Plans for Advanced Scenario Development (Thrust AT-1) in DIII–D

by
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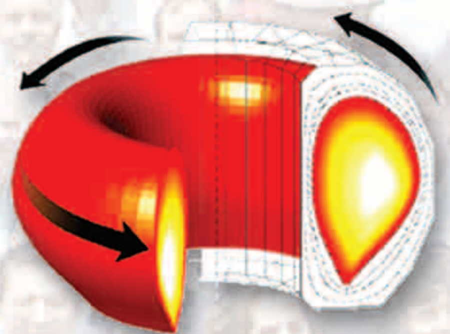
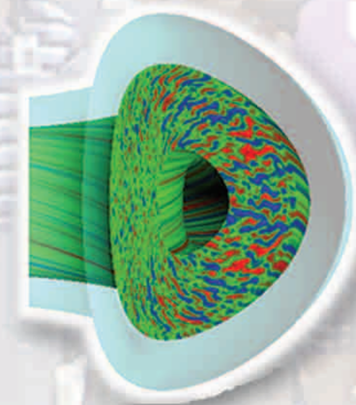


Presented to
DIII–D Program
Advisory Committee



January 31– February 2, 2006

Scope of Thrust

- **DIII–D program has concentrated the efforts toward steady-state scenario development into a single research thrust in recognition of:**
  - common expertise needed for success
  - limited resources (manpower and machine time)

- **The planning discussions for FY06 considered 4 scenarios previously addressed by 3 separate research thrusts in FY04/05 in addition to profile control:**
  - Weak shear
  - High β ITB
  - QDB
  - High ℓ_i
  - Profile control

Weak shear, High β ITB, QDB → **Elevated q_{min} (>1.5)**

Perspective and Motivation

- Steady-state operation would remove two key objections to the tokamak as a fusion powerplant (cyclic fatigue, low duty cycle), but at what cost? Experiments in present-day devices will supply the majority of the physics input to this question.

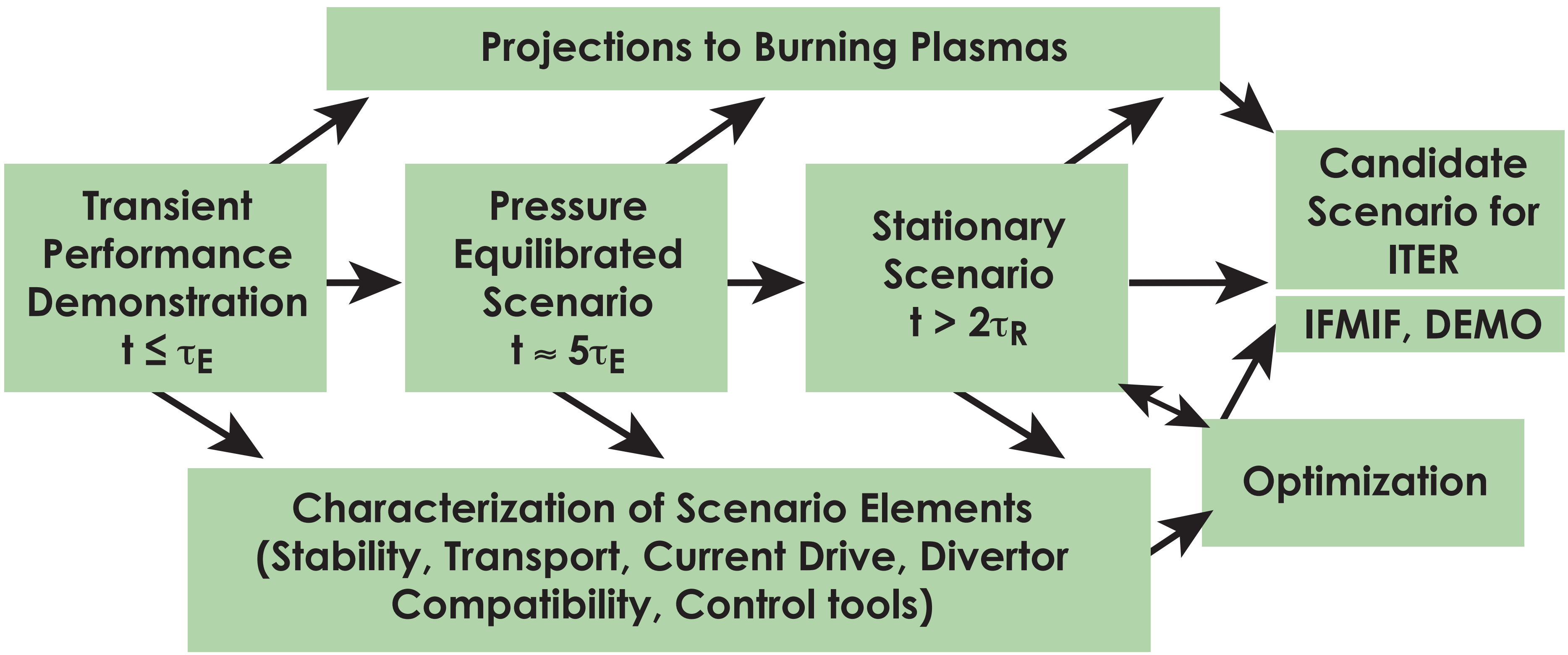
- Steady-state operation at $Q \geq 5$ is one of two plasma performance objectives of the ITER project.

- Key elements of the ITER design that have a significant impact on steady-state operation will be frozen in the next three years (divertor geometry, poloidal coil set, first wall material). DIII–D is capable of assessing the implications of these decisions in this time frame

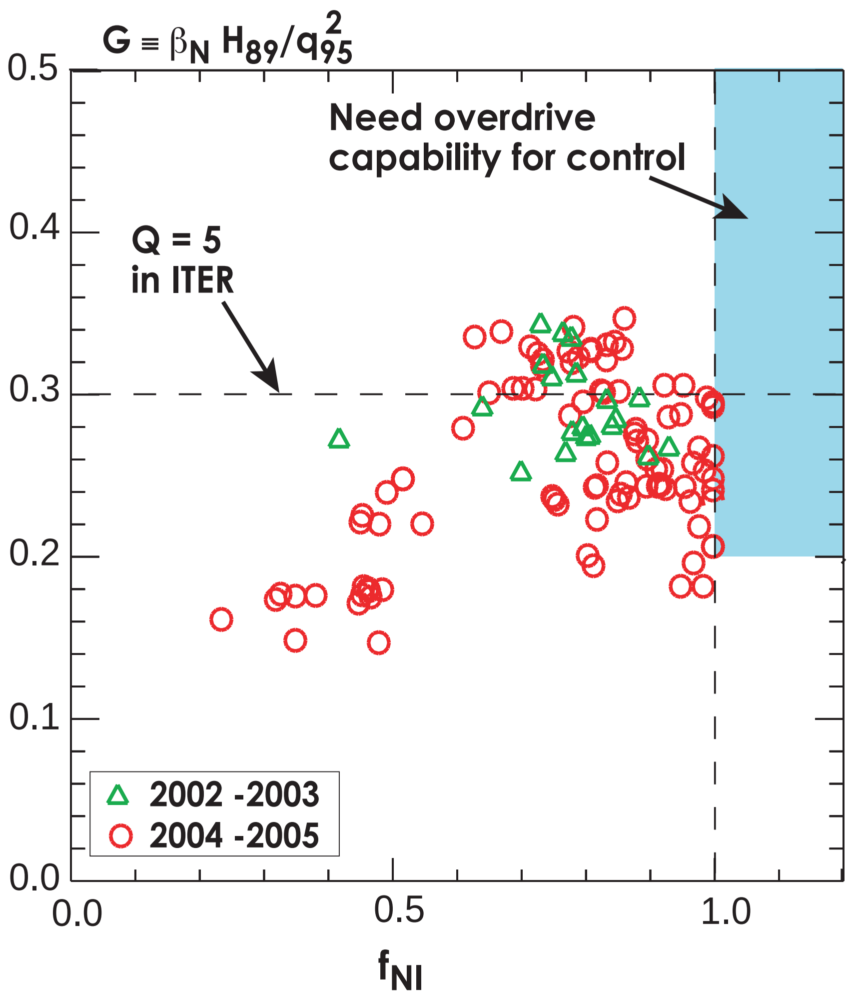
Long-Range Goals

- Demonstrate stationary tokamak discharges that project to high fusion gain in steady state for ITER and beyond
- Characterize the individual scenario elements sufficiently for extrapolation and scenario optimization for ITER and beyond
- Demonstrate active scenario control in the initiation and stationary phases

Development Path for Advanced Scenarios



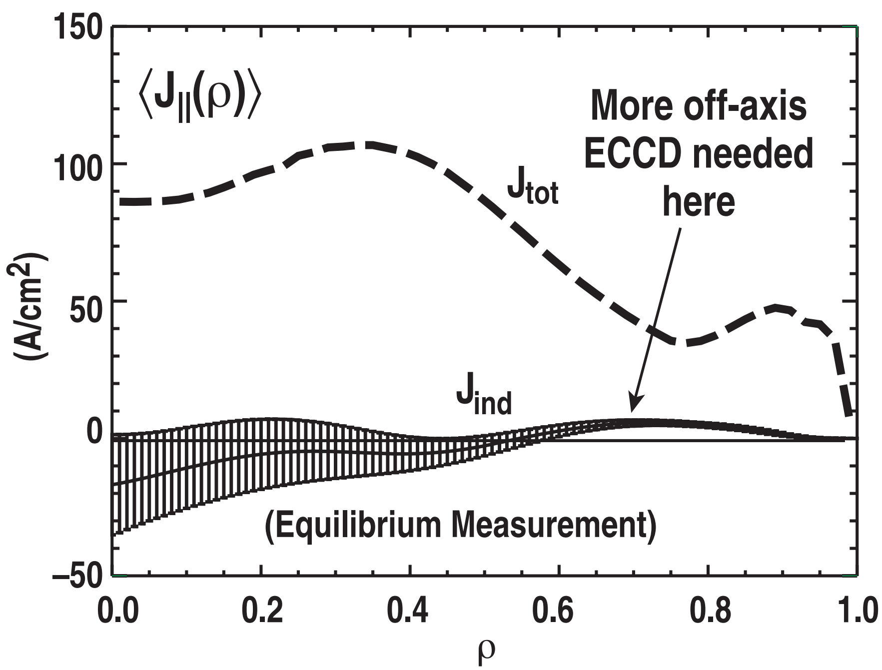
Status of Elevated q_{min} Scenarios - Full Non-inductive Performance Consistent with Q = 5 Steady-State in ITER



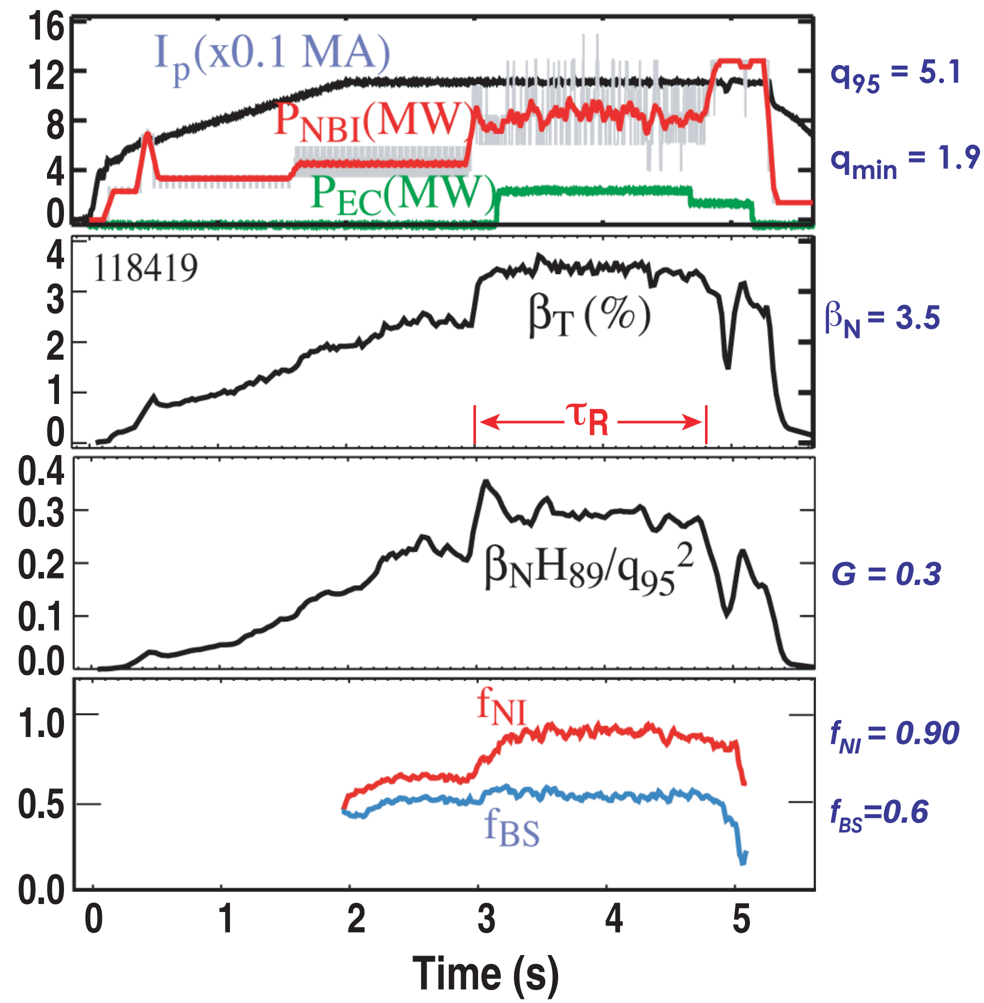
- **Full non-inductive discharges have well-aligned non-inductive current profiles, but are not completely stationary**
- **Present limitations are ideal stability and lack of ability to control the heating and current drive independently**
  - New divertor addresses stability issue by allowing stronger shaping with density control
  - ECH upgrades address need for more off-axis current drive
  - FW upgrades allow heating without central current drive (increased bootstrap and reactor-relevant transport)

Status of Elevated q_{min} Scenarios - Limited by EC System Power and Pulse Length

- **Increased EC power will allow more ECCD and farther out**



- **Increased EC pulse length will allow demonstration of truly stationary discharges**

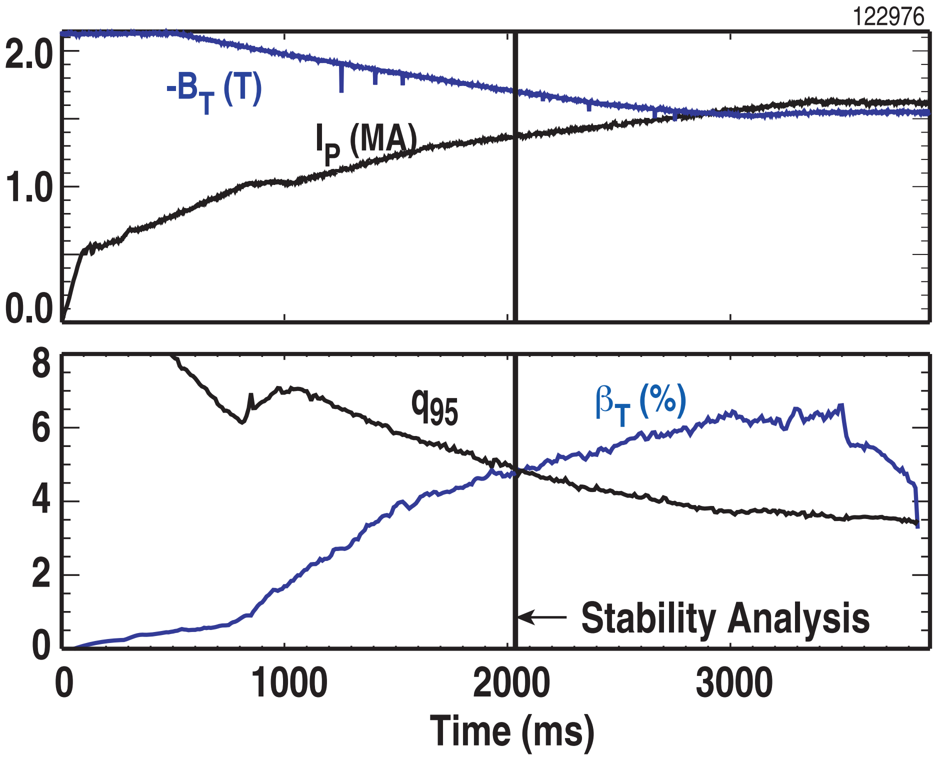


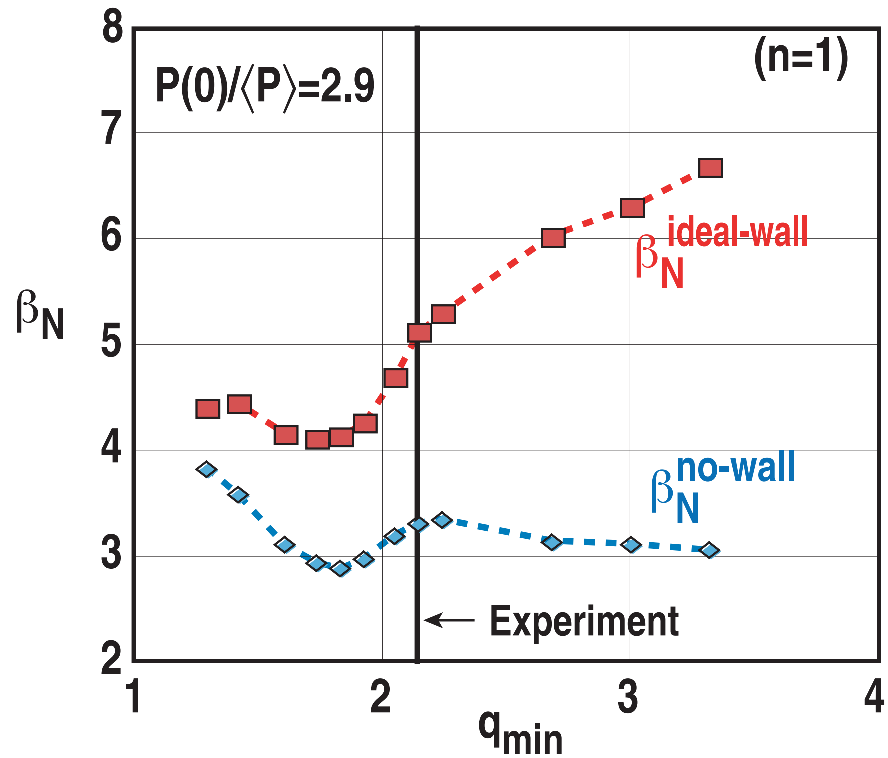
Comparison of Present DIII–D Discharges with ITER Simulations

	DIII–D	Murakami ITER	Polevoi ITER
R/a	2.75	3.1	3.1
q_{95}	5.0	5.0	5.0
β_N	3.6	2.8	2.8
$\beta_N/4\ell_i$	1.0	1.0	0.8
H_{98y2}	1.0	1.5	1.5 – 1.7
$\beta_N H_{89}/q_{95}$	0.3	0.3	0.3
n/n_G	0.4	1.0	0.8
f_{BS}	0.65	0.75	?

Status of Elevated q_{min} Scenarios – Ramping Techniques Allow Transient Access to Current Profiles with High n = 1 Limits

- B and I ramps give current profiles with $q_{min} > 2$ and $\ell_i \sim 0.6$
- Stability analysis predicts an ideal n=1 limit strongly increasing with q_{min}

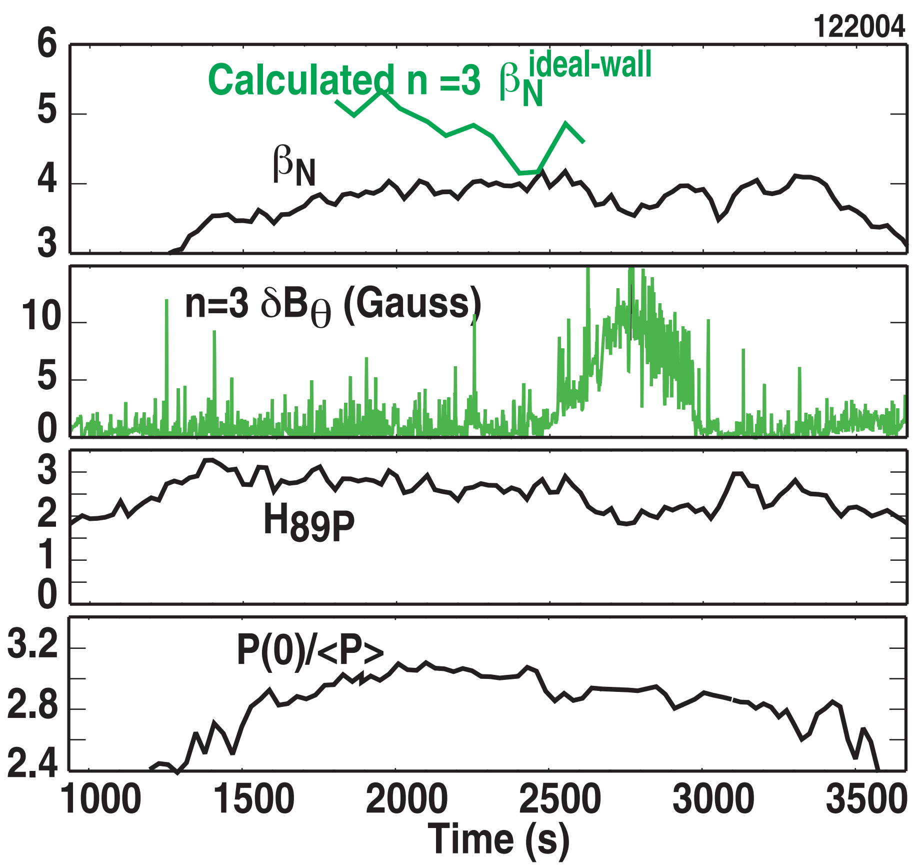


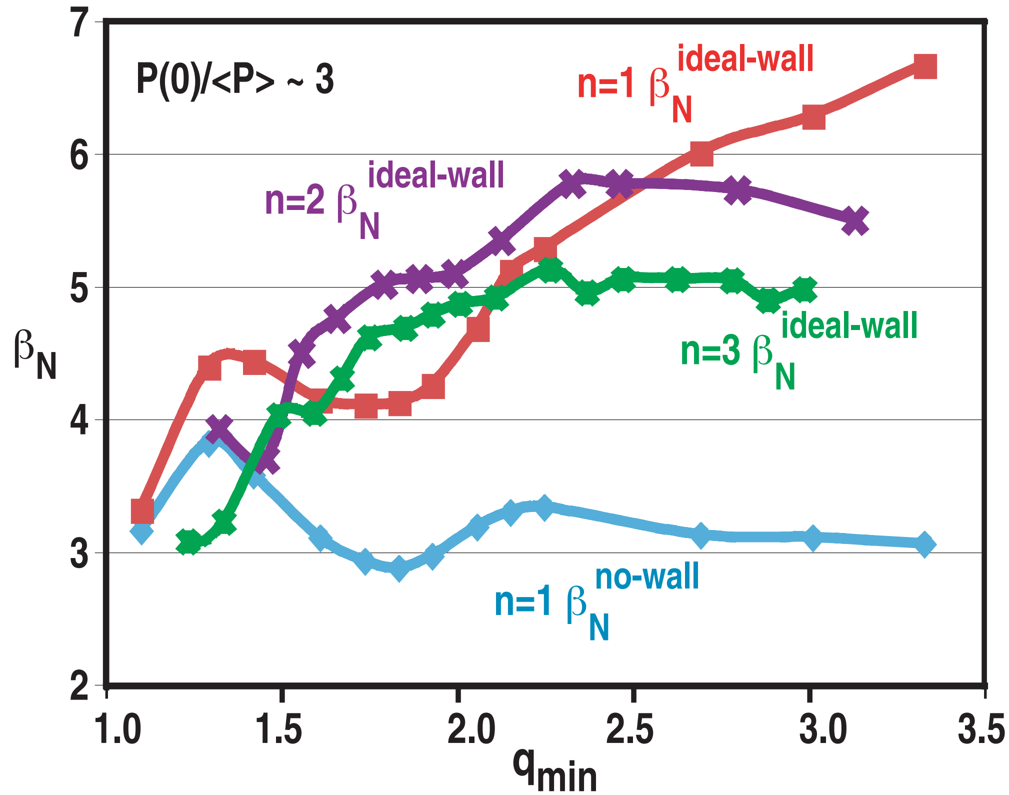


Status of Elevated q_{min} Scenarios - Demonstration of the Significance of ideal limits with n > 1

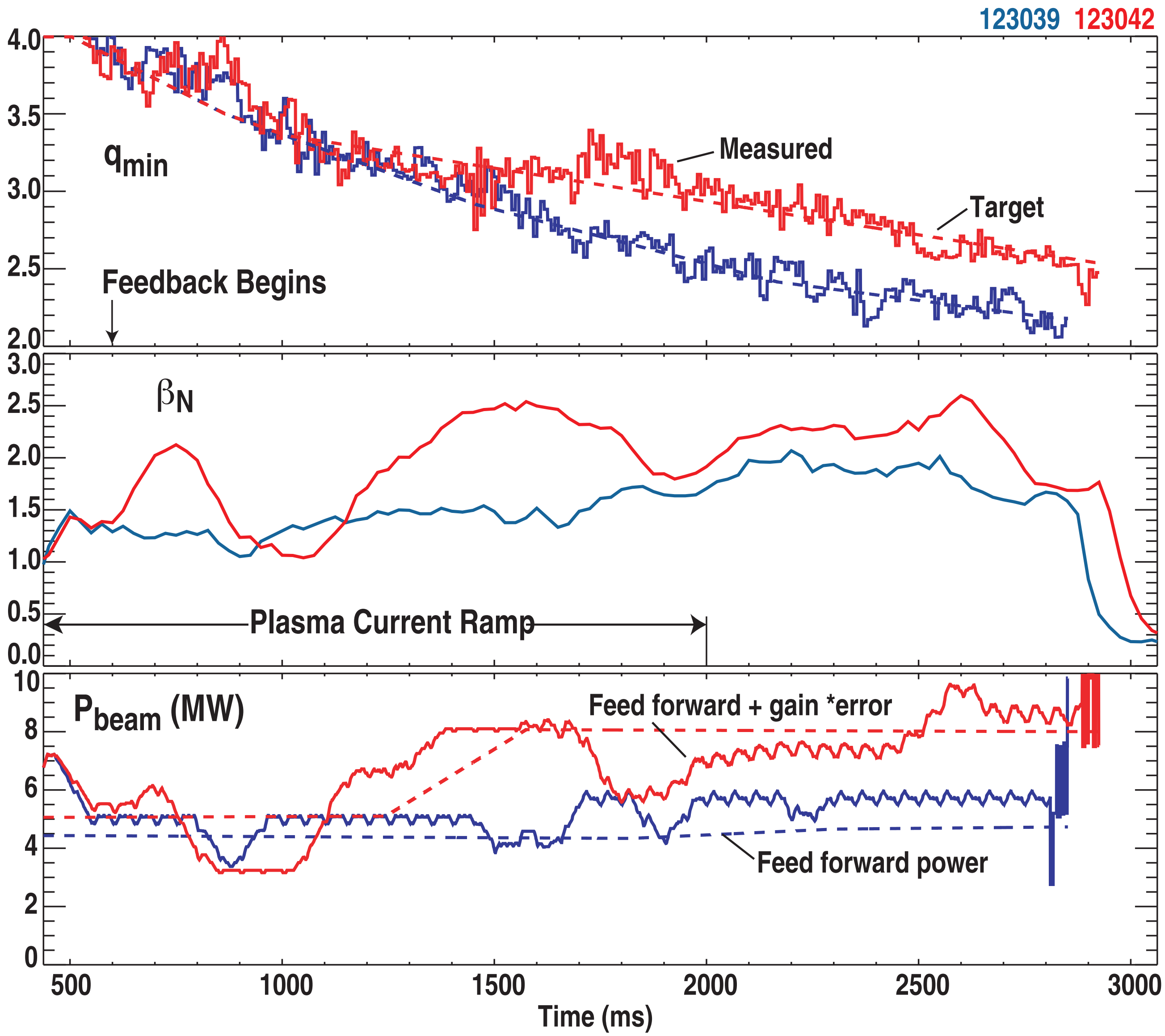
- Experiment sees onset of n=3 tearing when n=3 ideal limit reached

- Stability calculations predict n=3 is the limiting instability for q_{min} > 2





Status of Profile Control — q_{min} has been Controlled Using Neutral Beam Heating in H-mode



- Real-time equilibrium reconstruction with MSE provides q for feedback
- q_{min} and q(0) control also demonstrated in L-mode with ECH
- Simple conceptual model assumes rate of decrease of q is inversely correlated with power – control is through conductivity. not current drive
- Control of q(0) with NBI not successful ⇒ control of q_{min} and q(0) – q_{min} probably not possible with NBI alone

Status of QDB and High ℓ_i Scenarios

- QDB: only 1/2 day experiment in FY05 to test the effects of ECH on impurities and β
- High ℓ_i: 1 day experiment in FY04 reproduced previous transient high-performance results with the new divertor geometry and control system

Implications of New DIII–D Capabilities on the FY06/07 Plan

Lower Divertor:

- New pump will allow direct tests with density control of single null and double null plasmas
- Increased shaping with density control will benefit experiments on pulse extension and stationary phase current profile control

EC upgrade:

- Additional power and pulse length enable the current drive farther off-axis needed to reach stationary full non-inductive discharges

Counter beam:

- Reduces the power available for full non-inductive scenario work
- May bring new capabilities for optimization and control experiments

Key Physics Issued for Elevated q_{min} Scenarios That Could be Addressed the FY06/07 Campaign

- **Stationary Scenario Demonstartion**
  - Extension of q_{min} = 1.5 - 2.0 scenario to > $2\tau_R$
  - Extension of q_{min} > 2 scenario to > $5\tau_E$
- **Optimization**
  - Shape optimization
  - q profile optimization
  - β optimization of QDB
  - Transient demonstration of $\beta_N = 5$
- **Physics Characterization and Integration Issues**
  - Radiative divertor
  - Effects of $T_e = T_i$ and low rotation on energy transport

ITPA Commitment

Key Physics Issues for the High ℓ_i Scenario that Could Be Addressed in the FY06/07 Campaign

- **Stationary Scenario Demonstration**
  - Extension of q_{min} ~1 scenario to > $5\tau_E$
- **Optimization**
  - Use of shape and I coils to limit the edge current pedestal
- **Physics Characterization**
  - Stabilization of sawteeth with FW and EC
  - β limits vs. ℓ_i
  - Comparison of rotational and magnetic shear effects on energy transport

Key Issues in Profile Control That Could Be Addressed in the FY06/07 Campaign

- **Current Profile Control**
  - Development of model - based controller for generation of target q profiles
  - Open - loop measurements in stationary scenarios
  - Tests of central current control with FW
- **Density Control**
  - Establish density control in double-null plasmas
  - Test density control by means of the I coils in more extreme shapes
- **Scenario Control**
  - Detemine special control issues in plasmas with $f_{BS} > 0.8$

ITPA Commitment

Experimental Plan for FY06

- **Guidance is for 6 experimental days in a 12 week operational plan**
- **Tentative assignment of experimental days is:**
  - Elevated q_{min} (4 days)
    (Shape optimization, q profile optimization, pulse extension)
  - High ℓ_i (0 days)
  - Profile Control (2 days)
    (Target q controller)

Potential Longer Range Physics Objectives with Relevance to ITER

- Demonstration of stationary scenarios that project to Q=5 non-inductive operation in two regimes – one requiring wall or active stabilization of the RWM and one that operates below the free – boundary limits (May not require hardware upgrades beyond present incrementals)

- ITER advanced scenario start-up and control demonstration limiting DIII–D coils and controls to ITER limitations. (May require additional power supplies and control system development.)

- Characterization of transport in ITER-relevant advanced scenarios. (Will require EC, FW, and possibly NB upgrades.)

Potential Longer Range Physics Objectives with Applications Beyond ITER

- Optimize scenarios to maximize gain (DEMO-relevant) and fluence (relevant for nuclear testing)
- Characterize the influence of shape and q profiles on stationary scenarios
- Compare optimal steady state and pulsed tokamak performance
- Demonstrate advanced scenario operation with model-based control of all aspects of the discharge