Progress Toward Long Pulse, High Performance Plasmas in the DIII-D Tokamak

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A major focus of the DIII-D program is to develop the scientific basis for tokamak optimization, and to develop and demonstrate a high performance, steady-state tokamak operating regime.

Topics of this talk:

- ✧ Motivations for tokamak improvement.
- ✧ Progress we have made toward improved stability and confinement.
- ✧ Identification of the phenomena which are limiting further progress.
- ✧ Plans and prospects for dealing with these limitations.

Motivation for Improved Performance

- magnetic fusion reactor
  maintain high fusion power density ($\propto \beta^2 B^4$)

- steady-state $\Rightarrow f_{bs} \approx 1$ (in tokamak)
  increasing the bootstrap fraction means increasing q
  $\Rightarrow$ high q ($\propto f_{bs}^{1/2}$)

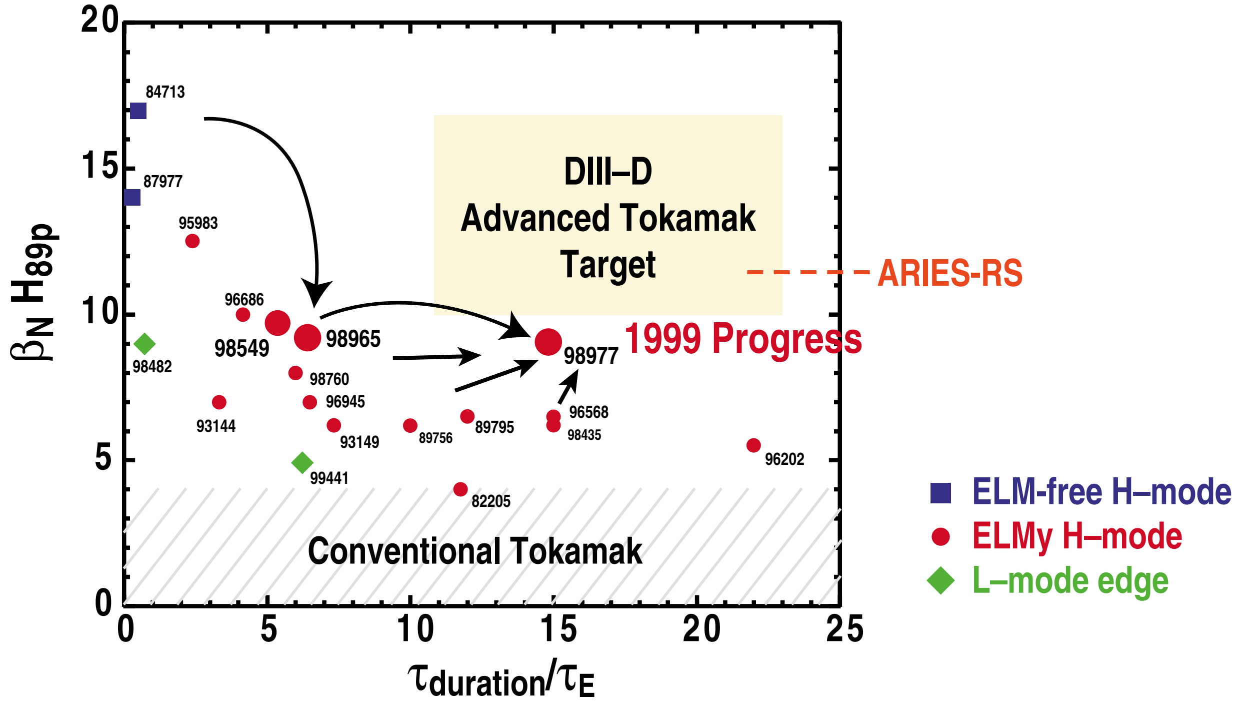
- stability must be improved
  $\Rightarrow$ increase β_N ($\propto$ q)

- must exceed ignition condition & maintain power balance during burn
  (maintain $P_{fusion}/P_{loss} \propto \beta\tau$)
  $\Rightarrow$ increase H ($\propto$ q)

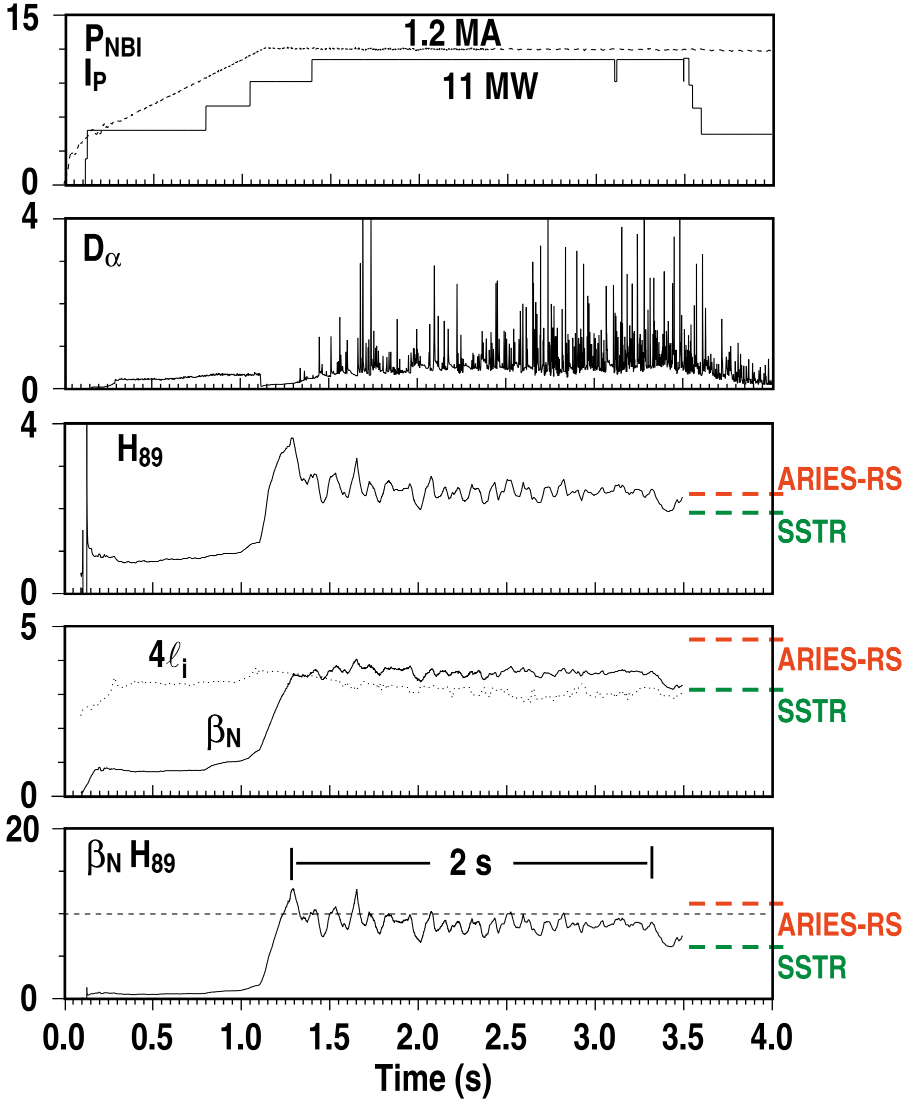
✳ for example: if a tokamak reactor plasma has $q \approx 3$, $\beta_N H_{89p} \approx 5$, and $f_{bs} \approx 40\%$, to reach $f_{bs} \approx 100\%$ at the same β would require $\beta_N H_{89p} \approx 12.5$ at $q \approx 4.7$.

DIII-D Goal & Progress in 1999

A principal near-term goal of the present DIII-D research program is a stationary plasma with $\beta_N H_{89p} \geq 10$, with no inductive current, a relaxed loop voltage profile, and > 50% bootstrap current.

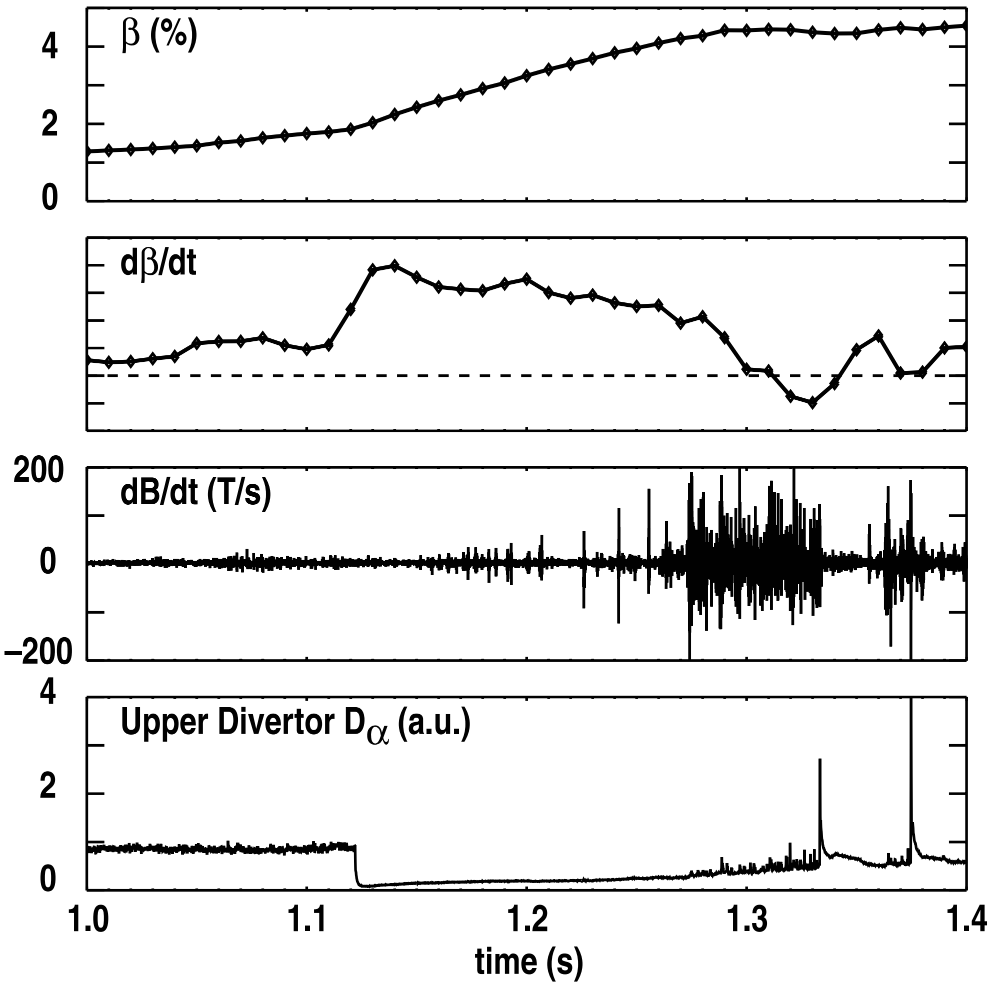


$\beta_N H_{89p} \geq 9$ for 2 sec (16 τ_E & ~1 τ_R)



- ✧ Discharge preparation to produce hot core with hollow current profile.
- ✧ Confinement meets reactor requirements.
- ✧ β exceeds no-wall limit
  - – no reduction when ELMs start.
- ✧ Flat-top β limited by a combination of high frequency modes, RWMs, and ELMs.
- ✧ Duration is many τ_E
  - – comparable to current relaxation time.

High Frequency Modes Limit Initial Rise of β & Delivered NB Power During Flat-top

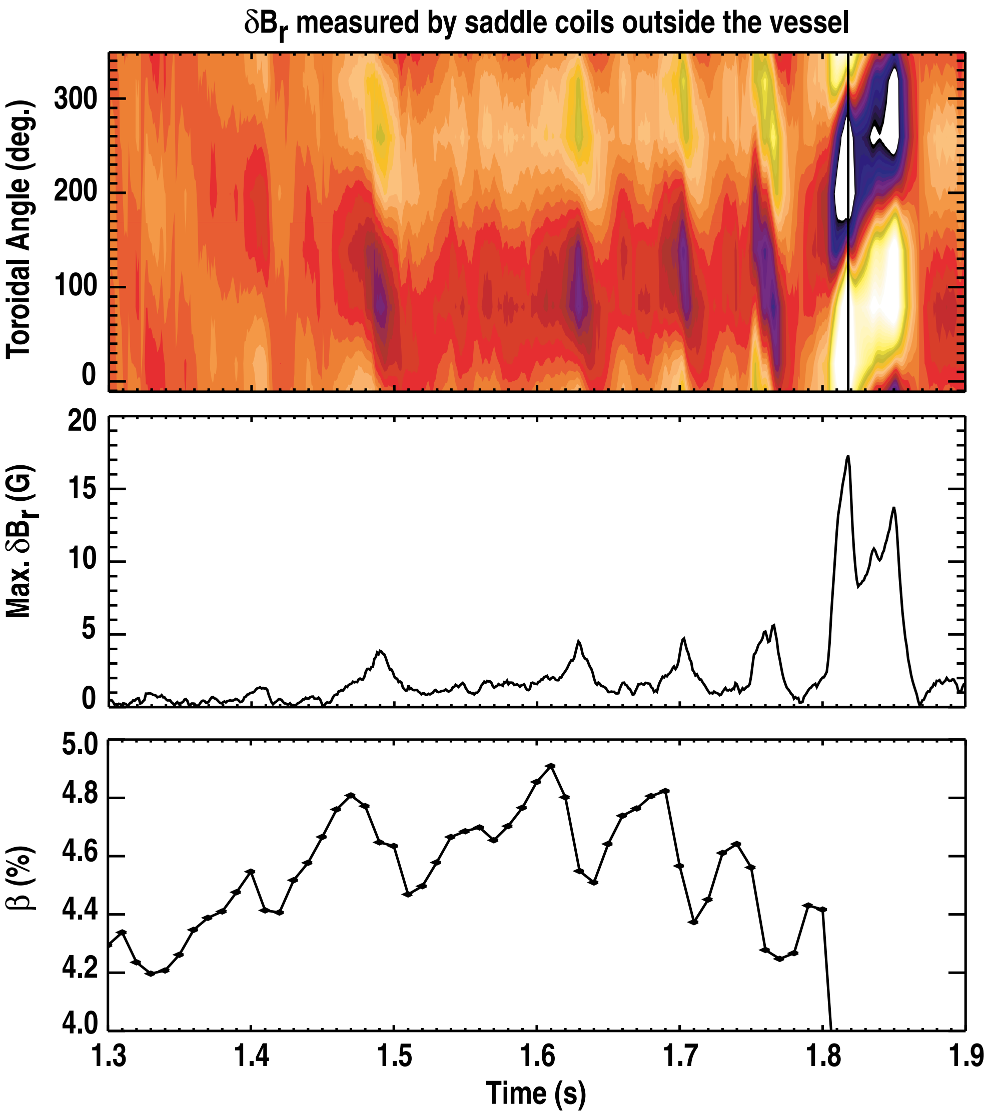


- Initial burst
  - – preceeds first ELM
  - – drives dβ/dt to zero

- Bursts continue throughout stationary phase
  - – limit NB H&CD

- Fluctuations are consistent with Alfvénic modes driven by fast ions
  - – f = 100-200 kHz
  - – n = 5-9
  - – onset not dependent on β or q profile

Resistive Wall Modes Limit Magnitude and Duration of High β

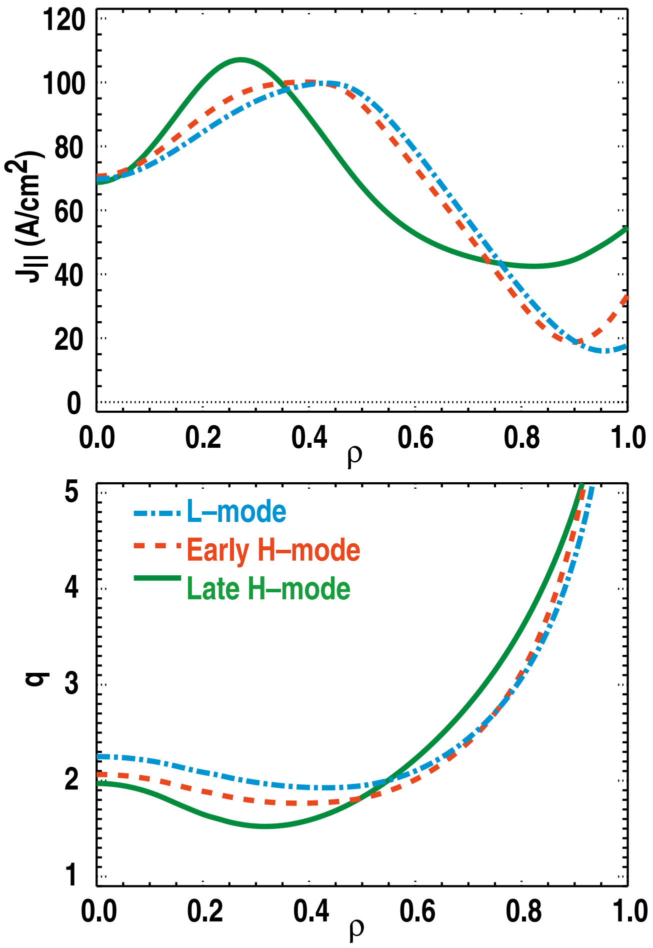


These have the characteristics of resistive wall modes:

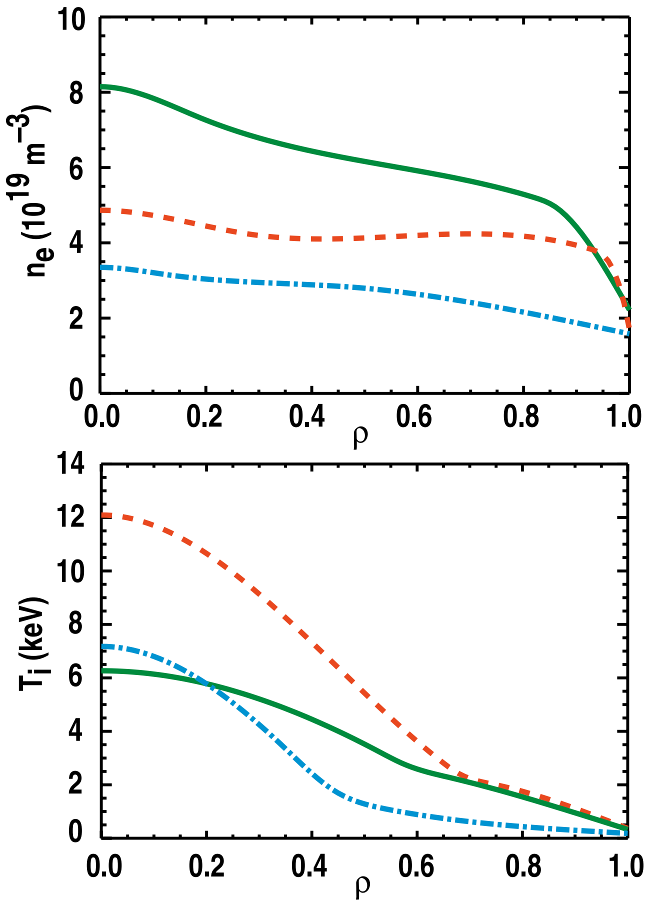
- Onset is at or above the ideal limit without a wall ($\beta_N \geq 4\ \ell_i$).
- Growth rate and real frequency (< 100 Hz) are consistent with characteristic wall time, not plasma rotation.

Steady-State Requires Density Control & Local Noninductive Current Drive

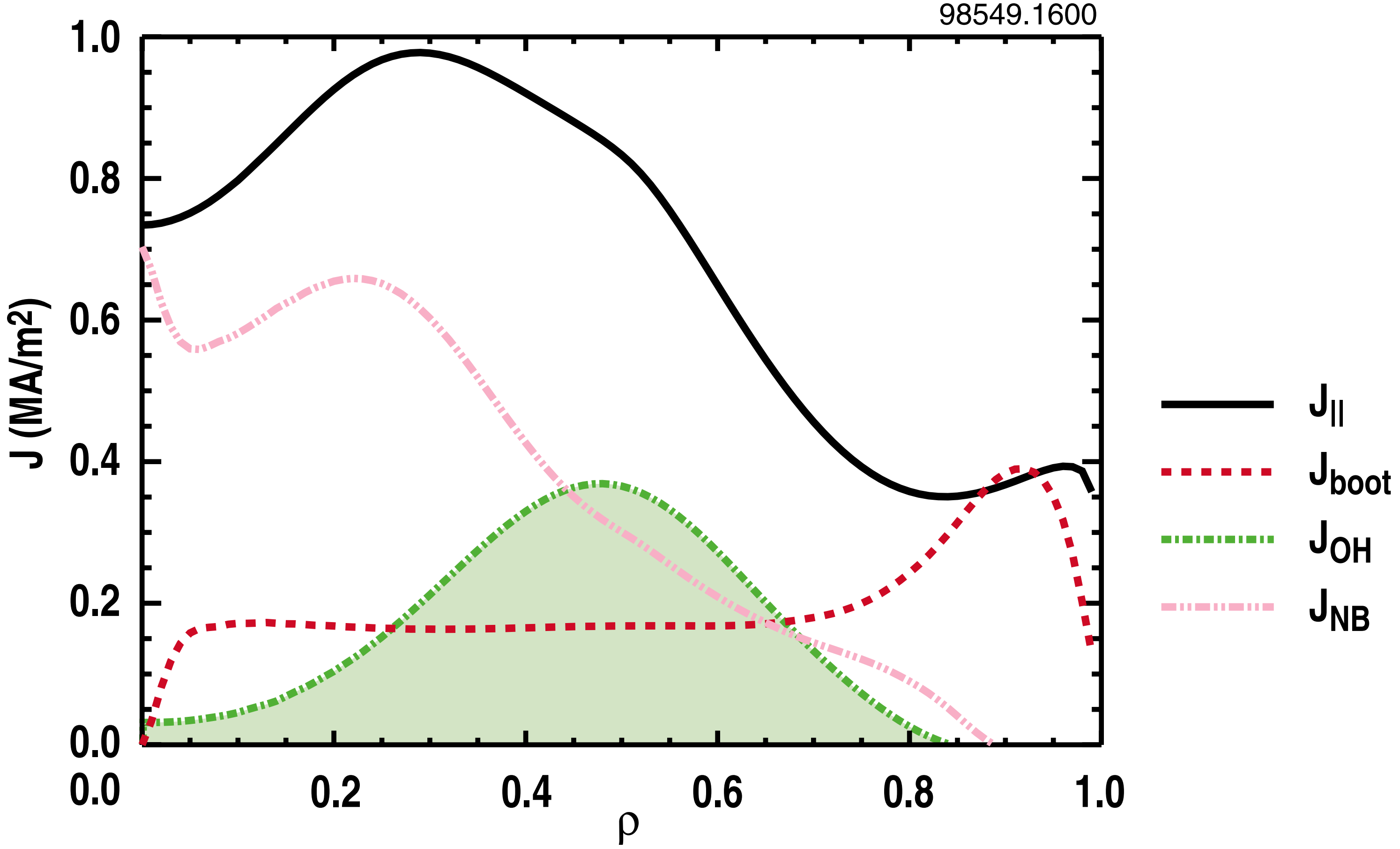
- **Current profile diffuses toward an unstable profile**



- **Density steadily increases at constant β**

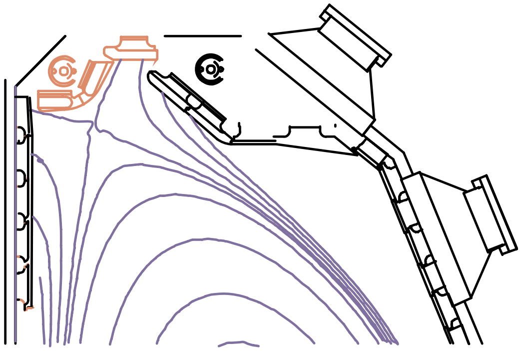


Need to Drive Noninductive Current at Half-Radius for Steady-state Operation (Replace Ohmic Current)

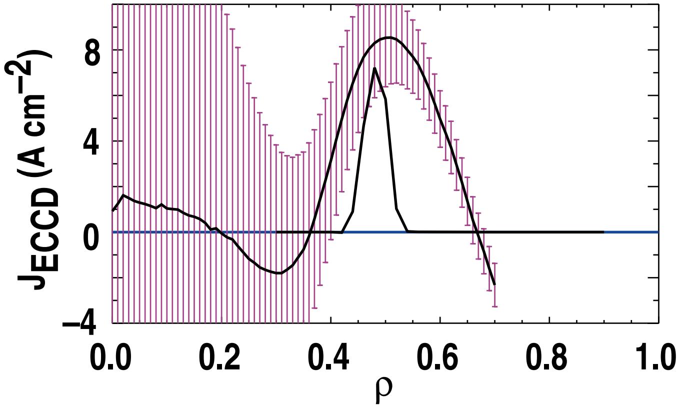


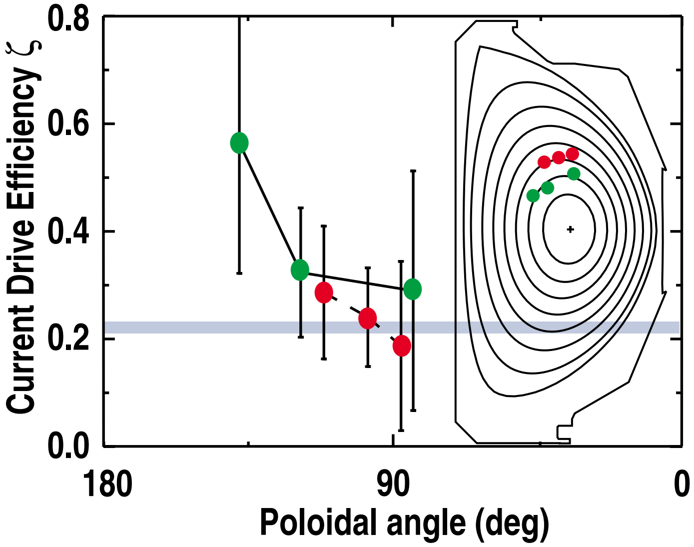
New Tools & Techniques Are Becoming Available

- Density control is needed to sustain efficient current drive.
- An additional cryopump and private flux baffle have been installed.



- An effective localized CD system is needed to maintain the current profile
- A 110 GHz ECH/ECCD system delivering ≥ 2.3 MW is being installed.





Plans and Prospects

- It is an indication of the success of this optimization effort that the β saturation is associated with several different stability limits (RWMs, fast-ion modes, ELMs, NTMs)

- The principal difficulty is the evolution of the current profile toward an increasingly unstable configuration.
  - ✓ Density control and local current drive will address this.
  - ✓ Fast-ion modes will be alleviated by density and beam energy control.

- The DIII-D program has research efforts concentrating on the physics of RWMs, NTMs, transport barriers, and the H-mode edge pedestal, and on applying new understanding to the control of these phenomena.
  - This work will help to further improve stability and confinement in tokamak (and other toroidal) plasmas.