Modeling the Impact of Pedestal Pressure and Current on the Ideal MHD Limits of the Steady State Hybrid Scenario

W. Boyes

with F. Turco, S. Sabbagh,
J. Levesque, and G. Navratil

Columbia University, New York

PPPL GSS
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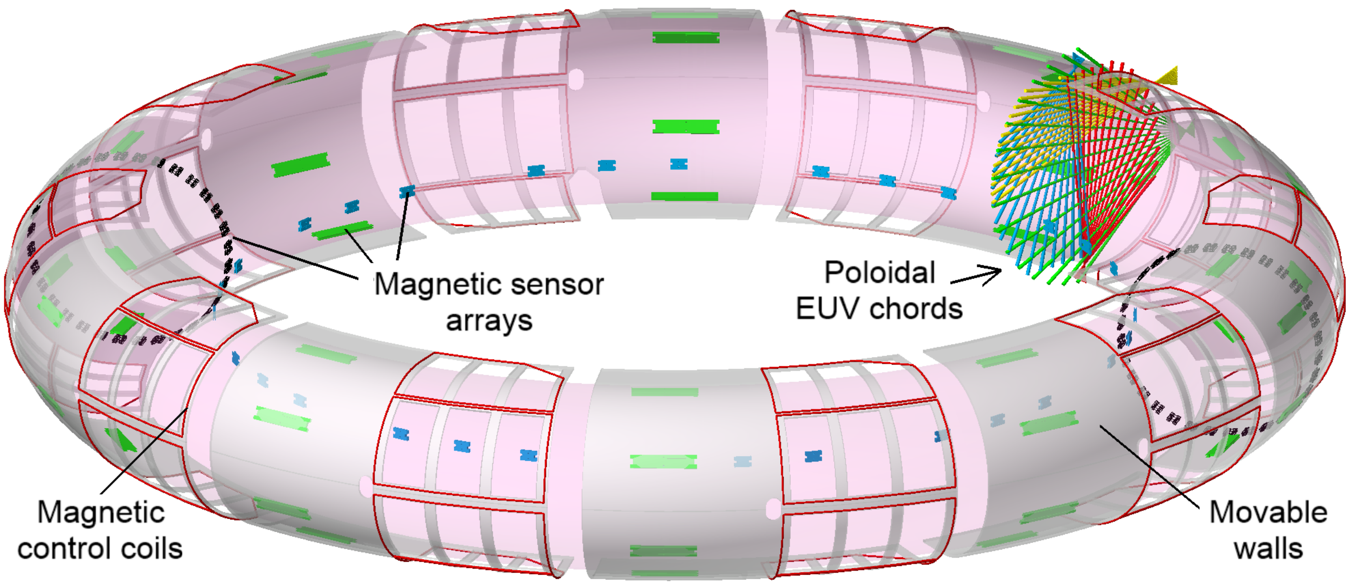
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

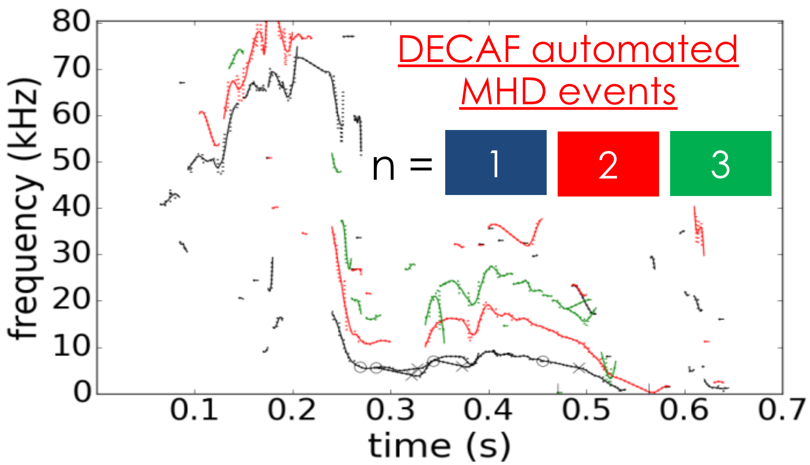
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

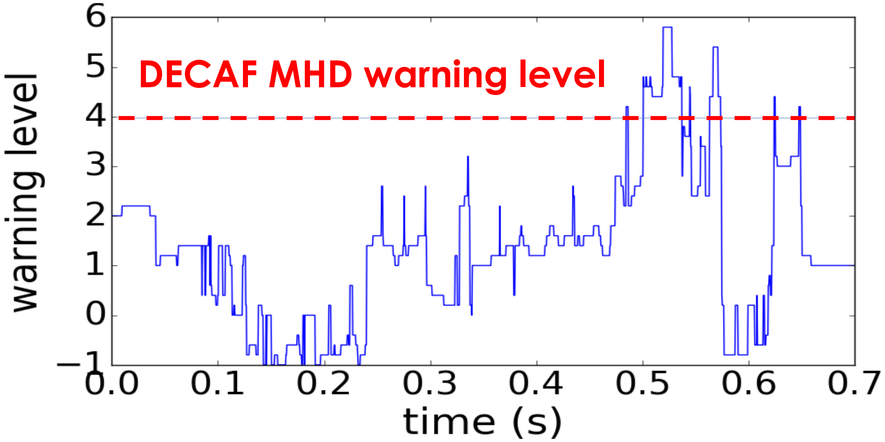
Columbia Plasma Lab

- **High Beta Tokamak - Extended Pulse (HBT-EP)**
  - **Studies MHD modes and feedback stabilization near the ideal wall stability limit using magnetic and extreme ultraviolet sensors coupled to in-vessel 3D magnetic actuator coils. Passive mode stability studies utilize a movable conducting first wall, allowing the boundary to be reconfigured between discharges.**



Disruption Event Characterization and Forecasting (DECAF) advances toward disruption prediction, real-time avoidance





S.A. Sabbagh, J.W. Berkery, Y.S. Park, *et al.*

Columbia University in the City of New York

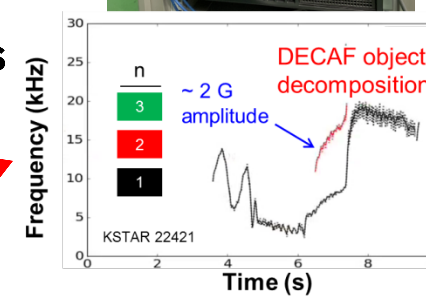
NFRI 국가핵융합연구소 National Fusion Research Institute

PPPL

CCFE Culham Centre for Fusion Energy

KSTAR NSTX-U MAST-U

- **Automated physical event identification with disruption warning**
- **Early forecasting with sufficient time for disruption avoidance**
- **Multi-tokamak analysis of large databases**
- **Real-time implementation on KSTAR begun**



Automated Disruption Event Chain

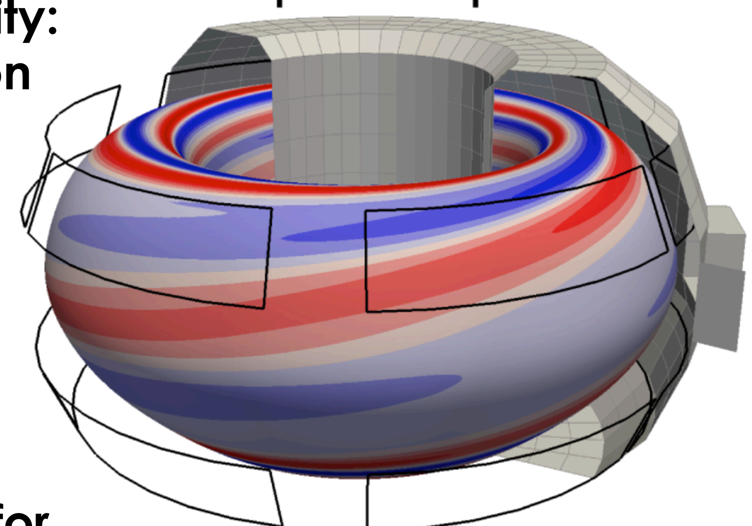
MHD warnings → **H-L back-transition** → **Off-normal plasma**

MHD-n1	BIF-n1	LTM-n1	PRP	IPR	WPC	DIS	VDE
(0.490s)	(+.005s)	(+.045s)	(+.068s)	(+.073s)	(+.073s)	(+.077s)	(+.080s)

Columbia Group at the DIII-D National Fusion Facility: stability and control for ITER and DEMO Scenarios

Plasma scenarios for fusion energy production are inherently non-linear systems, requiring integration of stability, performance and scalability

- Real-time control of low-n MHD instabilities with multiple helicities → GPU, physics-based algorithms
- Real-time sensing of the approach to instability: Active MHD Spectroscopy → model validation
- Obtain passive stability for the ITER Baseline Scenario → Maintain high fusion power and gain without disruptions in scalable plasmas
- Integrate a stable high-pressure core with a cool divertor region in steady-state plasmas for DEMO reactors



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Ideal MHD limits determine the operational space for most reactor-relevant tokamak plasmas

- **Both the high-gain ITER Baseline Scenario (IBS, Q=10 mission)**

  (moderate β_N~2, q_{95}~3)

  and the high-power Steady-State (ITER and beyond) plasmas

  (high β_N>3.5, moderate q_{95}~5-6)

  have issues with MHD stability (disruptions vs β collapses)

- **The shape of the current density (J) and pressure (p) profiles has been shown to correlate with the onset of tearing modes and RWMs in experiments**

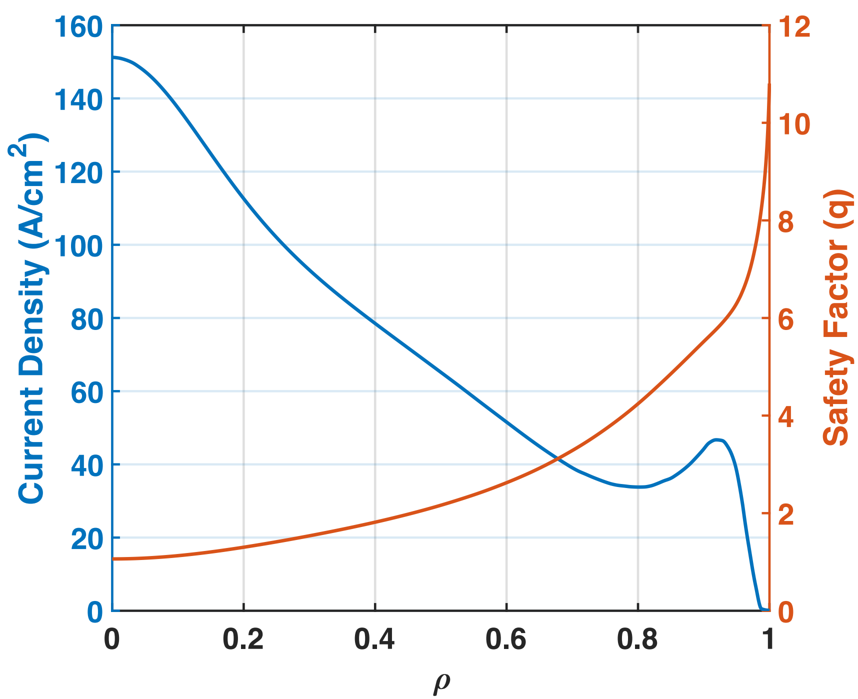
Precise and consistent ideal MHD limit calculations, with the correct equilibria and machine geometry

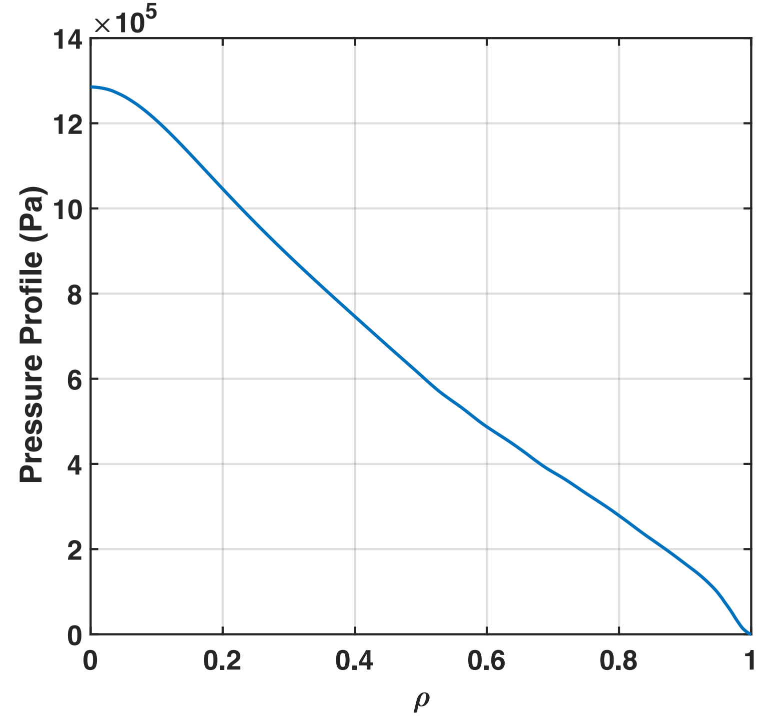
Calculating and understanding the MHD stability of existing plasmas

Exploring the operational space, to access high performance scenarios

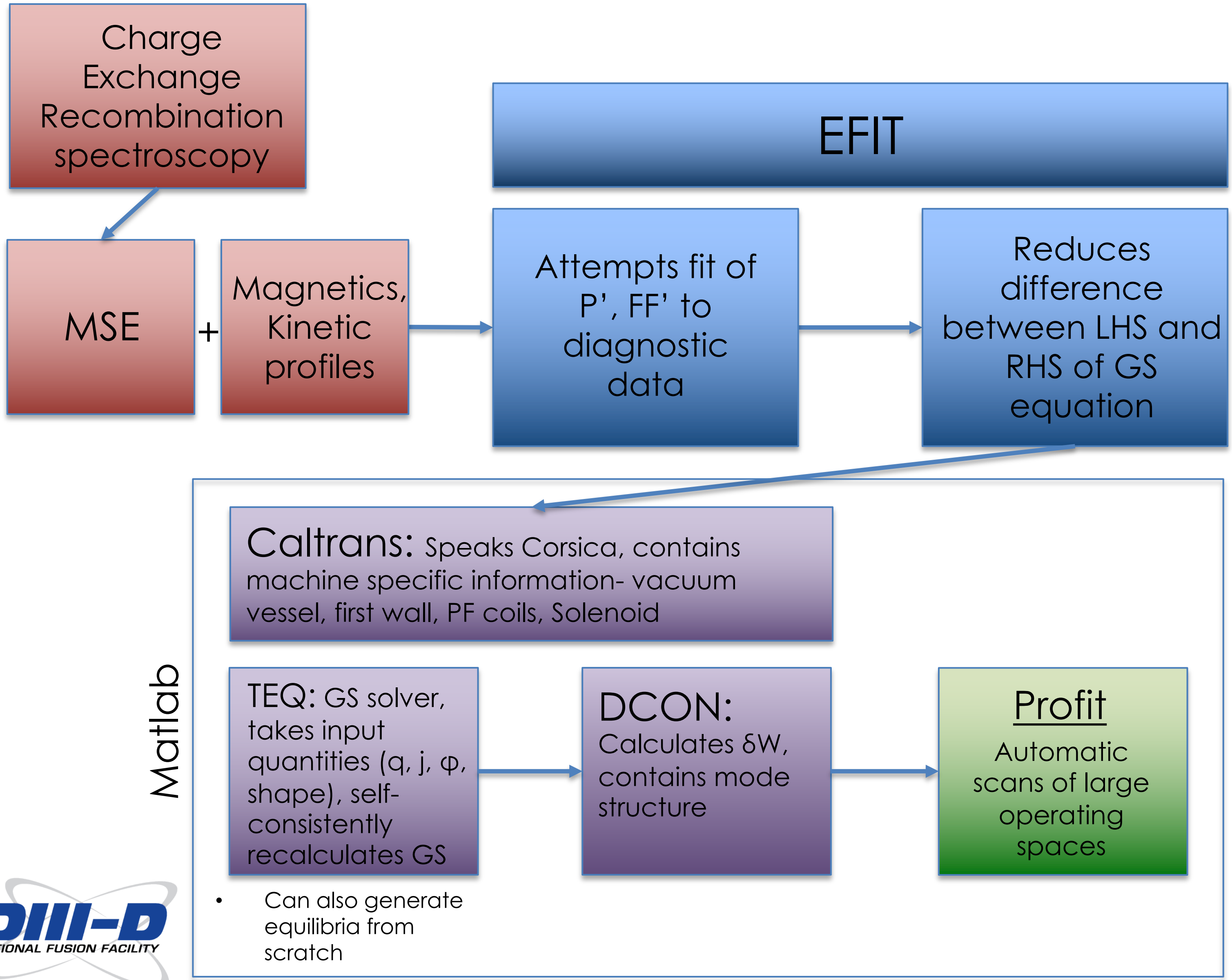
The steady-state hybrid scenario is a good testbed for ideal and resistive MHD modelling

- **One time slice in a reproducible, stationary hybrid plasma:**
  - β_N~3.5, q_{95}~6, DN shape
  - kinetic EFIT equilibrium reconstruction → separatrix, J, p, q, etc.
- **Systematically modify J and p shapes to mimic**
  - natural evolution to high-β access (pedestal growth)
  - various heating systems (core/edge ECCD, on-/off-axis NBI)
  - bootstrap current non-linear evolution





Several codes are coupled to calculate the stability of many equilibrium variations



Several codes are coupled to calculate the stability of many equilibrium variations

Charge Exchange Recombination spectroscopy

MSE + Magnetics, Kinetic profiles

EFIT

Fits P', FF' profiles to previous DIII-D experimental data from relevant diagnostic data

Both sides of the GS equation fitted to data, reducing their difference below a set tolerance, for us ~10^{-4}

Matlab

Caltrans: Speaks Corsica, contains machine specific information- vacuum vessel, first wall, PF coils, Solenoid

TEQ: GS solver, takes input quantities (q, j, φ, shape), self-consistently recalculates GS

DCON: Calculates δW, contains mode structure

Profit

Automatic scans of large operating spaces

Several codes are coupled to calculate the stability of many equilibrium variations

Charge Exchange Recombination spectroscopy

MSE + Magnetics, Kinetic profiles

EFIT

Attempts fit of P', FF' to diagnostic data

Reduces distance between LHS and RHS of GS equation

Matlab

Caltrans: Written in application specific language Corsica, contains machine specific information- vacuum vessel, first wall, PF coils, Solenoid

TEQ: GS solver, takes input quantities (q, j, φ, shape), self-consistently recalculates GS

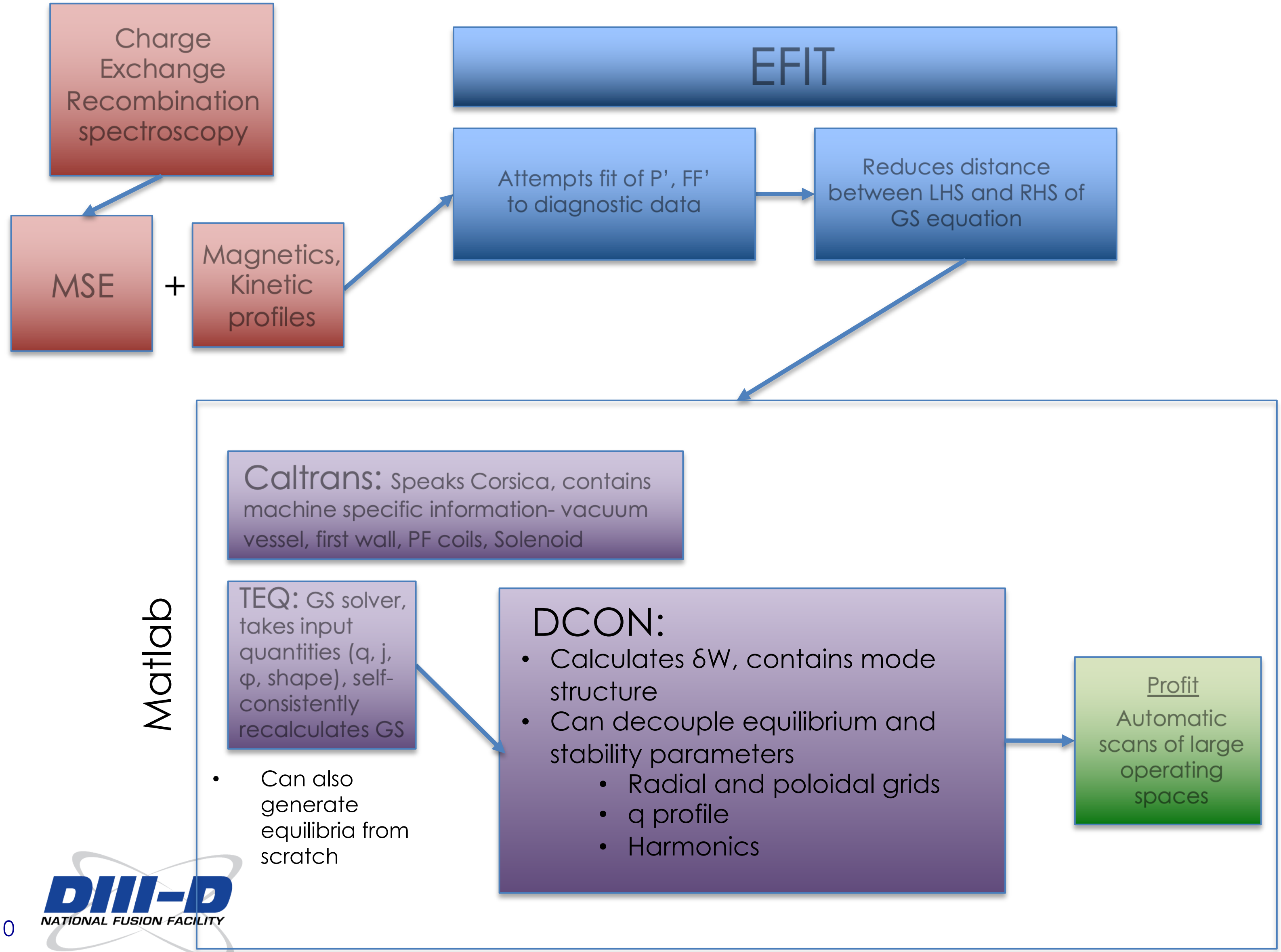
DCON: Calculates δW, contains mode structure

Profit

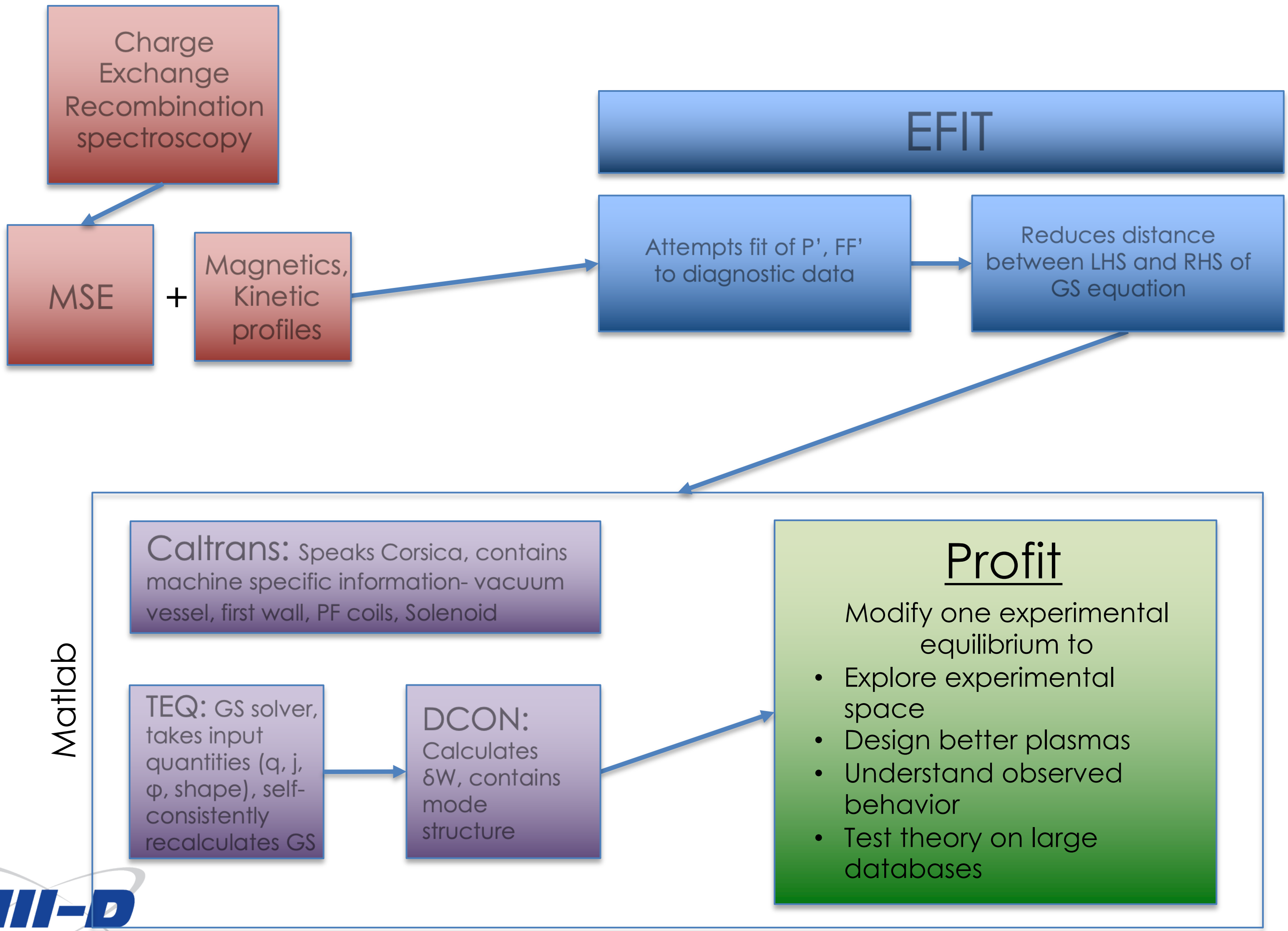
Automatic scans of large operating spaces

- Can also generate equilibria from scratch

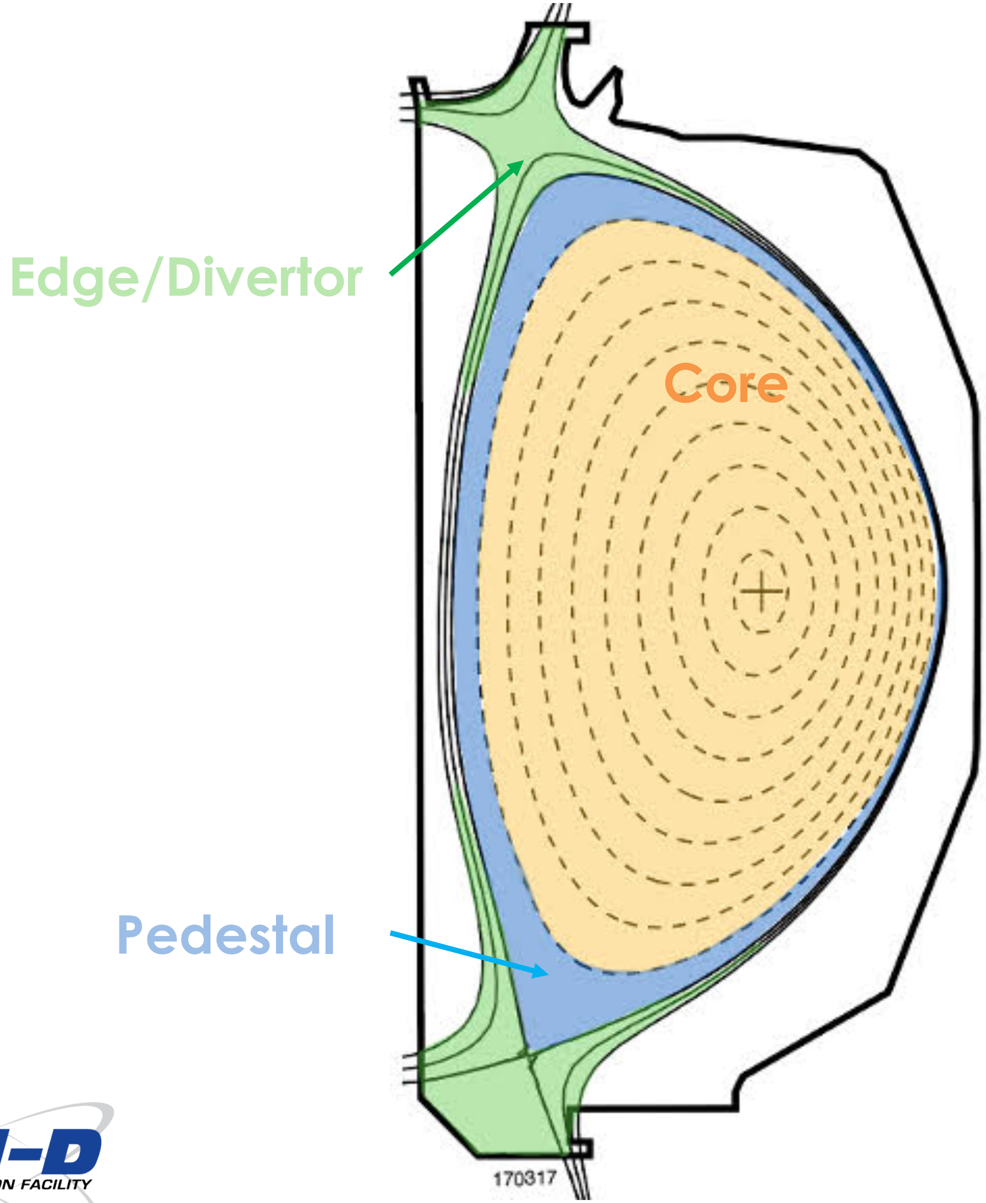
Several codes are coupled to calculate the stability of many equilibrium variations



Several codes are coupled to calculate the stability of many equilibrium variations

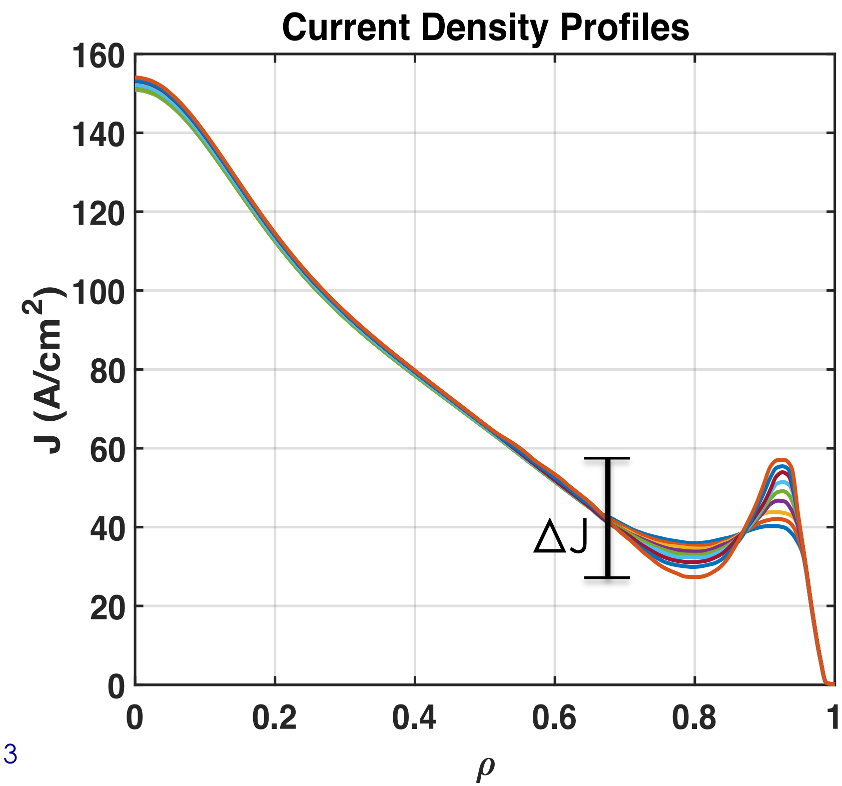


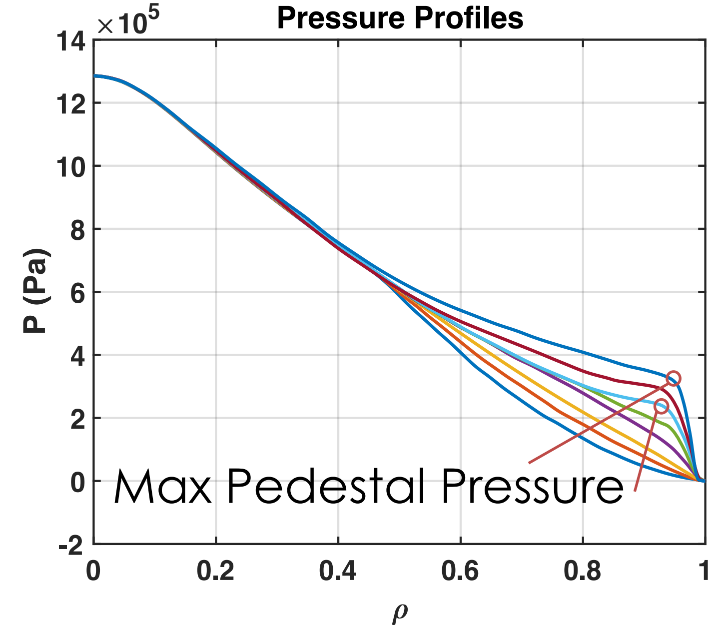
DIIID Shape

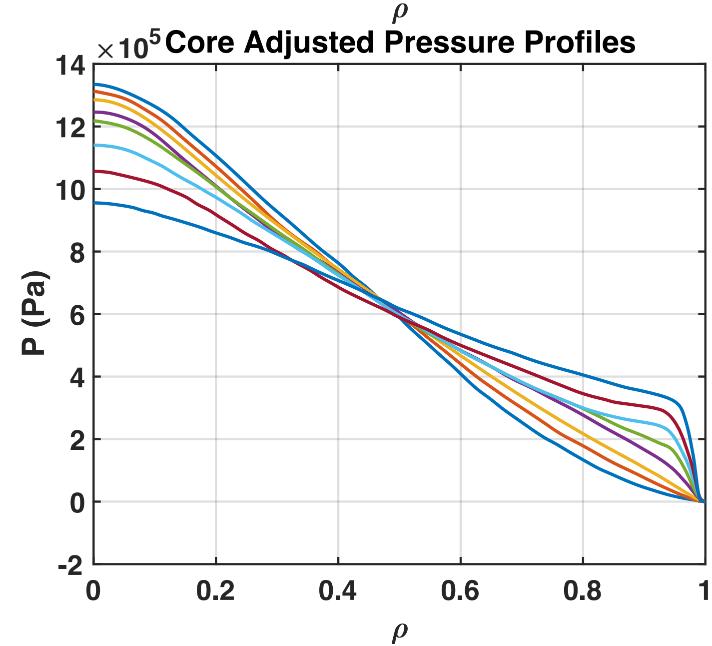


Shaping Kinetic profiles

- **Model bootstrap and ECCD profiles in the outer part of the plasma**
- **Scan location of deposition, holding total current constant**
- **Scan pressure pedestal gradient and max pedestal pressure**

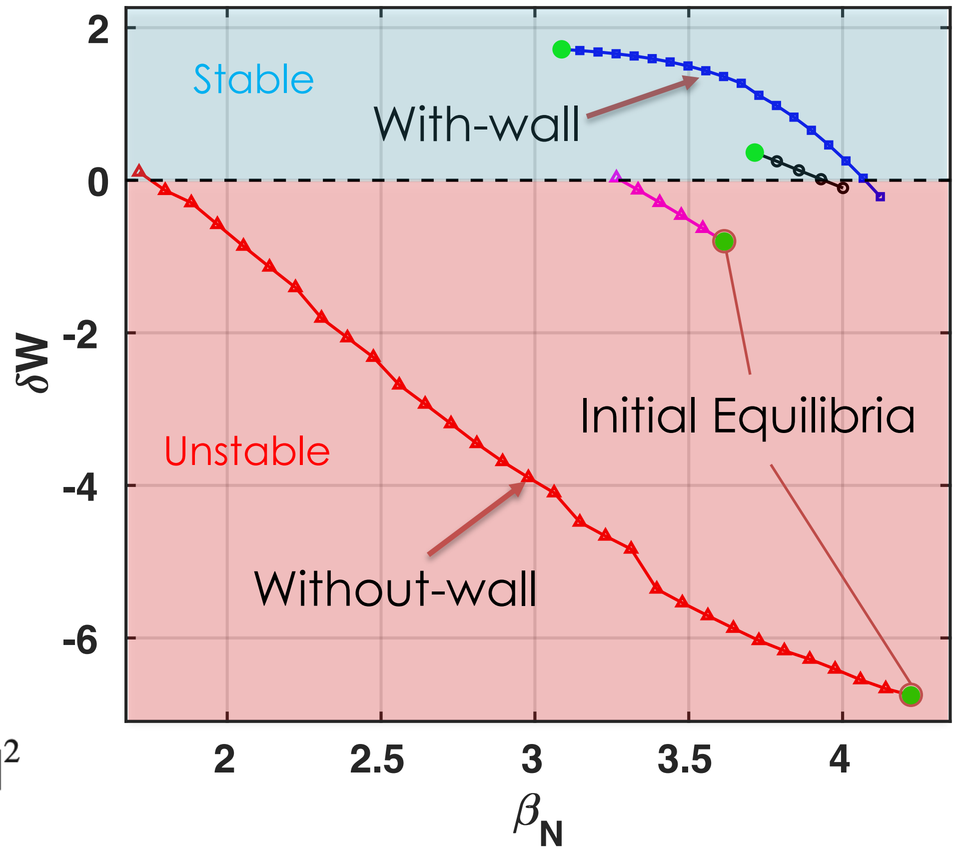






Finding Ideal Limits with DCON code

- **Free energy limit determines the change in plasma potential energy due to a perturbation**
- **DCON[1] evaluates the ideal free energy δW, we iteratively find the limit by increasing p**
- **Linear interpolation between ultimate and penultimate equilibria**



$$\delta W = \frac{1}{2}\int_V \left[\frac{1}{\mu_0}|\nabla \times (\xi \times \mathbf{B}_0)|^2 + \gamma P_0 |\nabla \cdot \xi|^2 - \xi^* \cdot \mathbf{J}_0 \times \{\nabla \times (\xi \times \mathbf{B}_0)\} - \xi^* \cdot \nabla(\xi \cdot \nabla P_0)\right] \mathrm{d}^3 x$$

[1] A. H. Glasser and M. S. Chance, Bull. Am. Phys. Soc. 42, 1848 (1997)

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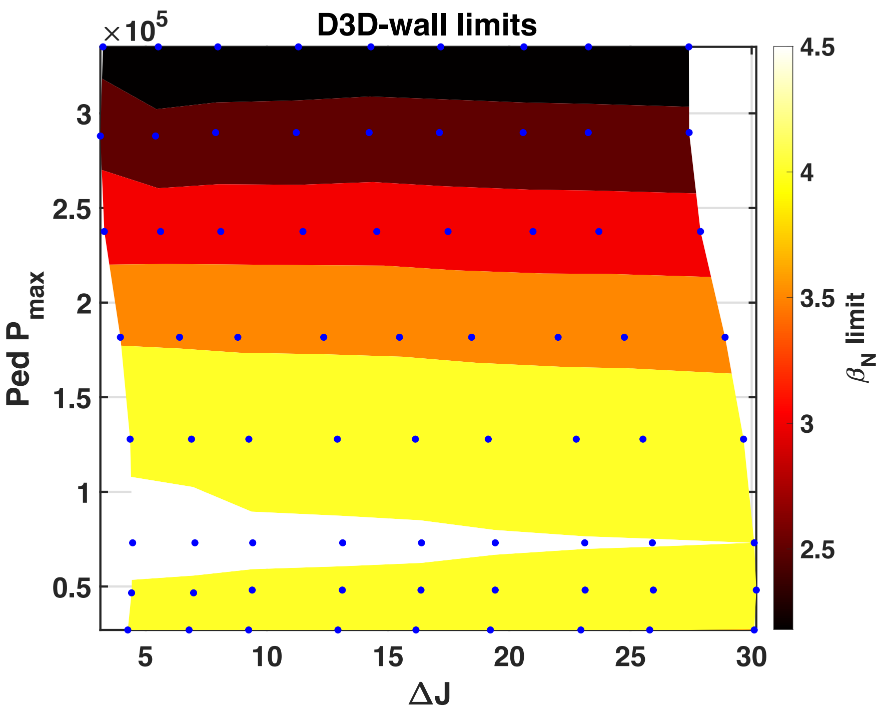
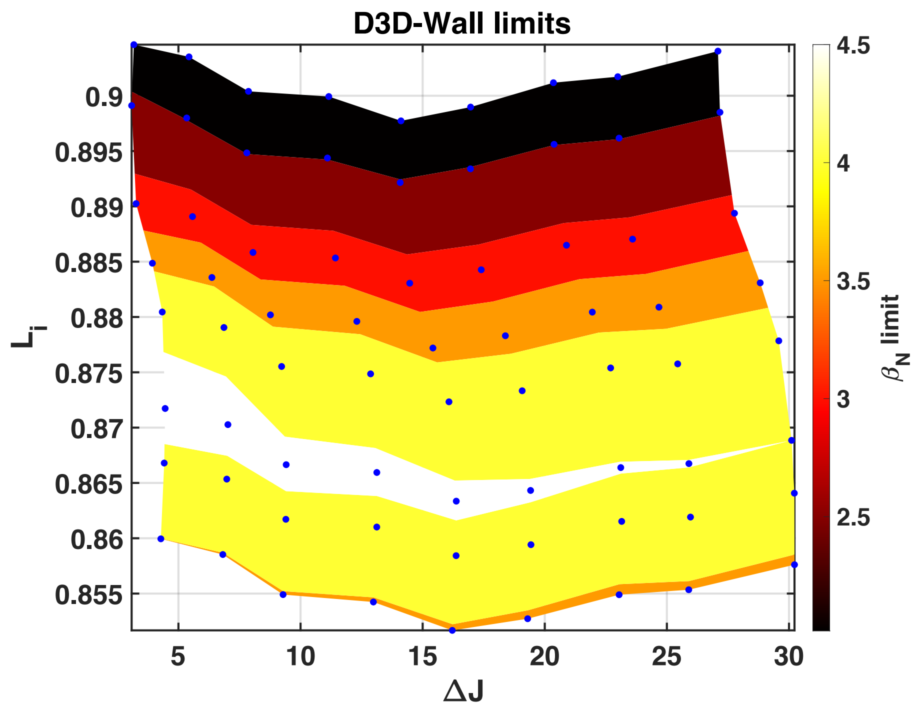
Map of ideal limits with varying pedestal J and p – with the DIII-D wall geometry (ideal)

- There is some dependence of L_i on the pressure profile shape, but within 4%
- The effect of the pedestal current is minimal (not surprising – almost constant integral near the edge)





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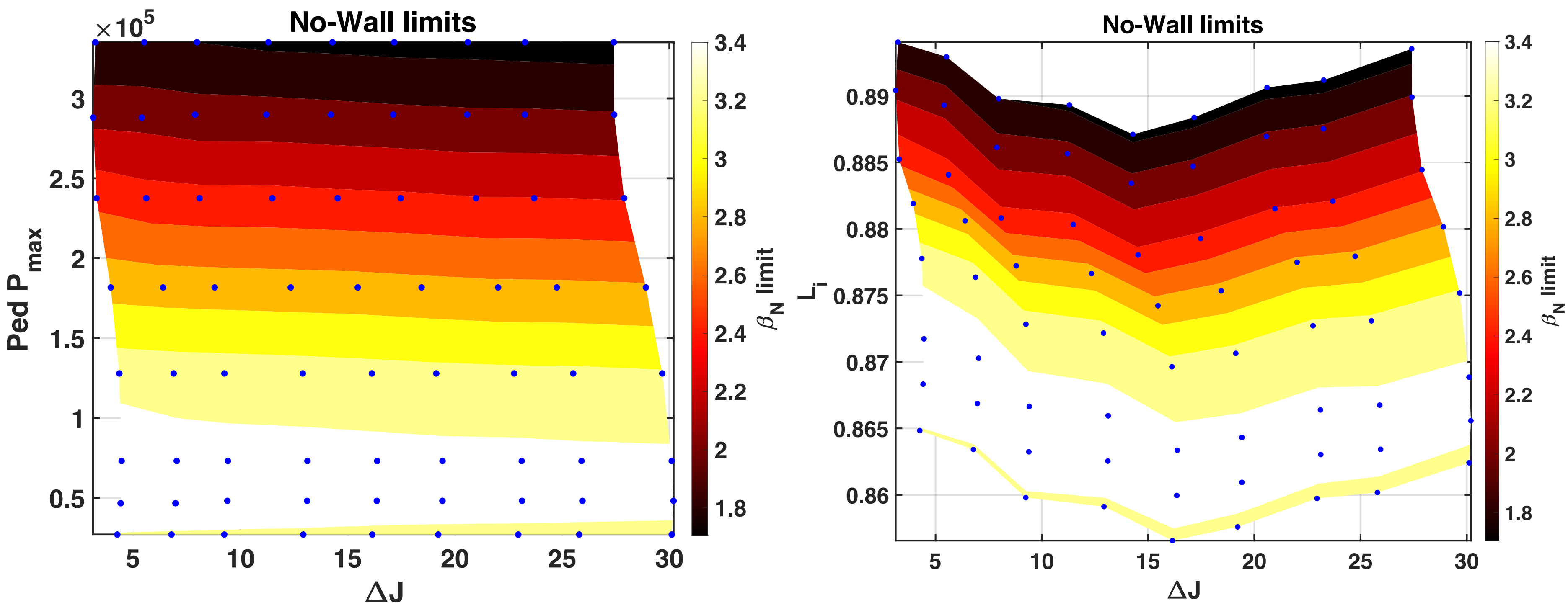
Map of ideal limits with varying pedestal J and p – without a wall

- **Wall-stabilization is a factor only in the magnitude of the limits**



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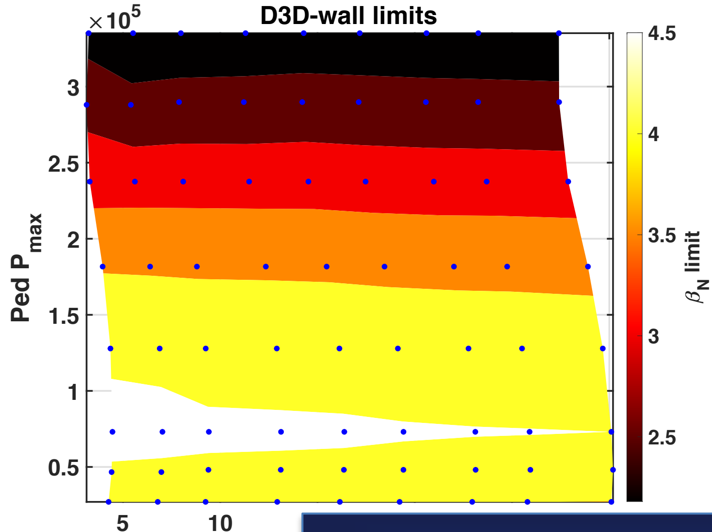
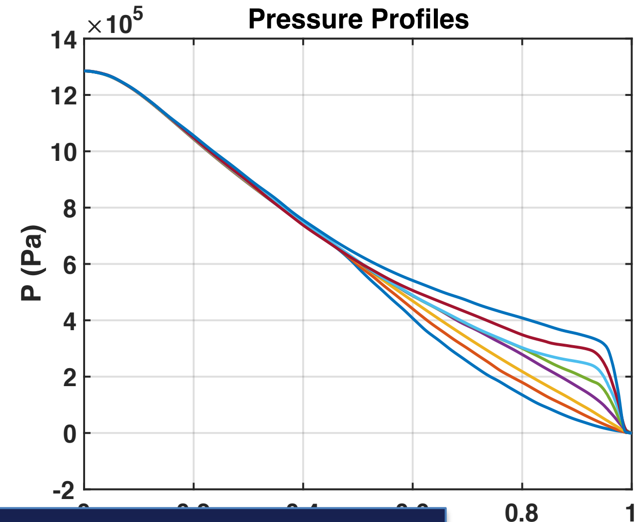
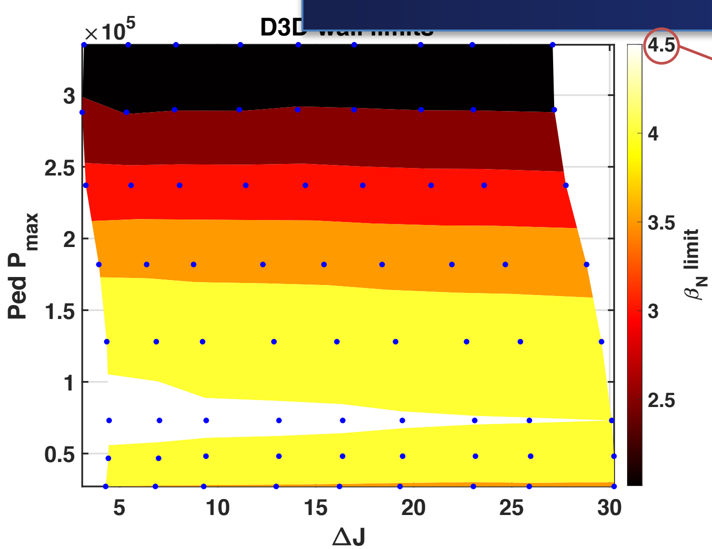
Pressure Profile Shape – does it matter?



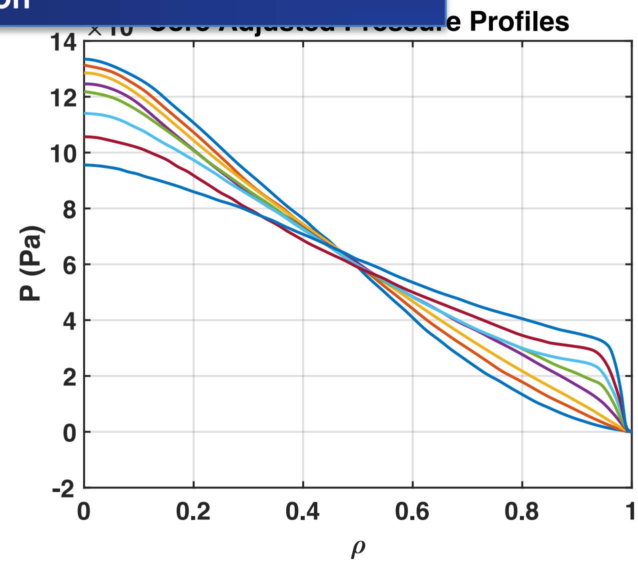


Contrary to common thinking

- Previous modeling did not fix the pedestal
- Dependence on peaking factor likely an artifact of profile parametrization



No



Discussion

- **Developed a workflow portable to any systematic change of plasma profile attributes**
- **Next steps include resistive wall and plasma stability calculations with PEST3, RDCON, and MARS**
- **In parallel with modelling the steady state hybrid scenario, efforts will commence to model the ITER Baseline Scenario (IBS)**
- **The method for increasing the pressure does not always reflect an experimental β_n ramp. Self-consistent transport model is required for that**

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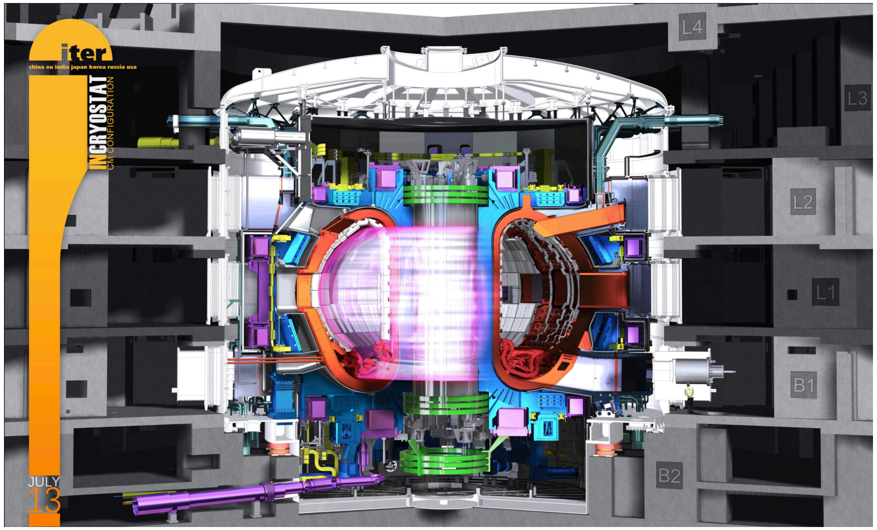
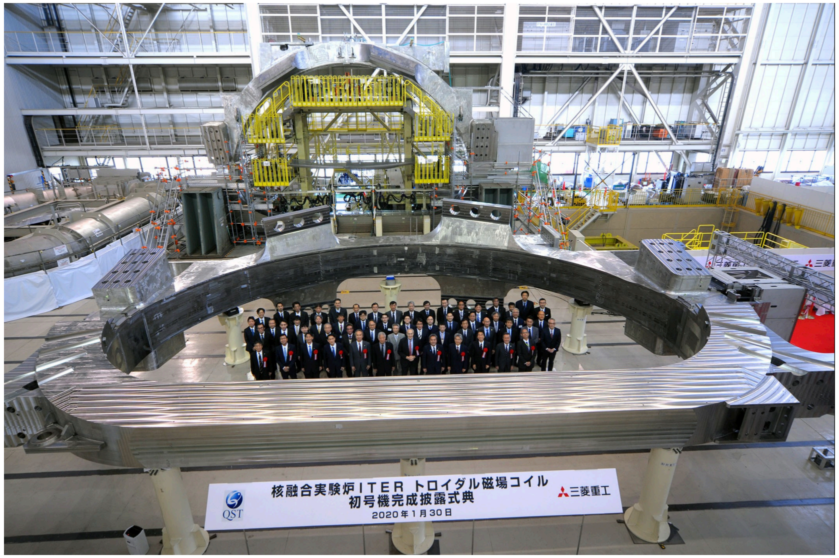
ITER

- 150 Million K core temperature – 10x the Sun's
- Target 500 MW output fusion power
- 100000 km of liquid He temperature (4 K) superconductor
- 6 m plasma major radius, 840 m^3 plasma

Interesting Questions:

- How does one control a burning plasma?
- What new physics occurs in a burning plasma?
- Do we have a good solution to the divertor power flux problem?
- Can we breed (enough) tritium?
- How do we best run ITER?
- Performance vs. Steady State





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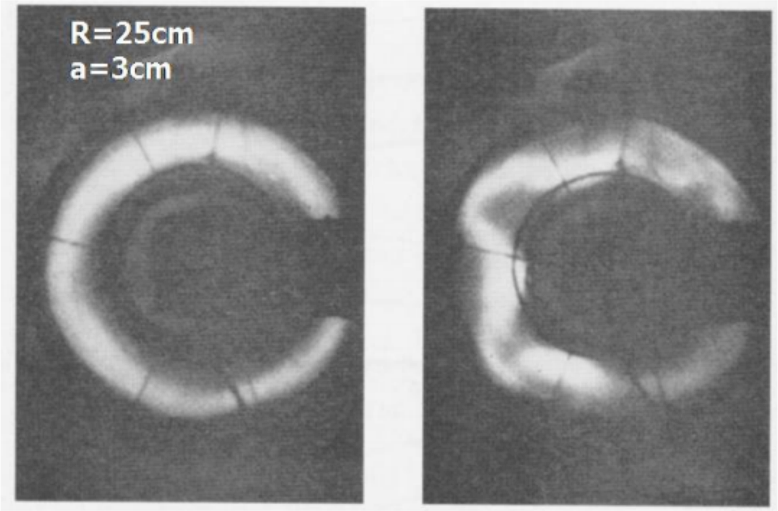
This information and more at https://www.iter.org/mach

Kink Modes

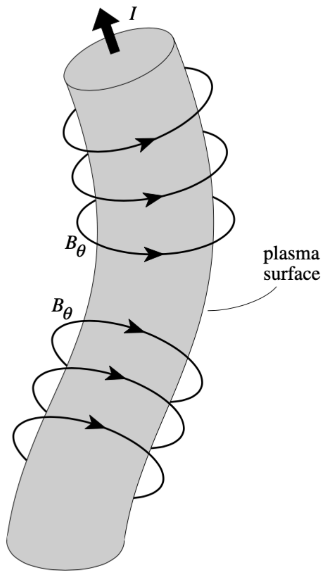
- Ideal MHD mode
- Growth from magnetic pressure in concave area increases
- Generic perturbation ξ will drive a mode or instigate instability



Shear Alfvén + Compressional Alfvén + Sound Wave

$$\delta W_P = \frac{1}{2}\int [\boxed{B_{1\perp}^2/\mu_0} + \boxed{(B_0^2/\mu_0)(\nabla\cdot\boldsymbol{\xi}_\perp + 2\boldsymbol{\xi}_\perp\cdot\boldsymbol{\kappa})^2} + \boxed{\gamma P_0(\nabla\cdot\boldsymbol{\xi})^2}$$
$$- \boxed{2(\boldsymbol{\xi}_\perp\cdot\nabla P_0)(\boldsymbol{\kappa}\cdot\boldsymbol{\xi}_\perp)} - \boxed{j_\parallel(\boldsymbol{\xi}_\perp\times\mathbf{b})\cdot\mathbf{B}_{1\perp}}]\mathbf{dr}$$

- Pressure Driven Interchange Modes - Current Driven Kinks



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*Information and diagram from Boyd T., Sanderson J. *The Physics of Plasmas* (Cambridge, 2003)

Linear Interpolation Script

- Previous scripts create a file taking last stable β_n value as limit
- Added a linear interpolation script to find δW zero crossing, for a more accurate ideal limit
- This avoids spurious "jumps" and provides smoothly varying limit trends