Advanced Tokamak Plasma Control in DIII-D

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BURNING PLASMA WITH SELF-GENERATED CURRENT PRESENTS NEW CHALLENGES FOR PLASMA CONTROL

- Strong coupling of transport, heating, and stability leads to a more "self-organized" plasma than in a short-pulse, externally heated tokamak:
  - Pressure profile → Fusion rate → Alpha heat deposition → Thermal transport → Pressure profile
  - Pressure profile → Bootstrap current → Current profile → Thermal transport → Pressure profile
- MHD instabilities can intervene in these loops:
  - Pressure, current density, and fast ion profiles → Instability → Profile Modification
- Highly coupled interaction between divertor/PFC, particle control systems
- Control of such a complex, nonlinear system represents a scientific and technical challenge, and requires an integrated, model-based approach
- Measurements required must be accurate, reliable, and have good coverage
- Today's plasma control represents only the beginning of what will be mature and routine in ITER…

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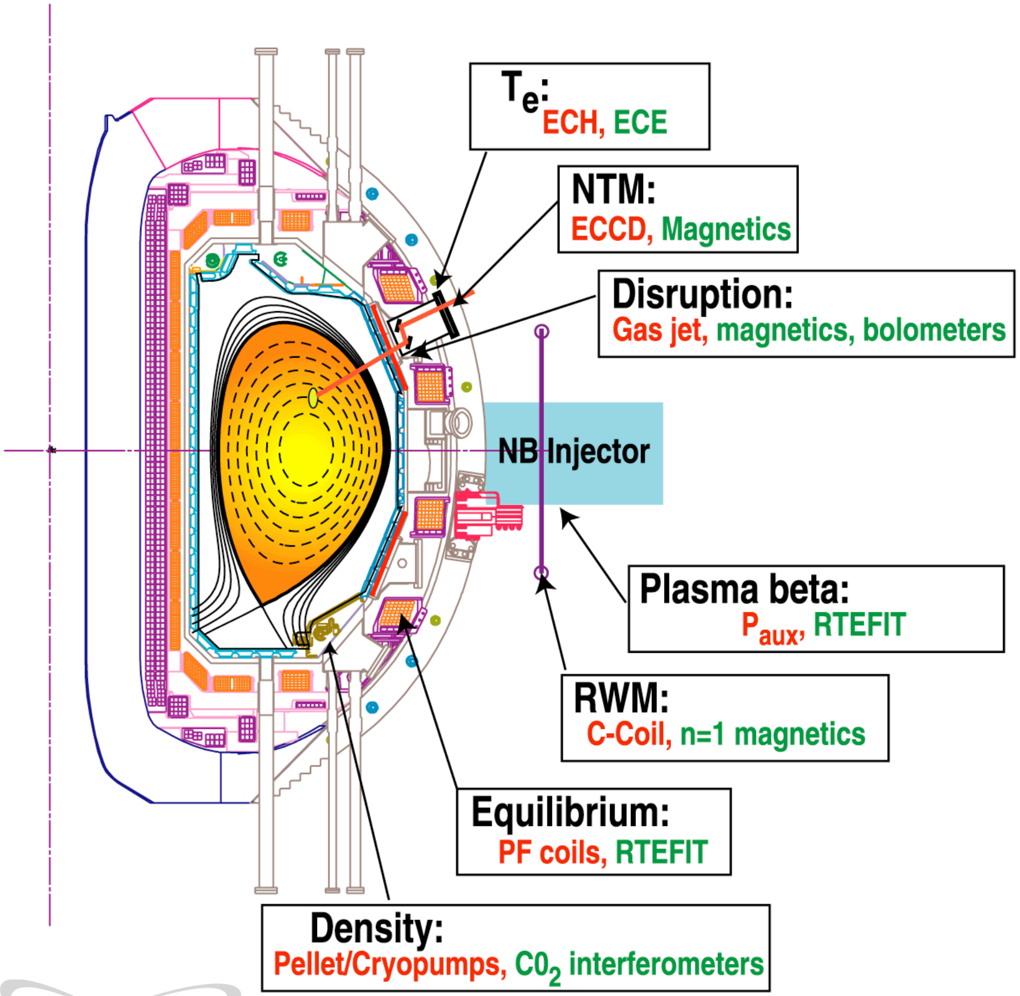
ADVANCED TOKAMAK PLASMAS NEED VERSATILE CONTROL

- **Operating point control:**
  - **Global parameters**
  - **Profiles**
  - **Transport, transport barriers**
- **MHD stability control:**
  - **Instability detection and avoidance**
  - **Resistive wall mode stabilization**
  - **Neoclassical tearing mode stabilization**
- **Particle control (impurities, n_D, n_T, …) and divertor operation**
- **Detection and mitigation of disruptions**
- **Integrated approach to plasma control**

DIII-D Plasma Control Elements

Quantities presently controlled: (Actuator, Sensor)



Under Development

Integrated control:
Expanded PCS
Validated models

Current profile control:
ECCD/FWCD, MSE

Optimized RWM control:
I-Coil
Expanded magnetics

Optimized NTM control:
Track q(r) changes
Multimode

Disruption detection, correction, mitigation:
MHD regulation — PCS
Expanded magnetics

ITER

Many highly coupled control loops

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ADVANCED TOKAMAK OPERATING POINT CONTROL

- Control of global quantities (I_p, β, n_e, etc…) is routine
- Advanced tokamaks need local profile control for
  - Avoidance of instabilities
  - Optimization and regulation of fusion power
- Real-time analysis of profile diagnostics is being developed
  - ECE, MSE, polarimetry, …
- Current density profile control is in its infancy
  - ECCD is an effective tool for modification of J(r)
  - Real-time control is not yet routine
- Particle control not yet under robust and coupled control (highly shape dependent, for example)

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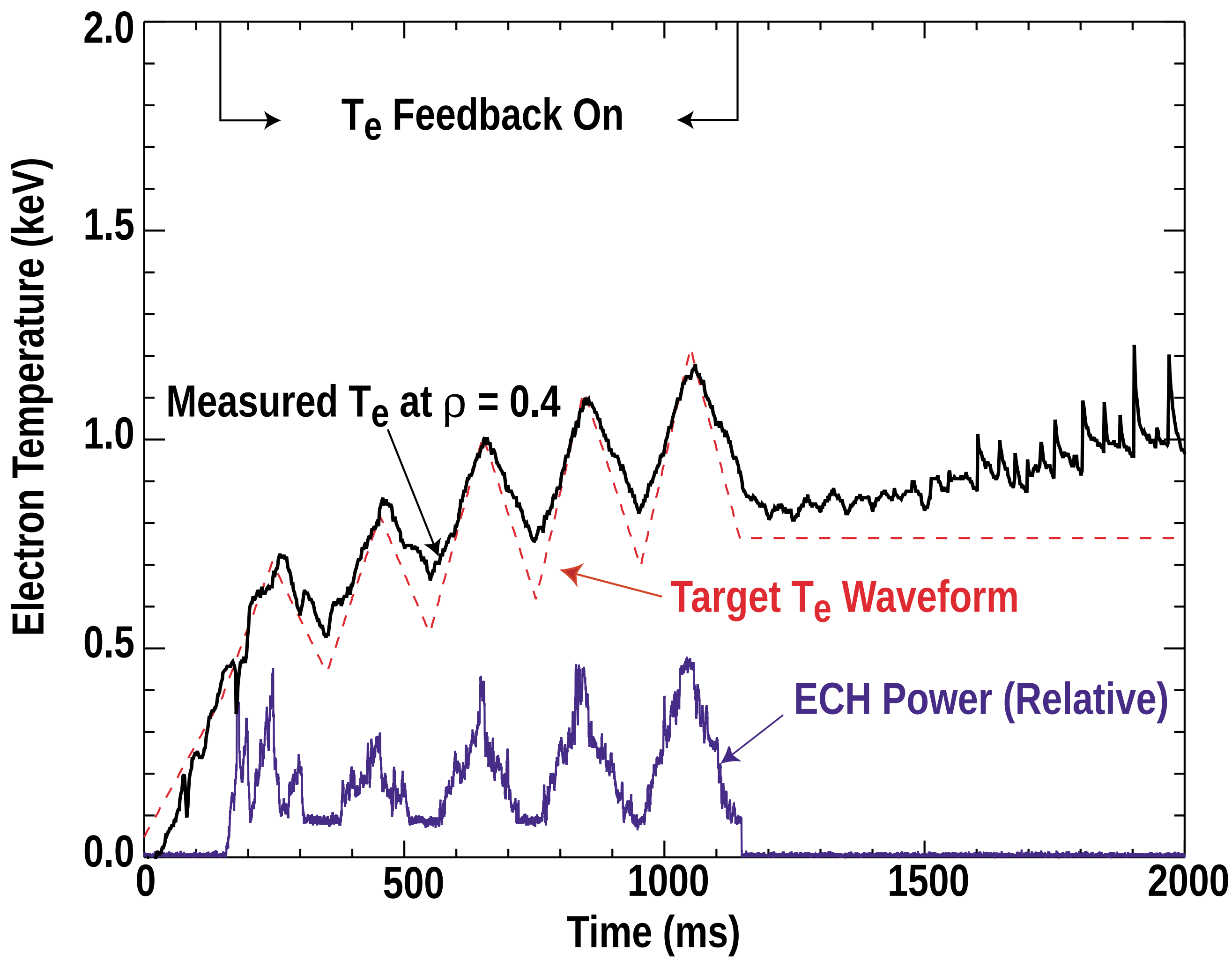
Local Electron Temperature Has Been Regulated with Electron Cyclotron Heating

- 2.5 MW of ECH applied at ρ=0.4
- Real-time ECE T_e measurement
- Variation of ±150 eV, 2.5 eV/ms
- Triangle target waveform followed with high accuracy dynamic tracking



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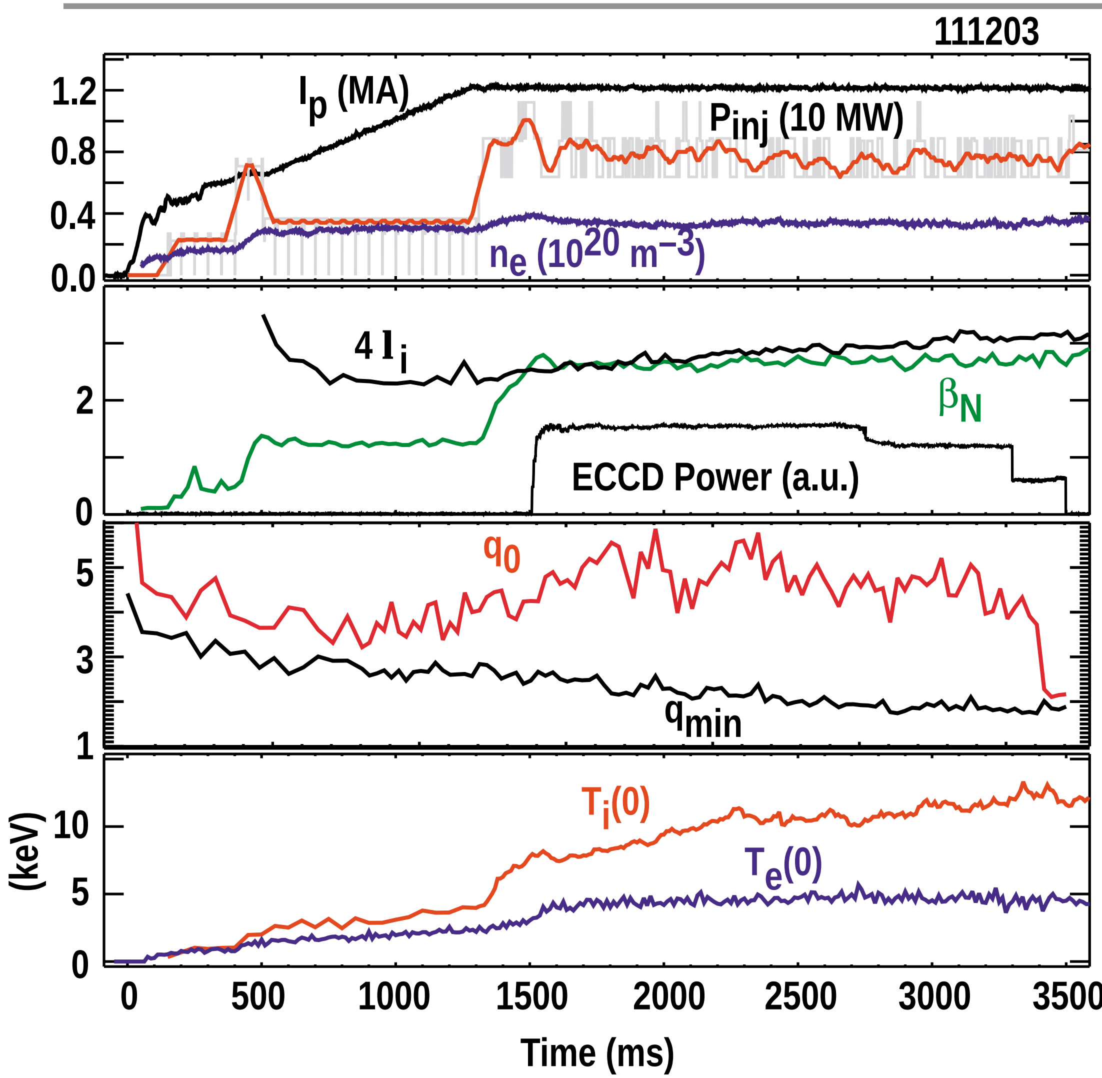
APPLICATION OF ECCD IN HIGH-β DISCHARGE RESULTS IN FAVORABLE CHANGES TO CURRENT PROFILE AND TRANSPORT



- **Early H-mode used to access high q_{min}**
- **$\beta_N \cong 2.8$, $H_{89} \cong 2.4$ maintained by feedback**
- **ECCD causes increase in central magnetic shear**
- **Both T_e and T_i increase with application of ECCD**

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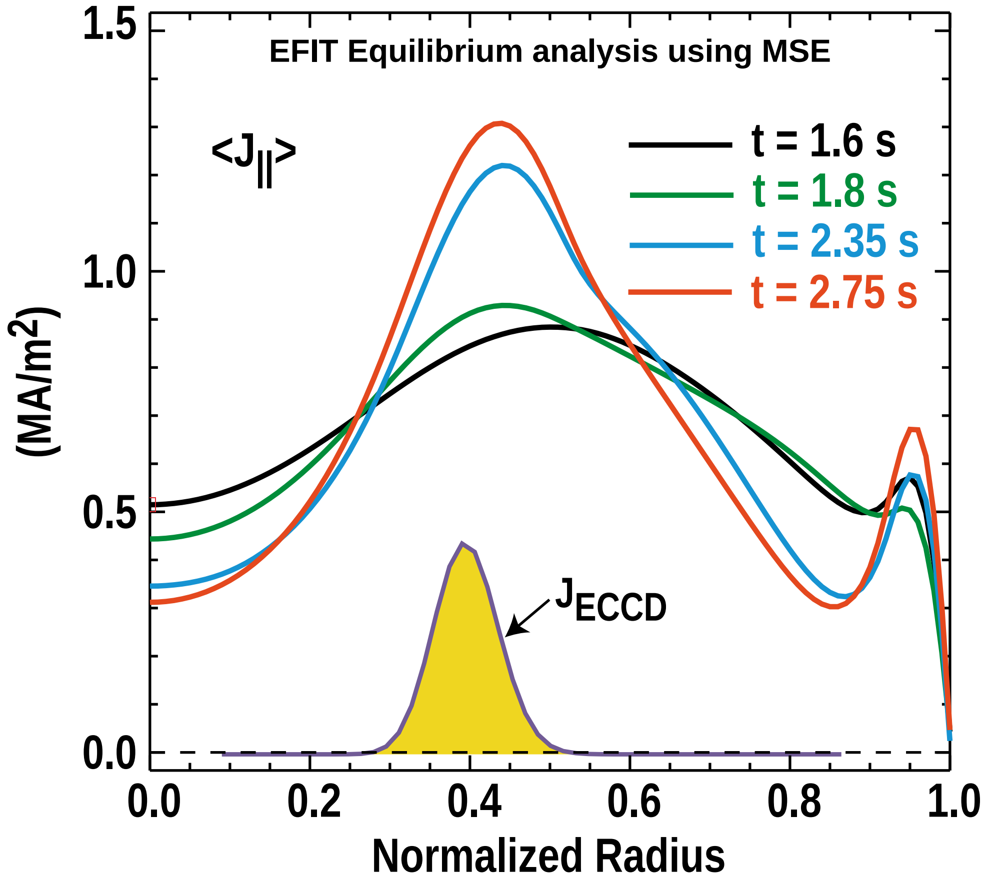
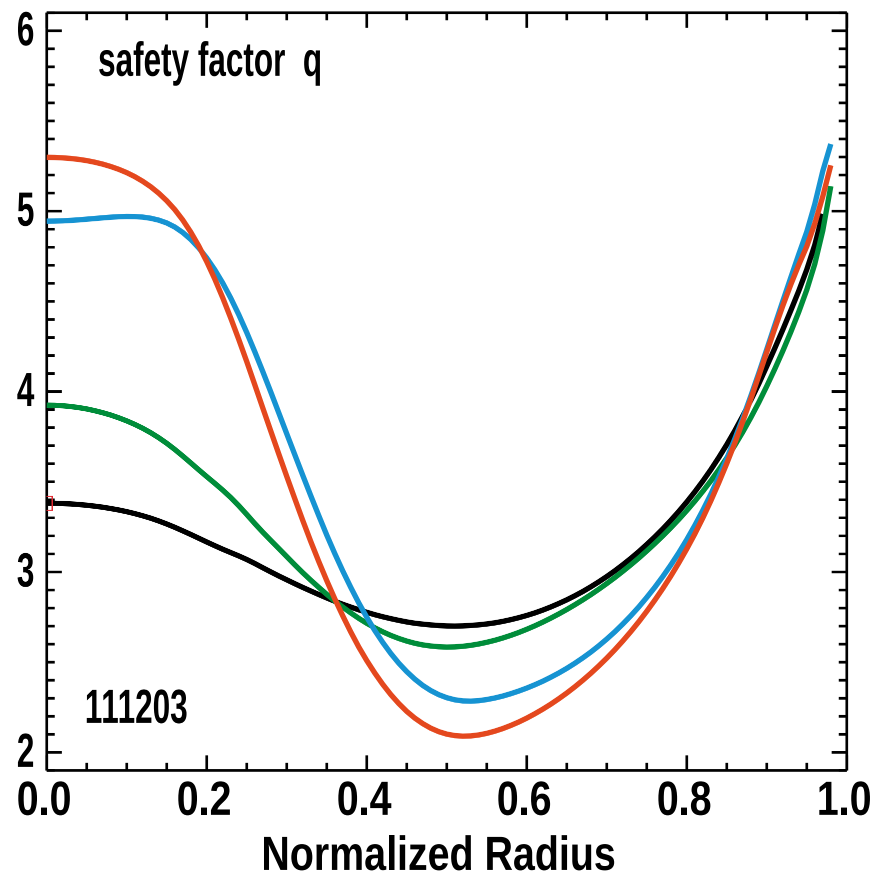
ECCD PEAKS CURRENT DENSITY AT RESONANCE LOCATION AND PRODUCES STRONGER NEGATIVE MAGNETIC SHEAR





- Clear evidence of q-profile modification also seen in quiescent double barrier (QDB) plasmas [E.J. Doyle, et al.]

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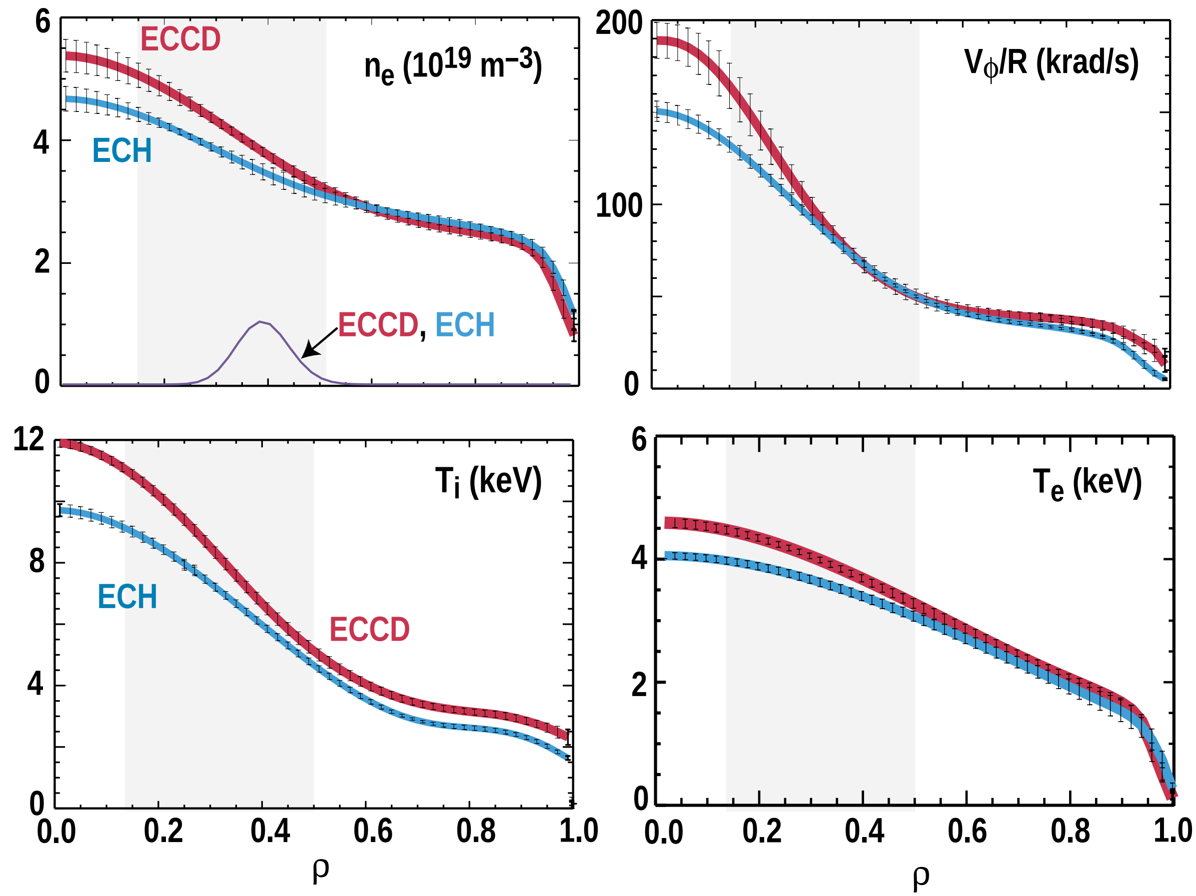
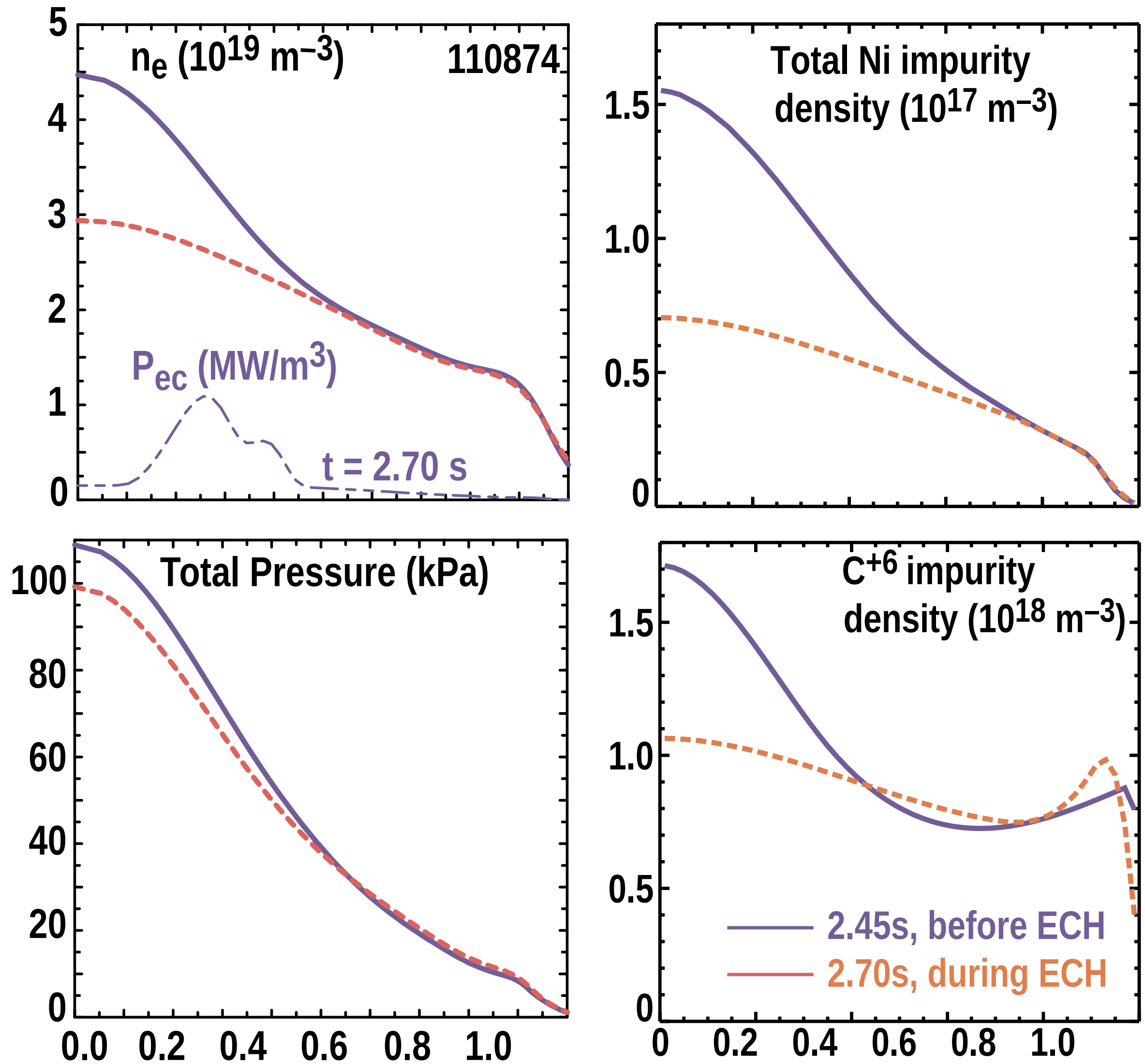
ECCD CAN TRIGGER FORMATION OF CORE TRANSPORT BARRIERS IN ADVANCED TOKAMAK DISCHARGES

- Core barriers seen in all four transport channels with ECCD
  - No barriers in ECH case with no current drive
- Gyrokinetic stability code analysis shows ExB shear and Shafranov shift stabilization are both important



ECH OR ECCD PROVIDES LOCALIZED CONTROL OF PROFILES AND HIGH-Z IMPURITY ACCUMULATION

- Central high-Z impurity accumulation due to density peaking is critical issue for ITB research
  - Profile control is essential
- ECH reduces density peaking, controlling central high-Z impurity accumulation
  - $n_e(0)/n_{av}$ decreases from 2.1 to 1.5
- Similar results with ECH on ASDEX-U



TRANSPORT CONTROL

- In a self-heated plasma, pressure profile must be controlled through transport:
  - ExB shear influences transport, but a burning plasma may have little beam-induced rotation
  - J(r) influences transport, but may be constrained by requirements for current sustainment

- Control of ITB is under development:
  - ECCD influenced ITB, but not tested with T_i=T_e
  - Requirements for diagnostic resolution?

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MHD STABILITY CONTROL

- **Long-wavelength kink or tearing modes can lead to disruption or degradation of confinement**

- **Avoidance of instability through control of operating point:**
  - **Real-time profile diagnostics measure operating point**
    - **Need adequate spatial resolution and coverage for local gradients (ITB)**
  - **Real-time calculation of relative MHD stability and approach to β-limits**
  - **Active MHD spectroscopy can provide direct measurement of the approach to stability boundaries**
    - **Need antennas to drive kHz-range magnetic perturbations**
    - **Can serve as proxy or backup for β-limit calculation**

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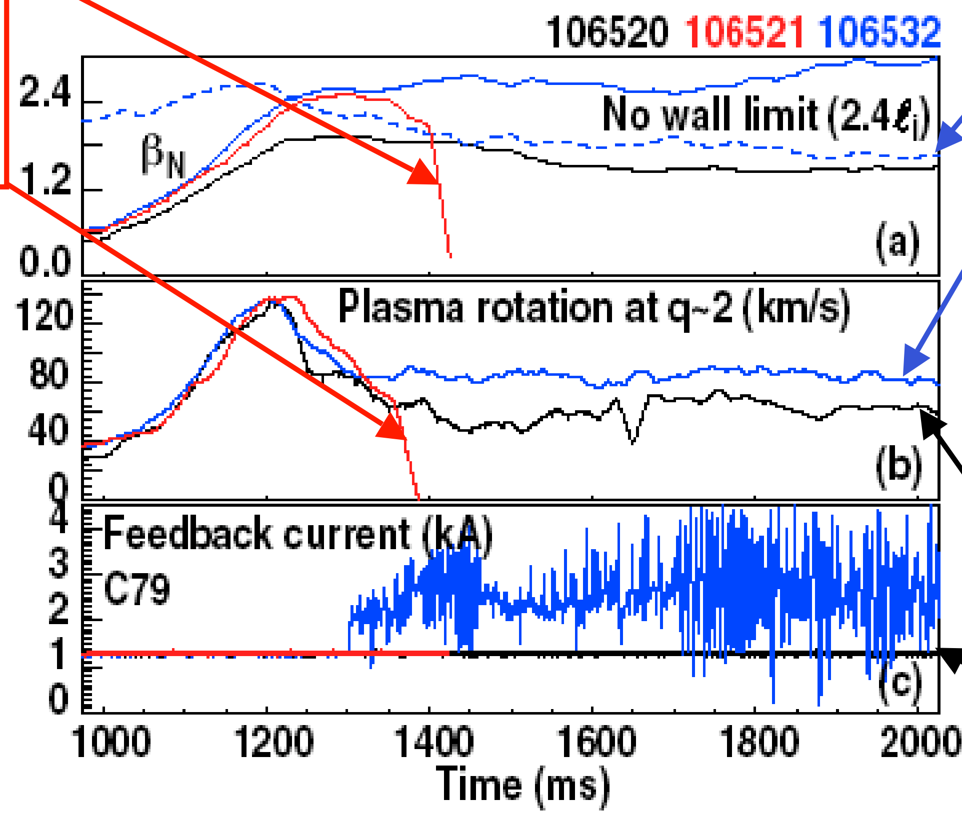
Resistive Wall Mode Stabilized by Rotation Sustained with Error Field Reduction

No error correction,
Above no-wall β-limit
→RWM grows…
→Rotation collapses
→ β_N collapses

With error correction,
Above no-wall β-limit
→ No RWM…
→ Rotation sustained
→ $\beta_N \sim 2\ \beta_N^{NoWall}$



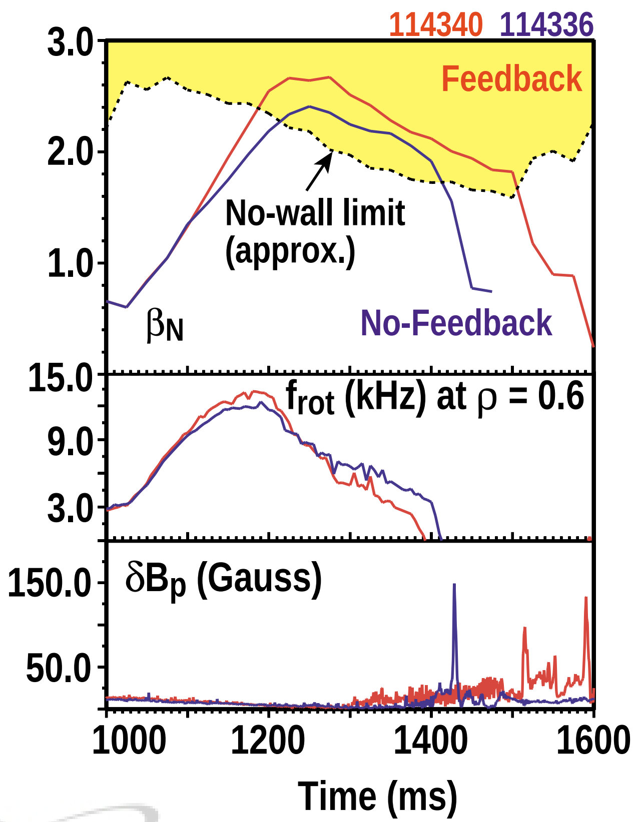
No error correction,
Below no-wall β-limit
→Rotation sustained

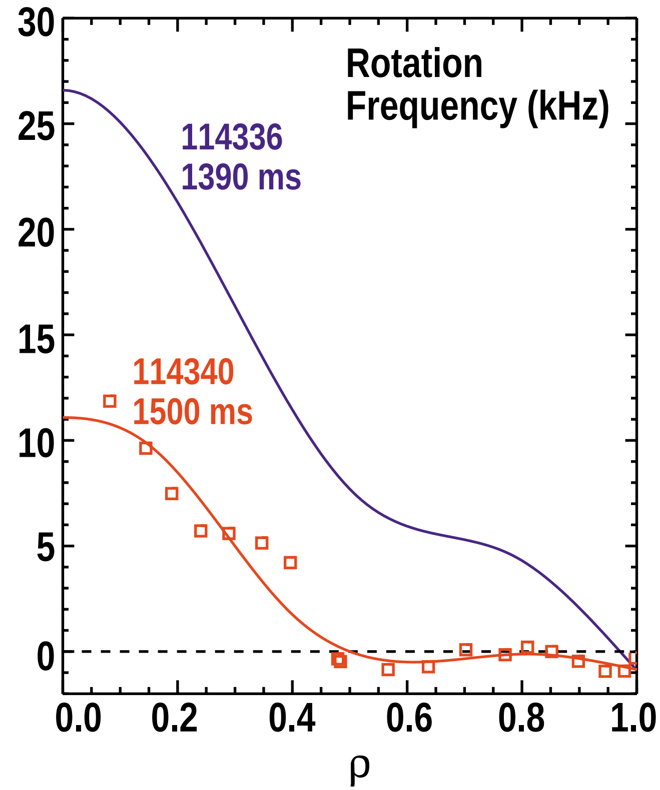
Stabilization of RWM by maintaining rotation enables sustained

$\beta_N \sim 2\ \beta_N^{NoWall}$!

FEEDBACK CONTROL WITH INTERNAL COILS STABILIZES RWM WITH LOW ROTATION

- Magnetic braking reduces rotation to zero in outer half of plasma
- Case without feedback becomes unstable at lower beta, even with rotation
- Feedback with internal coils maintains stability for > 100 msec





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RESISTIVE WALL MODE CONTROL

- Resistive wall mode stabilization by strong plasma rotation is effective, but extrapolation to a burning plasma is uncertain:
  - Critical rotation frequency for a burning plasma-sized device is not known
  - Burning plasma may have little beam-induced rotation
  - Likely to need error field correction coils
- Resistive wall mode can be stabilized by direct feedback control:
  - Needs control coils near or inside first wall
  - Poloidal and toroidal coverage of coils
    - See talk by G. Navratil
  - Accurate detection over long pulses may require non-inductive sensors

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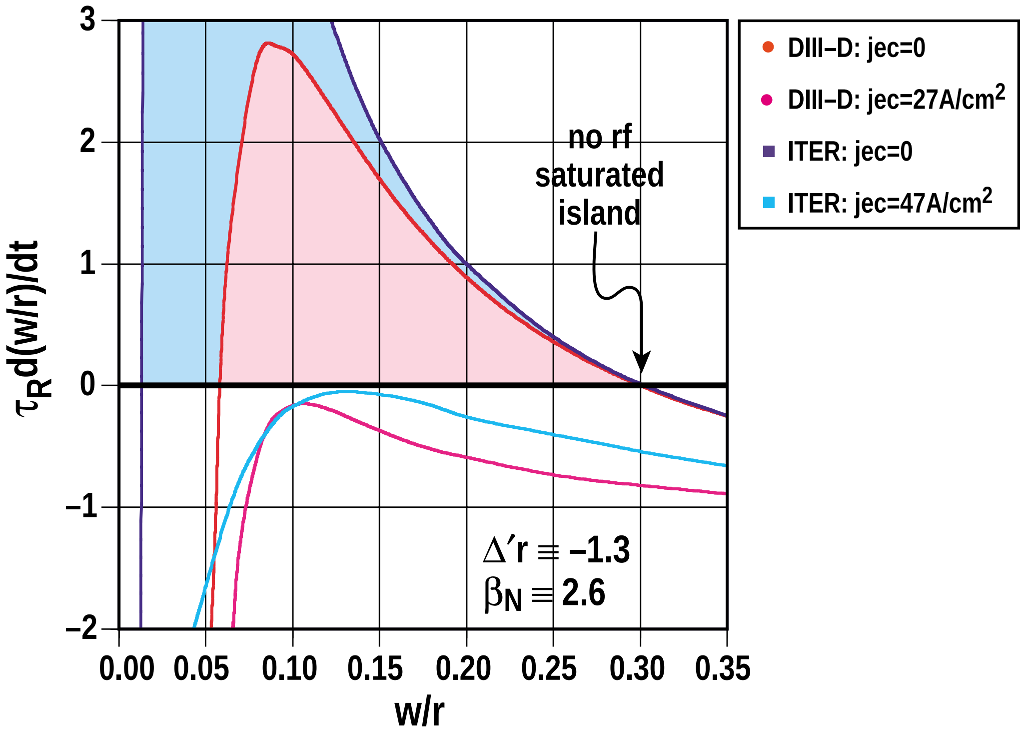
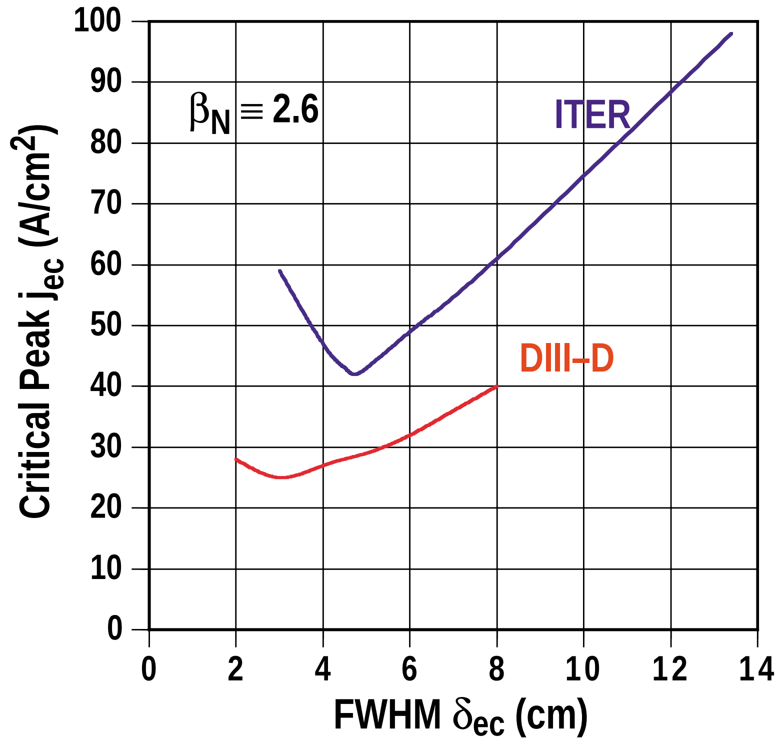
REQUIREMENT FOR J_{ec} IS MINIMIZED FOR FWHM $\delta_{ec} \sim w_{th}$ NTM THRESHOLD ISLAND WIDTH

- **Modeling assumes:**
  - **Good alignment**
  - $w_{th} \cong \sqrt{3}\,(w_{pol}^2 + w_d^2)^{1/2}$

- J_{ec} **for dw/dt < 0 for all w:**
  - **i.e. 2/1 NTM stabilized**





- **FWHM** $\delta_{ec} \equiv$ **4 cm**
  - **Evaluated at outboard midplane**

- w_{th} **= 3.9 cm in DIII-D, 3.7 cm in ITER**
  - w_{th}/r **=0.093 DIII-D, 0.029 ITER**

NEOCLASSICAL TEARING MODE CONTROL

- Neoclassical tearing modes can be stabilized by localized ECCD:
  - Suppression after mode appears uses simple search or nonlinear optimal alignment predictor
  - Sustained stabilization requires real-time location of rational surface
    - Neural network or physics-based predictors based on external magnetic data
    - Real-time q-profile analysis from equilibrium reconstruction with MSE (planned on DIII-D)
- EC power requirements depend on width of current drive layer (needs experimental verification):
  - Synchronous modulation of ECCD can improve efficiency

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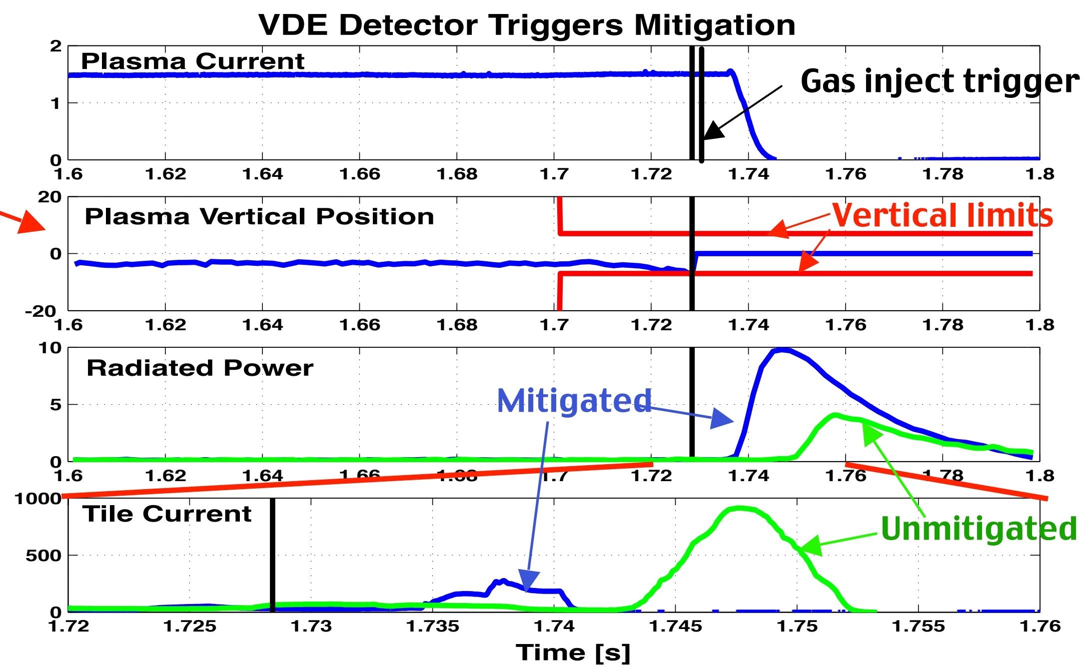
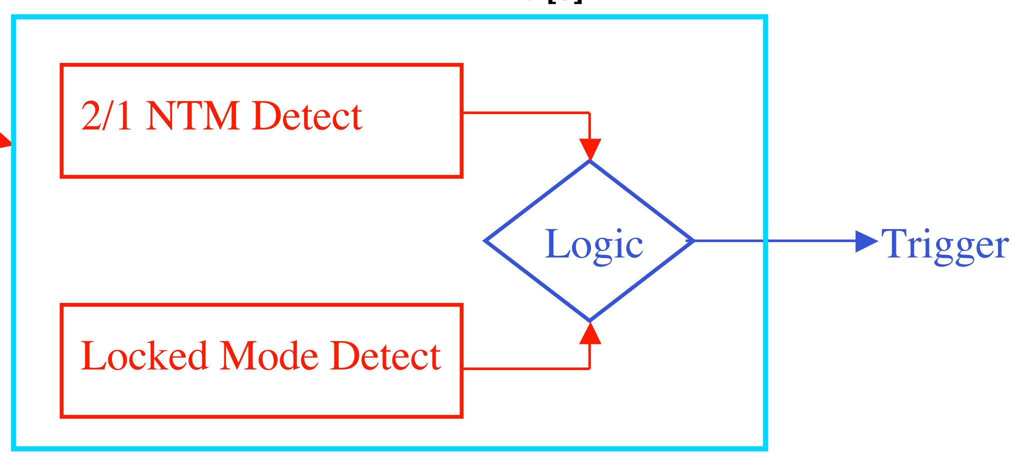
Disruption Detection and Mitigation with the DIII-D Plasma Control System

- **VDE detector:**
  - Detects plasma vertical position past threshold
  - Triggers gas injection system to mitigate
  - Trigger→quench ~5ms



- **Radiated power limit detector:**
  - Detects plasma radiated power fraction exceeding threshold

- **2/1-Locked mode detector:**
  - Detects presence of 2/1 NTM and growth of locked mode with disruptive dynamics



INTEGRATED PLASMA CONTROL IS NEEDED FOR OPTIMIZING ADVANCED TOKAMAK OPERATION

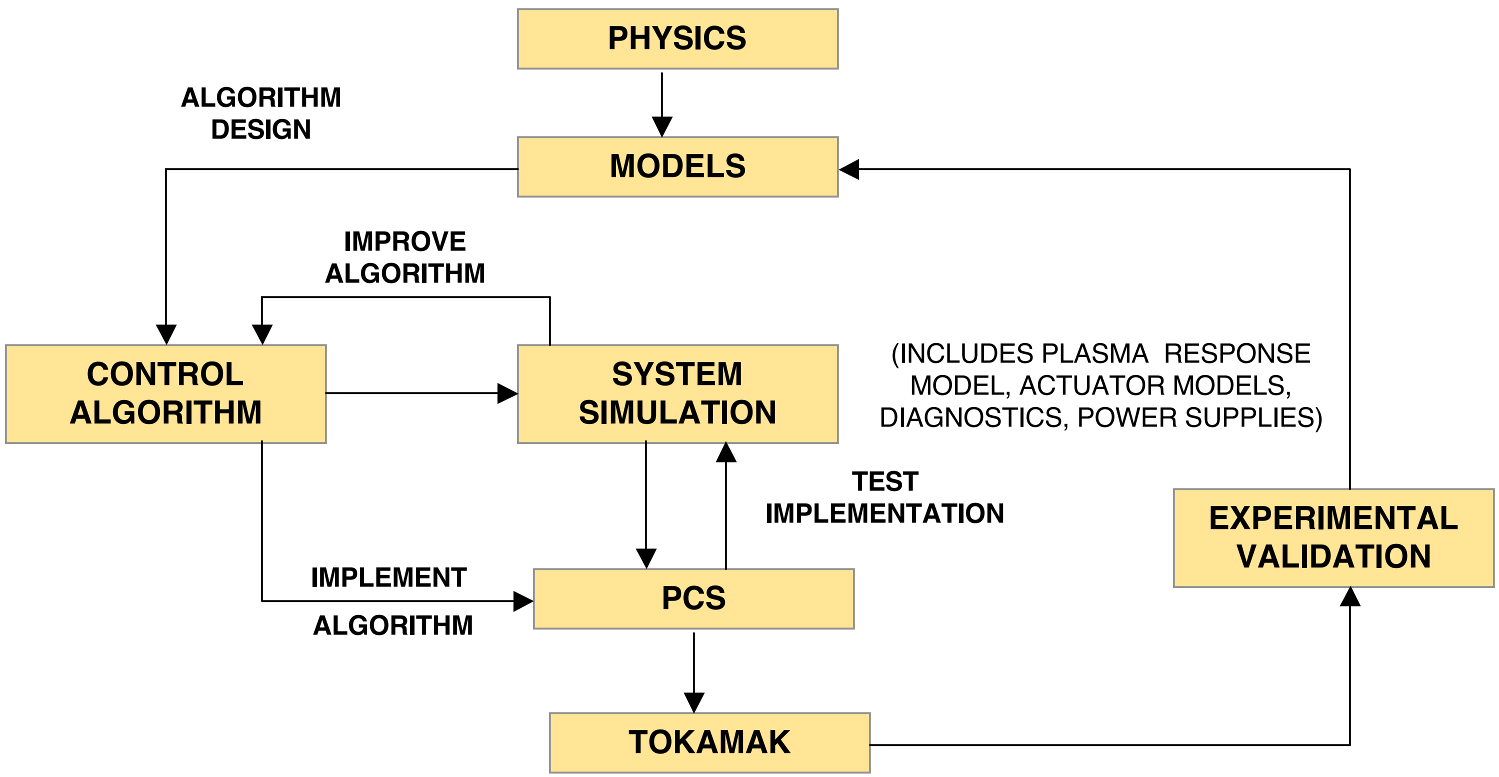
Integrated Plasma Control :

- Takes into account multivariable cross-coupling of complex plasma responses to external actuators (e.g. NTM stabilization by ECCD is affected by modification of q profile when ECCD is applied and by transport effects of varying NTM amplitude)

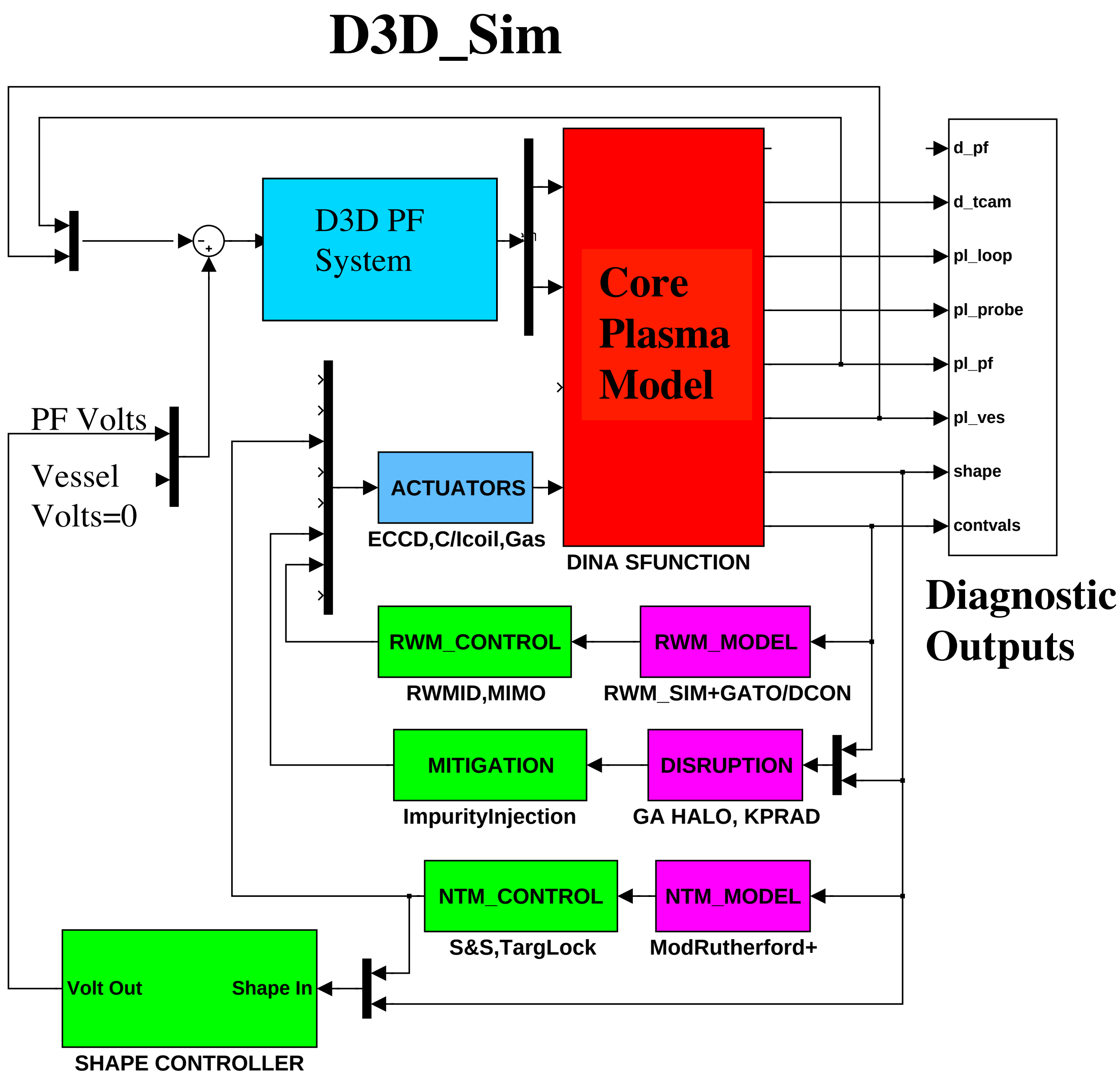
- Provides high reliability, high performance control for complex systems while minimizing machine operations development time required

- Combines all elements of control system design process:
  - Modeling (plasma response, actuators, diagnostics)
  - Model validation against experimental response
  - Algorithm/controller design based on validated models
  - Closed loop system simulation
  - Test of hardware/software implementation

INTEGRATED PLASMA CONTROL INCLUDES EFFICIENT DESIGN AND OFFLINE TESTING TO PRODUCE HIGH PERFORMANCE CONTROL ALGORITHMS



Detailed Simulations of Integrated Control Systems are Already Being Applied to MHD Control Development



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Summary and Conclusions

- Tools are available for detailed control of the operating point in advanced tokamak operation
  - Profile control and ITB regulation are not yet routine
  - Requirements on diagnostics must be considered and specified in detail; can differ between reference and AT scenarios
- Control of MHD stability is promising
  - RWM control may require rotation drive or closely coupled coils
  - Power requirements for localized ECCD depend on threshold island width and current drive width
- Other aspects of AT control (e.g. divertor, particle, fueling) need to be addressed
- Integrated, model-based control design and operation is essential