DIII-D Scenario Development and Control Research

by
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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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Talk Outline

- Brief view of fusion landscape & definition of scenarios & controls
- Summary of DIII-D capabilities – key actuators for scenarios & controls
- Highlights of ITER Q=10 scenario development
- Highlights of steady-state scenario development
- Highlights of controls research

ITER is a Big Step on the Way to Commercial Fusion – DIII-D Research Informs ITER & Potential Pilot Plants

ITER & Future Fusion Power Plants Will Need Operating Scenarios and Controls

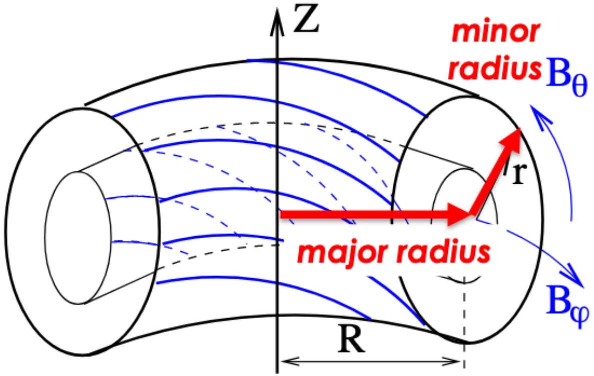
- **An operating scenario ≡ the objectives of control**
  - ***E.g., Ramp up to Q=10 with 500 MW fusion power, hold it for 400 s, ramp down safely***

- **Control ≡ the methods of achieving the objectives**
  - **Uncertainty and system noise force use of feedforward & feedback control**

Thanks to M. Walker for suggesting these definitions

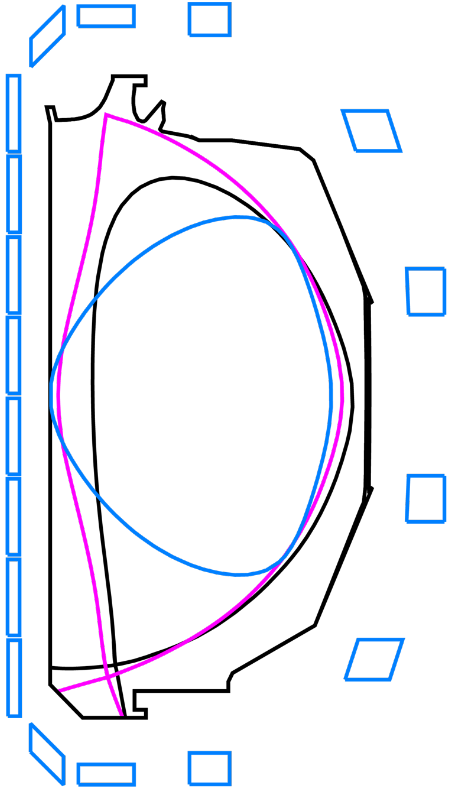
DIII-D is a Mid-Sized Tokamak Known for its Flexibility, Diagnosis, & Control of High-Performance Scenarios

- R=1.67 m
- a=0.67 m
- $B_T = [-2.17\ T, +2.17\ T]$
- $I_P = [-2\ MA, +2\ MA]$
- Large enough to be relevant, small enough to be flexible



18 Field Shaping Coils Allow a Wide Range of Shapes

- Almost any shape that fits in vessel can be run at some I_P
- Upper single null, lower single null, and double null
- Elongation κ up to ~2
- Triangularity δ from –0.5 to +0.8



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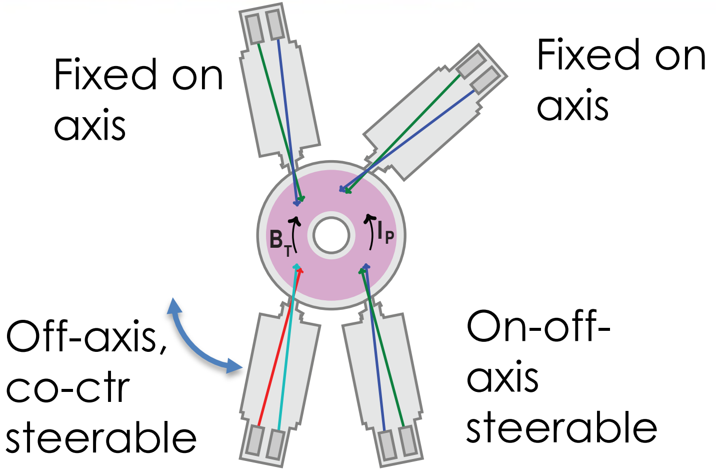
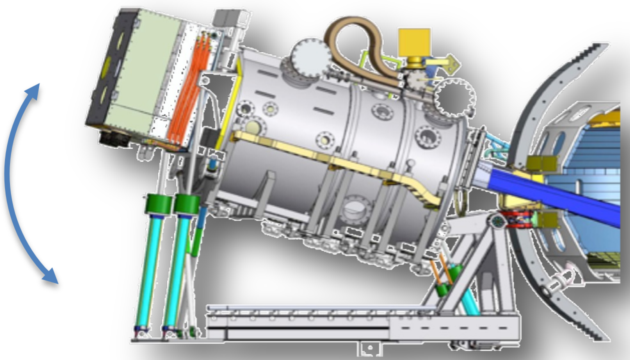
20 MW Neutral Beam Injection With a Mix of Injection Geometries Enables Many Things

- **Feedforward & feedback control of:**
  - **Plasma stored energy**
  - $\beta_N=(2\mu_o\langle p\rangle/B_T^2)/(I/aB_T)$
  - **Rotation, v**
  - **Current density, J**

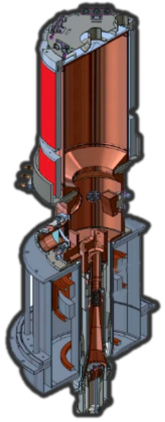
- **NBI-based measurements**
  - **Motional Stark Effect (J)**
  - **Charge Exchange (v, T_i, n_i)**
  - **others**

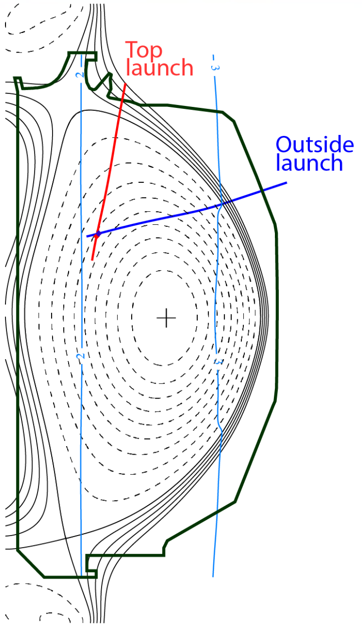


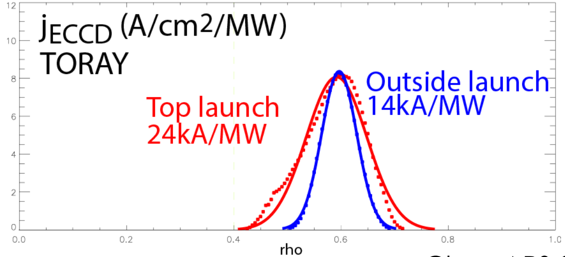


Microwave Electron Cyclotron Heating & Current Drive Provides J-Profile Control

- **Several 110 GHz gyrotrons amounting to ~3 MW delivered to plasma**
- **2nd harmonic X-mode: aim radially for only e-heating, or tangentially to drive local current**
- **Outside and top launch**
- **Can use to control magnetic islands**



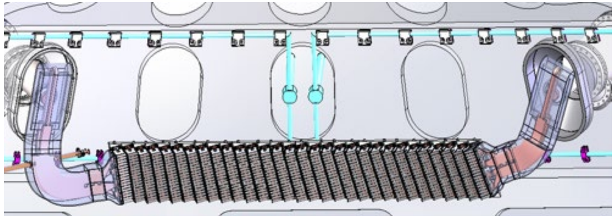


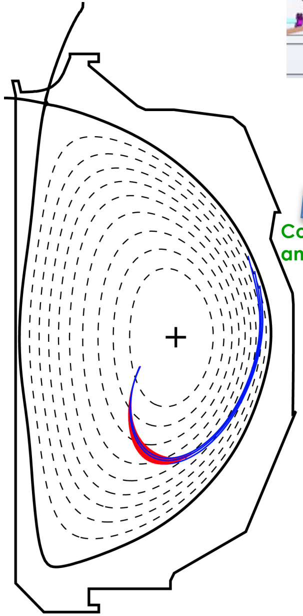


Chen APS 2019

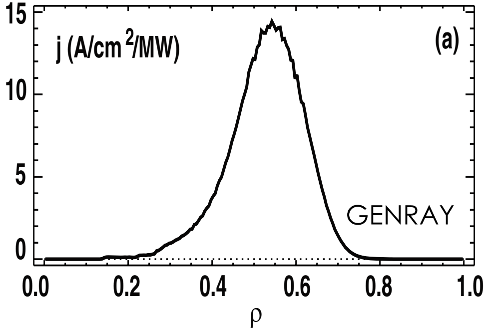
New High Harmonic Fast Wave “Helicon” 476 MHz Antenna is Installed

- **1.2 MW source power from klystron**
- **Comb-line traveling wave antenna**
  - 1 input port & 1 output port, power transfer through mutual inductance
- **Predicted to provide efficient off-axis current drive at mid-radius for advanced j-profile control at high β_e**
- **No density cut-off like ECH**
- **New next year: 4.6 GHz lower hybrid antenna to do a similar job**





Predicted 50-70kA per coupled MW @ ρ~0.55



Prater NF 2014

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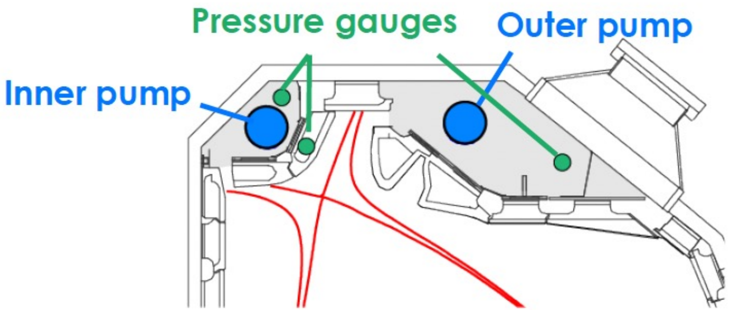
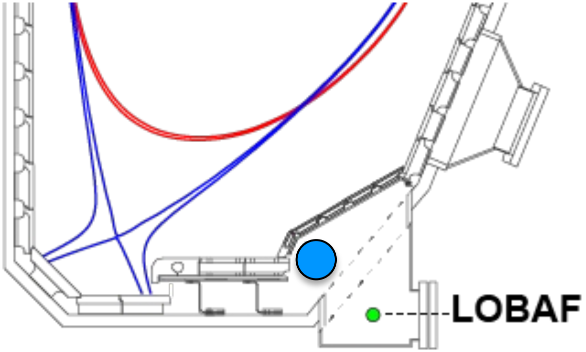
Upper & Lower Divertors Coupled to Cryopumps Enable Heat & Particle Removal

- Can pump strike points in double null (i.e., power plant?) or single null shapes (i.e., ITER)



- Enables density control for good ECH penetration

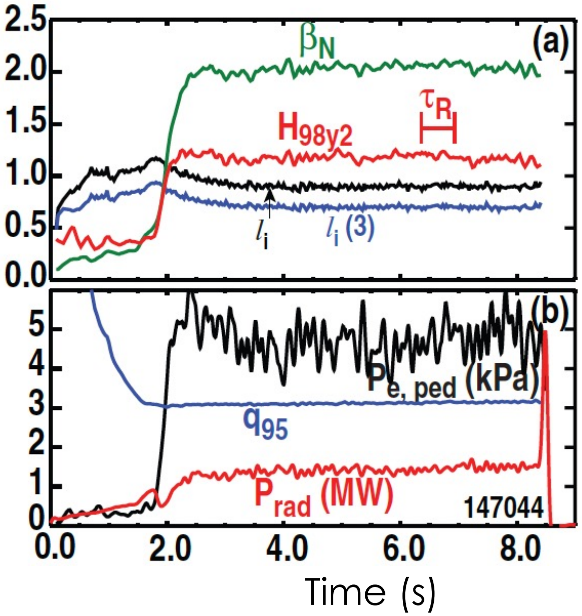
- Active divertor research program is driving geometry changes in near future



Up to ~10 s Pulses Limited by Coils, Power Supplies, & NBI Energy Still Allows Sustaining Plasmas for Few-Many τ_R

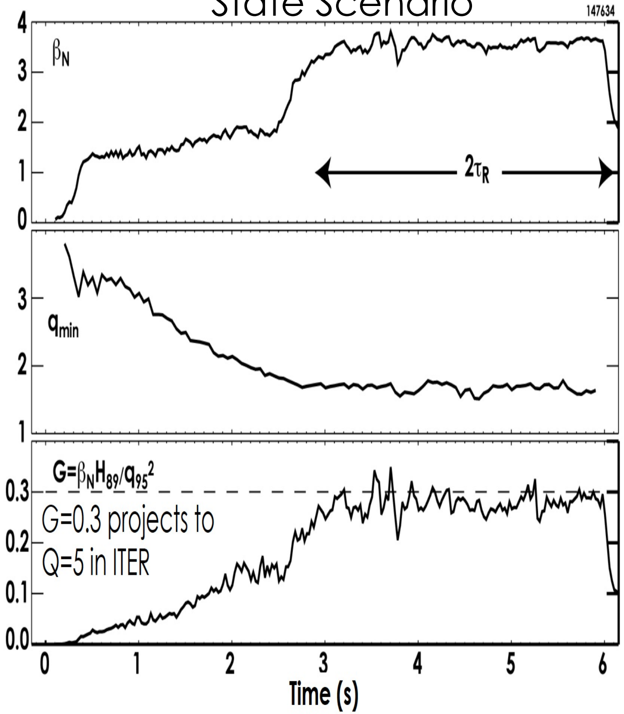
- τ_R=current profile resistive diffusion timescale
- Important for reaching and testing equilibrium close to final "relaxed" state

DIII-D ITER Baseline Scenario



Jackson NF 2015

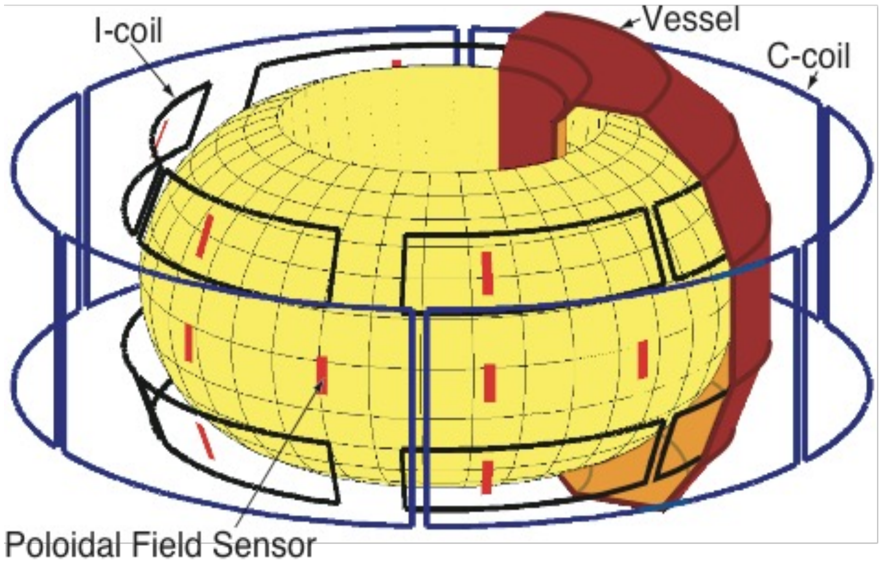
DIII-D Elevated-q_{min} Steady-State Scenario



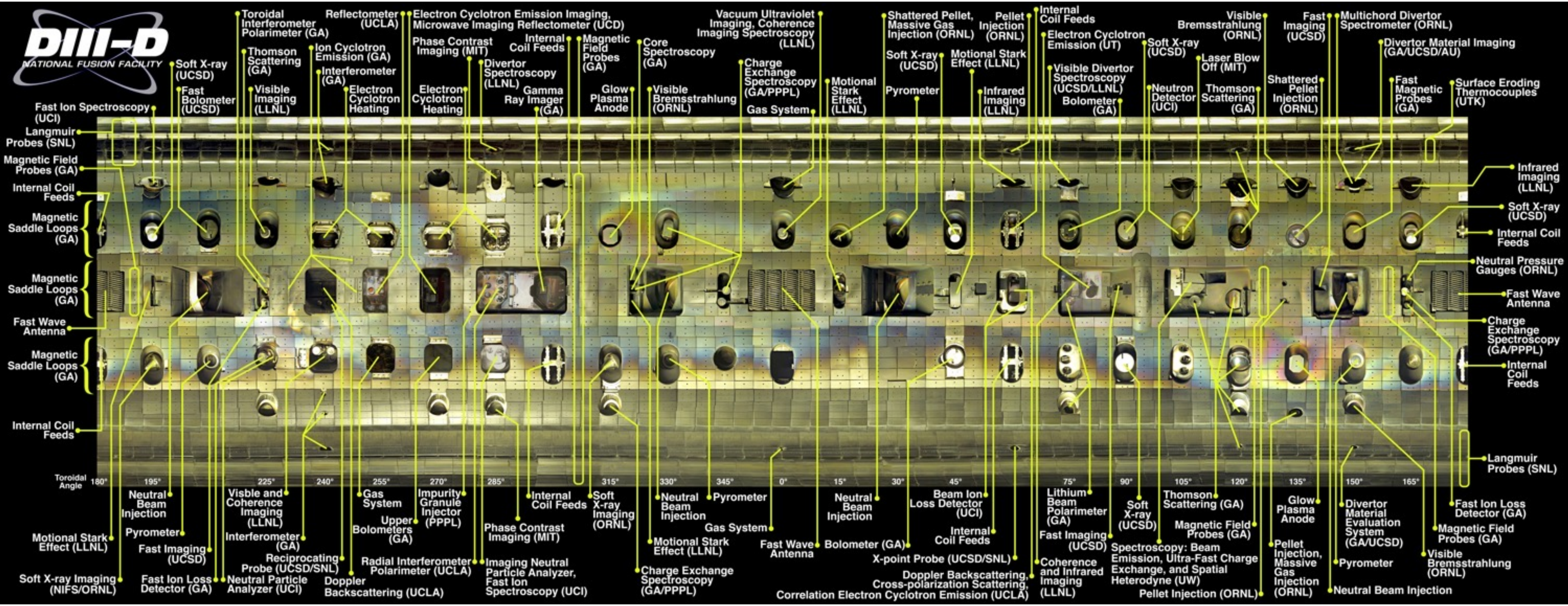
Holcomb IAEA 2012

Three Arrays of Non-Axisymmetric Perturbation Coils Do Many Jobs

- **Error field correction**
- **Resistive wall mode (RWM) feedback control**
- **"MHD spectroscopy" for probing stability**
- **ELM control**



Hundreds of Diagnostics Enable Detailed Physics Studies & Realtime Plasma Control



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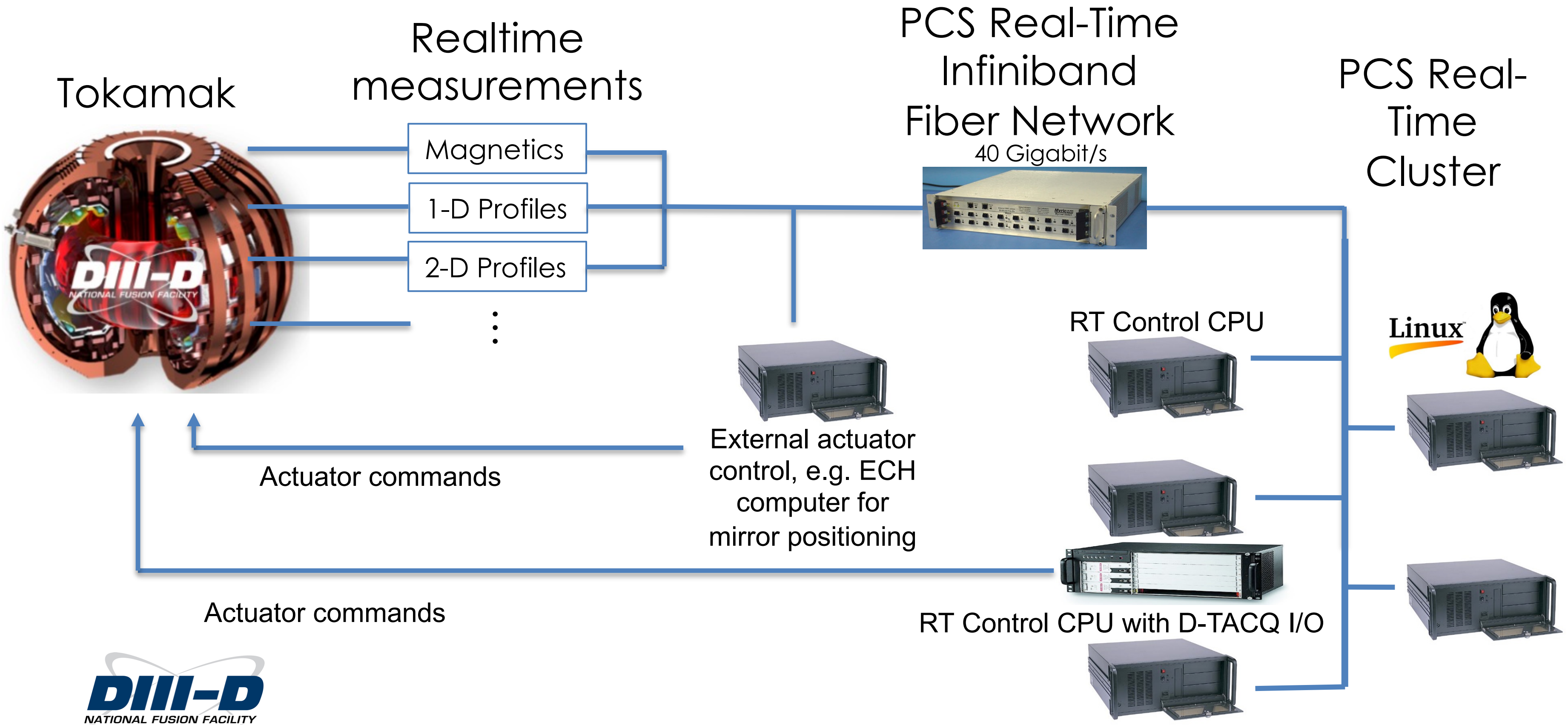
DIII-D Has a Mature Plasma Control System (PCS) That is Indispensable for Scenarios Research

***Now routine PCS tasks*:**

- Control of poloidal field coils to match target Ip, boundary shape, & strike point locations vs. time
- Realtime equilibrium reconstruction (EFIT)
- β_N feedback control using NBI
- Net torque or plasma rotation control using oppositely directed NBI
- Line-averaged density feedback control of gas valves
- Standard error field control using 3D coils
- “Dud detector”: switch to plasma ramp down if MHD modes detected
- Safety interlocks: e.g. shut down ECH when density too high
- PCS supports: PID, state space, MPC, event-driven, & ML-based algorithms

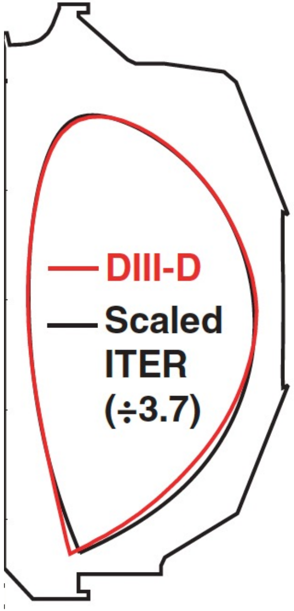
Active controls research to be covered later

DIII-D PCS is a Realtime Data Acquisition & Feedback Control Tool



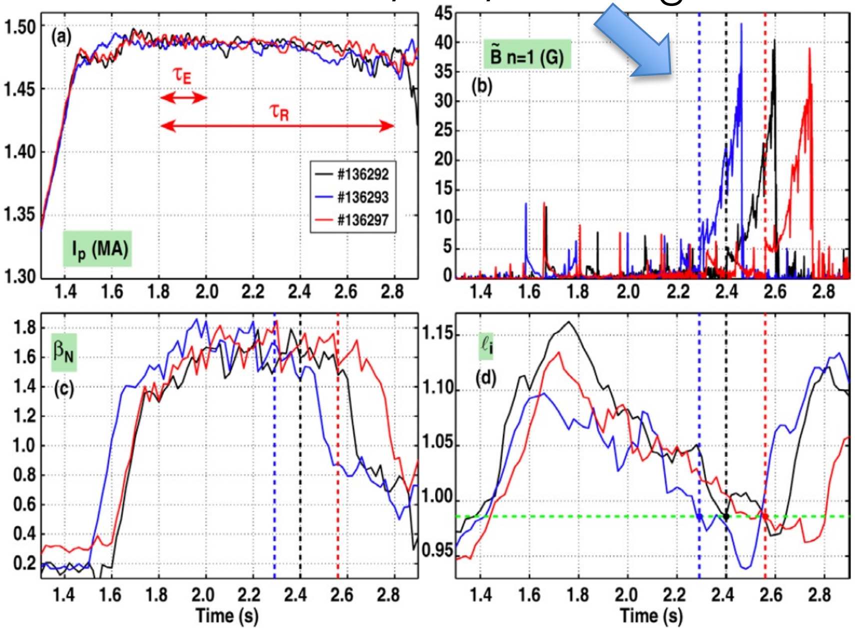
DIII-D is Pursuing the Development of the ITER Baseline Scenario (IBS) for Q=10 Operation

- **DIII-D can approximate the ITER shape and aspect ratio with a pumped strike point for density control**
- **IBS design point has q_{95}=3, β_N=1.8, H_{98}=1**
- **MHD stability and disruption avoidance has proven to be a challenge here**



Doyle, NF, 2010

m/n=2/1 tearing modes



Turco, NF, 2010

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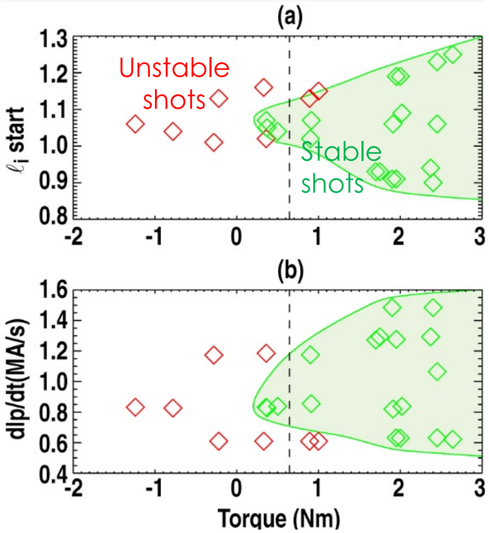
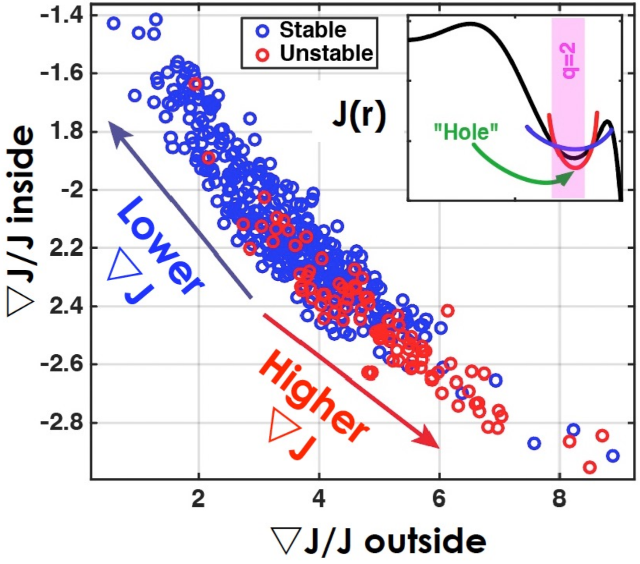
Large Effort Made to Get the Discharge Evolution Right to Maintain Stability

- **Initial scans showed less stability at ITER-relevant low rotation**



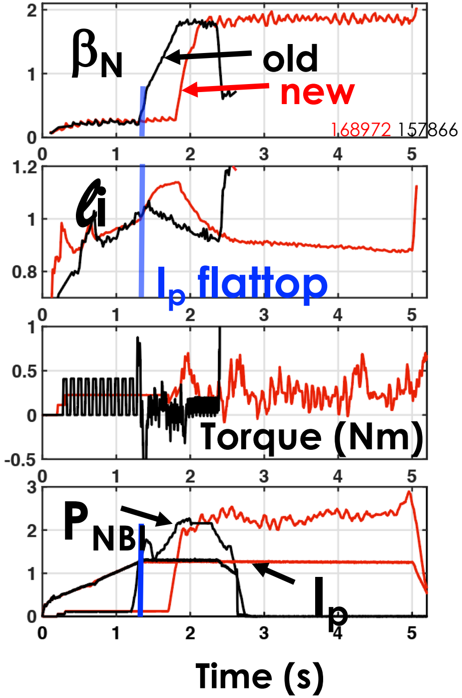
Jackson IAEA 2012

- **Found m/n=2/1 mode stability correlated with shape of J(r)**



Turco EPS 2016

- **Ramp up optimization led to stable low-torque flattop**



Turco, Luce APS 2017

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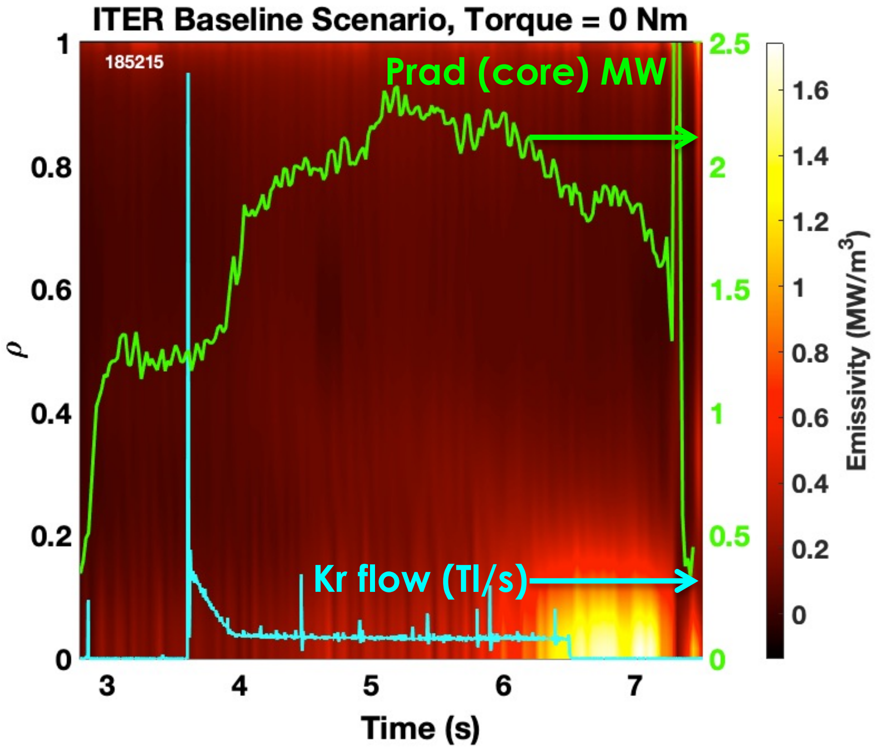
Present ITER Baseline Scenario Work Aims at More "Core-Edge Integration" Issues

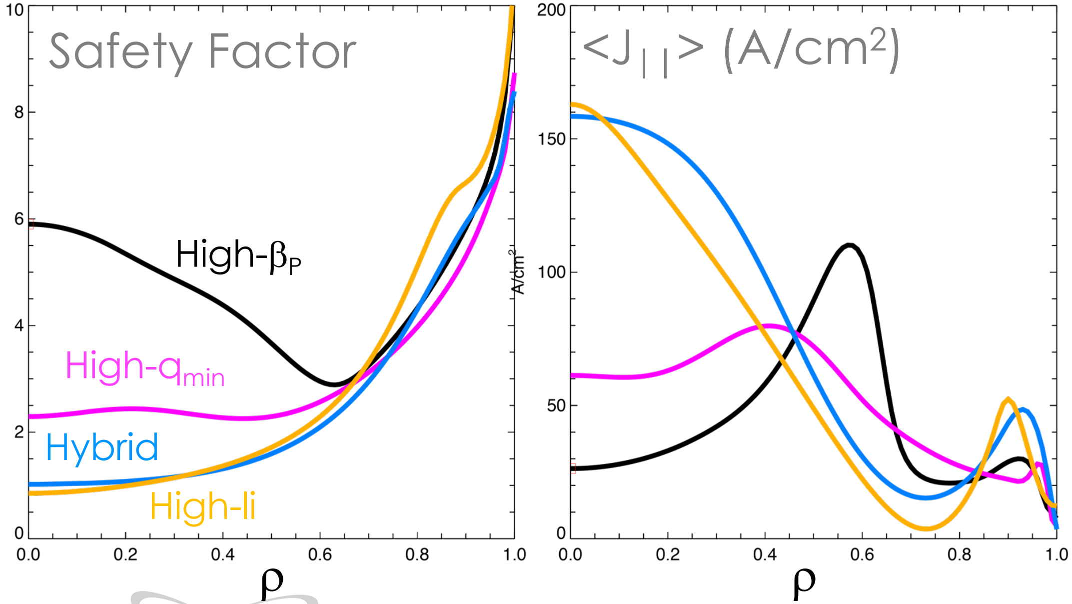
- Kr in DIII-D core has same radiative loss rate as W in ITER: can mimic & test impurity impacts
- IBS can handle 20-35% radiation fraction before core cooling leads to sawtooth suppression and accumulation
- Next steps: investigate IBS with lower $P/P_{L\text{-}H}$, burn control, ELM control (RMP, QH)



Turco, APS, 2021

DIII-D Pursues High-β_N Non-Inductive Scenario Development for ITER Q=5 Mission & a Fusion Pilot Plant

- **A range of scenario options exists typically characterized by q- or j-profile**



	Possible Advantages	Challenges
High β_P	Low disruptivity, high f_{BS}, high H from ITB	RWM limits; maintain ITB at lower q_{95}?
High q_{min}	High ideal MHD β_N-limits, high f_{BS}	q>2 tearing modes; high H w/o ITB?
Hybrid	Anomalous j-diffusion: q_{min}>1	Lower f_{BS}; high H w/o rotation?
High li	High-β_N w/o wall stabilization	Lower f_{BS}; requires low pedestal

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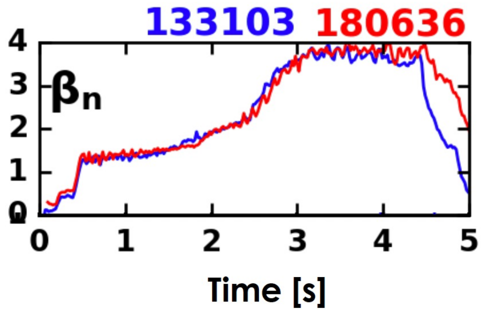
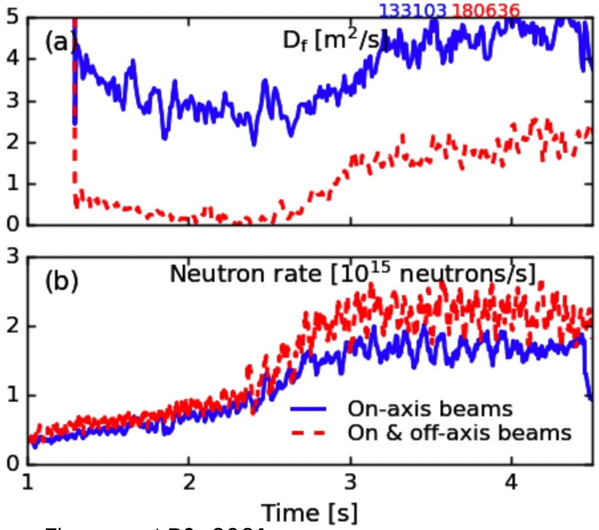
High-q_{min} Development Goal: Add Off-Axis H&CD to Broaden J and P for Higher Expected Performance

- Sustained q_{min}~1.5, q_{95}~6.2, β_N~3.8 possible now
  - Marginally stable to 2/1 NTMs

- Addition of off-axis NBI can broaden profiles, raise β_N limits, & reduce anomalous fast-ion transport
  - Predicted n=1 kink ideal limit: ~4 → ~5

- Near future: push to q_{min}>2, β_N >4 with more ECCD, Helicon, LHCD, stronger DN shaping

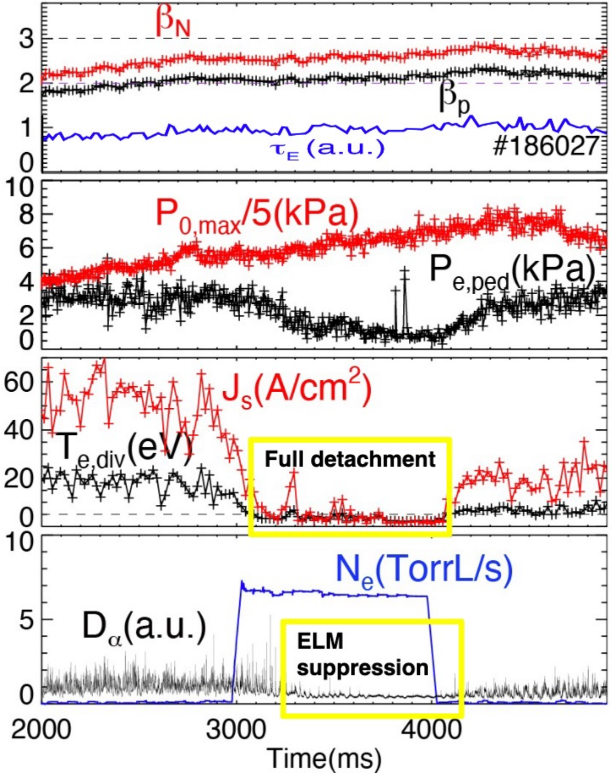


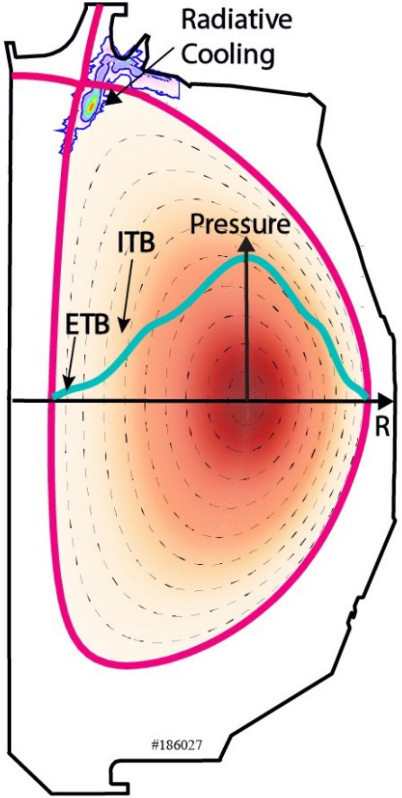


Thome, APS, 2021

High-β_P Scenario Recently Made in ITER-Like Shape With Good Divertor Integration

- **Neon seeded, cool detached divertor with β_N>2.5**
- **Small/no ELMs**
- **Maintains low H-mode pedestal & high-radius internal transport barrier**
- **No loss of confinement with detachment**





S. Ding, H. Wang, L. Wang, APS, 2021

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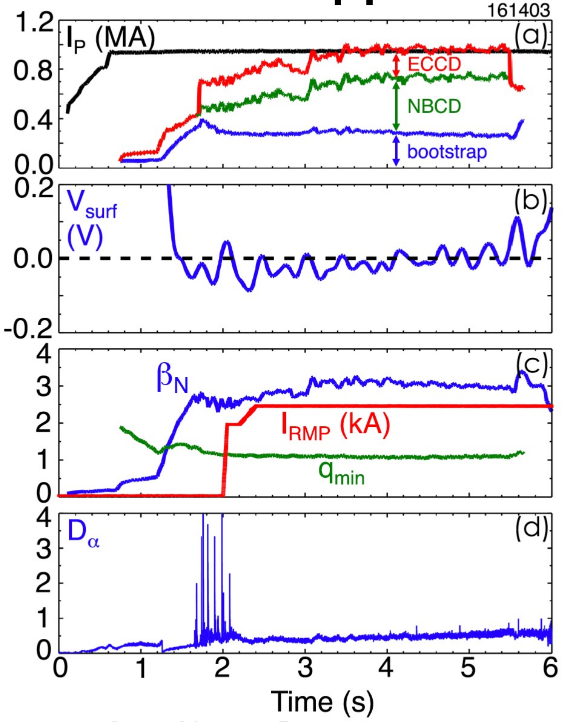
High-β Hybrid Scenario is Being Pushed in More Reactor Relevant Directions

ITER-shaped, non-inductive, RMP-ELM-suppressed



Petty, NF, 2017

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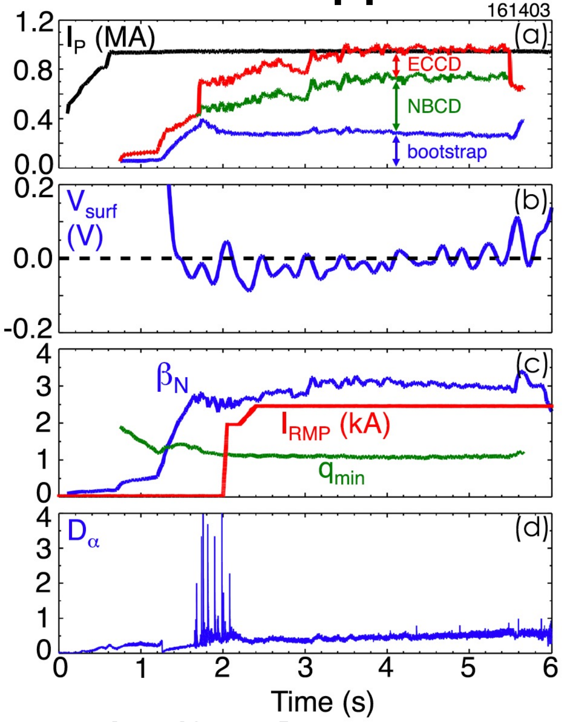
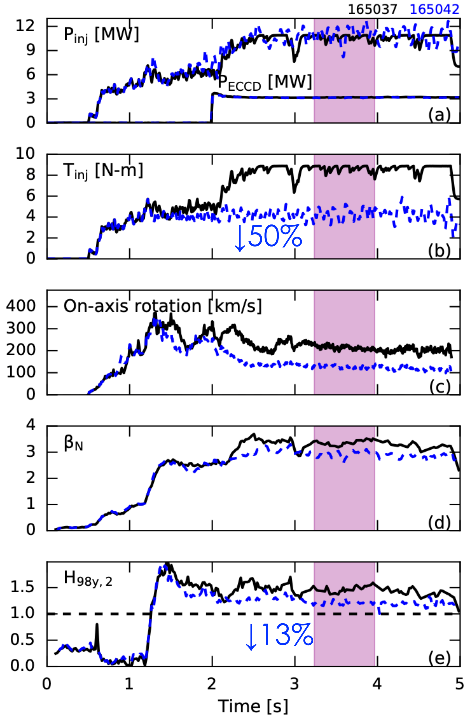


Petty, NF, 2017

Reducing torque at fixed power drops H_{98}



Thome, NF, 2021

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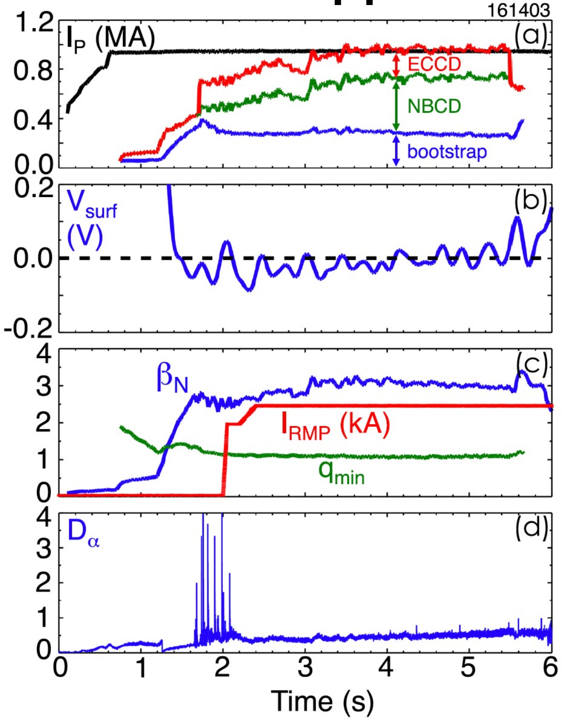

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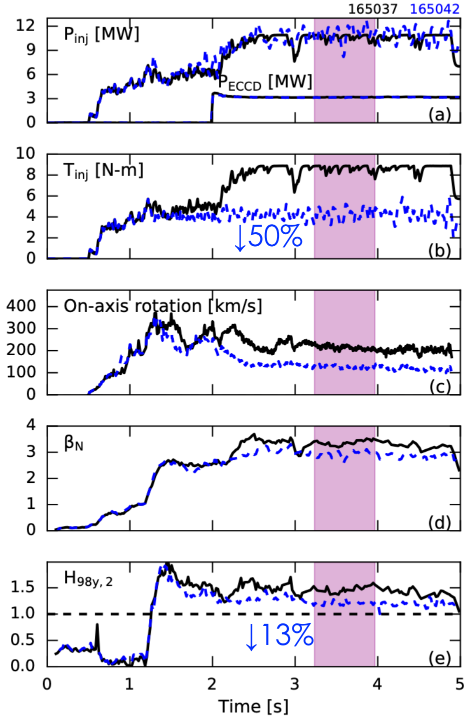
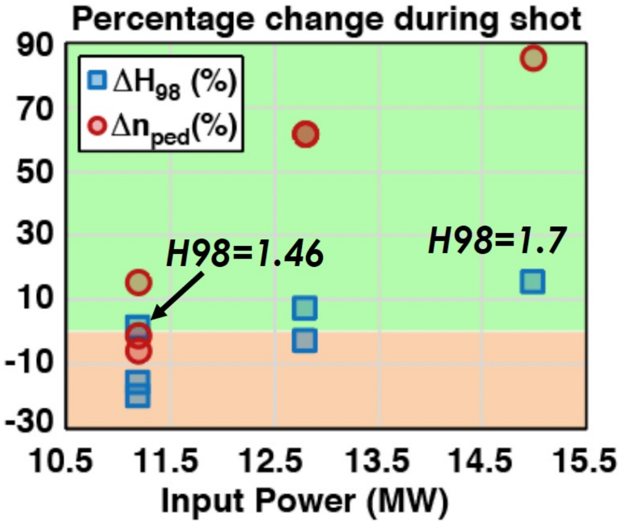


Thome, NF, 2021

Above power threshold, increasing density increases pedestal & H_{98}



Turco, APS, 2020

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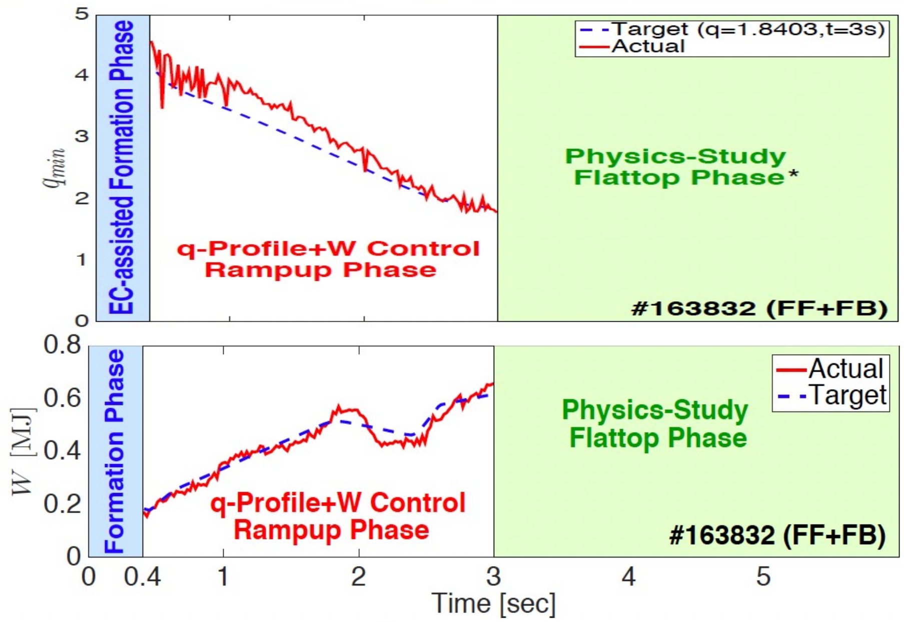
DIII-D Plasma Controls Research Aims to Support DIII-D Physics Research, & Provide Control Solutions for ITER

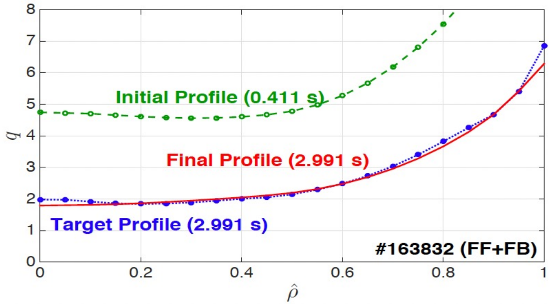
- Simultaneous real-time control of multiple plasma profiles, e.g., q and T_e
- Control of proximity to stability & controllability boundaries
- Asynchronous off-normal & fault response to prevent disruptions
- Feedback control of D_2 and impurity puffing for radiated power & divertor detachment control

Simultaneous Control of Profiles & 0D Quantities is an Active Research Topic With Several Possible Approaches

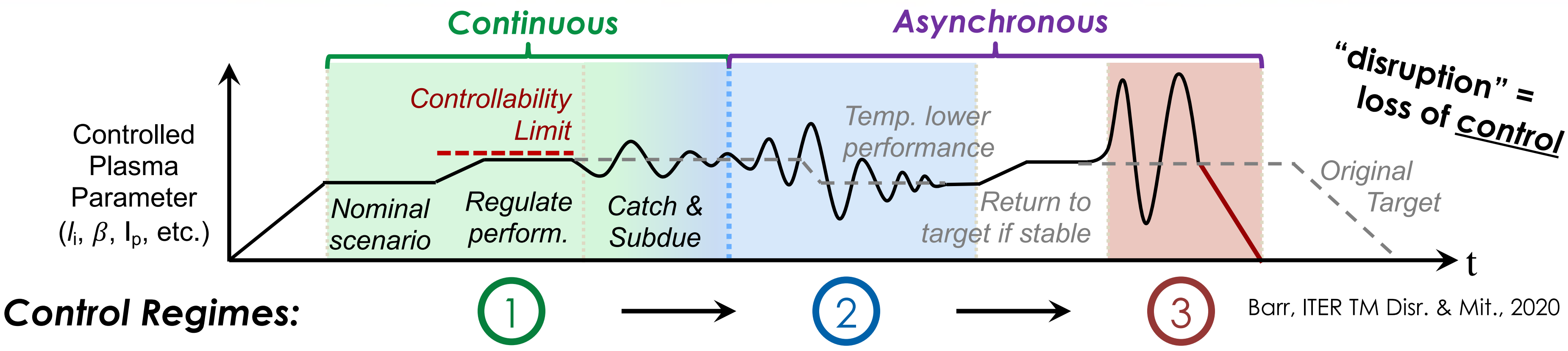
- **Example useful for scenario development: q(r)+W_{total}**
- **Goal: achieve target q(r) & W at t=3 s regardless of initial conditions**
- **Control NBI, ECH, I_P waveforms**
- **1st principles-driven model solves 1D ψ_P diffusion eq., models n(r) & T(r) evolution, & solves 0D power balance eq.**
- **Feedforward + model-predictive feedback control**



Schuster, APS, 2016



Proximity Control & Asynchronous Response Are Key Parts of DIII-D's Disruption Prevention Strategy



1. Continuous Prevention:

- Regulate proximity to stability/controllability limit
- *Should prevent 99%+ of disruptions!*

2. Asynchronous Response:

- Detect state-change, do something different, e.g:
- Try to suppress tearing mode with ECCD, or
- Temporarily de-rate scenario, then return

3. Emergency Avoidance:

- Go to rapid controlled shutdown (large piggyback study on DIII-D)
- Fire disruption mitigation system as a last resort

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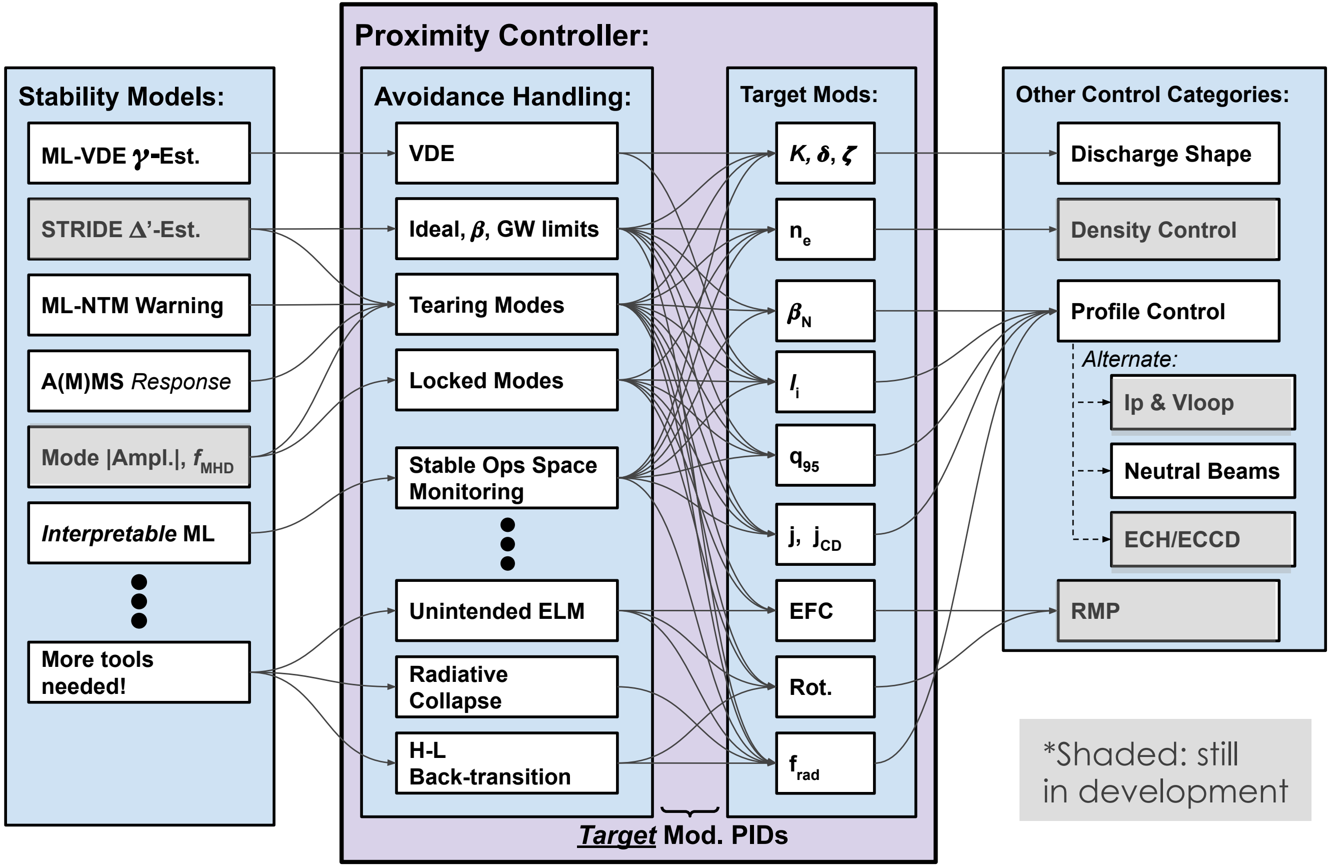
A Proximity-to-Instability Control Architecture is in Place & Being Tested

- **Determine proximity from models**
- **Modify parameter(s) to regulate proximity**



*Shaded: still in development

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Barr, ITER TM Disr. & Mit., 2020

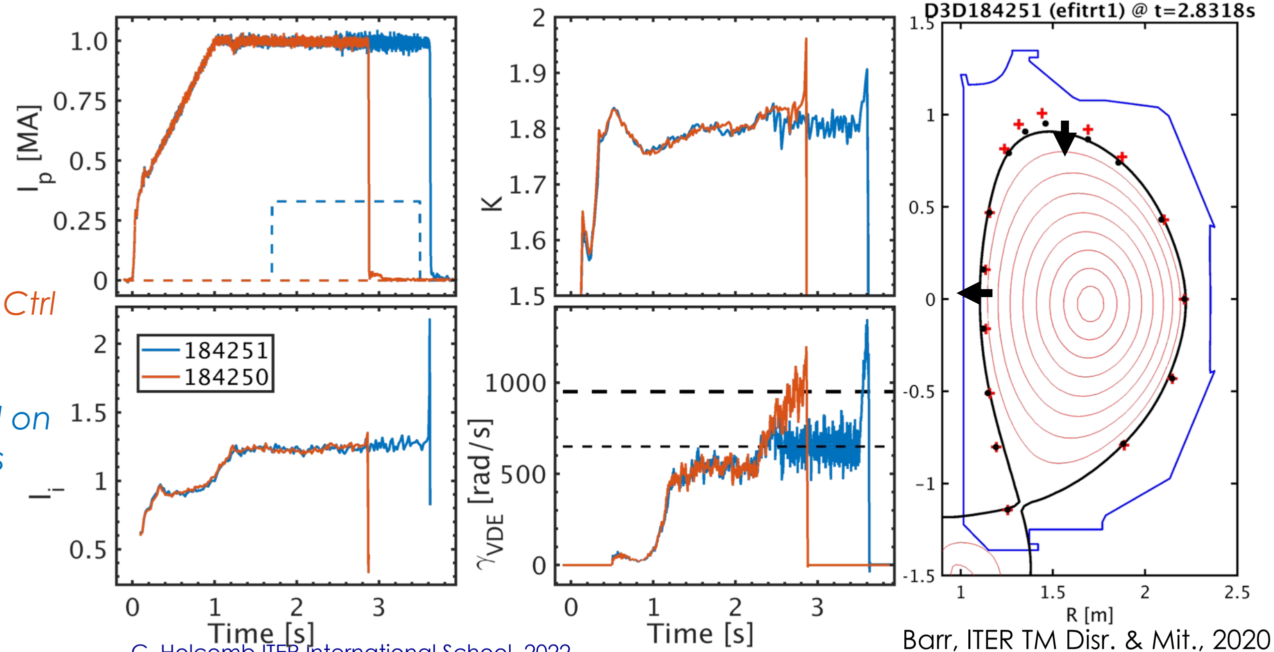
Example: Real-time VDE-γ Estimator Enabled Robust VDE Avoidance By Controlling Plasma Shape

- **VDE reliably prevented until Proximity Controller disabled**
  - Example: (red) pre-shot κ-target ramp to induce VDE
    (blue) Prox. control when γ>threshold: reduces κ, inner-gap

- **Real-time VDE-γ estimators:**
  rigid motion,
  or ML-based

Red:
No Prox Ctrl

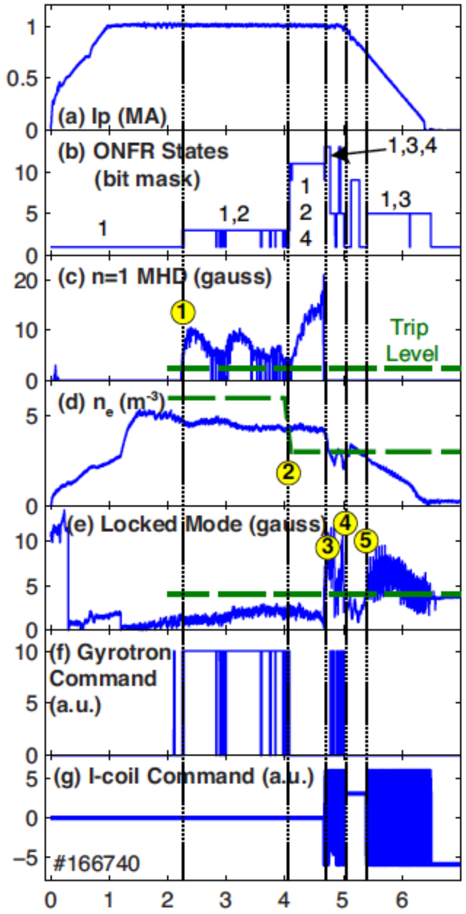
Blue:
Prox Ctrl on 1.75-3.5s



Barr, ITER TM Disr. & Mit., 2020

Example of Asynchronous Response to a Sequence of Events Starting With a Tearing Mode:

1. **n=1 NTM detected:** apply ECCD to suppress
2. **Density exceeds ECCD cut-off limit:** turn off ECCD
3. **NTM locks to wall & density falls:** apply 3D coils to rotate island and fire ECCD to reduce it
4. **Mode disappears:** Turn ECCD & 3D coil off
5. **Locked mode comes back:** Turn 3D coil back on, ramp down Ip

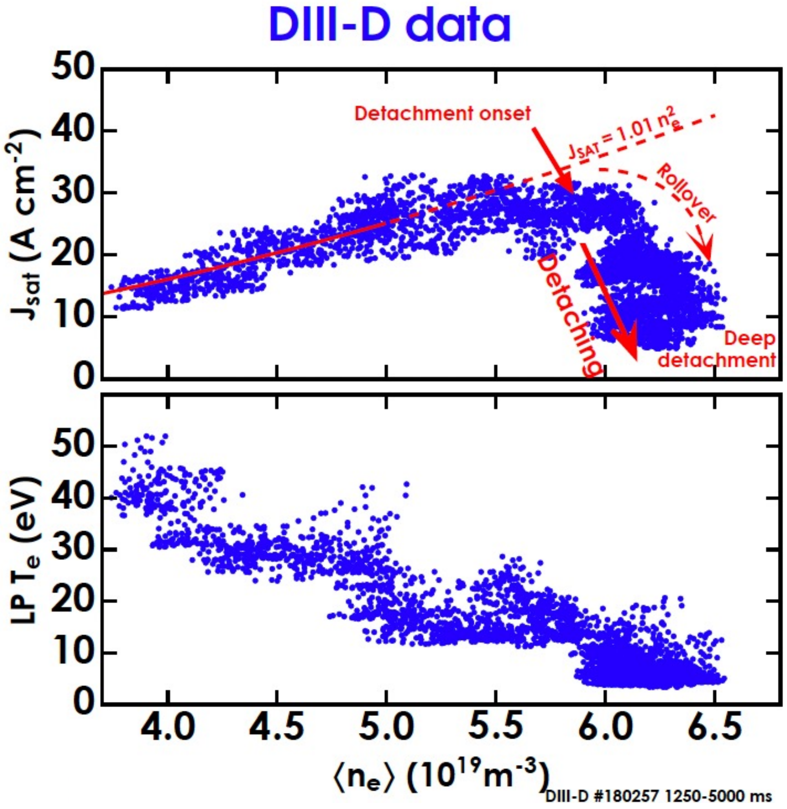


Eidietis, NF, 2018

Realtime Detachment Control is Important for Protecting Divertor While Maintaining High Performance Core

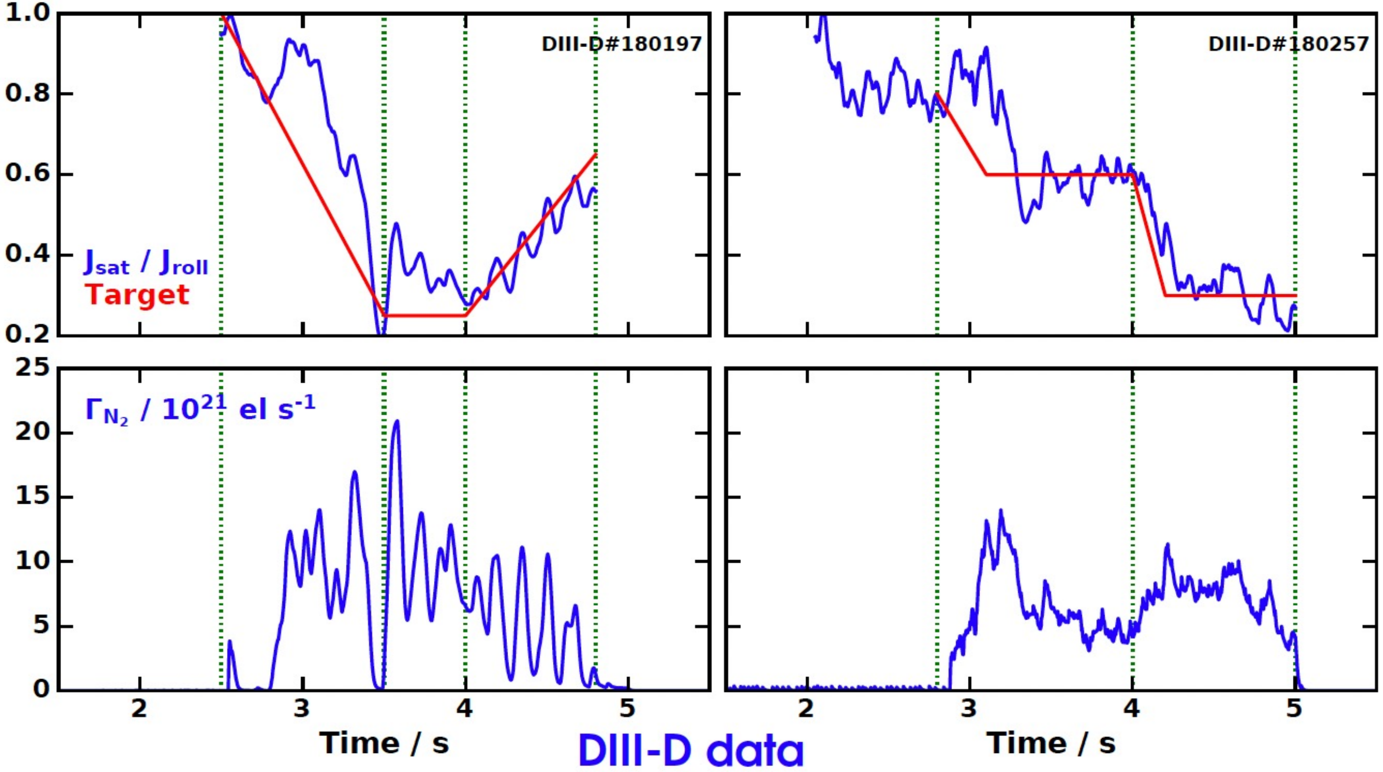
- **Attached ≡ high heat & particle flux at divertor plate → possible damage**
- **Detached ≡ fluxes dissipated away from plate in plasma; surface T_e< ~1 eV**

- **Langmuir probes measure ion saturation current to infer detachment**
  - Attached: $J_{SAT} \propto \langle n_e \rangle^2$
  - At start of detachment J_{SAT} "rolls over" with $\langle n_e \rangle$
  - Deep detachment characterized by $J_{SAT} \rightarrow 0$



Eldon, PSI, 2021

Feedback Control of Detachment Targets Using PID Loop Between Langmuir Probe & N_2 Gas Puff Demonstrated



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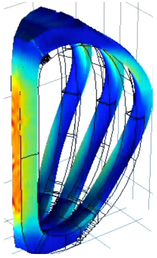
Eldon, PSI, 2021

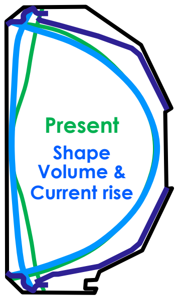
Future Looking: DIII-D Plans Several Upgrades to Expand Scenarios and Controls Research

Raise B_T to 2.5 T

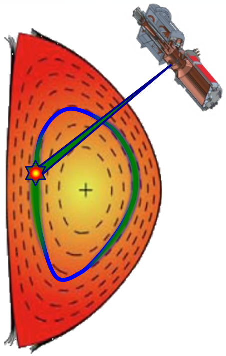


(stresses)

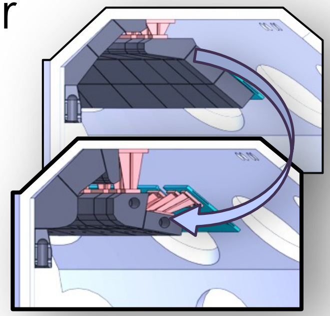
Shape & volume increase



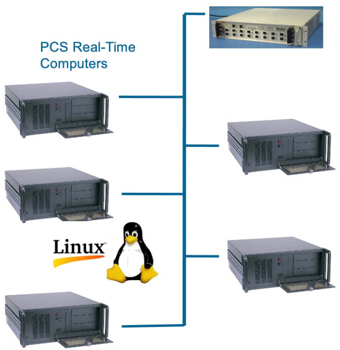
Raise P_{NBI} to 25 MW & P_{ECH} to 14 MW



New divertor geometries for better core-edge integration



PCS upgrade & offline duplicate to mimic ITER constraints & develop algorithms



New power supplies to emulate ITER PF coil control

Summary and Final Thoughts

- Actuators, diagnostics, and PCS make DIII-D a flexible tokamak for scenario and control research
- Key focus areas include ITER support, advanced scenario development, and core-edge integration
- DIII-D is a great facility for early-career scenario & controls experts to hone their skills while contributing to ITER & future fusion endeavors