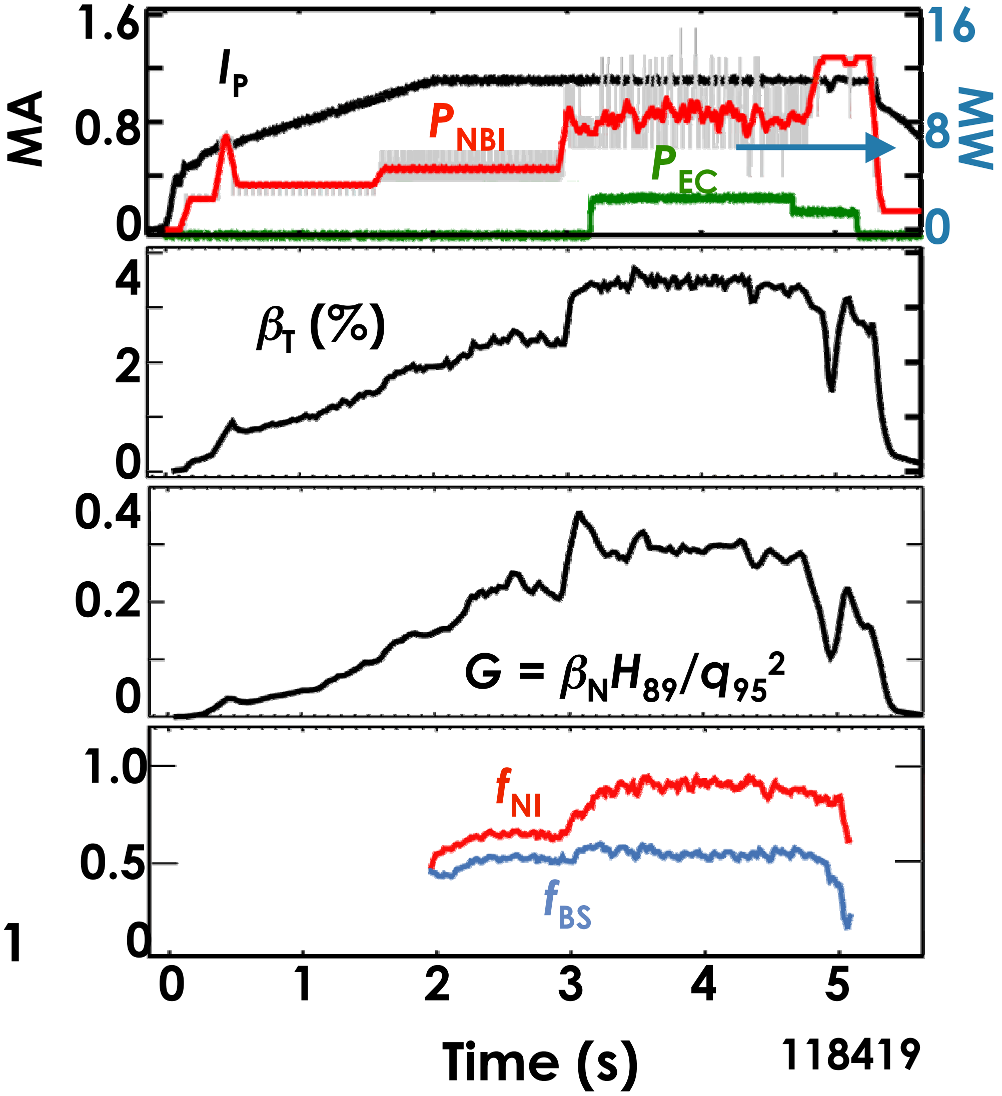
- Reliable operation at $\beta_N \approx 3.5$
- $H_{89} \approx 2.3\text{-}2.4$

  Ability to modify confinement allows some control over central current

Nearly full noninductive, stationary discharge obtained, limited only by gyrotron pulse length

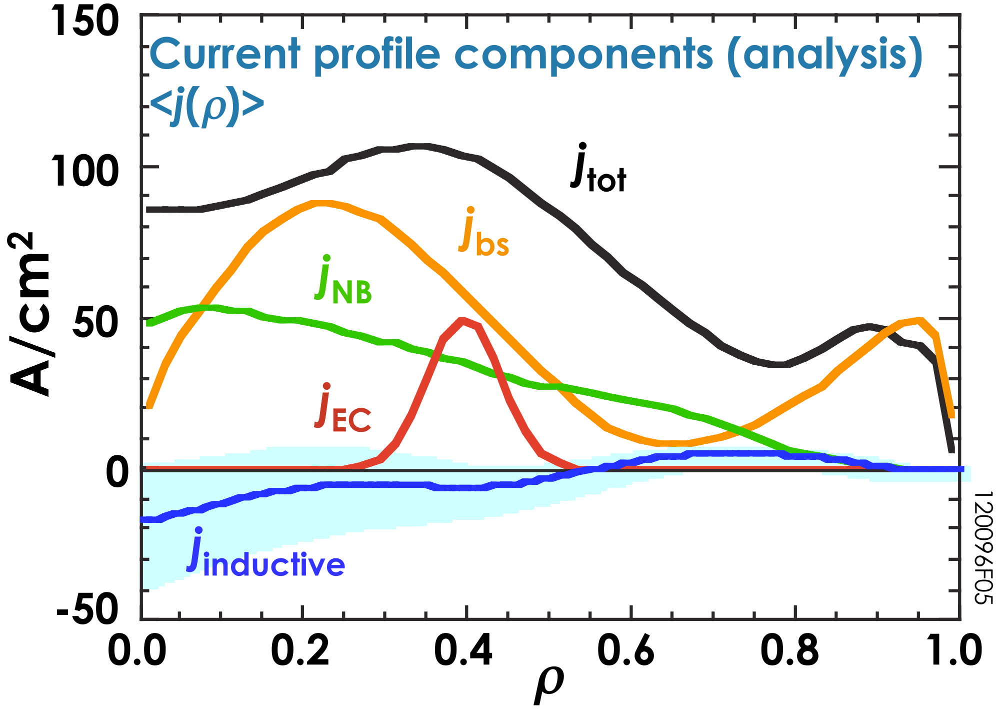


- **MSE signals stationary**
  - ⇒ Current profile not evolving
- **$f_{NI} \approx 90\%$ for 1 τ_R (~1.8 s)**
- **$f_{BS} \approx 63\%$**
- **$\beta_T = 3.7\%$ $\beta_N = 3.5$ $q_{95} = 5.1$**
- **$G = \beta_N H_{89}/q_{95}^2 = 0.3$**



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

- **Parameters consistent with ITER Q = 5 steady-state scenarios**
- **Duration of the fully noninductive condition limited by pressure profile evolution, leading to MHD instability after about 0.7 s**



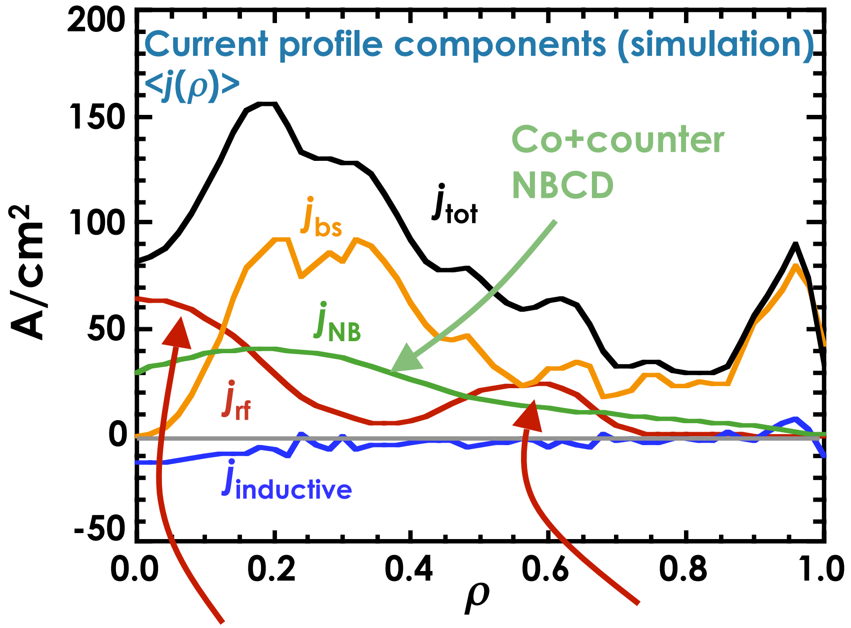
$G = 0.3$ $\beta_T = 3.6\%$

$f_{BS} = 60\%$ $\beta_N = 3.5$

$H_{89} = 2.4$

Integrated modeling supports both DIII–D AT program and ITER scenario development

- **Integrated modeling continues to be an important part of AT research on DIII–D**
  - Design experiments
  - Interpret results
  - Develop physics models for application to ITER and beyond
- **Modeling with GLF23 indicates that in-principle steady state operation is possible with hardware improvements now being made on DIII–D**
  - ECCD and fast wave
  - Double-null pumped divertor
- **Same modeling capability is being applied to ITER**
  - Credible AT scenarios exist



FWH and CD for q_0 control, increased η_{ECCD}

ECCD at $\rho = 0.6$

P_{EC} = 4.5 MW **I_p = 1.19 MW**

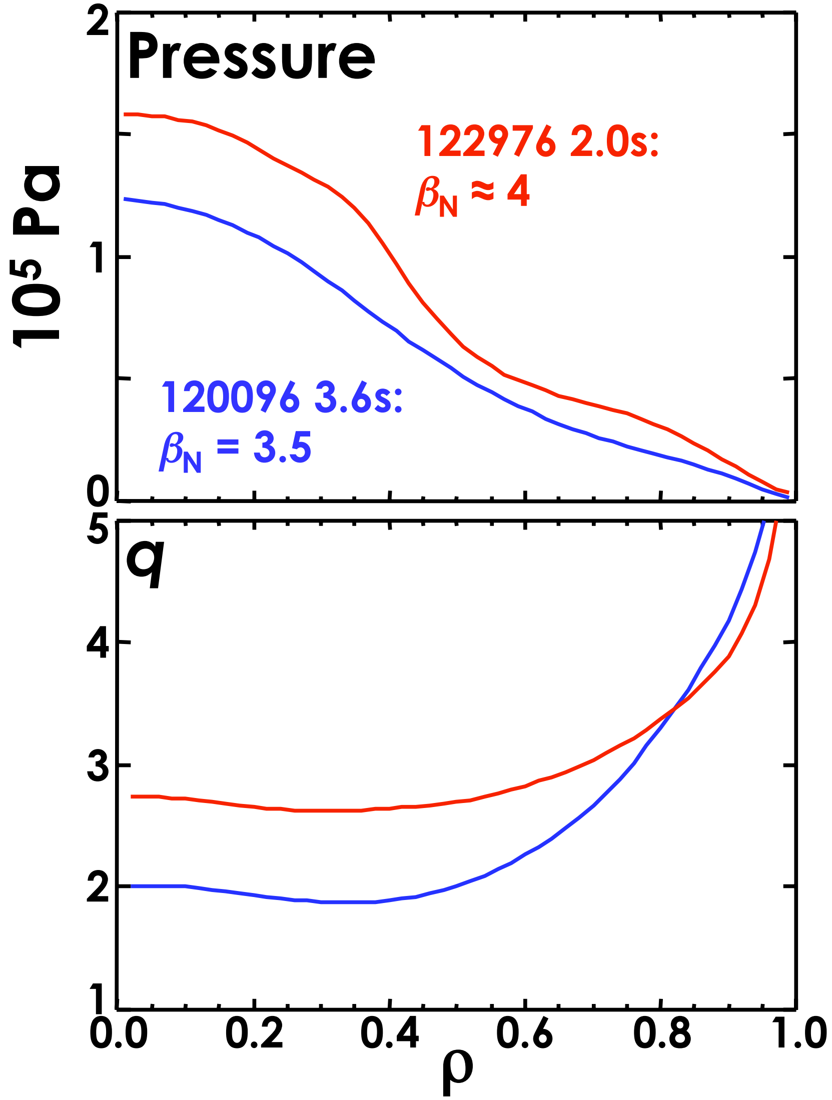
P_{NB} = 6.8 MW **B_T = 1.86 T**

P_{FW} = 3.5 MW **β_T = 4.1%**

β_N = 3.8

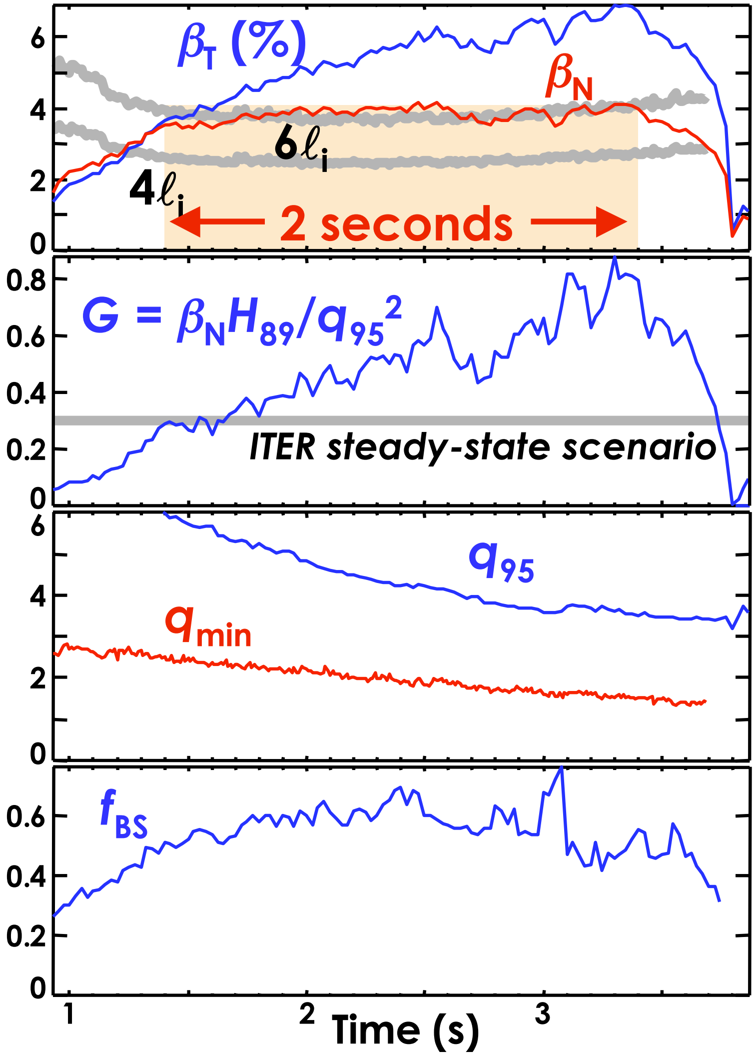
Non-stationary discharges can reach higher levels of fusion performance

- **$\beta_N \approx 4$ obtained and sustained for 2 s with**
  - Elevated *q*
  - Broad current profiles
  - Internal transport barriers
- **Challenge: Can these conditions be maintained under stationary conditions?**
  - Even if not possible with tool set in DIII–D, this research may identify techniques for application in ITER



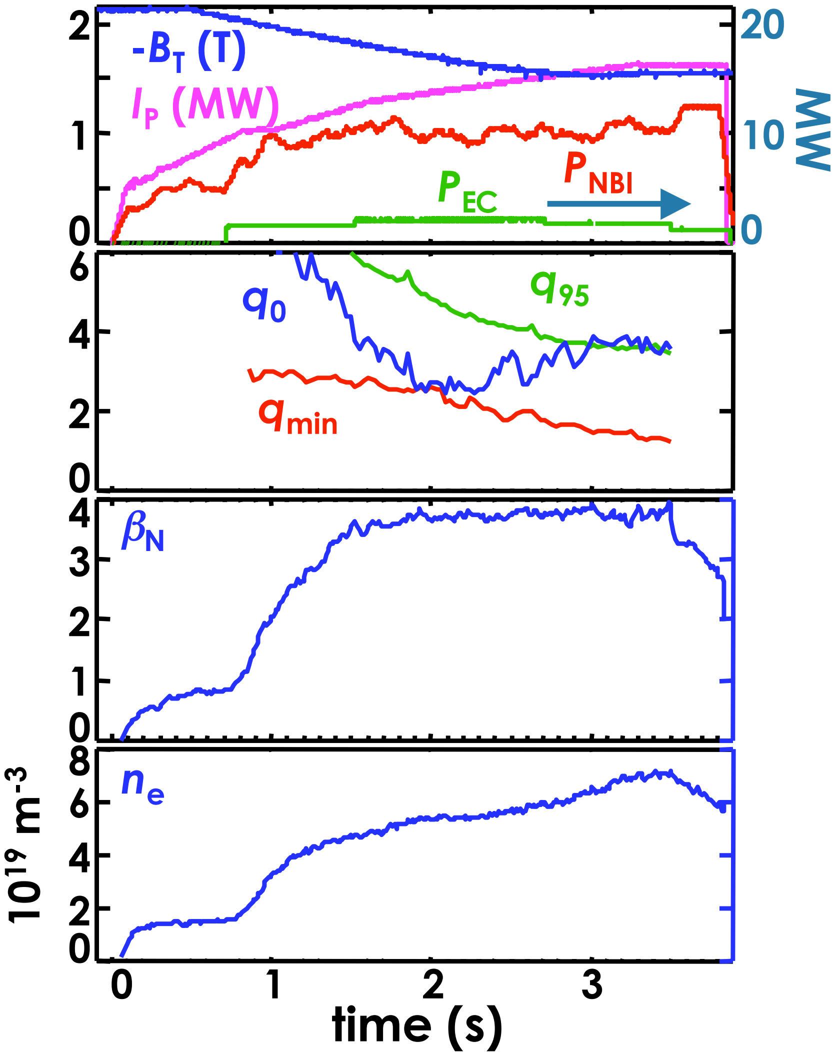
$\beta_N \approx 4$ maintained for 2 s with elevated *q* profile

- **$\beta_N > 6\ell_i$ for ~2 s**
  - Relies on wall stabilization of the *n*=1 external kink mode (no-wall stability limit ~$4\ell_i$)
- **High energy confinement ($H_{89} > 2.5$) $\Rightarrow$ high fusion gain factor *G***
- **High q_{min} $\Rightarrow$ high bootstrap fraction f_{BS}**



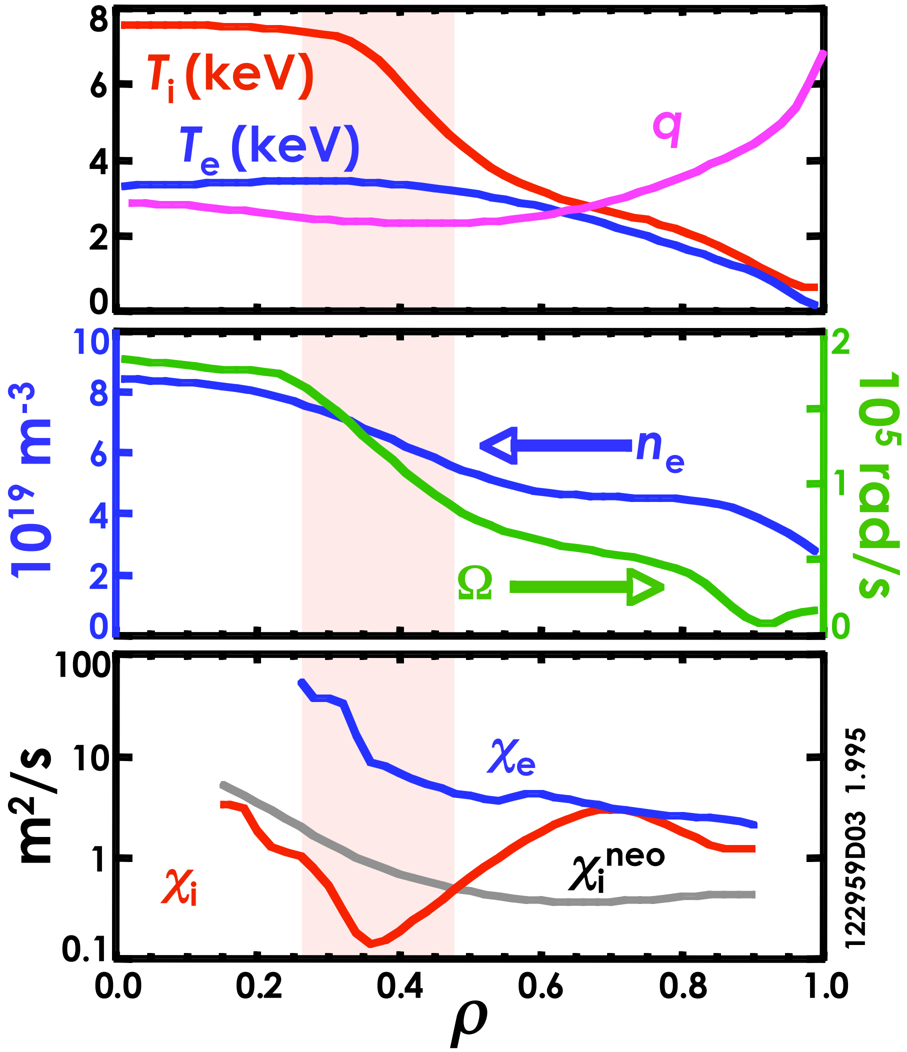
Simultaneous ramping of I_P and B_T and early neutral beam heating create broad current profiles

- **Off-axis ECCD helps broaden current profile**
  - Broadens pressure profile
  - Reduces MHD activity
- **High performance phase generally limited by current profile evolution**
  - NTM occurs as q_{min} evolves



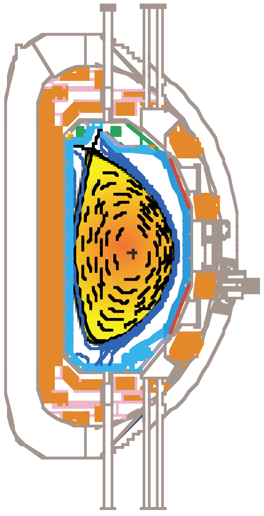
High β is achieved in the presence of an internal transport barrier

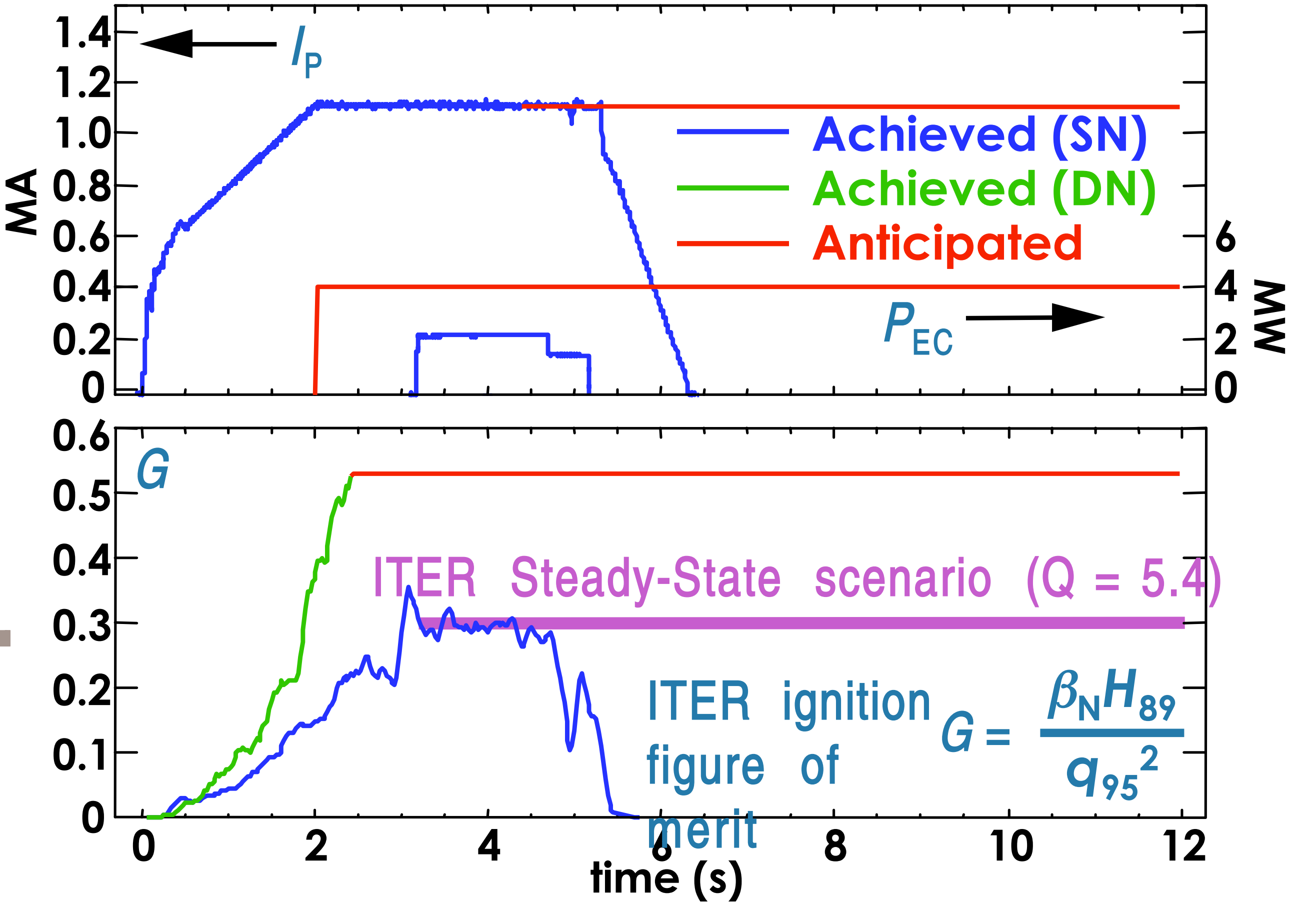
- **TRANSP analysis indicates presence of ITB in the ion thermal channel**
  - Contrasts with previous experience: Low β limits usually associated with peaked profiles in ITB discharges
- **High β_N limit to n=1 kink mode calculated with ideal DIII-D wall for experimental pressure profile**
  - DCON ideal MHD stability code predicts $\beta_N^{\text{ideal-wall}} > 6$ ($\sim 11\ell_i$)
  - Enabled by broad current profile and wall stabilization

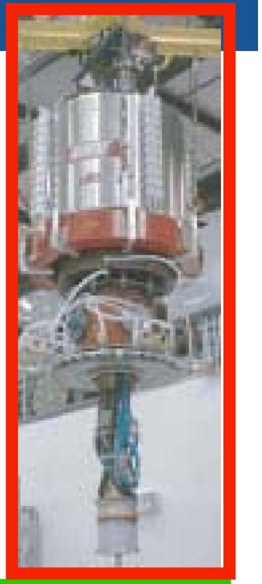


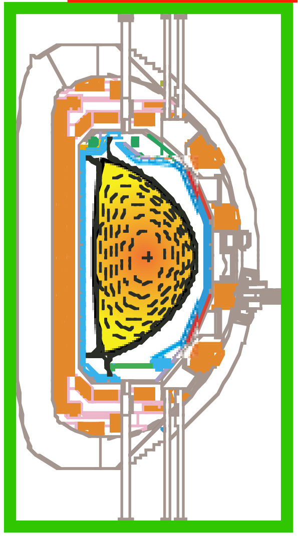
DIII-D can develop the scientific basis for ITER steady-state Advanced Tokamak studies

- **Facilitated by long-pulse gyrotrons and density control in strongly shaped plasmas**









Also coming: counter- NBI and fast wave heating and current drive

AT research in DIII–D continues to build a scientific basis for high performance steady-state operation

- **Performance achieved:**
  - Fully noninductive operation with $\beta_N \approx 3.5$
    - $f_{NI} \approx 100\%$ for 0.5 - 1.0 s (fully relaxed)
    - $f_{NI} \leq 95\%$ for up to $1\times\tau_R$
  - Maintained $\beta_N \approx 4$ for 2 s with elevated *q* profile and internal transport barrier
- **Experimental efforts supported by integrated modeling to**
  - Plan and interpret DIII–D experiments
  - Build physics models to design AT scenarios for ITER and beyond
- **New tools will allow continued progress**
  - Pumped double-null divertor will improve access to high β and quantify benefits of double-null operation
  - Increased power and pulse length for current profile control

Advanced scenario development at the 2005 APS/DPP conference

- **Murakami UI2.05**: ***Progress Toward Fully Noninductive, High Beta Conditions in DIII-D***
- **Garofalo UI2.03**: ***Access to Sustained High-Beta With Internal Transport Barrier and Negative Central Shear in DIII-D***
- **Tool development supporting current and future *AT* research**
  - DIII–D facility enhancements: Tooker B03.15*, Boivin CP1.02
  - Current profile control: Ferron B03.03* (next!)
  - Active feedback control of RWM: Okabayashi B03.11*, Jackson CP1.19, Strait CP1.22
  - Fast wave heating and current drive: Pinsker QP1.06

…and others in the B03 oral session and CP1 and QP1 poster sessions

***This session**