DIII-D: Recent Physics Results, Implemented and Planned Hardware Upgrades

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Presented at
The 21th IEEE/NPSS Symposium on Fusion Engineering
Knoxville, Tennessee
September 26-29, 2005

OutLine

- **Physics**
  - Tokamak scenarios
  - Plasma instabilities
    - Resistive Wall Modes (RWMs)
    - Edge Localized Modes (ELMs)
    - Neoclassical Tearing Modes (NTMs)
    - Disruption Mitigation
- **Hardware**
  - Plasma Control System (PCS)
  - Long Torus Opening Activities

Conventional, Hybrid and Advanced Tokamak Scenarios

Conventional ($\beta_N < \beta_{N,\ no\text{-}wall}$, $H_{89} \sim 2$, $f_{BS} << 1$)

– Pluses: High Fusion Gain, Physics Appears to Be Robust, Passive Control

– Minuses: High Plasma Current Required for High Fusion Gain

Hybrid ($\beta_N \sim \beta_{N,\ no\text{-}wall}$, $H_{89} > 2$, $f_{BS} \sim 0.5$)

– Pluses: Longer pulses (OH-drive), High Fusion Power Density at Reduced Engineering Parameters, Passive Control

– Minuses: Physics not yet fully established

Advanced ($\beta_N > \beta_{N,\ no\text{-}wall}$, $H_{89} > 2$, $f_{BS} \sim 1$)

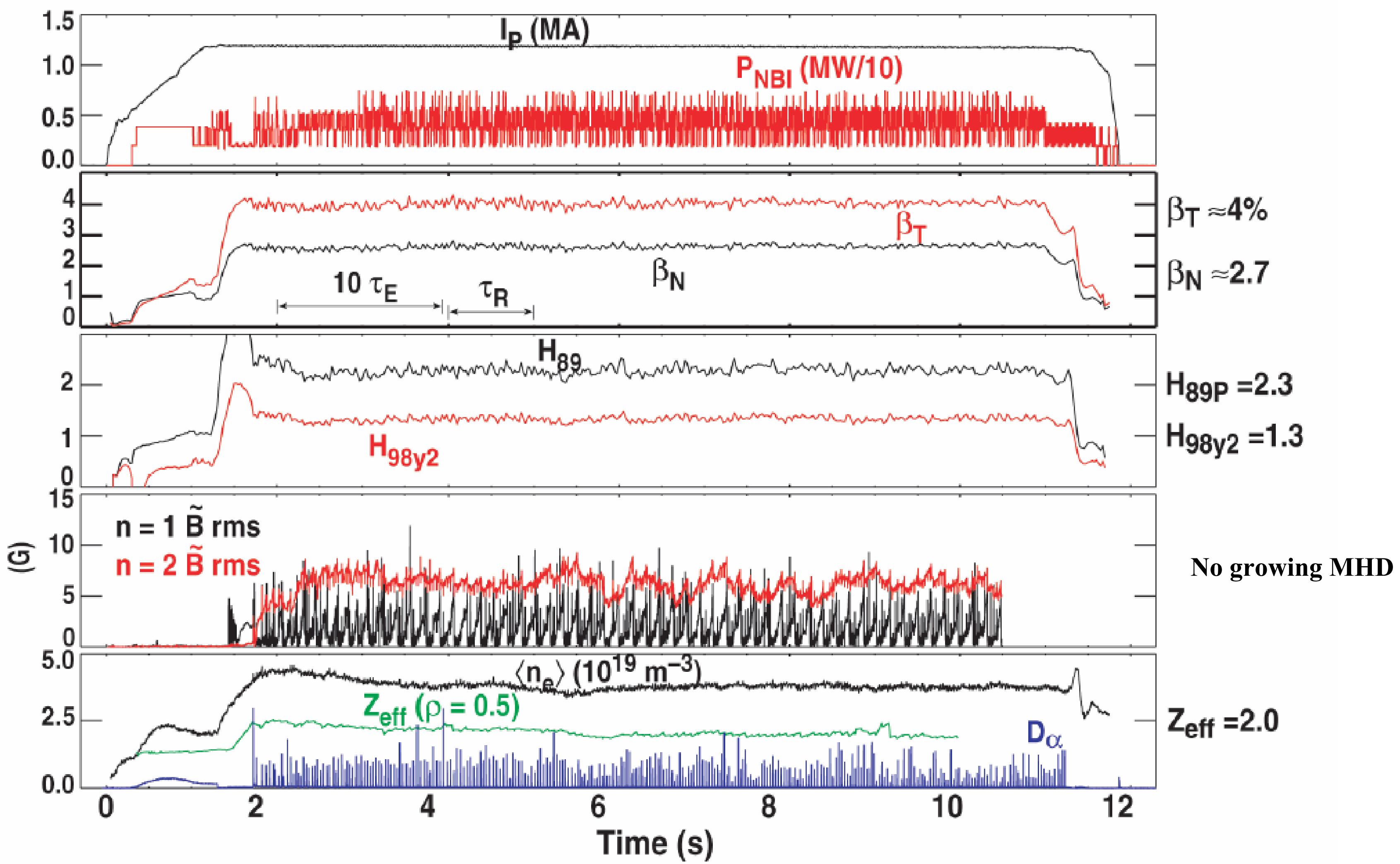
– Pluses: Steady-State, High Fusion Power Density

– Minuses: Significant physics issues remain, Active Control of MHD Instabilities Required

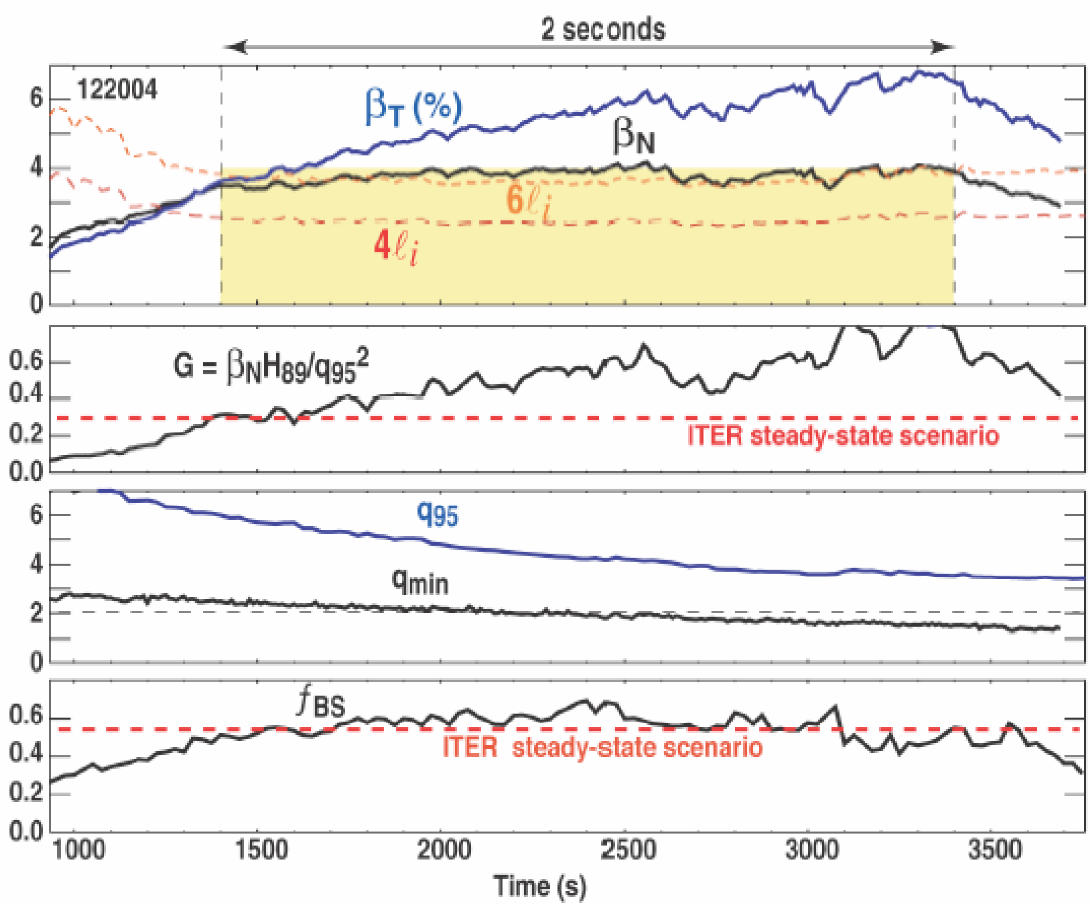
Increasing Complexity/ Payoff

$\beta_{N,\ no\text{-}wall}$ is the theoretical plasma pressure limit if there was no wall

Hybrid Scenario: Experiments Have Demonstrated Truly Stationary (> 9 τ_R), High Performance Operation



Progress Toward High Performance Advanced Tokamak Scenario: β_N 50% above the no-wall limit maintained for 2s with elevated *q* profile



ℓ_i is the plasma internal inductance

- **$\beta_N > 6\ell_i$ for ~2 s**

  Relies on wall stabilization of the n=1 external kink mode (no-wall stability limit ~$4\ell_i$)

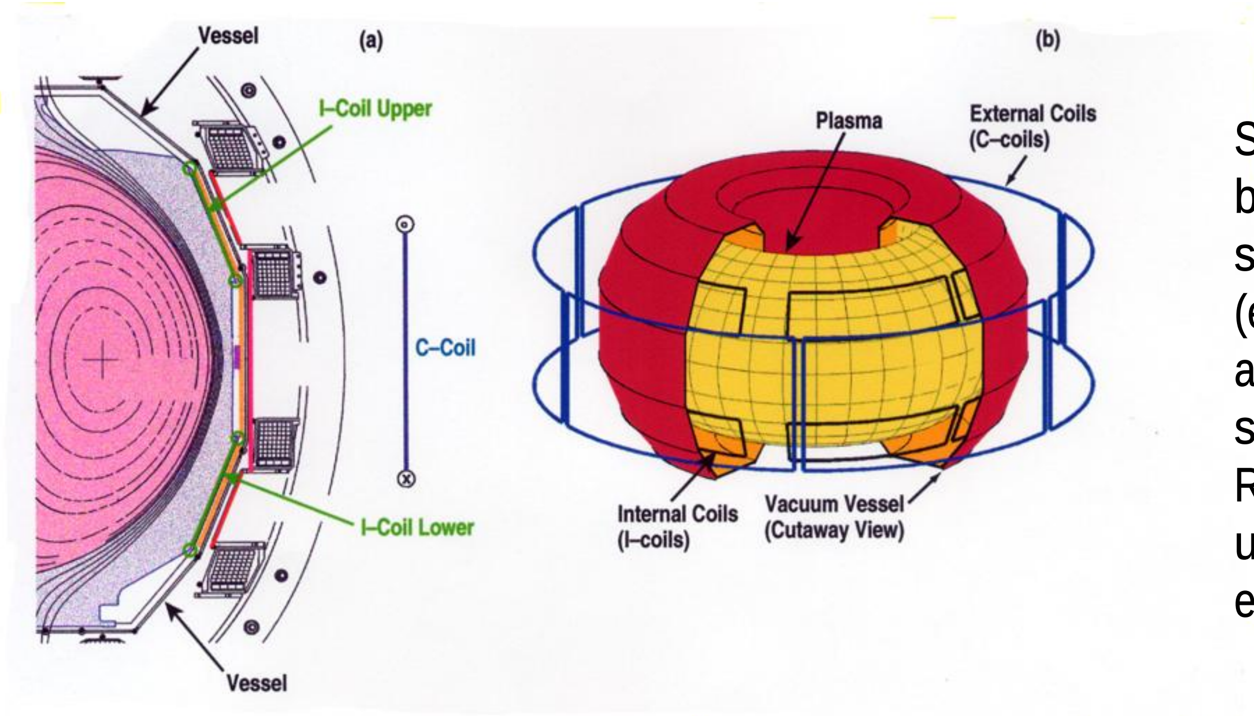
- **High energy confinement, H_{89} >2.5 for ~2 s, leads to high fusion gain factor, G**

- **High q_{min} leads to high bootstrap current fraction, f_{BS}, up to 70%**

f_{BS} is the bootstrap fraction, the fraction of plasma current driven by the plasma itself

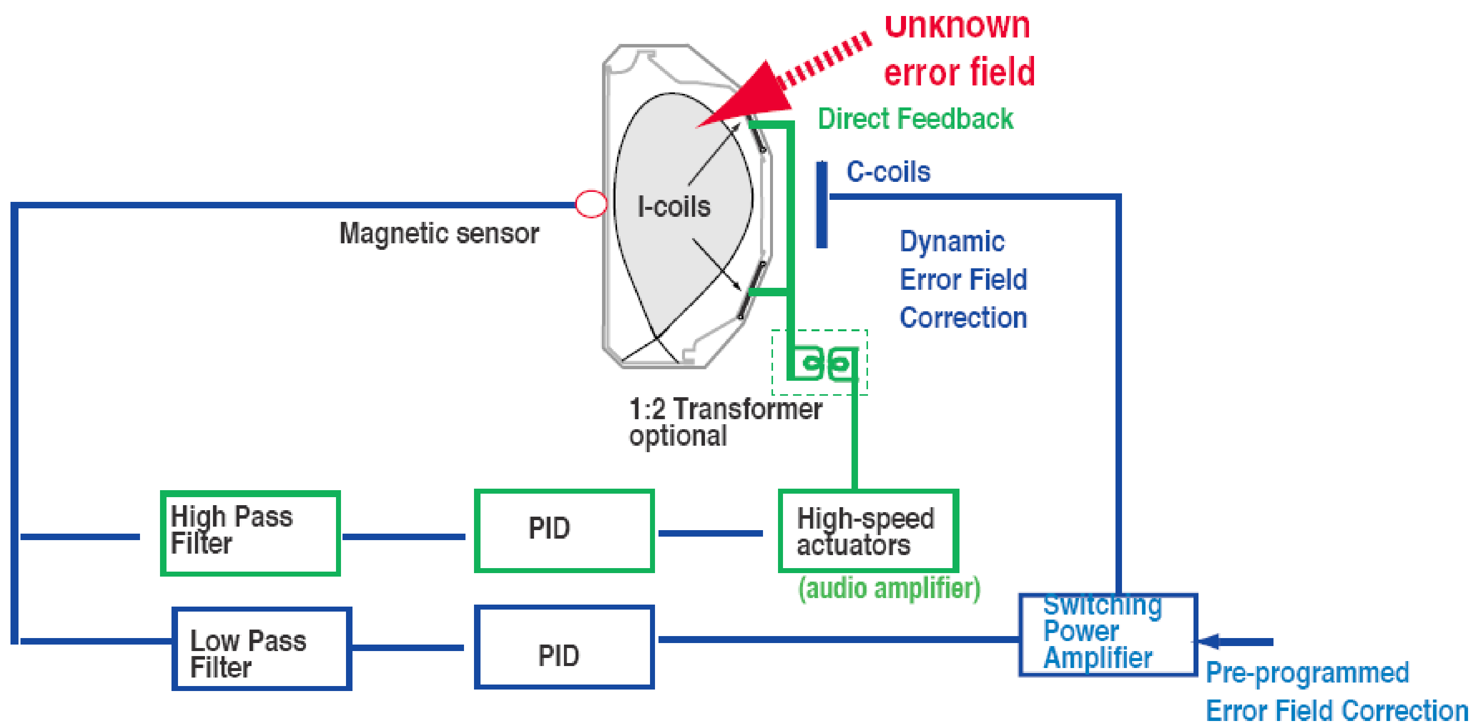
DIII-D Has a Mix of Tools To Minimize Error Fields, Resistive Wall Modes At High Plasma Pressures And ELMs

6 section, external C-coil
12 section, internal I-coil
5 C-supplies each @5 kA, 350 V or 7kA at lower voltage tap
4 Low Speed Switching Power Amplifiers (SPAs) each @5 kA, 300 V, ~ 4 - 5 s
6 audio amplifiers (200 A, 0.1 – 20 kHz)

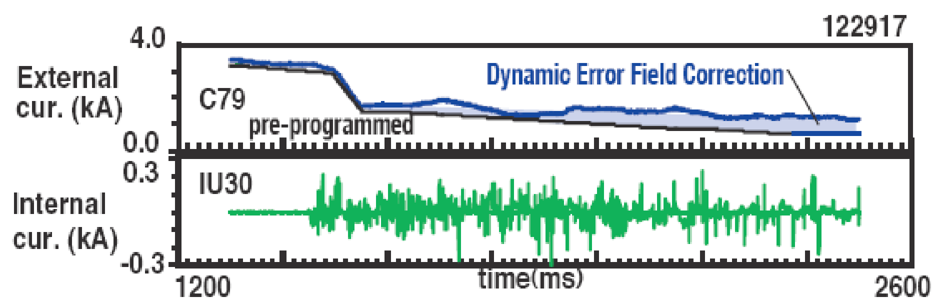


System provides for both rotational stabilization of RWM (error field correction) and feedback stabilization of the RWM. System is also used to reduce or eliminate ELMs

Independent Operation of Dynamic Error Field Correction (External Coils) and RWM Direct Feedback (Internal Coils) is Efficient and Effective



- D.E.F.C: larger current with low frequency
- Direct feedback: lower current with higher frequency



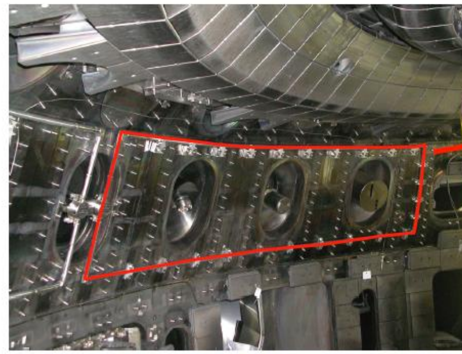
The Internal I-Coils Also Provide A Flexible System For ELM Control

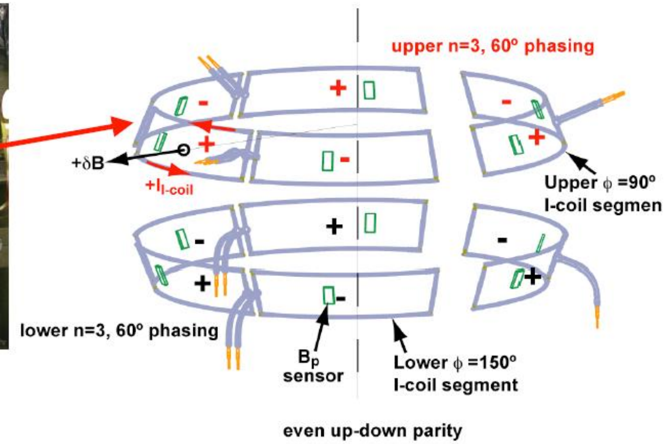
Small islands might be responsible for the ELM suppression

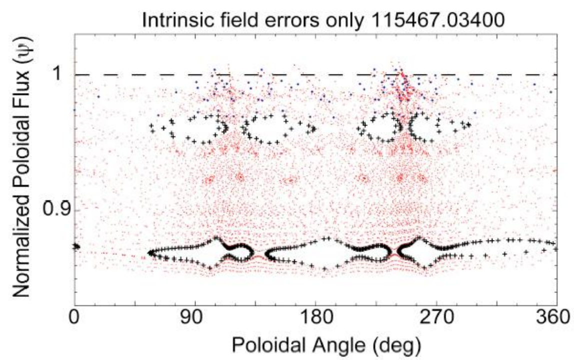
Relatively small impact on core confinement

Enhance magnetic and density fluctuations with no indication of increased stochasticity

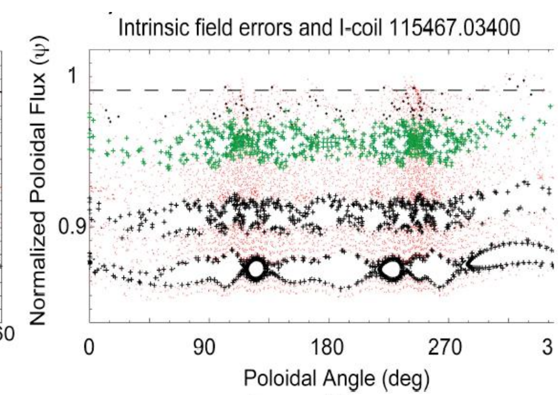
Even parity is better than odd





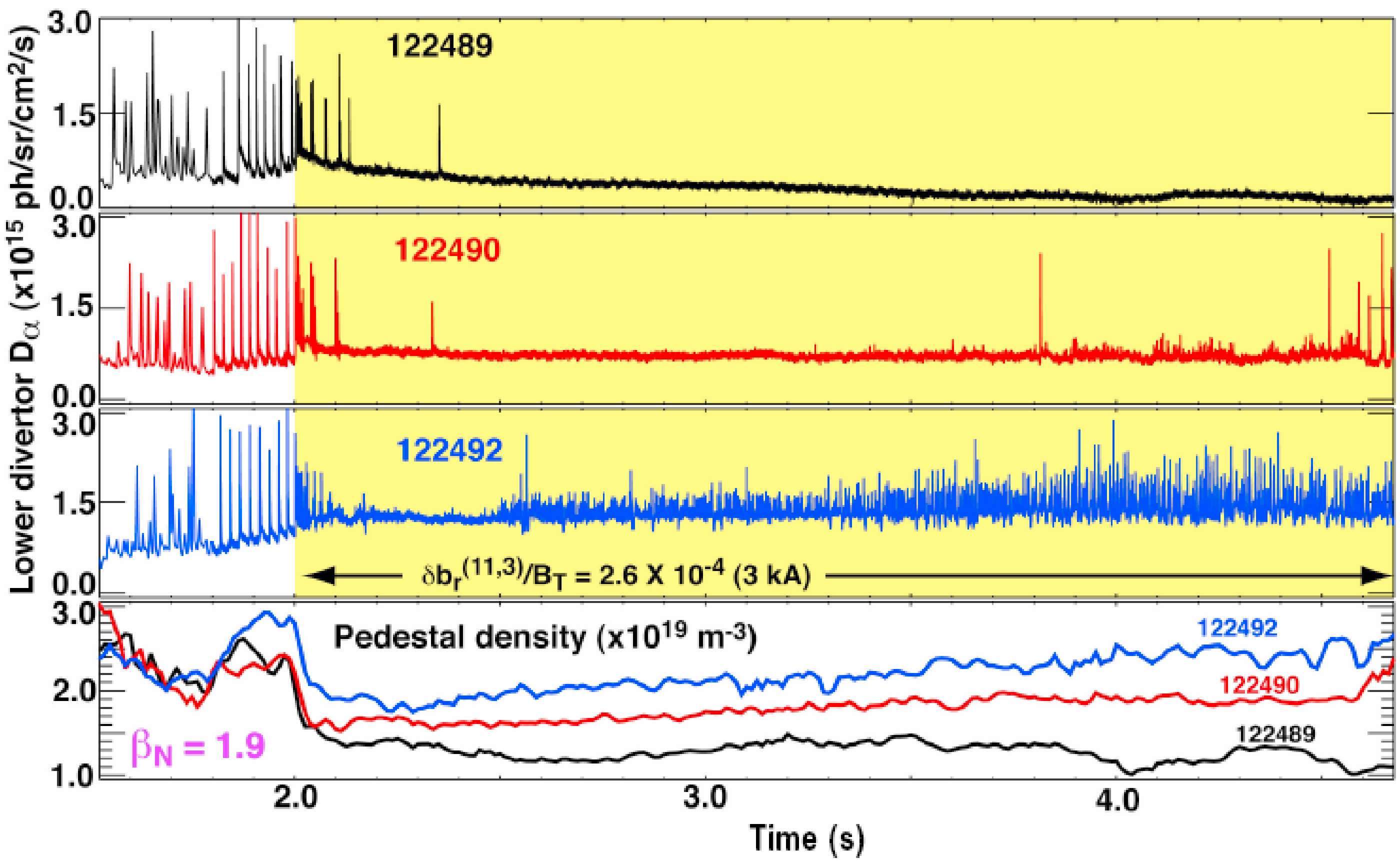


I-coil off



I-coil on

ELMs Eliminated Below a Critical Pedestal Density Using I-coils



ELMs are suppressed as pedestal n_e (υ^*_e) increases.
Recent experiments performed at pedestal collisionalities close to those anticipated in ITERS showed ELM suppression

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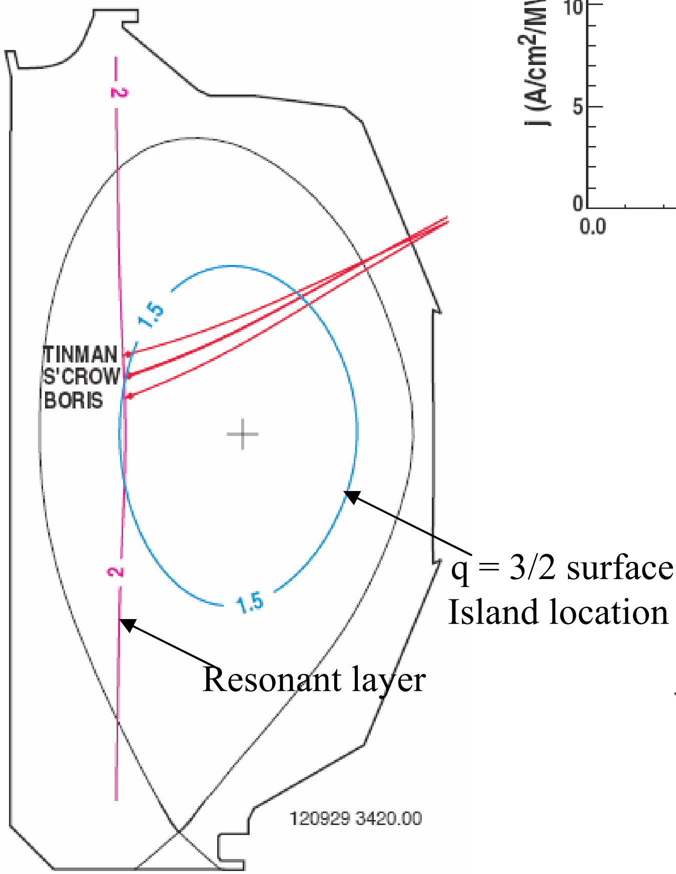
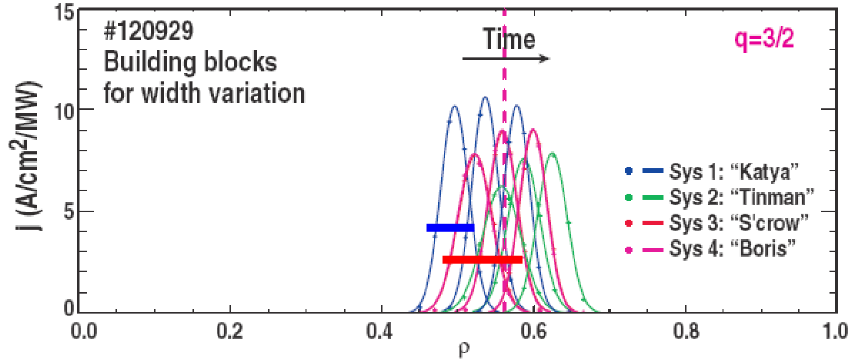
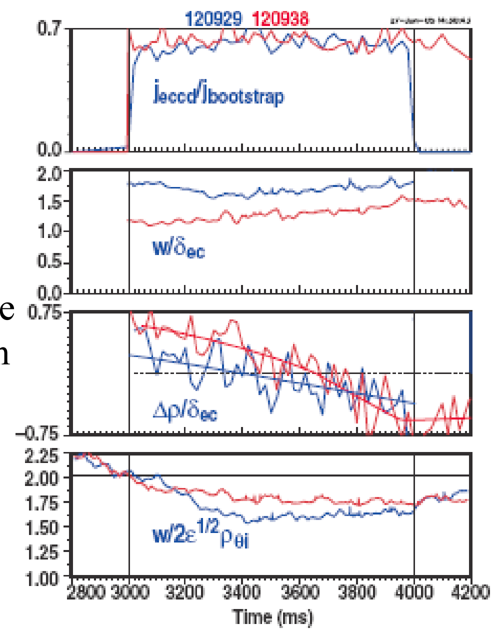
GENERAL ATOMICS

Neo-classical Tearing Modes m/n = 3/2 and 2/1 Have Been Stabilized by ECCD.

Wider ECCD Is Less Effective Neo-classical Tearing Mode Suppression







Blue case: Sys 1

Red case: Sys 2,3 and 4

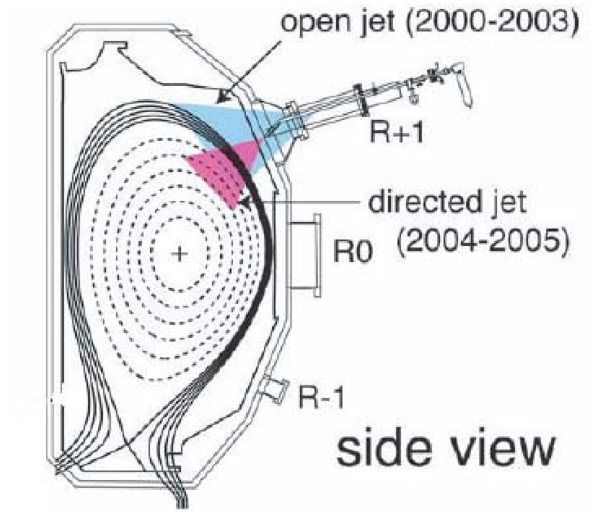
The gyrotrons are modulated to give same current density

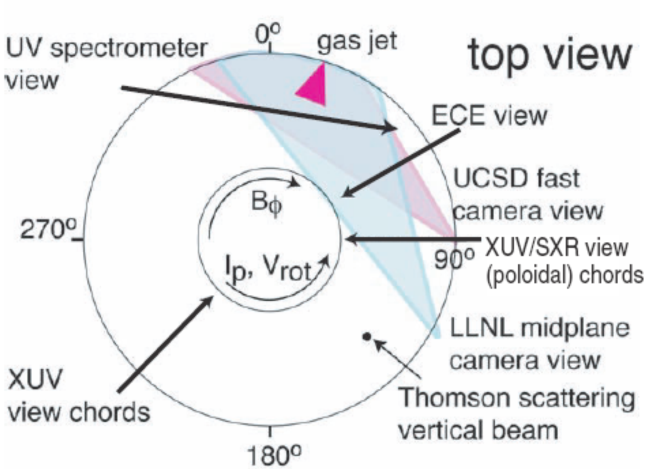
Island width compared to ECCD width

Misalignment of ECCD with island compared to ECCD width

Island width decreases most in blue case; meaning more effective stabilization

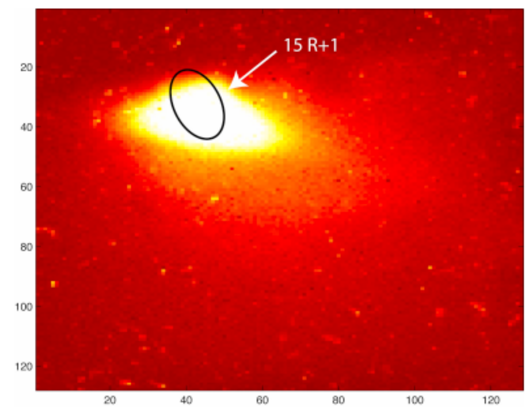
Successful Disruption Mitigation on DIII–D Using Massive Gas Puffing





Recent experiments investigated neutral penetration

Fast camera picture confirms little neutral penetration during thermal quench (radial view toward injection port)



1 ms after jet hits Plasma

Gas: Argon

When the cold front reaches sufficiently far into the plasma core, typically around q=2, an explosive growth of MHD instabilities occurs.

Most of the plasma thermal energy is radiated away.

DIII-D Plasma Control System Upgrades

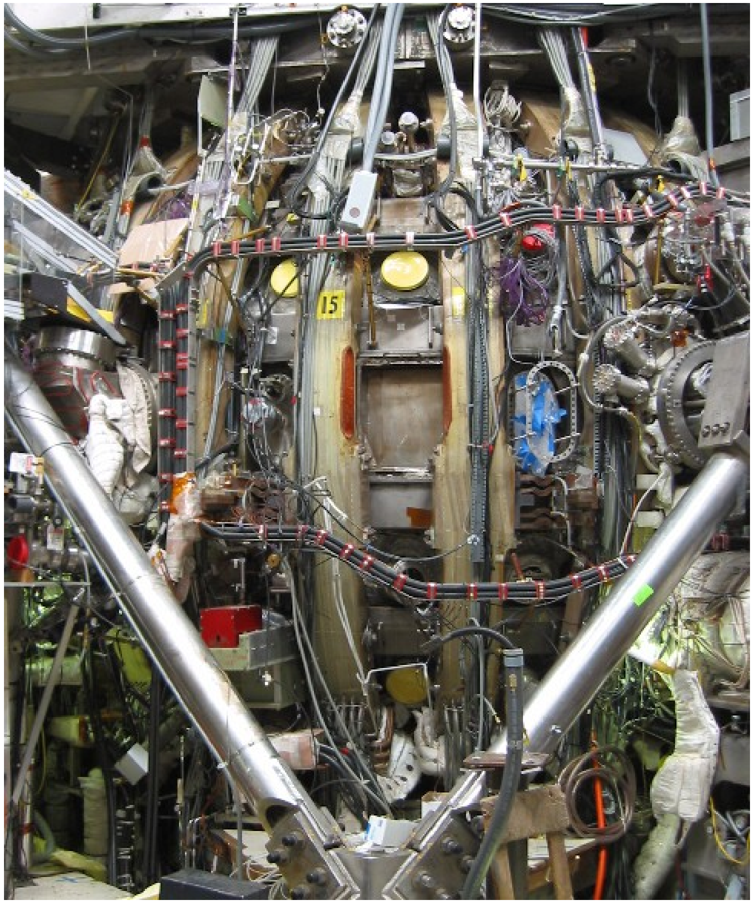
- **Control algorithm improvements**
  - Introduced Kalman Filter (to discriminate against RWMs & ELMs, increases S/N)
  - Integrated Audio amps into the RWM suppression algorithm.
  - 3/2 and 2/1 q-surface reconstruction for NTM control.
  - 2 point feedback control of T_e
  - Development of feedback control of q-profile using NBI, ECCD (and FW begun)
  - Advanced shape controller (MIMO) demonstration

- **Hardware Upgrades**
  - Total PCS processors increased from 9 to 13
  - Total More CPUs dedicated to Real-Time EFIT, with and without MSE
  - Remote CPUs in Thomson (32 ch), MSE (32 ch) and ECE (32 ch) labs
  - Dedicated RWM control CPU and new ADCs reduce latency (to 35 μs)

Several Major Tokamak & Facility Upgrades Are Foci of Long Torus Opening Activities

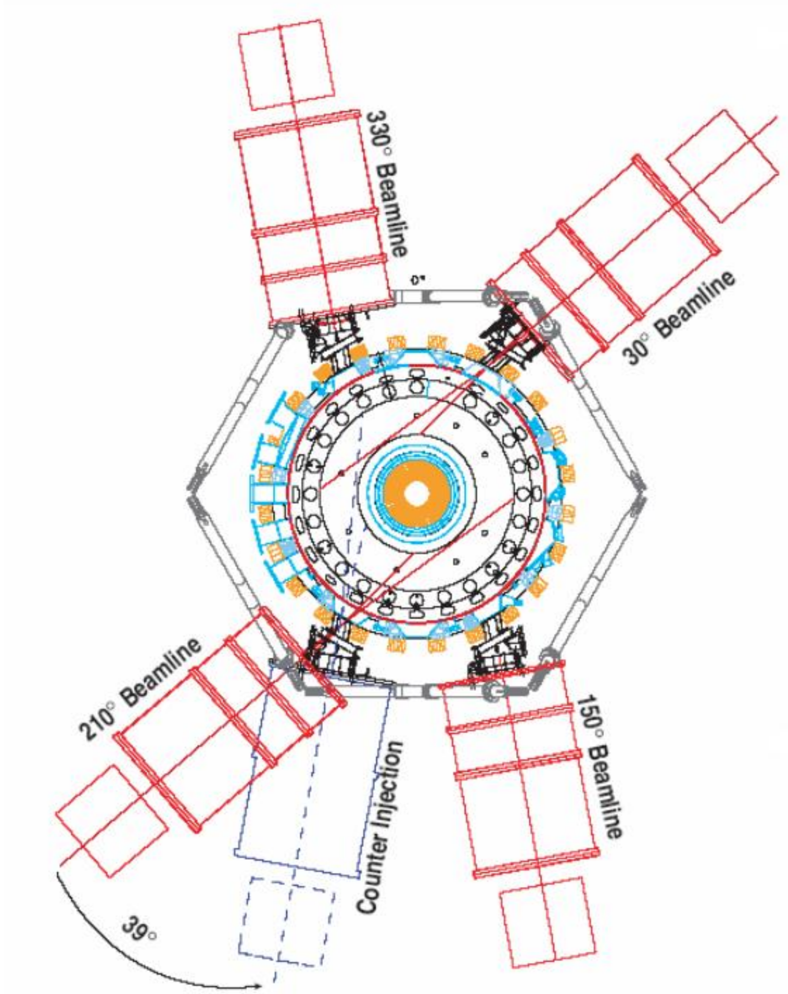
- Rotate the 210 neutral beam line
- Install new high triangularity lower divertor
- Buy 3 long pulse 1 MW gyrotrons
- Refurbish and build equipment for new gyrotrons
- Conditioning new gyrotrons
- Install 2 new cooling towers
- Upgrade TF-coil system to 10 s

- Fast Wave Upgrade
- Plasma Control System Upgrade
- …



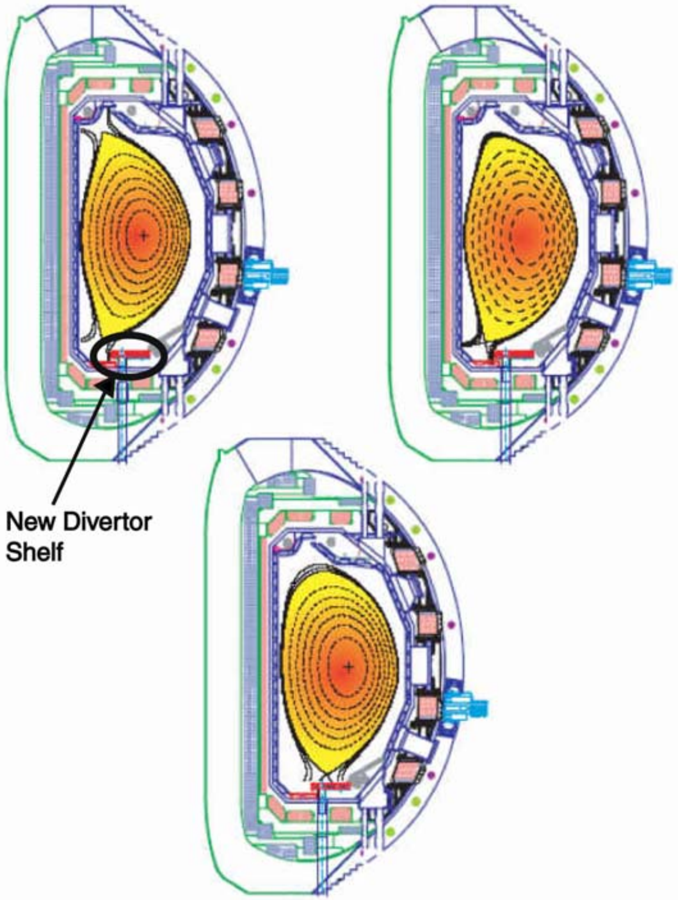
The Long Torus Opening Period is 4/18/05 – 5/8/06

Rotation of 210° Beamline Opens New Regimes for Physics Studies and Improved Plasma Measurements



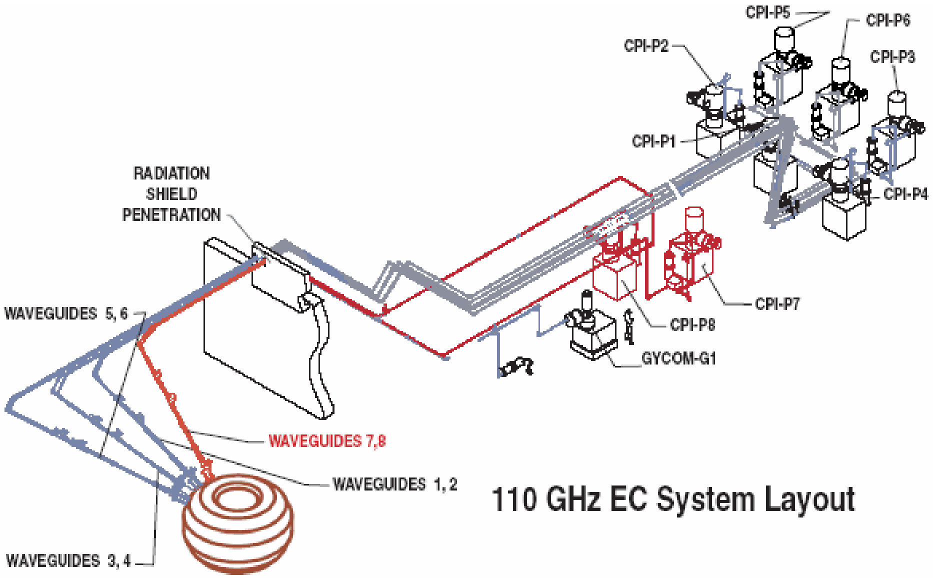
- **New Physics**
  - QH-mode (ELM-free) regime with central co-rotation
  - Understanding physics of rotaion
  - RWM stability with low rotation
  - NTM stabilization with modulated RF
  - Transport barrier control (separate ExB and Shafranov shift effects)
  - Fast ion physics
  - Physics of neutral beam current drive
- **Diagnostics**
  - MSE measurement viewing co- and counter beam allows separation of E_r and j
  - Co and Counter CER view allow direct measurement of cross section corrections

New Divertor Modification Provides Physics Capability and Maintains Shape Flexibility

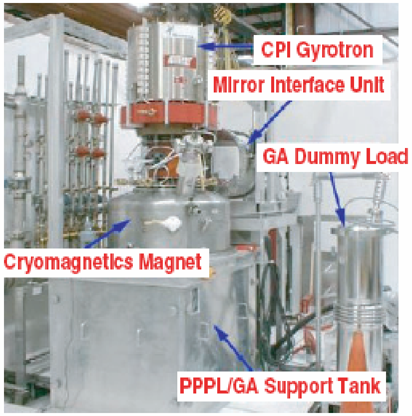


- **Density control at high performance**
  - SN and DN AT and QH–mode
- **Pedestal physics with range of ν^* (n_e)**
- **Mass transport physics (tritium uptake)**
  - Microbalance diagnostics
  - Reduced carbon source from tile edges
- **Optical access to the inner divertor leg**
- **Detachment control via pumping**

Motivation for Upgrading the ECH System

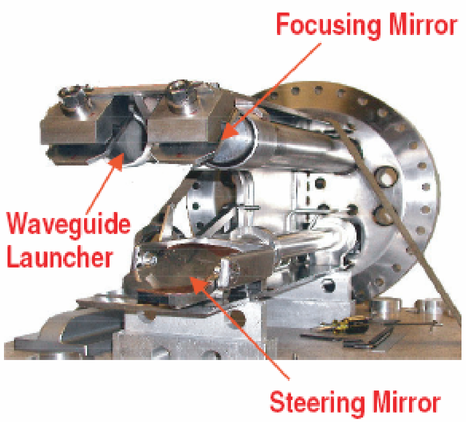


110 GHz EC System Layout

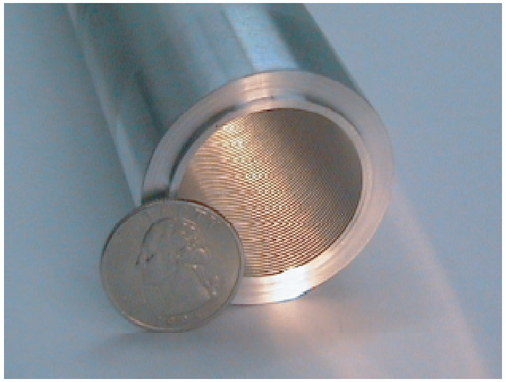


High Power Gyrotrons

- **Enables**
  - Current profile control
  - Sustainment of high performance
  - Tearing mode stabilization or avoidance
  - Transport barrier studies
  - Modulated transport and critical gradient studies
  - Electron heating



EC Launchers



Low Loss Corrugated Waveguides

Cooling System Upgrade Will Meet the Expanded Long Pulse, High Power Needs of the DIII-D Program

- **Two aging cooling towers are being replaced**
- **Heat exchangers for ECH are being upgraded**

Milestones

- **1/30/06 Complete installation of the lower divertor**
- **3/31/06 Close DIII-D Vessel**
- **4/10/06 Start Power Supply testing**
- **4/26/06 Start NB conditioning**
- **5/8/06 Start Plasma Physics Operation**
  - NB should be ready with 7 sources
  - ECH should be ready with 4 – 6 gyrotrons
  - Fast Wave should be ready with 3 transmitters