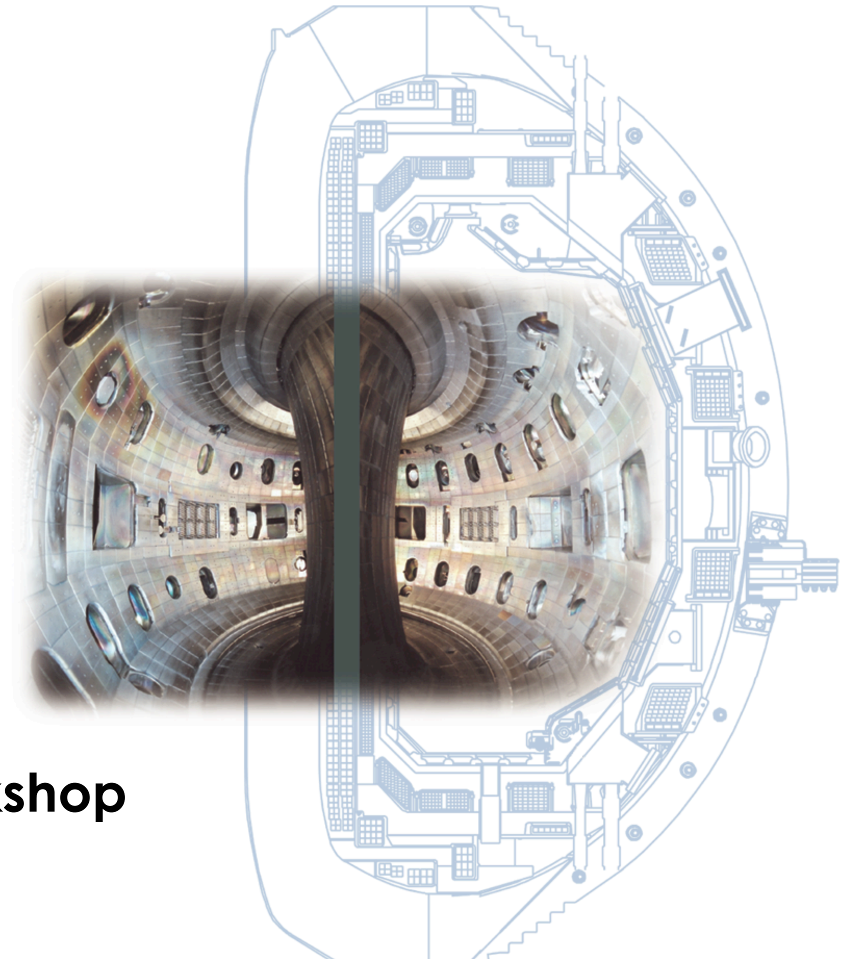
Broad q-profile and High q_{min} For Demonstration of Sustained β_N~5

by
Andrea M. Garofalo



DIII-D Advanced Tokamak Workshop
General Atomics, San Diego
February 27-28, 2007

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

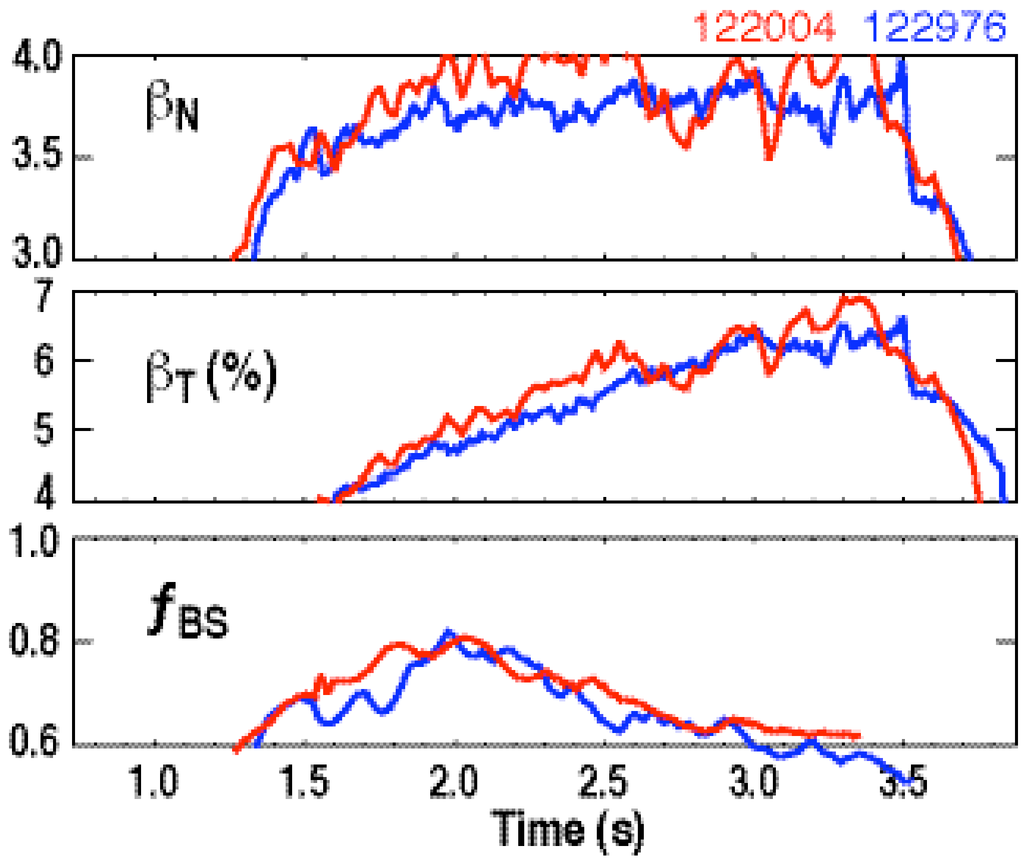
Columbia University

Demonstration of Existence of AT Reactor-like Plasma States Is Essential to Our Program

- **Sustained operation at very high beta may be accessed with a broad q-profile having high qmin (>2)**
- **In the next few years, DIII-D should vigorously pursue the long-pulse demonstration of very high beta, high confinement, high f_{BS} plasmas, continuing the use of non-stationary techniques**
  - This demonstration will provide, through parametric studies and simulations, the knowledge to assess the requirements for demonstration of similar high performance equilibria in true steady-state
  - TGLF/ONETWO simulation capability should be brought up in parallel to new experiments
- **Transition to steady-state to be approached smoothly over the years, as more external current drive capabilities become available**
  - Steady-state requirement of large external current drive at large minor radius (ρ~0.6) should be anticipated (pessimistic case)
  - New experiments may lead to reduced requirements, if ITB radius can be increased

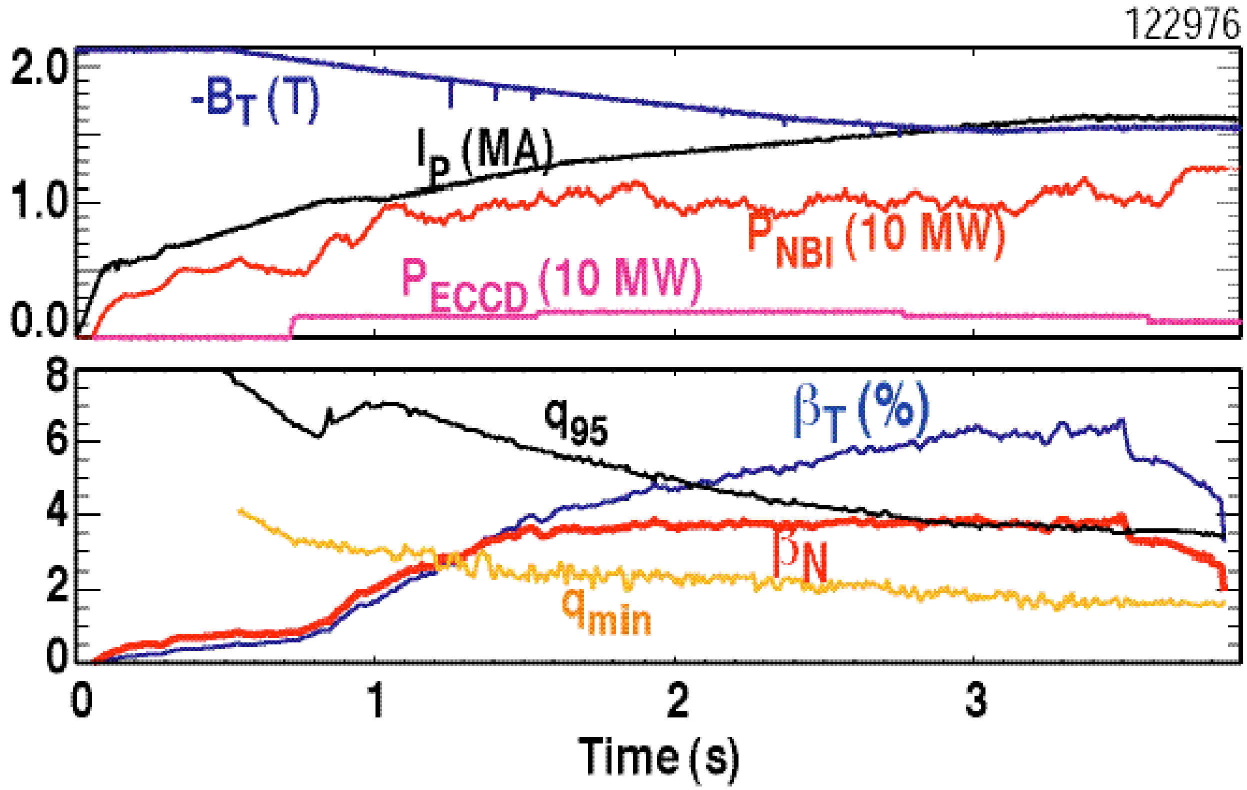
"High-β ITB" scenario is the basis for this proposal

- **An AT reactor aims at $\beta_N \geq 5$, $\beta \geq 8\%$, $f_{BS} \geq 90\%$ (ARIES-AT)**
- **"High-β ITB" experiments in DIII-D have reached closest to this target in long-pulse discharges**
  - Garofalo, PoP 2006
  - Doyle, PPCF 2006
  - Greenfield, IAEA 2006



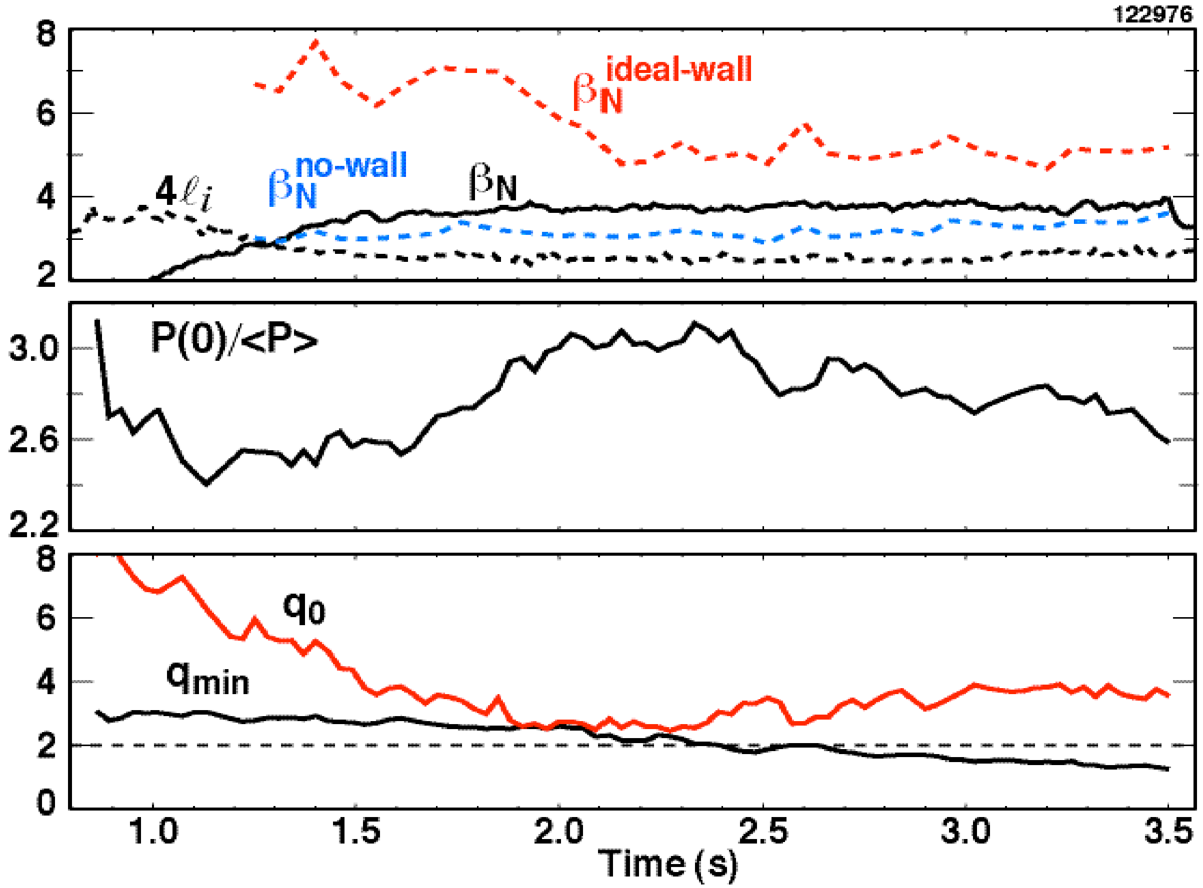
Broad q-profile Plasmas Generated Using Simultaneous Plasma Current and Toroidal Field Ramps

- **Neutral beam-line re-orientation and high-δ lower divertor already should have a large impact on the physics of this scenario plasmas**
  - One or two years of experiments in the short term are needed to develop a new scenario that includes density control and counter-NBI



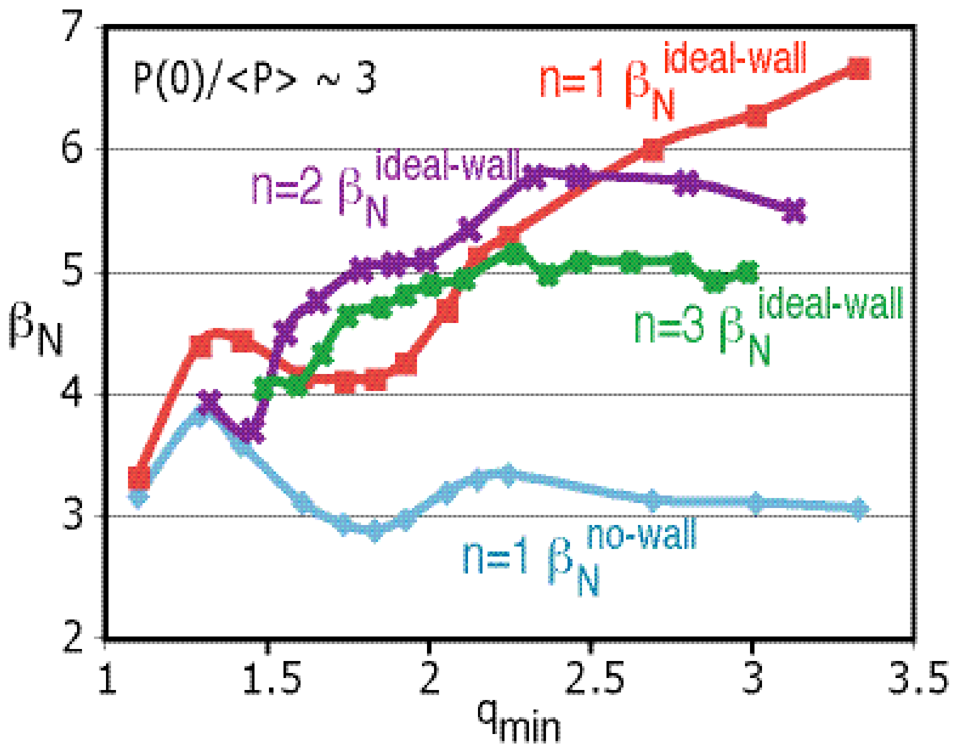
High Ideal-wall Beta Limit Calculated for n=1 Kink with ITB and Relatively Peaked Pressure Profile

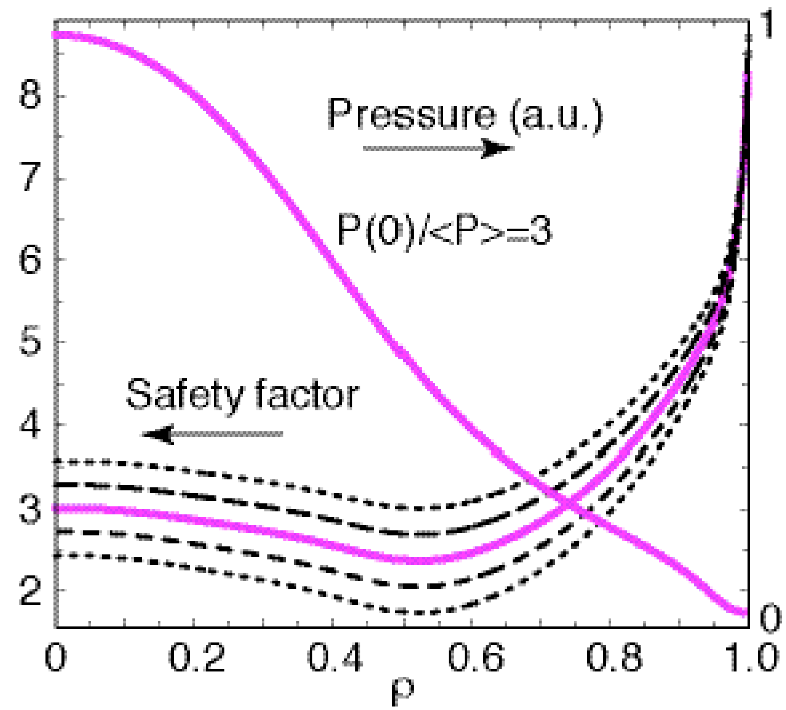
- **Previously, stability limits in plasmas with core transport barriers have been observed at moderate values of β_N (<3)**



Broad q-profile and High q_{min} Lead to High Ideal-wall Beta Limits

- **n=1,2,3 wall stabilized at $\beta_N \geq 5$ for $q_{min} > 2.1$**
- **Ideal wall limits calculated with P(0)/<P>~3**
  — Optimal pressure peaking for simultaneous stability of n=1,2,3



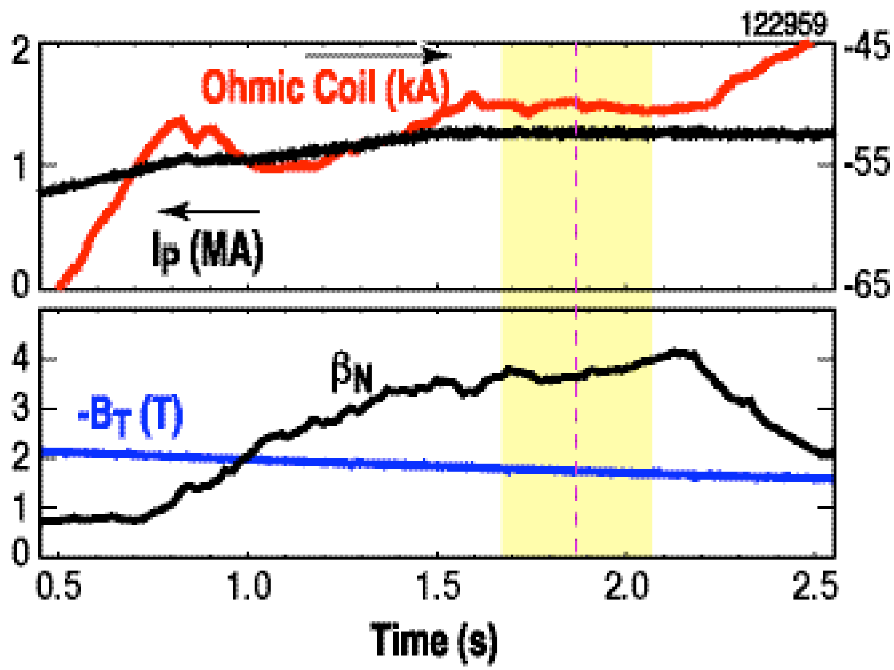


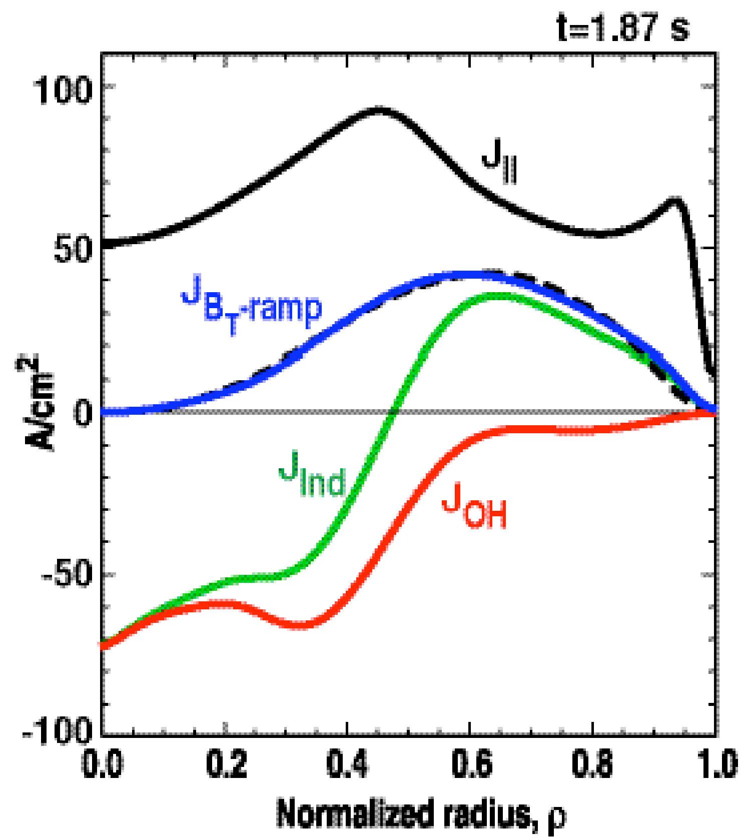
Toroidal Field Ramp-down Drives Large, Off-axis, Parallel Current

- **Two components of the flux-averaged, parallel, inductive current density**

$J_{\mathrm{OH}} \sim \sigma\, d\psi/dt$ (toroidal flux evolution)

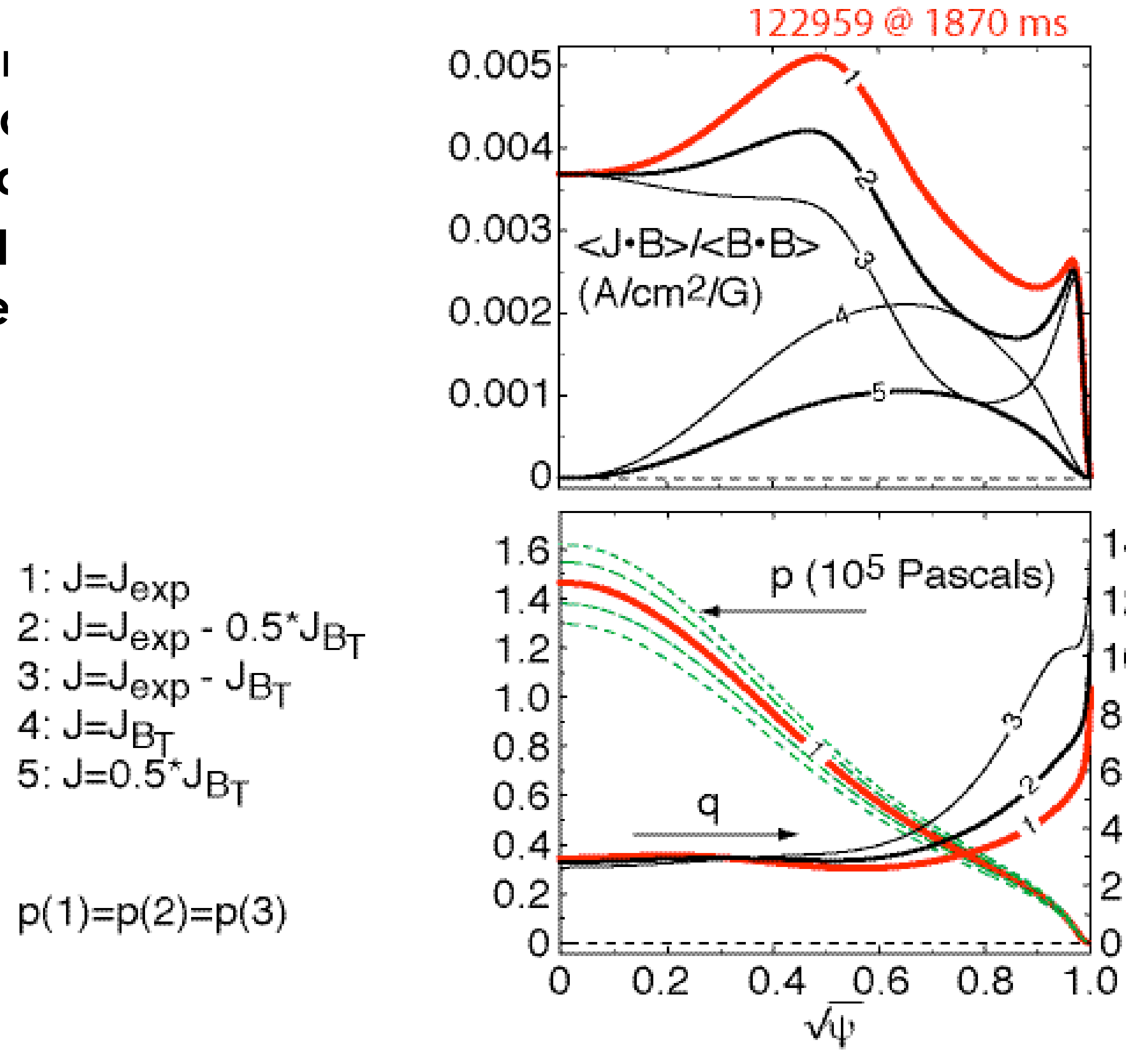
$J_{\mathrm{B_T}} \sim \sigma\, d\phi/dt$





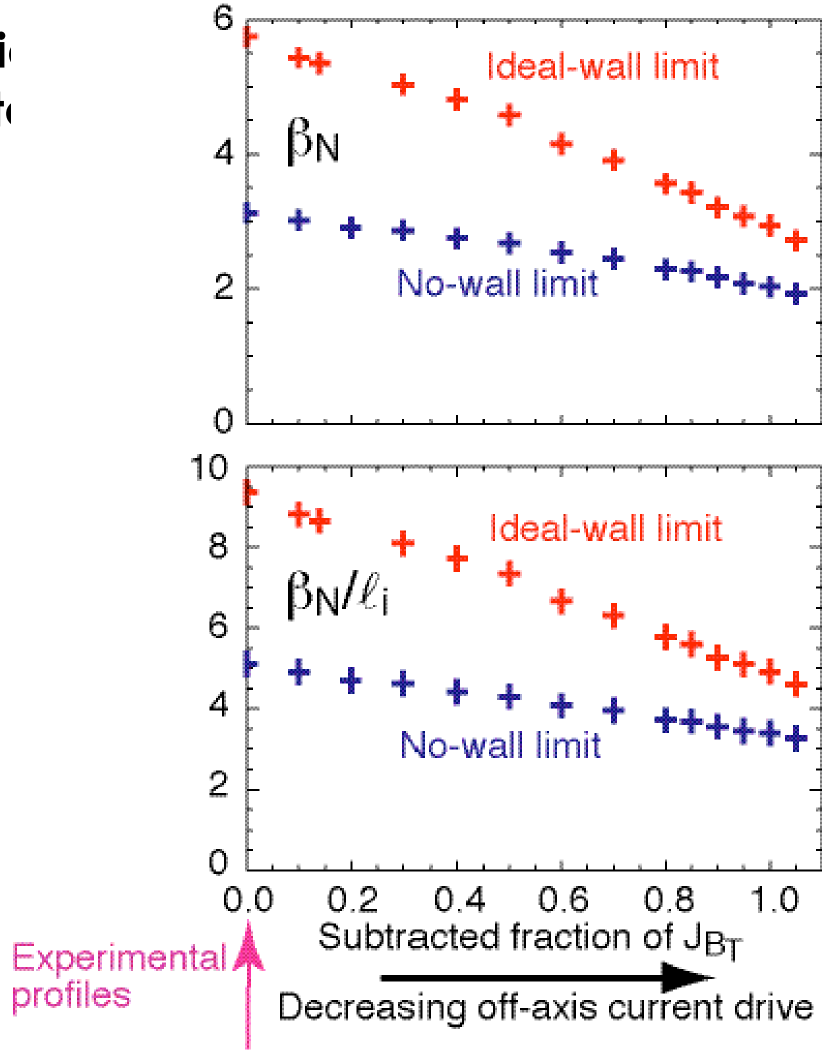
Stability Analysis Shows Off-axis Current Drive Increases Beta Limits

- Experimental current de
  altered by subtracting fr
  driven by toroidal field r
- Equilibrium recalculated
  constant pressure profile



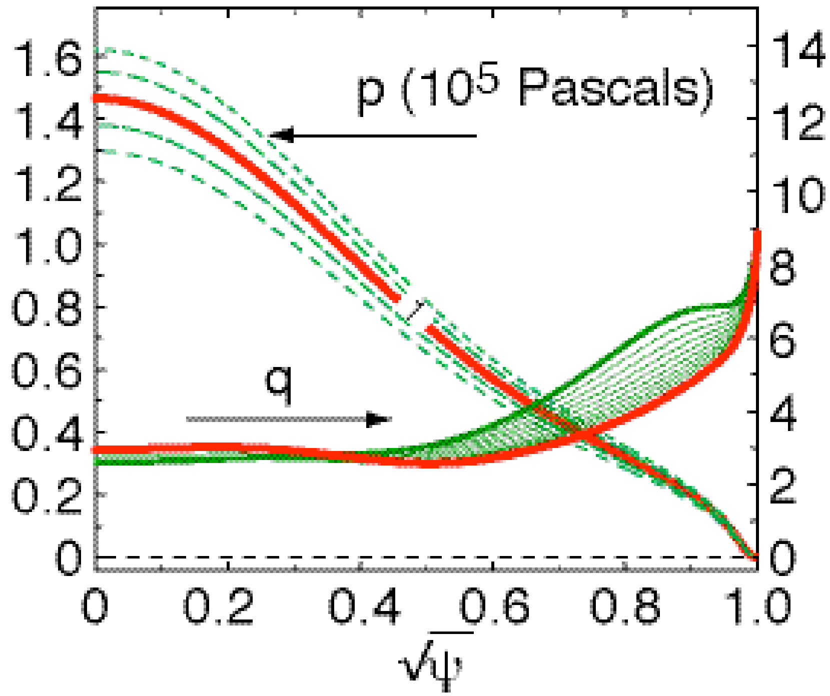
Stability Analysis Shows Off-axis Current Drive Increases Beta Limits

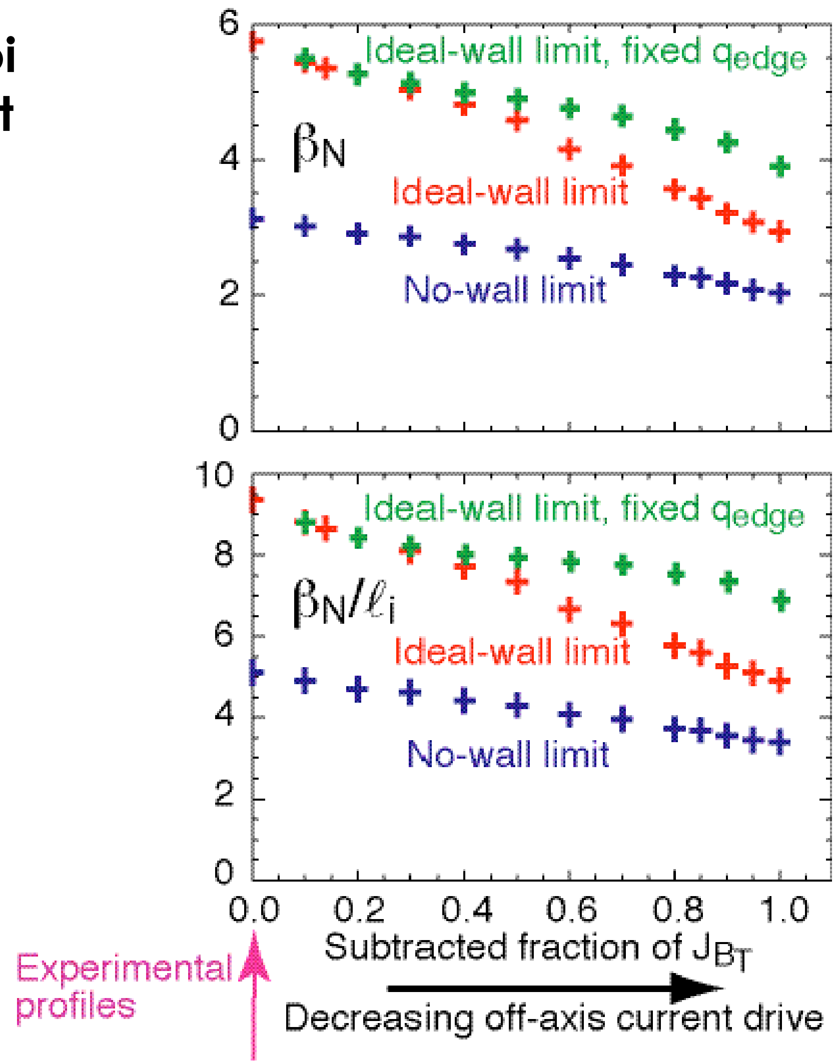
- **Removing current density due to toroi… field ramp-down reduces beta limits t… standard values**
- **DCON calculations of n=1 beta limit**



Stability Analysis Shows Off-axis Current Drive Increases Beta Limits

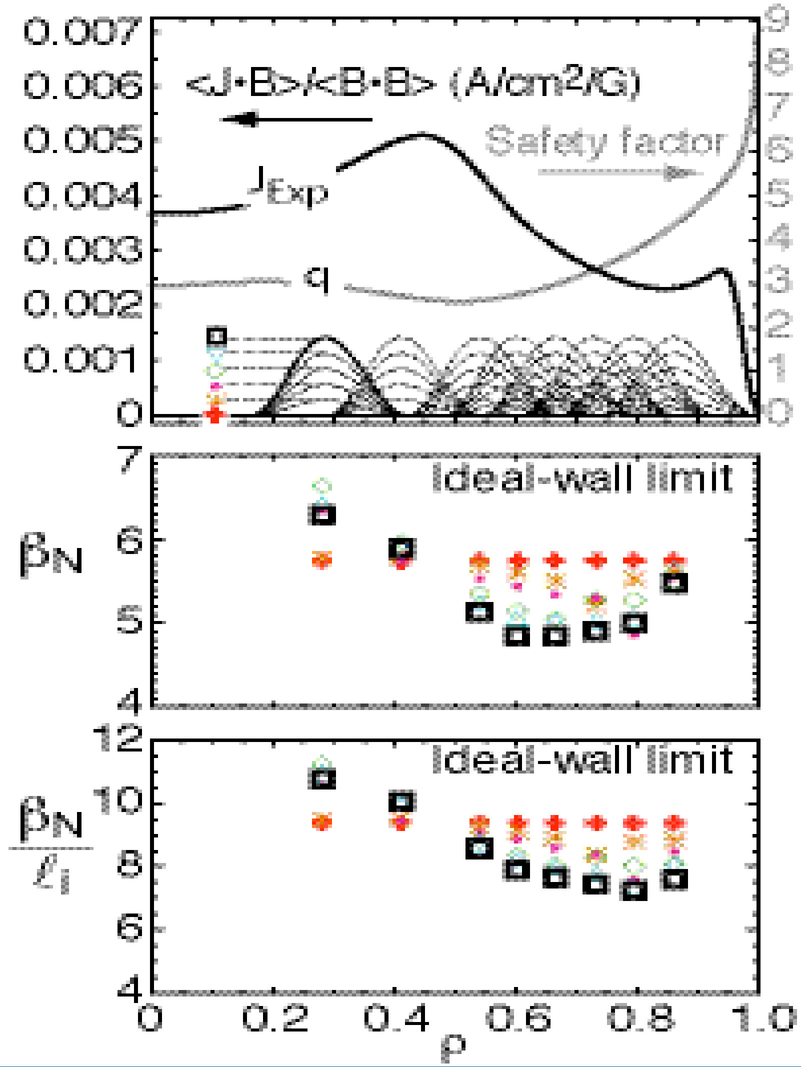
- **Removing current density due to toroi field ramp-down reduces beta limits t standard values**
- **DCON calculations of n=1 beta limit**
- **Variation of q_{95} not a major factor**





DIII-D NATIONAL FUSION FACILITY

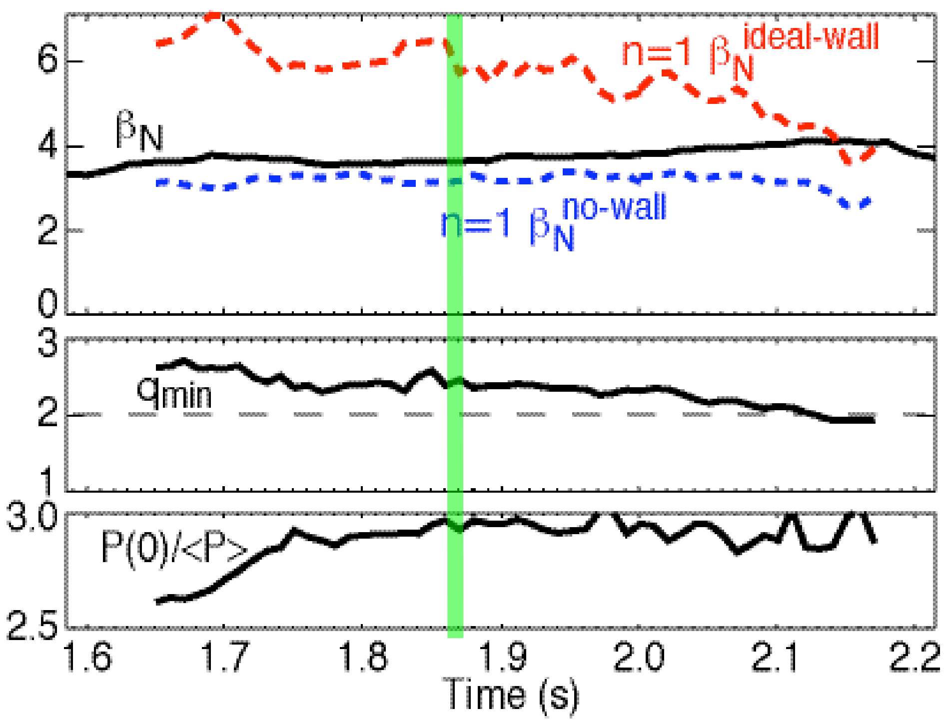
Current Drive at ρ~0.6 Yields Largest Stability Improvement

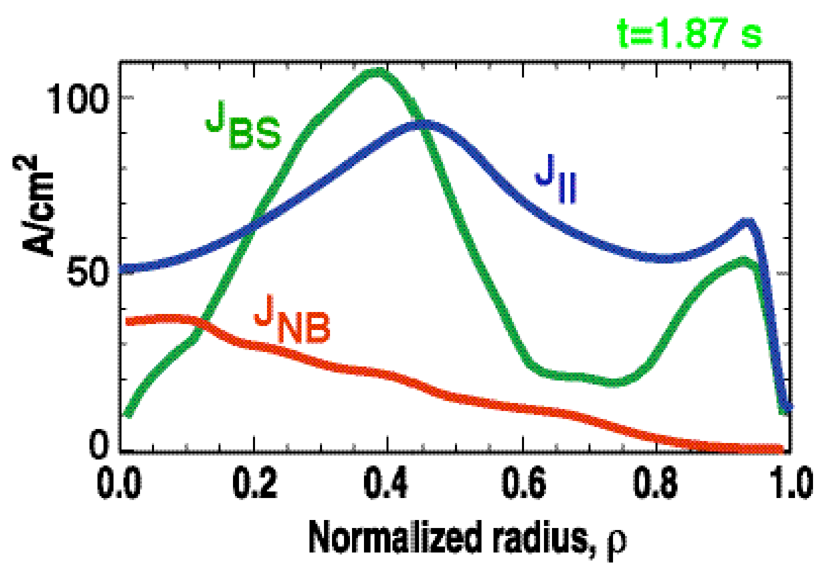


- **ρ=0.6 is approximately the radius of the outer q=3 surface**

Ideal n=1 Kink Mode is Observed at the Wall-stabilized n=1 Beta Limit

- B_T ramp-down at constant I_P drives rise of β_N
- Noninductive current overdrive leads to q_{min} drop

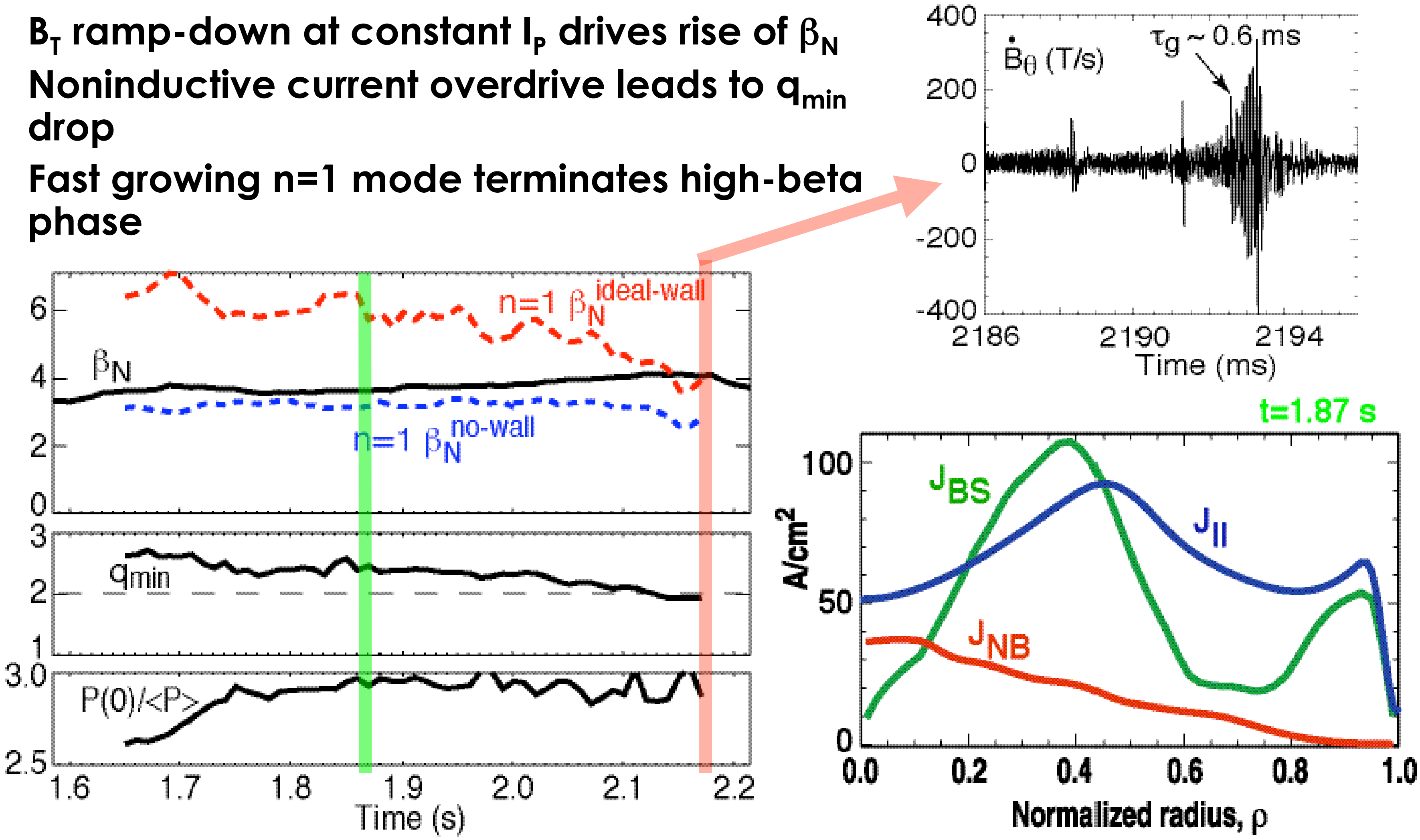




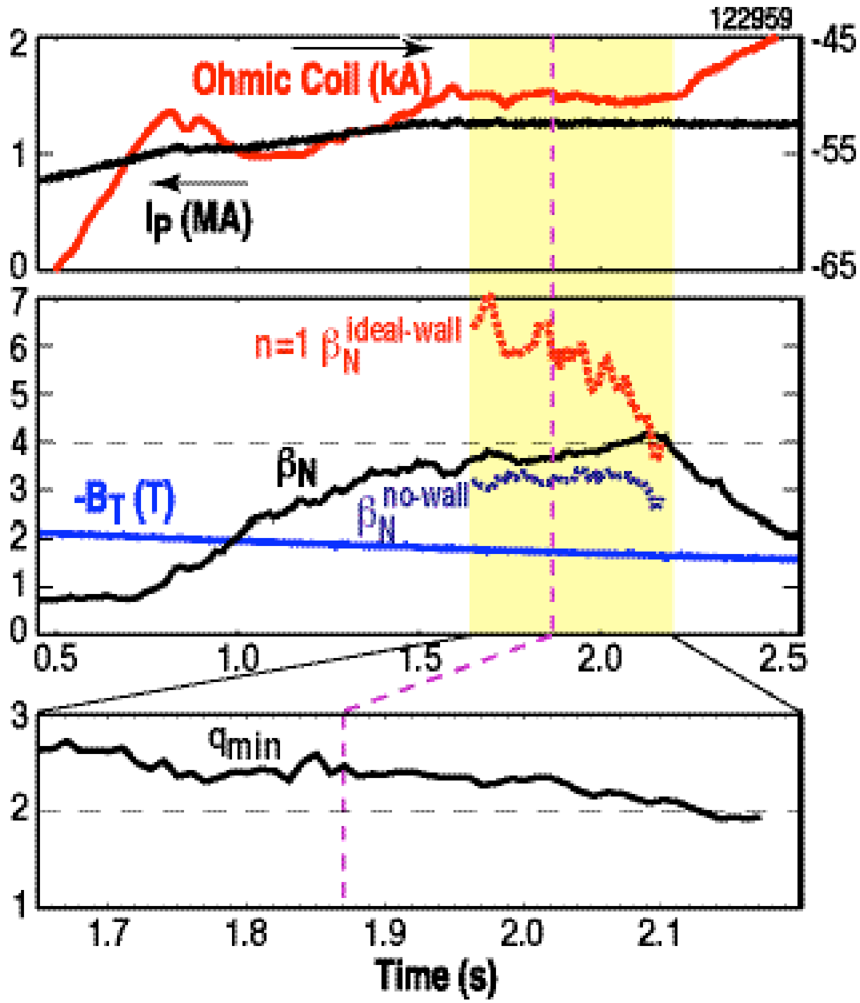
DIII-D
NATIONAL FUSION FACILITY

Ideal n=1 Kink Mode is Observed at the Wall-stabilized n=1 Beta Limit

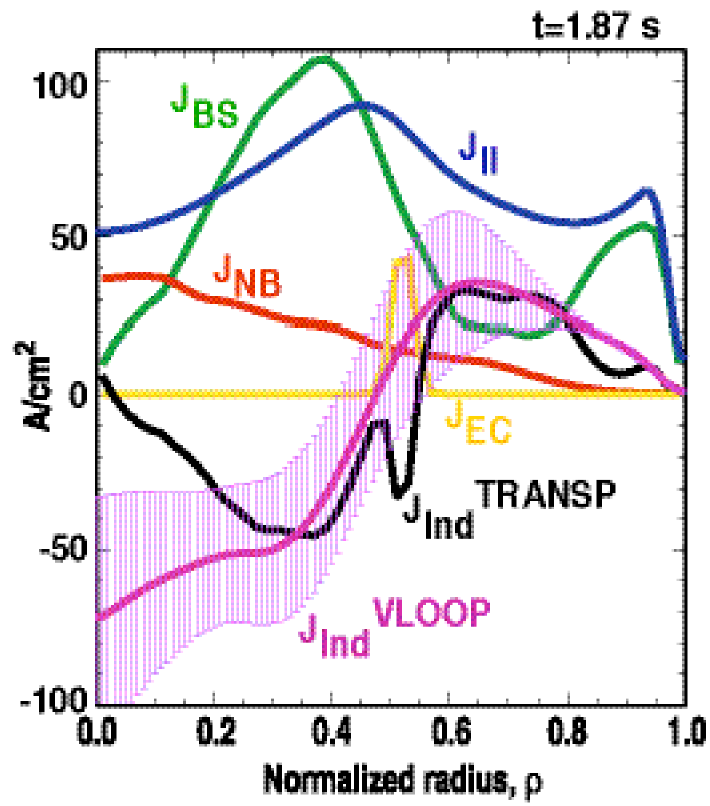
- B_T ramp-down at constant I_P drives rise of β_N
- Noninductive current overdrive leads to q_{min} drop
- Fast growing n=1 mode terminates high-beta phase



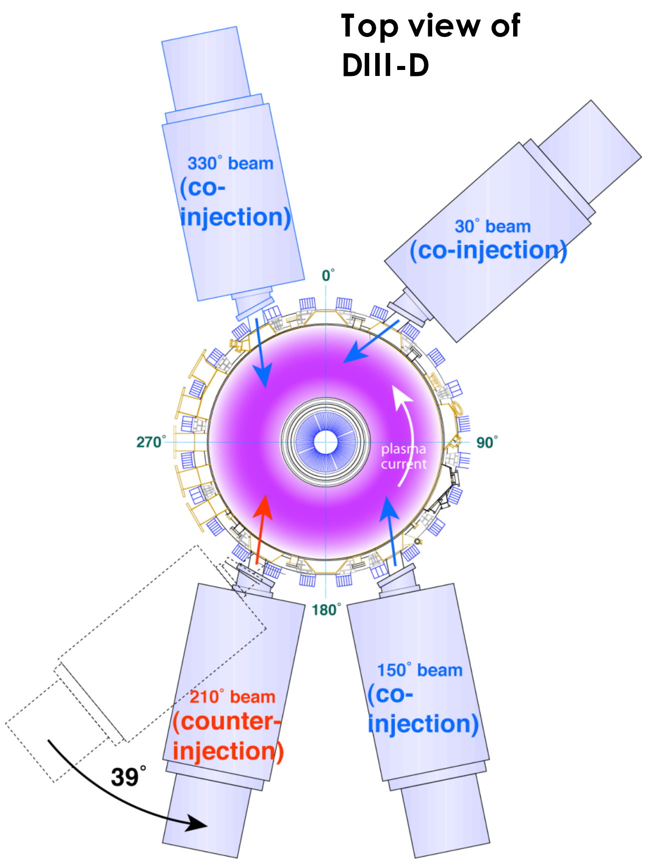
High q_{min} Sustainment Requires Compensation of the Core Bootstrap + NB Current Overdrive



- **Steady-state will require at least also ~400 kA (Ip~1.2 MA) of current drive at ρ~0.7**



Beamline Re-orientation Could Provide Effective Tool For Compensation of Core Current Overdrive



210° neutral beamline was rotated 39°

- **Balanced injection reduces plasma rotation => lose RWM stabilization?**
- **Recent experiments using balanced NBI in DIII-D (and JT-60U) show that the plasma rotation needed for RWM stabilization is much slower than previously thought**
  - ~O(0.1%) of Ω_A
  - Previously, magnetic braking experiments suggested that RWM stabilization required mid-radius plasma rotation ~O(1%) of the Alfven frequency, Ω_A

Summary

- **High q_{min} (>2) <u>with</u> broad current profile yield high ideal-wall beta limits for n=1,2,3 with moderately peaked pressure profile P(0)/<P>~3**
- **Access to sustained β_N>4, β>5 %, f_{BS}>80% by compensating core current overdrive with counter-NBI**
  - One or two years of experiments in the short term are needed to develop a new scenario that includes density control and counter-NBI
  - TGLF/ONETWO simulation capability should be brought up in parallel to new experiments
  - Steady-state requirement of large external current drive at large minor radius (ρ~0.6) should be anticipated (pessimistic case)
    - **Keep B_T ramp-down for co-current drive at large minor radius**
    - **New experiments may lead to reduced requirements, if ITB radius can be increased**
    - **Reduce ramp rate as more steady-state current drive capability (ECCD power) becomes available**