DIII–D Plasma Control

by
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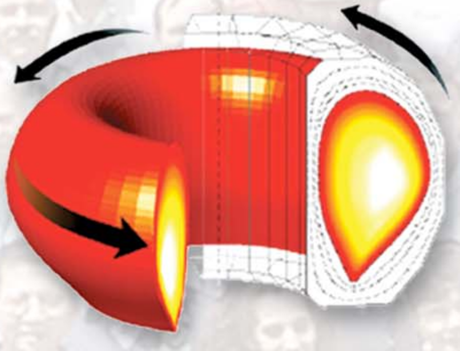
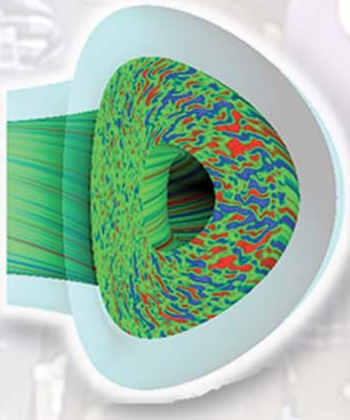
DIII–D PCS Team



Presented to
DIII–D Program
Advisory Committee



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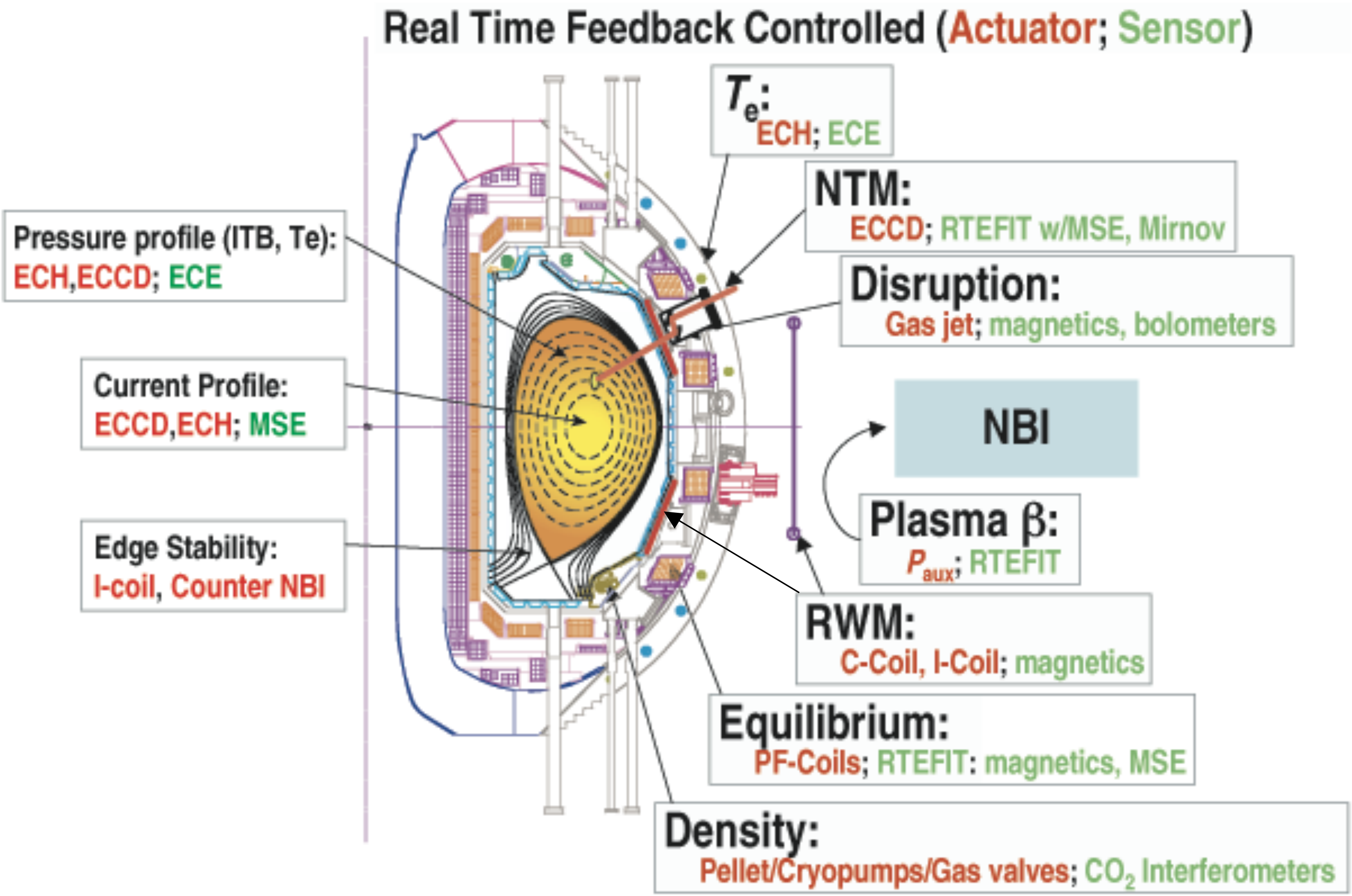
DIII–D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Outline

- **DIII-D plasma control overview**
- **Control development for experiments in 2005**
  - RWM actuators
  - NTM algorithms
  - q-profile control
- **Advances in use of the DIII-D Plasma Control System and design tools worldwide:** NSTX, PEGASUS, MAST, EAST, KSTAR
- **DIII-D plasma control plans for 2006**
- **Plans for continuing DIII-D PCS use at other devices**
- **Support for ITER plasma control needs**

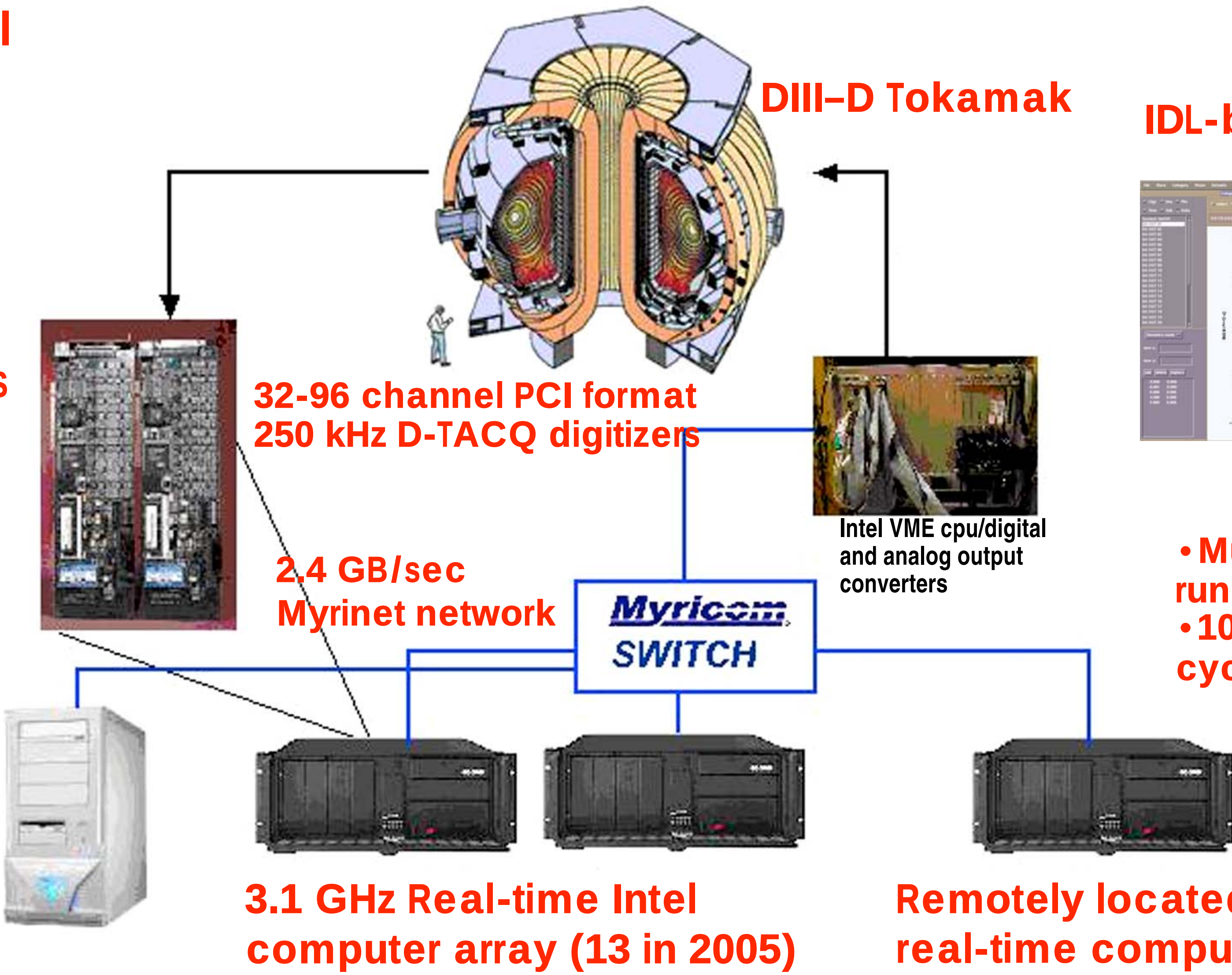
DIII-D Advanced Tokamak Control Involves Many Actuators, Sensors, and Integrated Control Algorithms



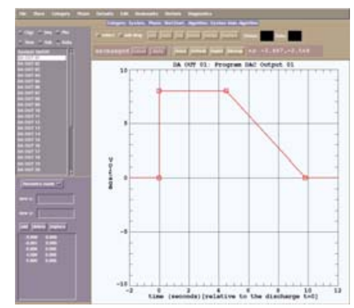
DIII-D PCS is a Flexible, Scalable Multi-cpu Control System Supporting Arbitrarily Complex Algorithms

DIII–D plasma control system hardware structure

- **Commercial Off-The-Shelf components**
- **Linux-based OS and C-code allows complex algorithms, rapid modification and development**
- **PCS real-time Network Gateway computer and user interface host**

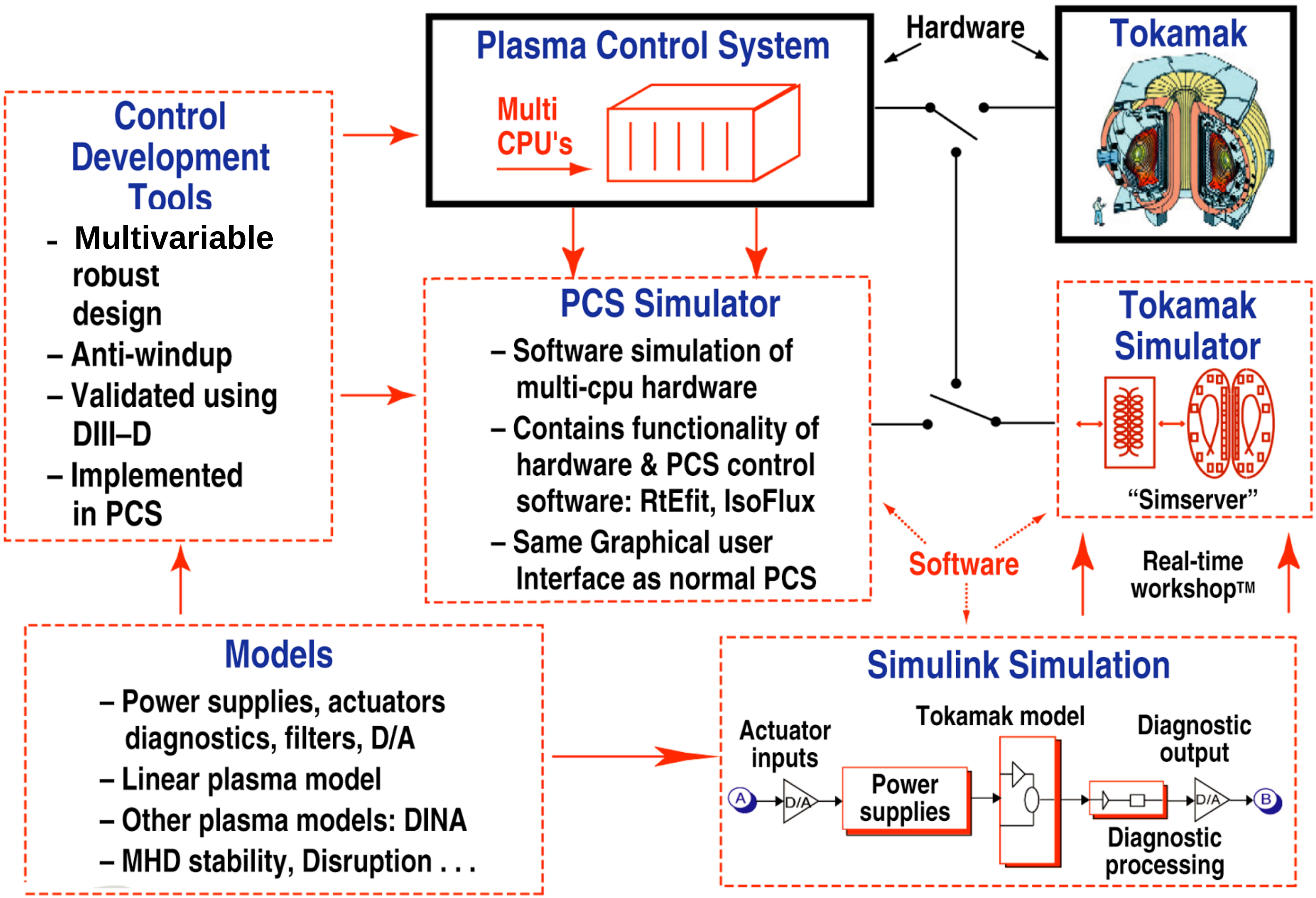


IDL-based GUI



- **Multiple CPUs run in parallel;**
- **10 μs -10 ms cycle times**

Integrated PCS/Simulation Environment is a Complete Plasma Control Package



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Outline of Accomplishments 2005 (I)

- **Software Upgrades**
  - Real-Time EFIT q-profile analysis improvements
    - rtEFIT with 32 ch. MSE, E_r correction, spline parameterization, 33 x 33 grid equilibrium producing q-profile every 4-8 ms
    - 3/2 and 2/1 q-surface reconstruction for NTM control
  - Improved β_N feedback control algorithm
  - Real-Time Thomson T_e and n_e profiles (32 channels)
  - Real-Time CER algorithm "CERREAL" development begun with T_i and v_{tor} profile reconstruction (8 ch) demonstrated
  - NTM suppression algorithm constrains a chosen q-surface (2/1, 3/2) to coincide with a fixed ECCD deposition location using rigid body radial shifts or B_T variation

Outline of Accomplishments 2005 (II)

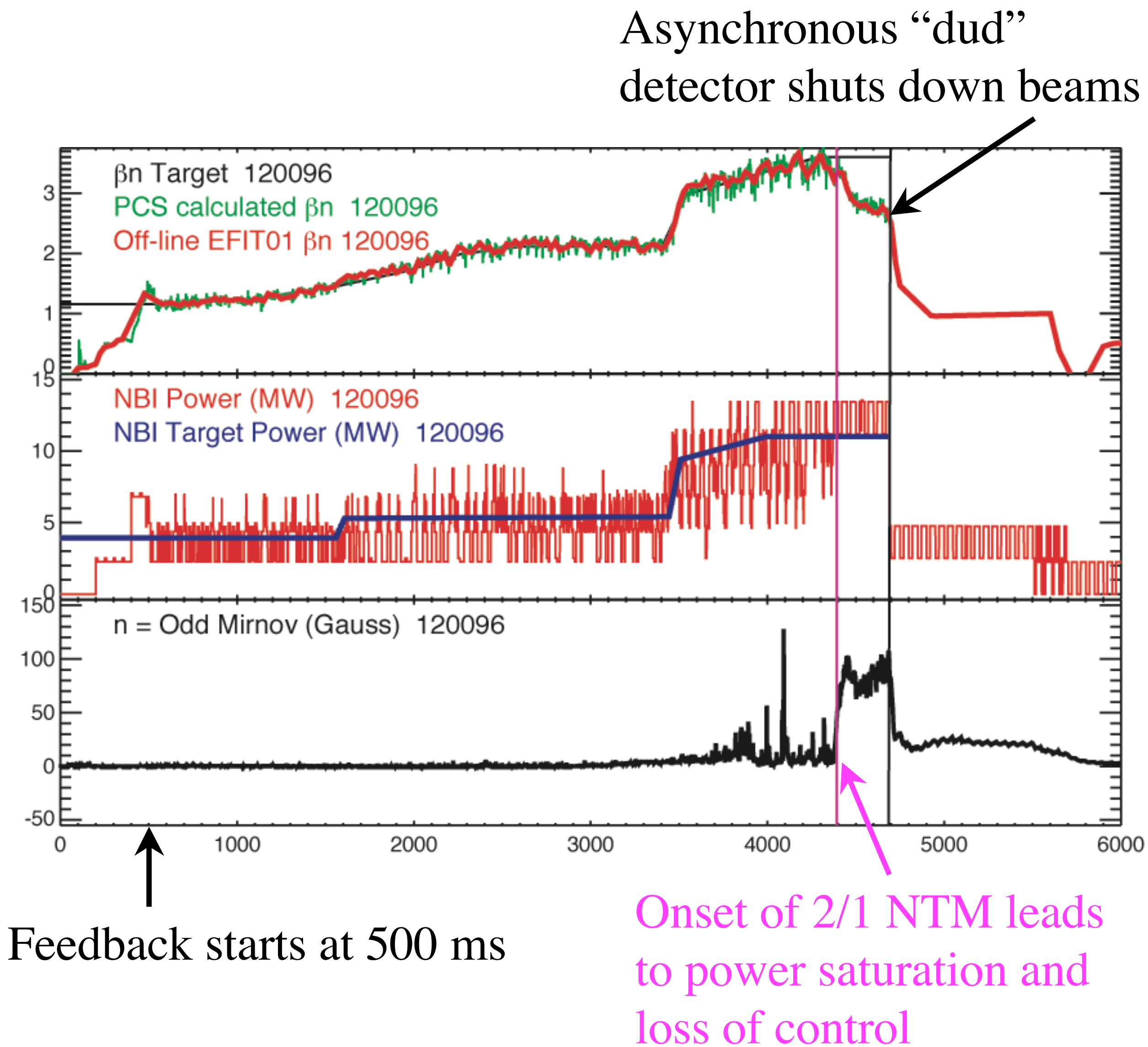
- RWM control algorithm improvements
  - Introduced Kalman Filter [Far-Tech]
  - Integrated audio amps into the RWM suppression algorithm
  - Simplified the user interface by utilizing I-coil patch panel data
- Development of feedback control of q-profile using NBI, ECCD/ECH [and FW] begun
- Advanced shape controller (model-based linear-nonlinear) demonstration

• Hardware Upgrades

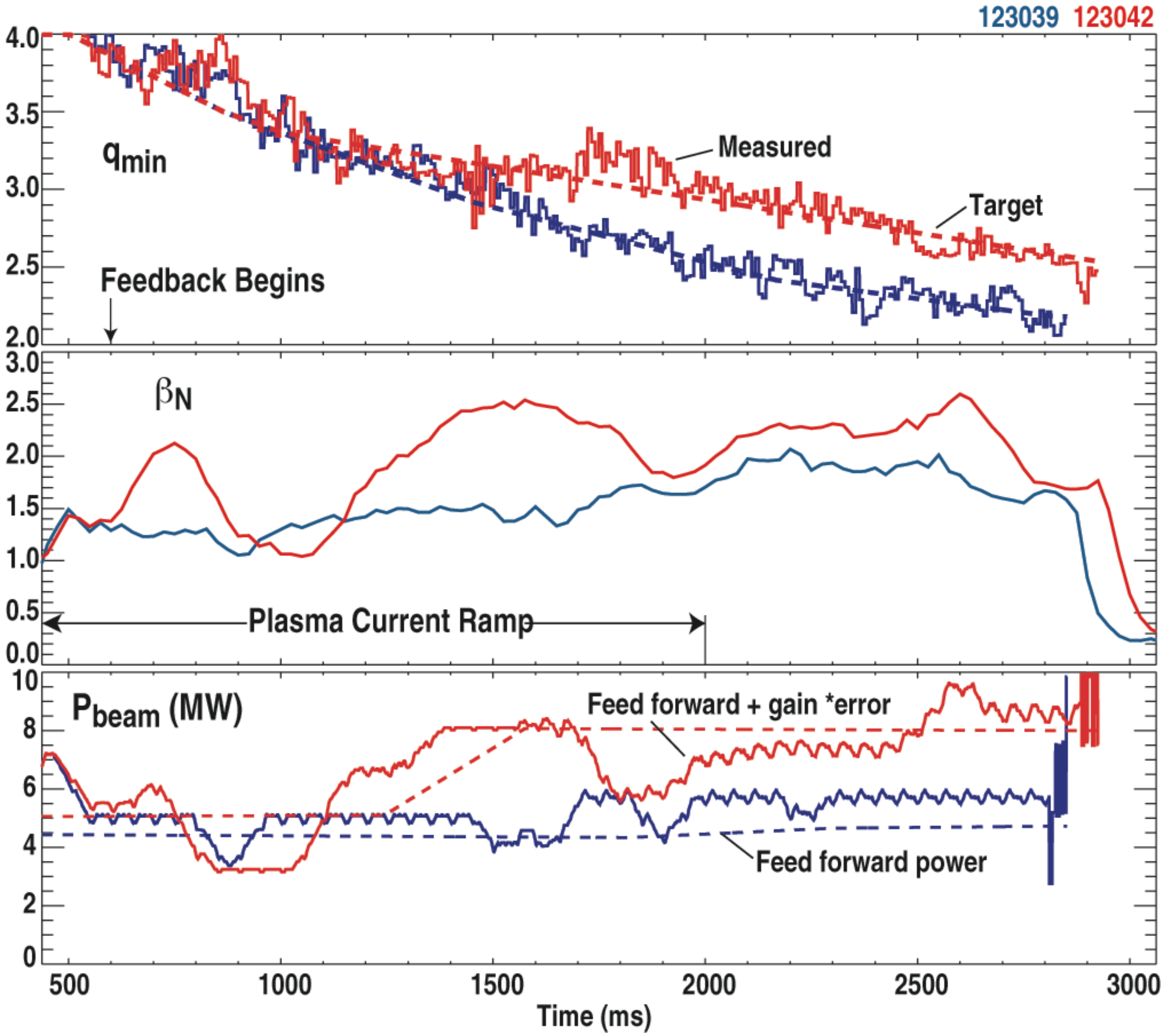
- Total PCS processors increased from 9 to 13
  - More CPUs dedicated to Real-Time EFIT, with and without MSE
    - 3/2 and 2/1 q-surface reconstruction for NTM control.
  - Remote CPUs in Thomson (32 ch), MSE (32 ch) and ECE (32 ch) labs
  - Dedicated RWM control CPU and new ADCs reduce latency (to 35 us)
- Control Room Real-Time displays increased from 4 to 7

β_N Feedback Control Has Been Improved

- Upgrades to real-time EFIT
- Improved PID gains
- Improved beam sequencing software
- Ability to handle beam faults gracefully
- Starting β_N feedback early in discharge helps improve shot-to-shot reproducibility

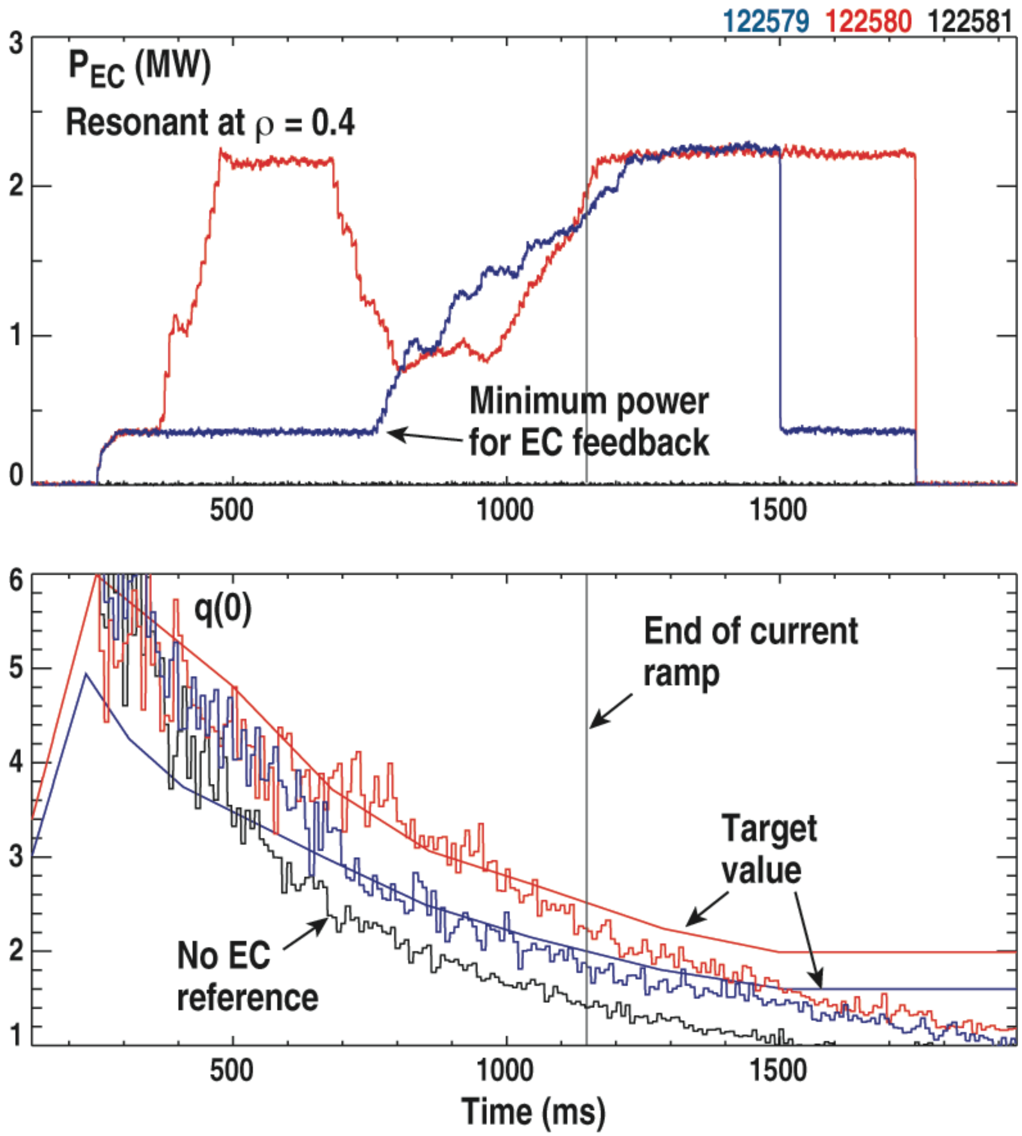


q_{min} Has Been Controlled to High Values for Long Duration Using Neutral Beam Heating in H-mode



- Control works in rampup and flattop
- Proportional gain only
- Large power demand on NBI can drive plasma to β-limit
- Control of q_{min} and $q(0)-q_{min}$ not possible with only NBI

Closed-loop Control of q(0) Evolution Using Off-Axis ECH is Effective Until Power Saturates



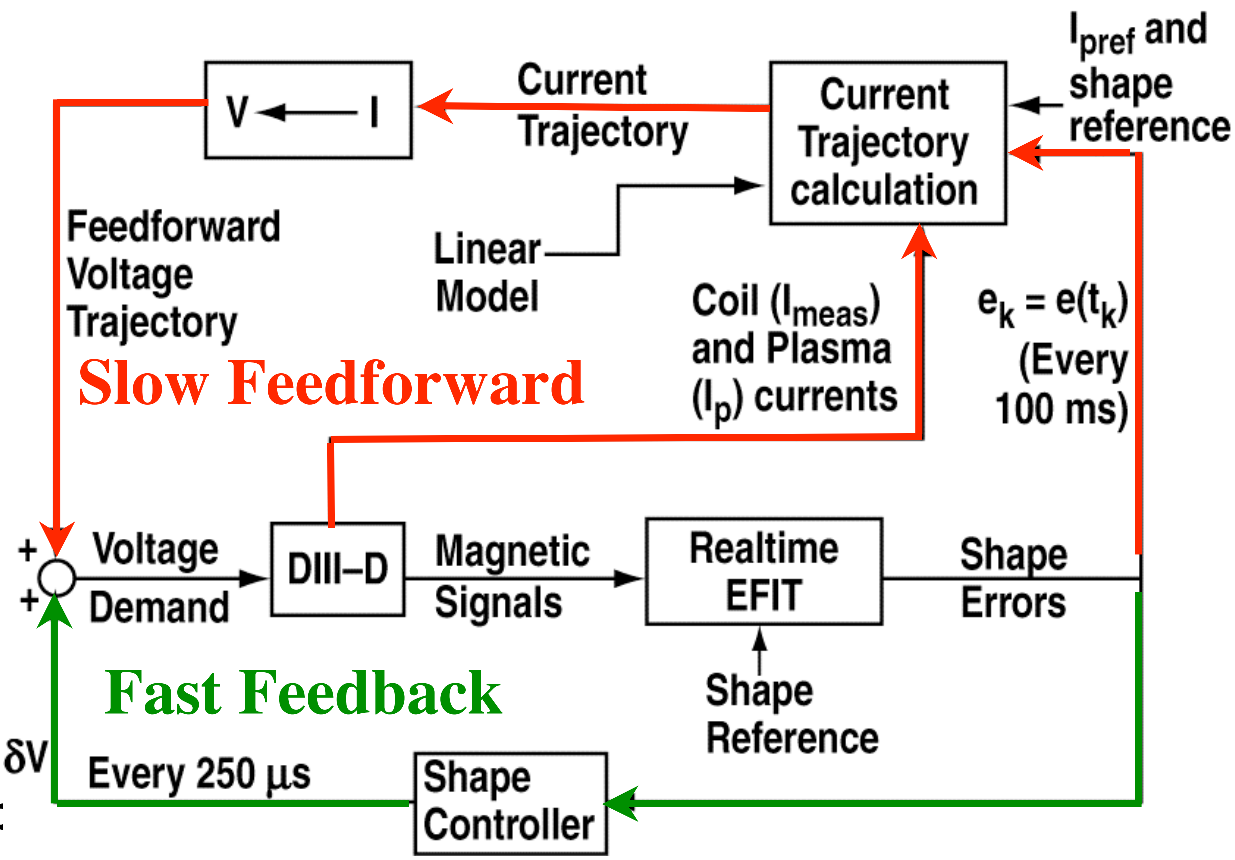
- **L-mode**
- **Control works during current ramp; insufficient EC power to maintain target in flattop**
- **Proportional gain only**
- **Two different targets show good tracking of target in either good (red) or degraded (blue) breakdown conditions**

New Integrated Shape + Coil Current Control Keeps Currents Away from Coil Limits

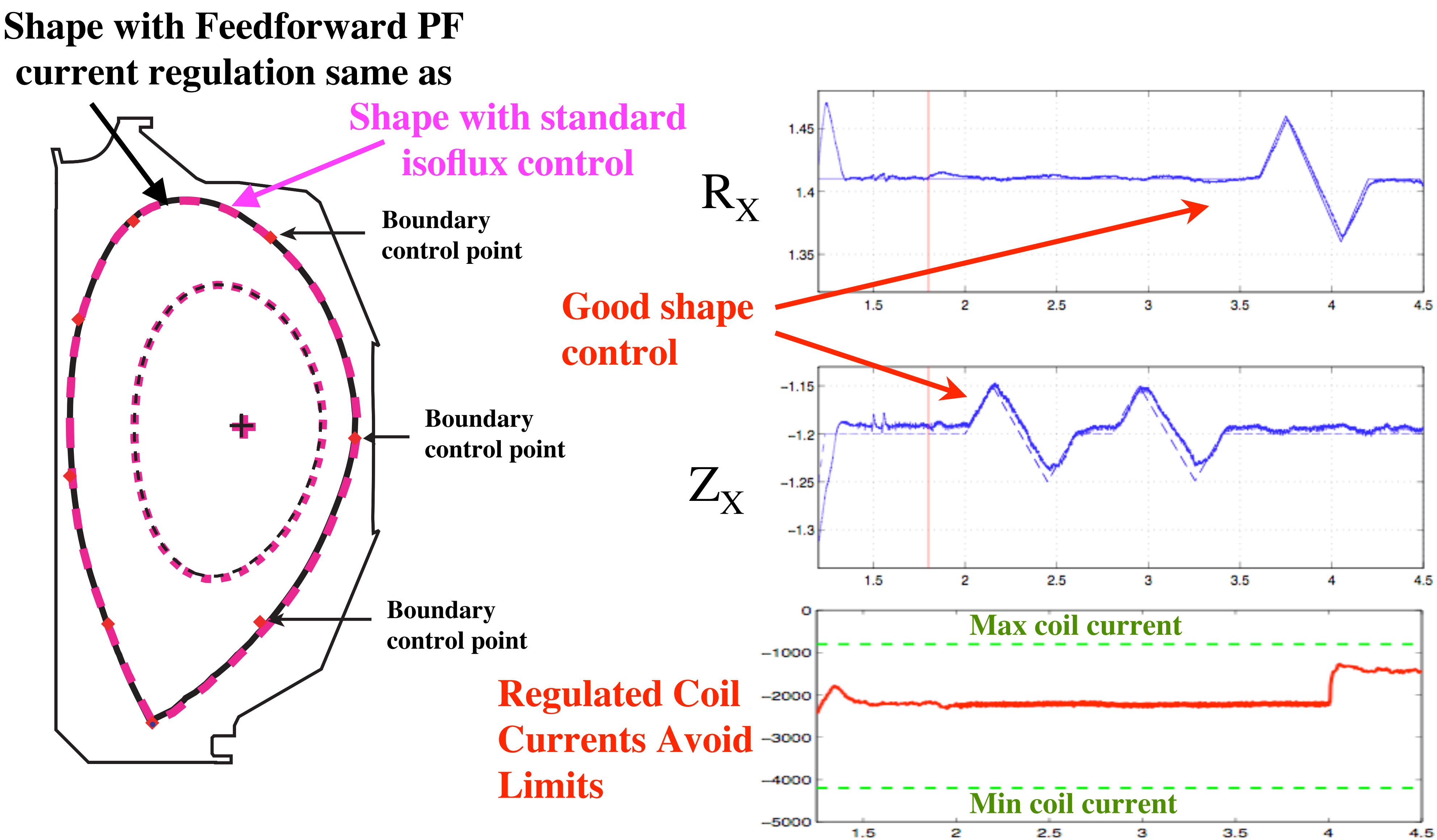
- **Coil current command trajectory calculated from weighted cost functional to maximize distance from coil limits and maintain desired shape:**

$$\min_{\Delta I_F} \left[\left\| W \left(e_k + G_{ep} \Delta I_p + G_{eF} \Delta I_F \right) \right\|^2 + \varepsilon \left\| \Delta I_F \right\|^2 \right]$$

- **Slow Feedforward loop updates every 100 ms, fast feedback loop updates every 250 μs**

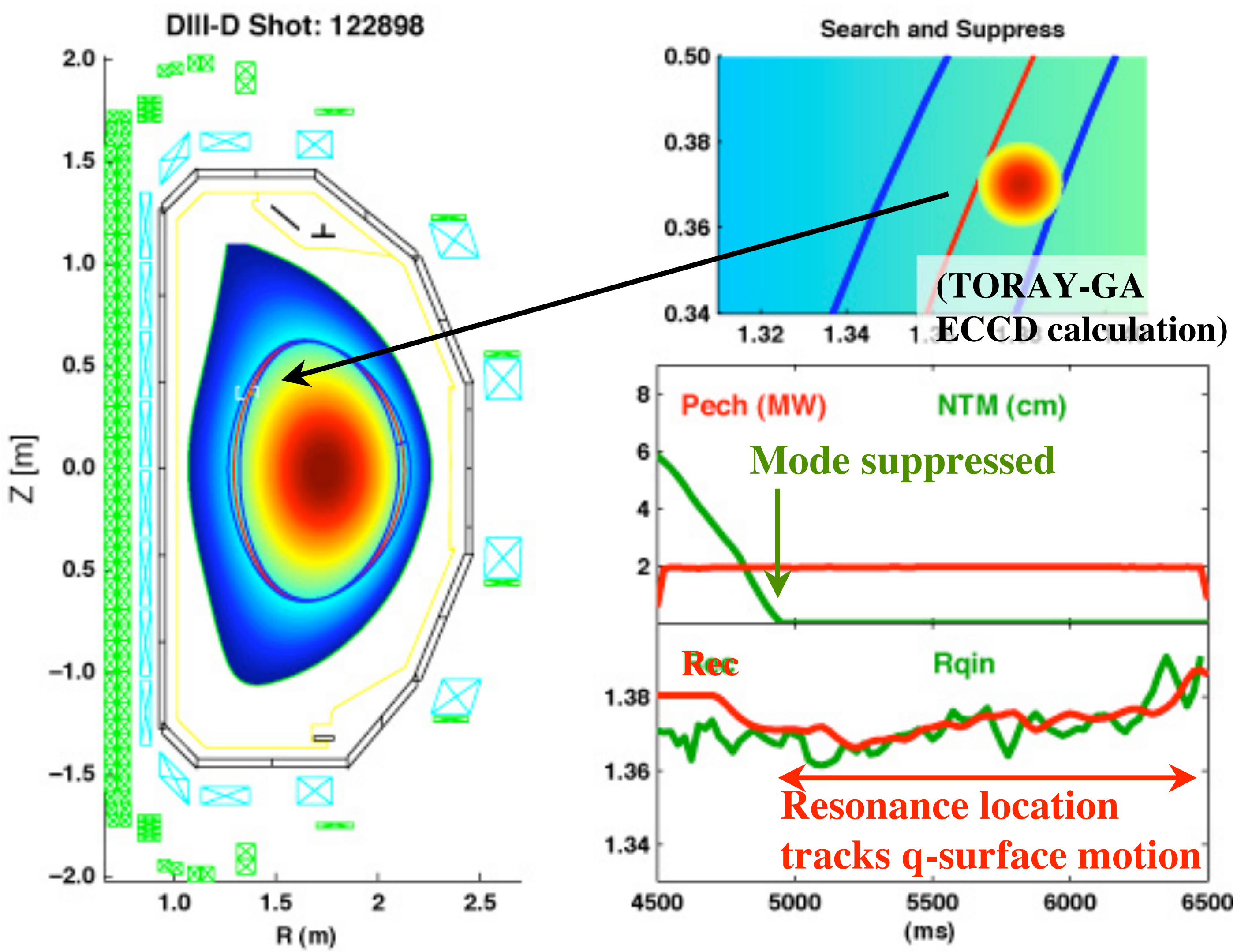


2005 Experiments Demonstrated Model-Based Multivariable Control with PF Current Regulation



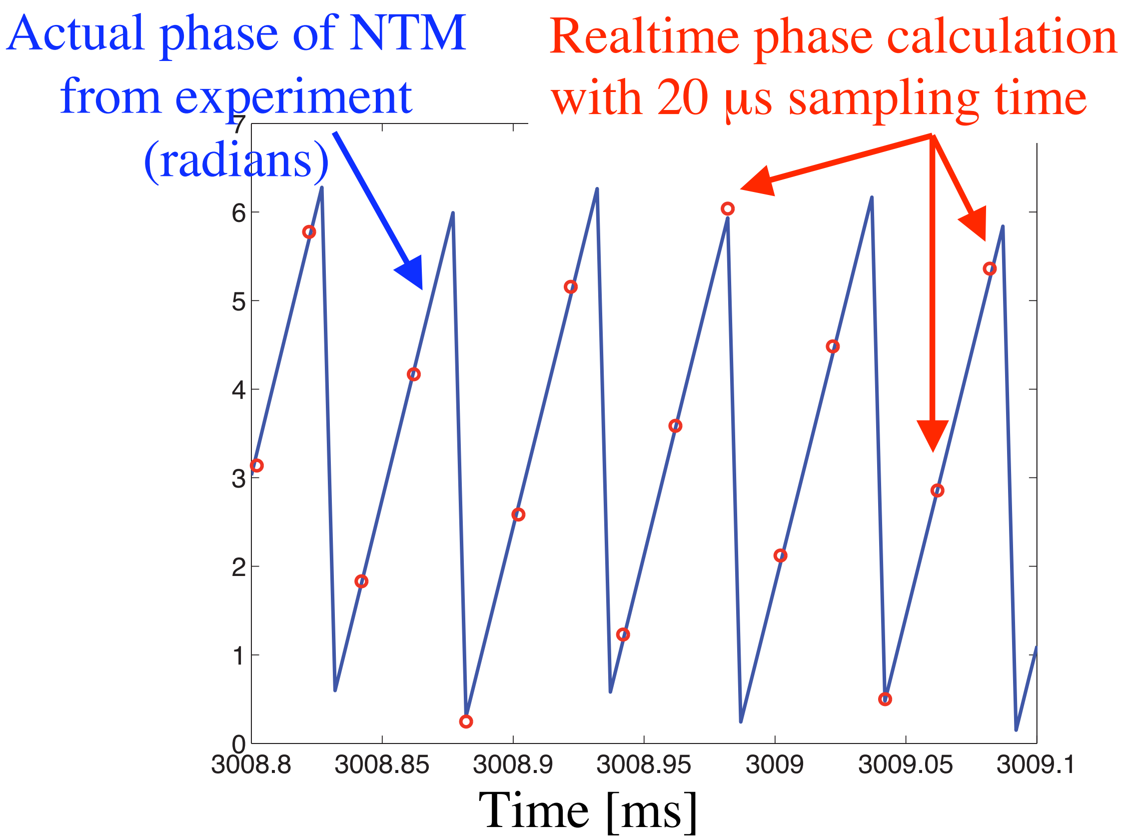
Active Tracking Maintains ECCD/q-surface Alignment Following Suppression of NTM

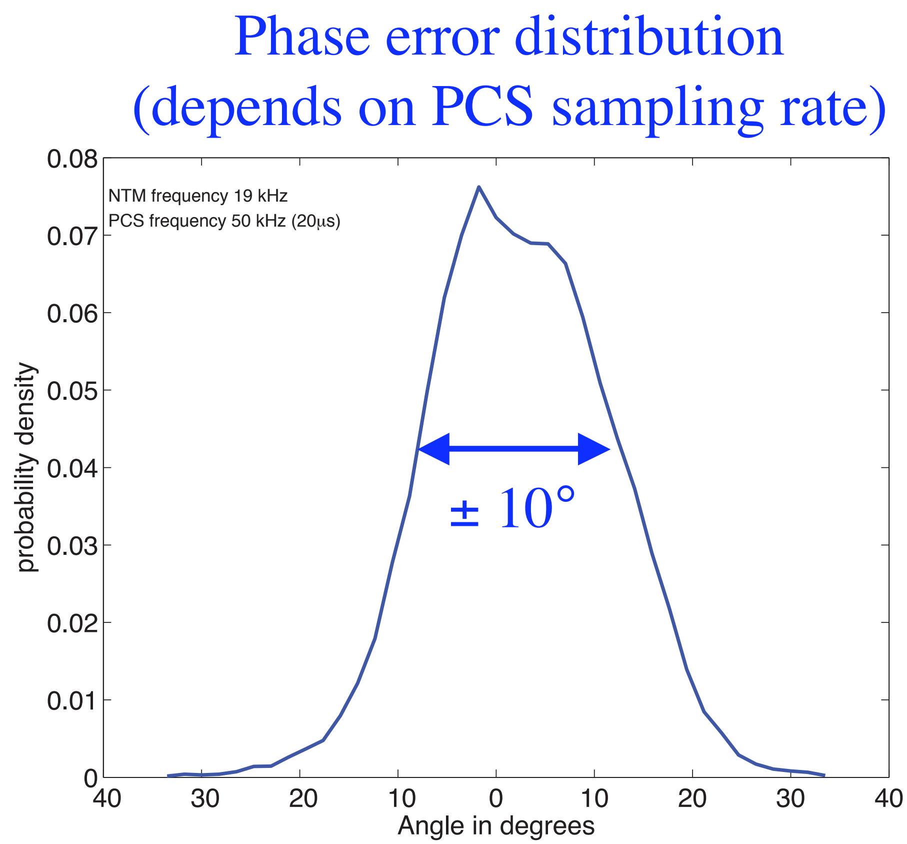
- **After island suppressed, evolution in equilibrium detunes alignment**
- **"Active Tracking" maintains alignment as profile evolves**
  - Realtime q-profile from rtEFIT + MSE
  - Assumes no change in ECCD location (not true when density varies and refraction is large)
- **Compensator for density/refraction changes implemented in PCS in 2005**



Algorithm for Realtime NTM Phase Determination Has Been Developed and Tested Offline

- **Rotating NTM island frequency/phase must be determined in realtime for modulated ECCD to be applied at O-point, not X-point by PCS**





Plasma Control Plans for 2006-07 (I)

- **New integrated plasma rotation/β_N control** **[LTOA counter-beam]**
  - Realtime CER
  - Model-based controllers

- **Improved RWM control**
  - 6 new audio amplifiers (for total of 12) **[LTOA]**
  - Improved model-based control algorithms
  - Operational use of Kalman filters
  - Integrated use of rotation control for low rotation targets
  - Faster PCS (~10 μs cycle time)

- **Improved NTM control**
  - Gyrotron modulation control
  - Realtime spectrum analysis for frequency/phase of modes
  - Realtime mirror steering (multiple modes)
  - New long-pulse gyrotrons **[LTOA]**

Plasma Control Plans for 2006-07 (II)

- **Realtime EFIT**
  - 65x65 grid
  - Include MSE channels viewing counter-beam **[LTOA]**

- **Improved q-profile controller with ECCD/ECH, FWCD**
  - Model-based control design
  - Target q-profile control for advanced scenarios
  - Collaborations with Lehigh Univ., CRONOS Team (EU), SWIPP (China)

- **Model-based multivariable shape controllers in operational use**
  - High-performance control for advanced scenarios
  - New divertor configuration control **[LTOA]**

- **Upgraded impurity injection gas valve for disruption mitigation [LTOA]**
  - 10x previous throughput; exceed runaway e^- suppression density

Use of DIII-D PCS at US and International Tokamaks Will Expand in 2006-07

- **EAST/DIII-D PCS will control first plasma operations ~June 2006**
  – EAST PCS installed at ASIPP September 2005
  – PF coil excitation tests to be controlled by EAST PCS ~ March 2006

- **KSTAR/DIII-D PCS development will produce 3 evolutionary steps**
  – v2.0 = version with basic Day One capability (but e.g. no RTEFIT; installation on-site at NFRC February 2006)
  – v2.5 = version consistent with KSTAR network/hardware solution (to be developed at GA in collaboration with visiting NFRC personnel ~ August 2006)
  – v3.0 = version providing full Day One plasma operation capability

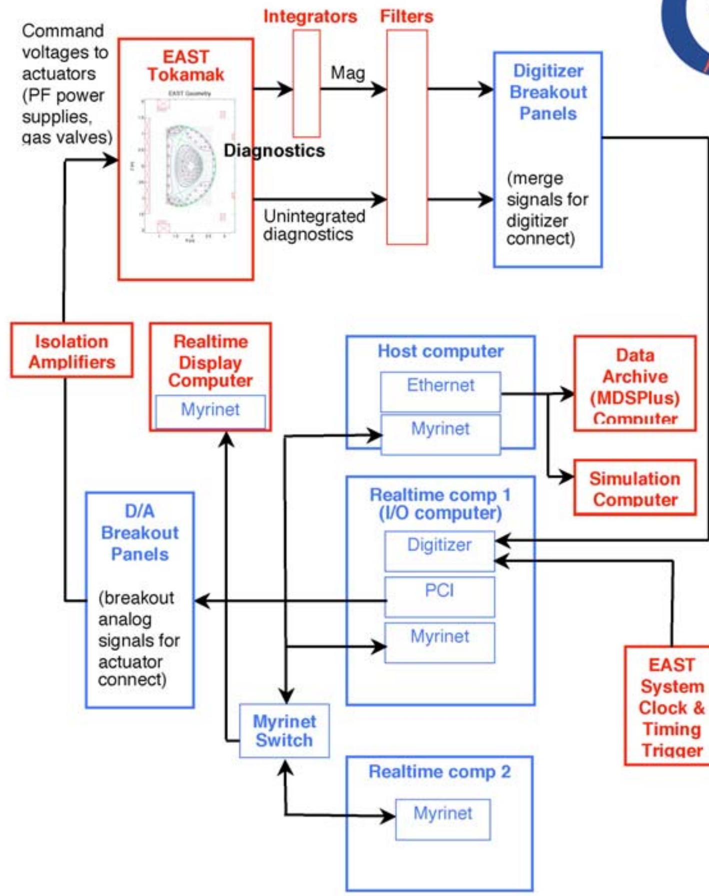
- **PEGASUS/DIII-D PCS will be installed and operational**
  – Modeling/simulation tools for optimal magnetics determination
  – Magnetic predictor-based shape control

- **NSTX/DIII-D PCS will continue development at PPPL**
  – Realtime EFIT and isoflux control for high shaping
  – Initial multivariable model-based axisymmetric controllers

DIII-D PCS Now Common to KSTAR and EAST Provides Path for Critical Control Experience to Pass to ITER

EAST PCS installed/running at ASIPP (9/05)

- DIII-D PCS also operating on NSTX, MAST, PEGASUS (soon...)
- Common, generic PCS infrastructure software
- Machine-specific algorithms and hardware/network solutions
- Common, generic modeling/simulation tools



EAST PCS is a turnkey system based closely on DIII-D PCS

Design Tools Enable Optimization of EAST Field During Breakdown and Initial Plasma Current Ramp

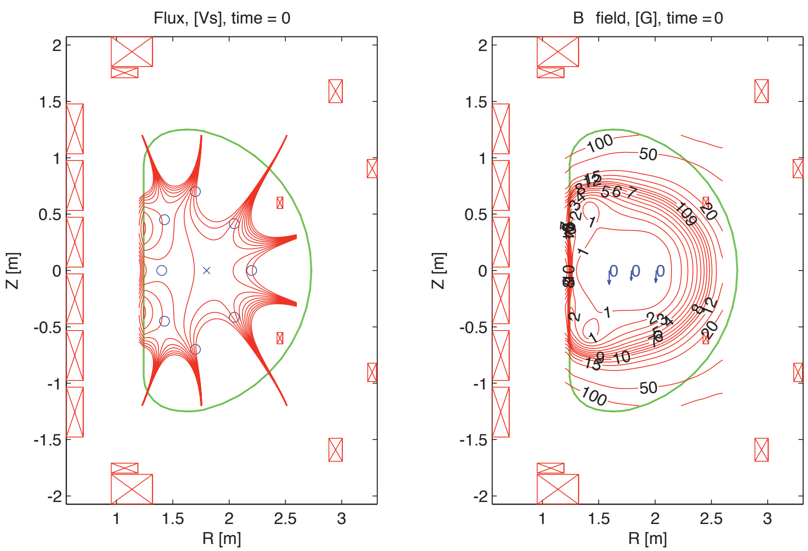
- **Eigenmode least square optimization determines optimal voltage/PF current trajectories including eddy currents and limits on coil current and slew rates**

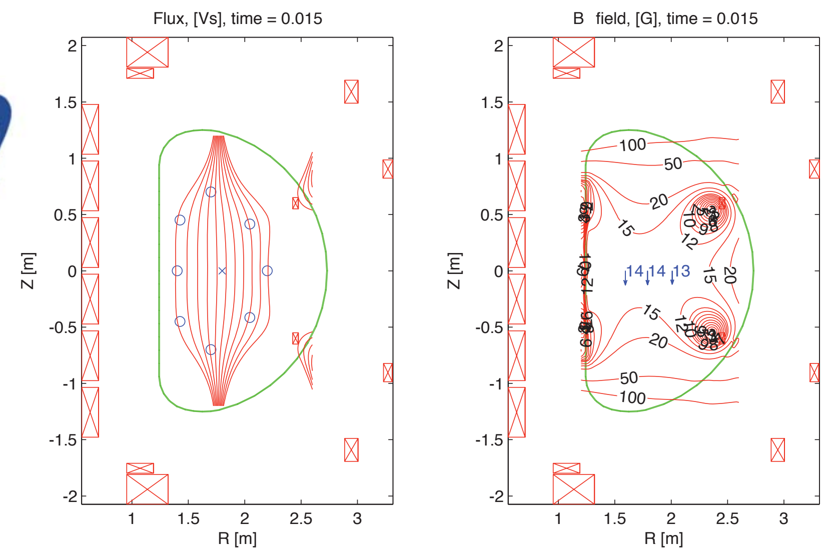
$$[\mathbf{I}] = [\mathbf{E}][e^{\gamma t}][\mathbf{E}]^{-1}\left\{[\mathbf{I}_0] - [\mathbf{R}]^{-1}[\mathbf{V}_0] + [\bar{\mathbf{L}}][\dot{\mathbf{V}}_0]\right\} + [\mathbf{R}]^{-1}[\mathbf{V}_0] - [\bar{\mathbf{L}}][\dot{\mathbf{V}}_0] + [\mathbf{R}]^{-1}[\dot{\mathbf{V}}_0]t$$

where: $[\bar{\mathbf{L}}] = [\mathbf{R}]^{-1}[\mathbf{L}][\mathbf{R}]^{-1}$; I = Current, L = Inductance, R = Resistance, V = Voltage, γ = Eigen values

Breakdown (0 ms)
Low poloidal field ~ 0
Toroidal E-field ~ 0.3 V/m

Ramp-up (15 ms), Ip ~ 12kA,
Vertical field, B_z ~ 14G
Stabilizing Field Curvature





DIII-D Plasma Control Program Will Continue to Make Key Contributions to ITER in 2006-07

- **Development and demonstration of ITPA urgent controls**
  - RWM feedback stabilization in low rotation targets
  - NTM stabilization with modulated, broad-deposition ECCD
  - ELM control with stochastic fields
  - Disruption mitigation with impurity gas injection

- **Model-based controller design**
  - Nonlinear axisymmetric control solutions for SC coils
  - Resistive wall mode controllers, ELM discriminators

- **Valuable control experience with EAST, KSTAR**
  - Long pulse shaped plasmas, superconducting coils

- **Simulations that connect to PCS for control verification**
  - Integrated control of shape, MHD instabilities; operations issues (e.g. disruption effects)

Summary and Conclusions

- **Plasma control development for 2006-07 will provide all required resources to support DIII-D experimental plan:**
  - Plasma rotation/β_N control for transport, RWM studies
  - Realtime CER for rotation feedback
  - 10 μs cycle time capability for faster RWM algorithms
  - Gyrotron modulation, mode frequency/phase detection for NTM control
  - Improved model-based controllers for q-profile regulation, RWM stabilization, shape control

- **Development and use of DIII-D PCS at US and international tokamaks will expand in 2006-07, contribute to ITER:**
  - First plasma operation in EAST will use EAST/DIII-D PCS
  - Initial use of PEGASUS/DIII-D PCS at Univ. of Wisconsin
  - KSTAR/DIII-D PCS installed at NFRC/KSTAR and in hardware-integration phase at GA
  - Model-based controllers, control-level simulations for ITER