

Transient-Free Operations With Physics-Based Real-time Analysis and Control

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Mechanical & Aerospace Engineering

**Jointly appointed with the Andlinger Center for Energy
and the Environment**

and the Plasma Physics Laboratory (PPPL)



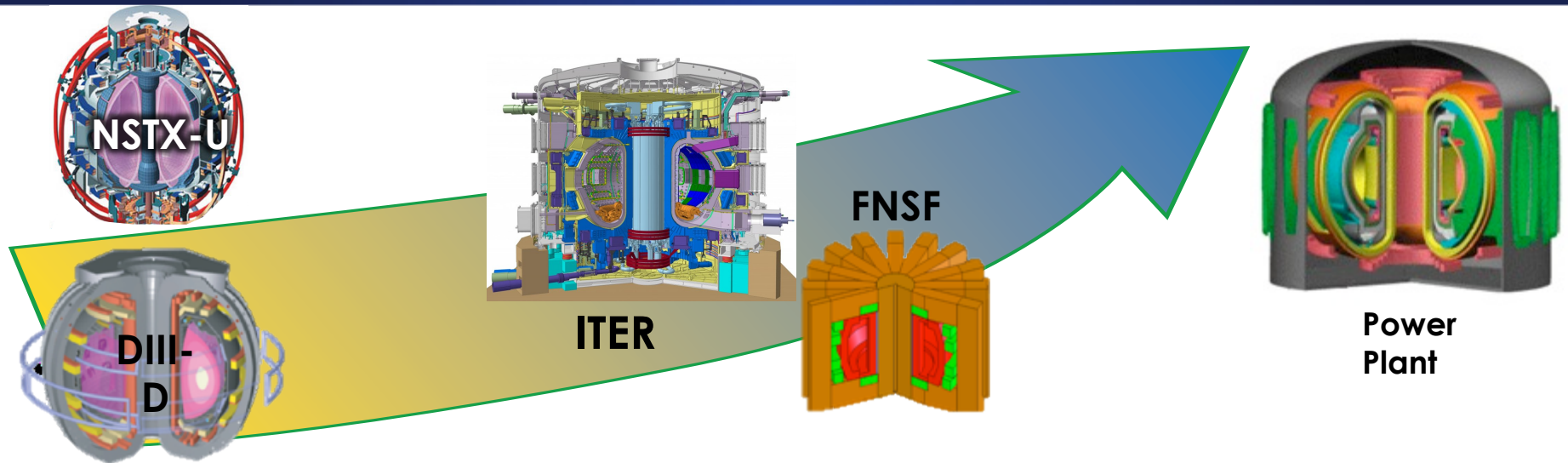
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This work supported in part by U.S. Department of Energy under DE-SC0015878 and DE-FC02-04ER54698.



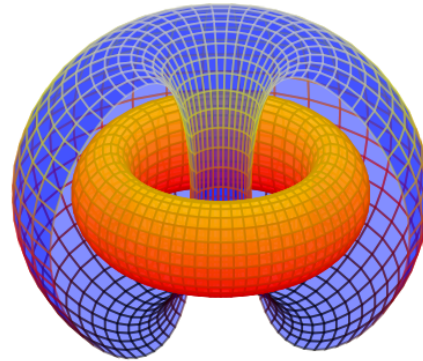
Real-time Stability Calculations for Plasma Control and Disruption Avoidance



- For cost-effective commercial fusion power plants to be feasible, we need to **operate close to stability limits**
- There must also be almost **no disruption** in fusion power reactors and very few disruptions in ITER
- This necessitates **real-time stability analysis** for plasma control and disruption avoidance

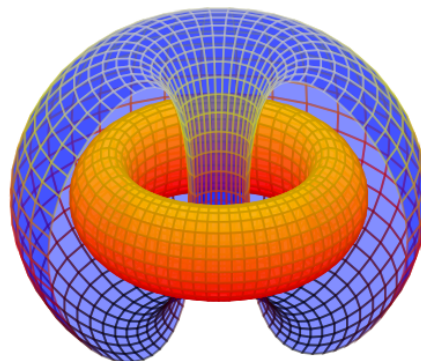
Steer the plasma away from unstable equilibria with Real-time Stability Analysis and Control

Stable Equilibrium



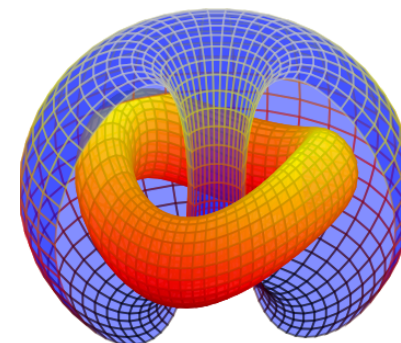
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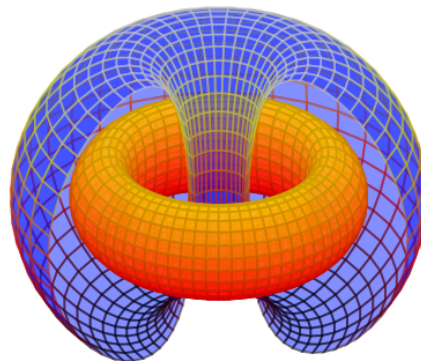
$\Delta t \sim 1s$

Unstable Equilibrium



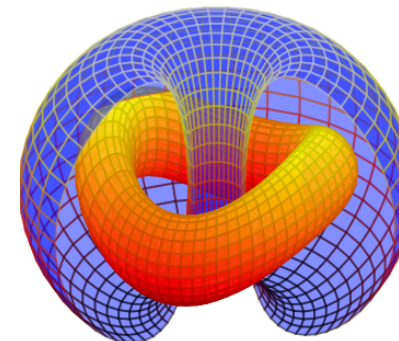
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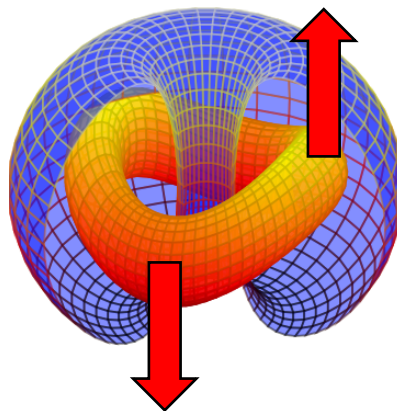


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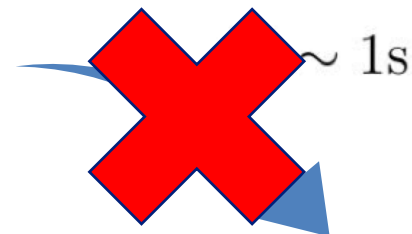
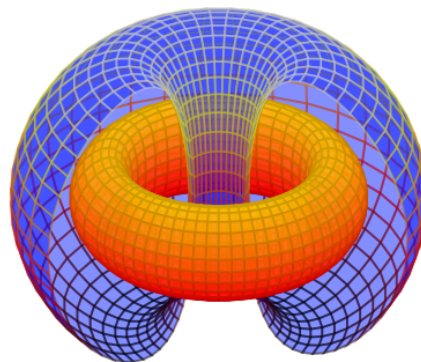
Unstable Mode Growth



$\Delta t \ll 1s$

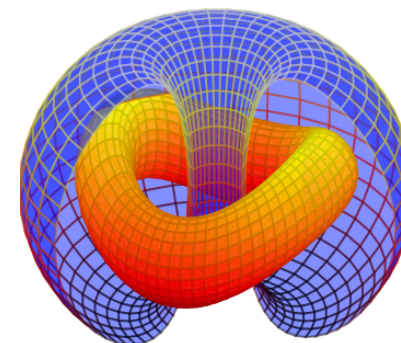
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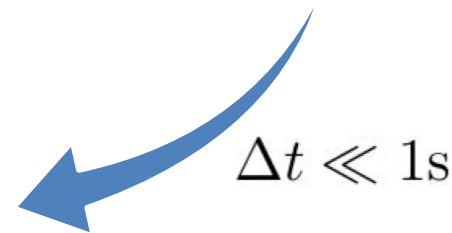
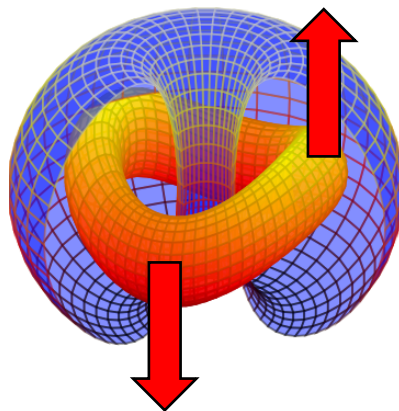


$\sim 1s$

Unstable Equilibrium

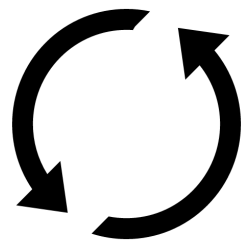


Unstable Mode Growth

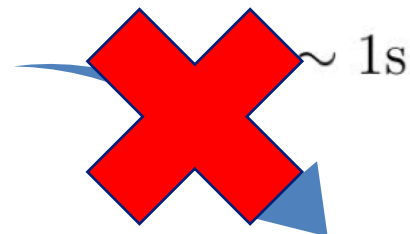
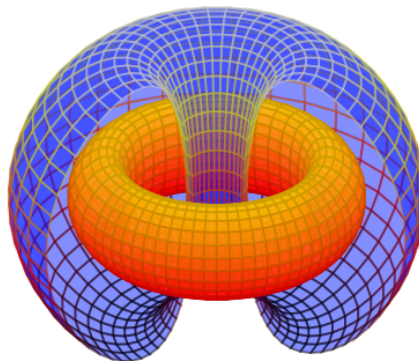


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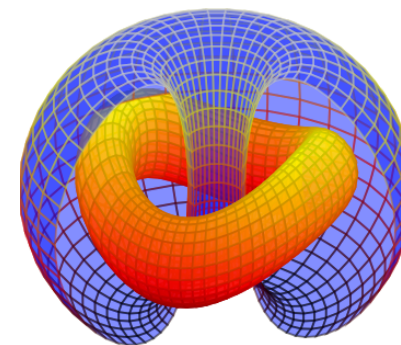
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Stable Equilibrium

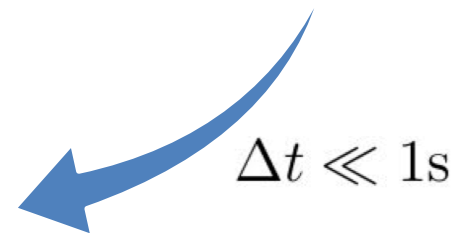
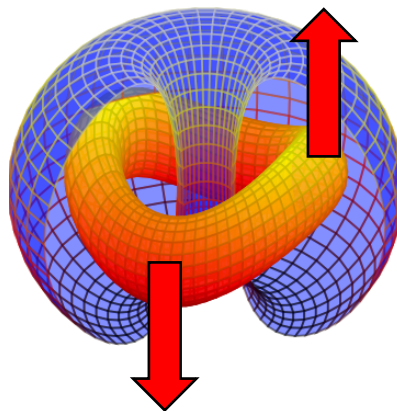


Unstable Equilibrium



- Develop fast algorithms to analyze stability in real-time

Unstable Mode Growth



Real-time Computational Analysis for Fusion Adds New Challenges

- In order to produce real-time stability computation useful for control, we need to:
 1. >>99% reliability
 - Use a well known analysis and tested codes → **Ideal MHD**
 2. Take the physicist out of the loop
 - **Automated** Real-time Kinetic Equilibrium reconstruction

1. Real-Time Kinetic Equilibrium Reconstruction

2. Real-time Stability Calculations

Real Time Kinetic Equilibrium Reconstruction Will be Implemented by Adding P and J Constraints to EFIT

- EFIT solves the Grad-Shafranov Equation

$$\Delta^* \psi = -\mu_0 R^2 p' - \mu_0^2 f f'$$

$$J_R = -\frac{1}{R} \frac{\partial f}{\partial Z}$$

$$J_Z = \frac{1}{R} \frac{\partial f}{\partial R}$$

- ψ constrained by magnetics
- J constrained by magnetics and MSE

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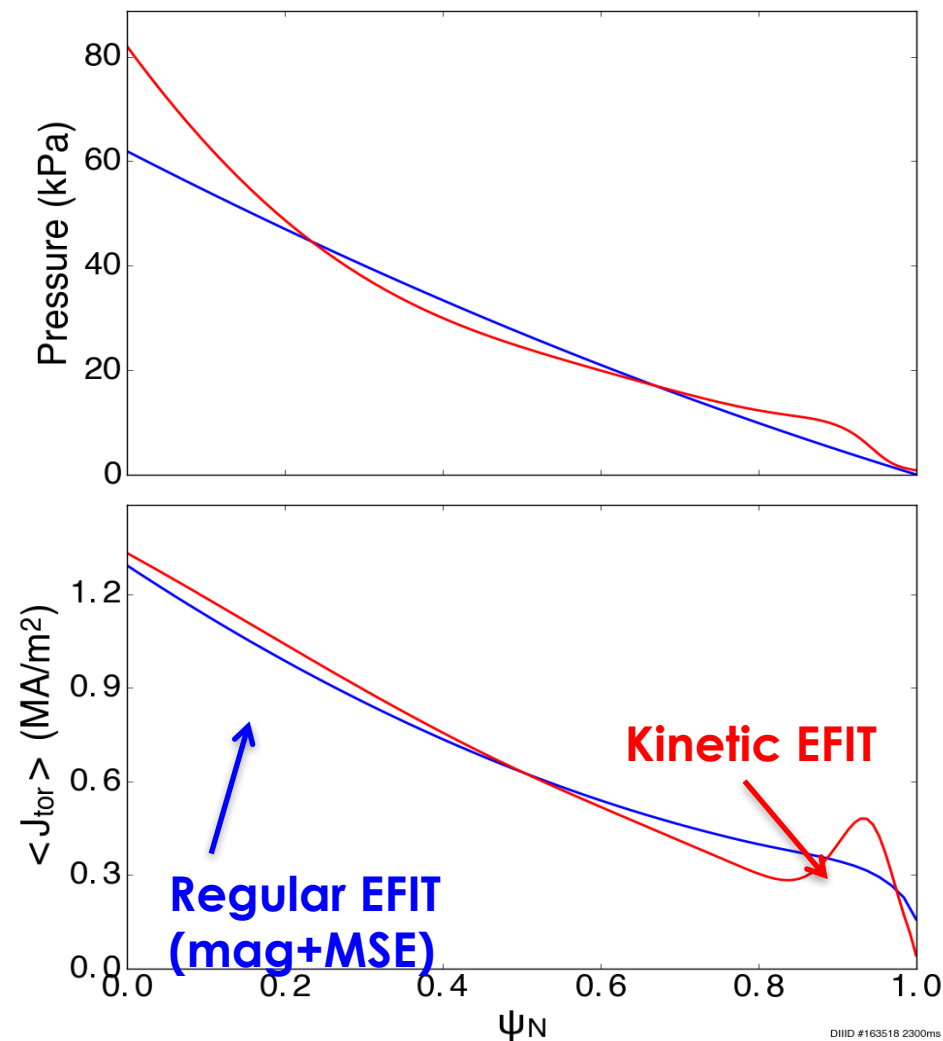
- ψ constrained by magnetics
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-

New • Additional constraints in a kinetic EFIT:

- p is constrained by TS, CER, and fast ion calculations
- J is further constrained by $J_{BS} + J_{OHM} + J_{ECCD}$ calculations

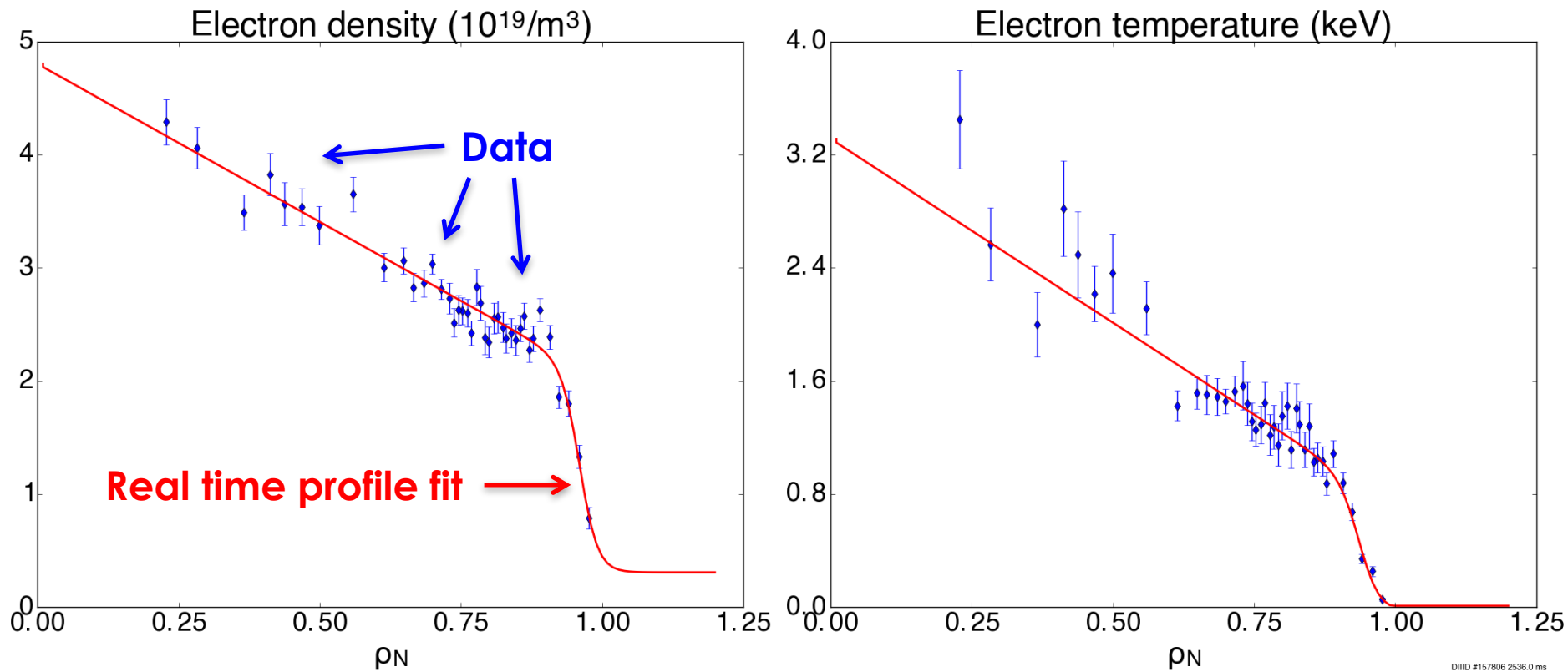
With **David Eldon** and **John Ferron**

Real Time Kinetic Equilibrium Reconstruction Difference between regular versus kinetic-EFIT



- Pedestal pressure gradient and the resulting bootstrap current introduces errors throughout the profiles
- Critical to constrain equilibria for stability analysis

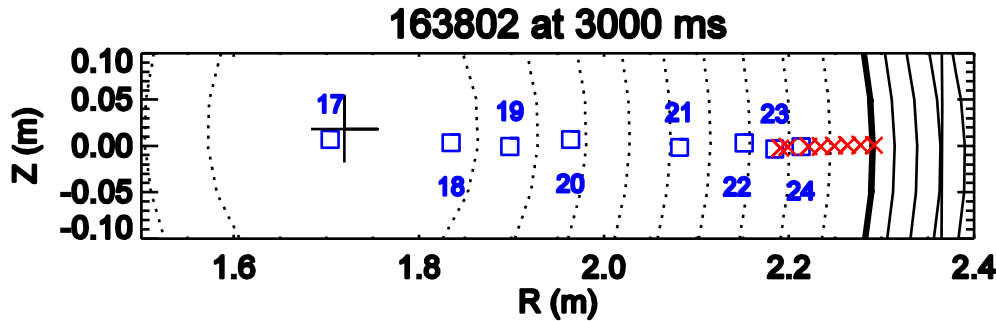
Real-time Thomson Working at DIII-D



- We acquire the Thomson data in real-time.
- Calibrate and fit it \rightarrow Input to auto-kefit

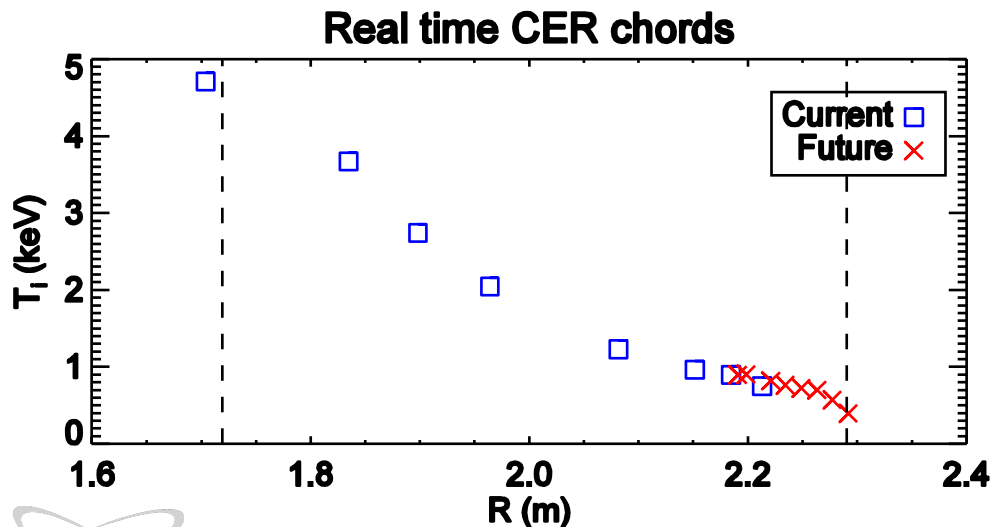
DIII-D #157806 2536.0 ms

RT-CER constraints on the Current and Pressure



□ Core CER channels already acquired

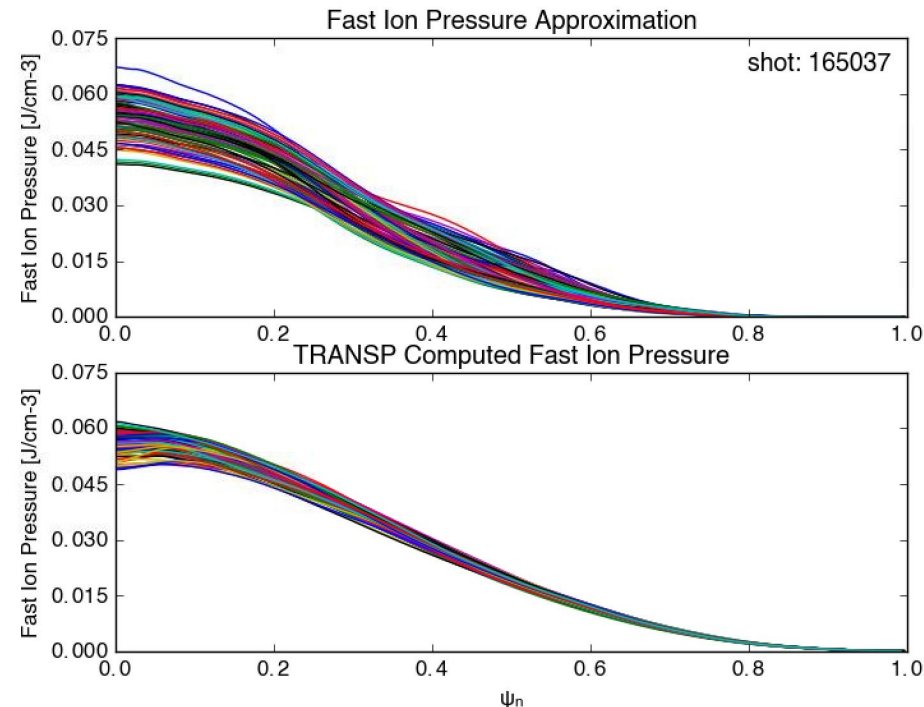
✗ Edge CER chords for pedestal are added this year



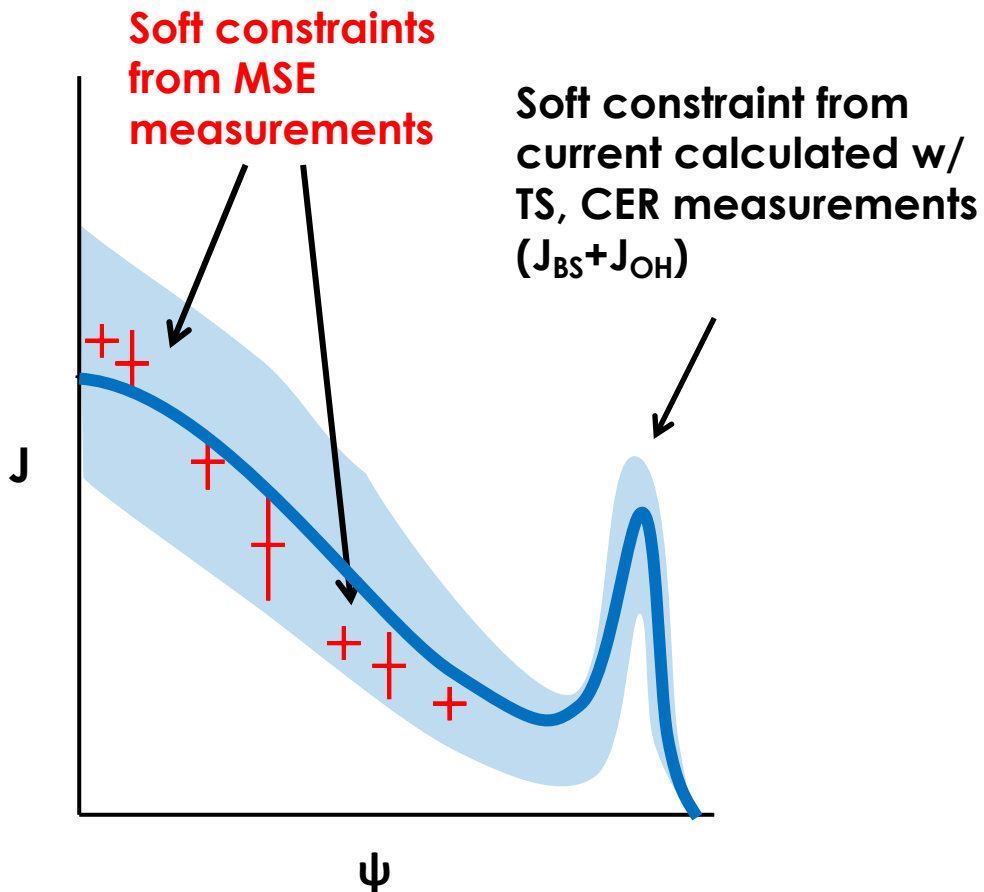
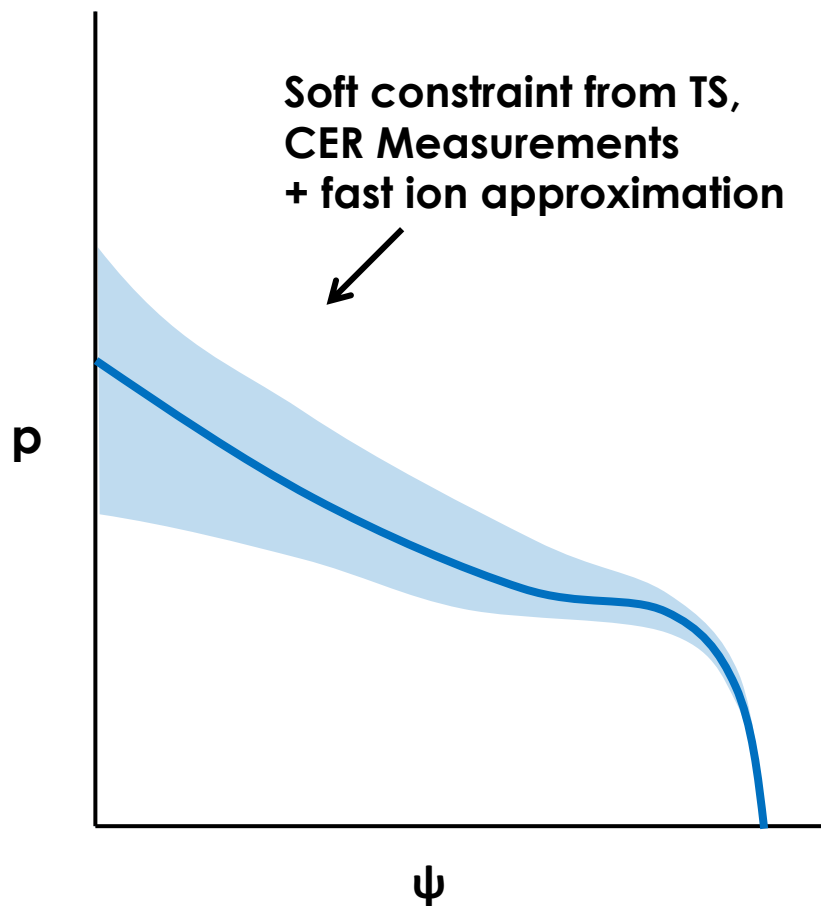
- Calibration and fitting for getting Ion temperature and density are to be tested this run campaign

Fast Ion Approximation Tool (FIAT) provides quick access to fast ion profiles (Bill Eggert)

- **Fast ion pressure:**
- **FIAT surveys 1000s of shots**
 - Read fast ion profiles from ONETWO results
 - Fit fast ion profiles w/ Gaussian & record amplitude and width
- **→ Fast function for estimating fast ion profiles then can be used in real-time**



Add soft constraints on the Current and Pressure to RT EFIT



- RT-Thomson (two years ago), RT-CER (this year)

auto_kEFIT is Built on the Assumption that There is No User Input During the Workflow (David Eldon)

The screenshot shows the OMFIT GUI with the following fields and options:

- Device = 'DIII-D'
- Shot = 161409
- Times [ms] = [2500, 3000, 3500]
- Radius of time window for generating EFIT constraints (ms) = 25.0
- Select approximation/quality level
 - Form constraint from dataset = electron_and_ion_fits
 - Method for estimating fast ion profiles = FIAT_result
- User interface: Developer interface (selected)
- Plots: Basics, CER, Thomson, Profile fits, Constraints, EFIT (selected)
- EFIT information and comparisons
 - Do EFIT comparison at time = 3500
 - EFIT comparison plot
 - Include kinetic EFIT in EFIT comparison plot
 - Include baseline EFIT in EFIT comparison plot
 - Include BENCHMARK kinetic EFIT in EFIT comparison plot
 - Include EFIT04 in comparison plot (used in mapping)
 - Include kinetic constraints in EFIT comparison plot
 - Kinetic vs. baseline EFIT comparison will be available when both kinetic and baseline EFITs have been generated.
 - Generate baseline (non-kinetic) EFIT for comparison

A red arrow points to the '<<< GO >>>' button in the center of the developer interface.

- Offline Testing Started → Online Development
- Pick your shot & timing and press GO!
- Aim: No Human Intervention requirement

1. RT-Kinetic EFIT

2. Real-time Stability Calculations

How can we achieve rt-Stability calculations (Alex Glasser)

- **Need for Control:**
 - Two time scales of crucial importance are
 - Energy confinement time, τ_E , \rightarrow pressure profile to equilibrate
 - Current relaxation time, τ_R , \rightarrow plasma current density profile to equilibrate
 - In DIII-D, $\tau_E \sim 200$ ms & τ_R is ~ 2 s, in ITER both $>$ seconds.
- **How to get it:**
 - The fastest Stability Calculations: Single core DCON 5 s for $n=1$ and 10 s for $n=2$.
 - Parallelizing DCON
 - Parallelize the coordinate transfer
 - Parallelize into subdomains (ODE)
 - Initial results show we can get to ~ 200 ms computation time

Stability Analysis: Using RT-EFIT + DCON

- Start with **non-resistive DCON** with the wall
- Solves the ideal MHD (low toroidal number)
- Using the Energy Principle

$$\delta W = \frac{1}{2} \int_{\Omega} d\mathbf{x} [Q^2 + \mathbf{J} \cdot \boldsymbol{\xi} \times \mathbf{Q} + (\boldsymbol{\xi} \cdot \nabla P)(\nabla \cdot \boldsymbol{\xi}) + \gamma P(\nabla \cdot \boldsymbol{\xi})^2]$$

- The Ξ_{ψ} which minimizes the 'action' δW_P is seen to satisfy the Euler-Lagrange equation:

$$\left(\mathbf{F}\Xi'_{\psi} + \mathbf{K}\Xi_{\psi} \right)' - \left(\mathbf{K}^{\dagger}\Xi'_{\psi} + \mathbf{G}\Xi_{\psi} \right) = 0$$

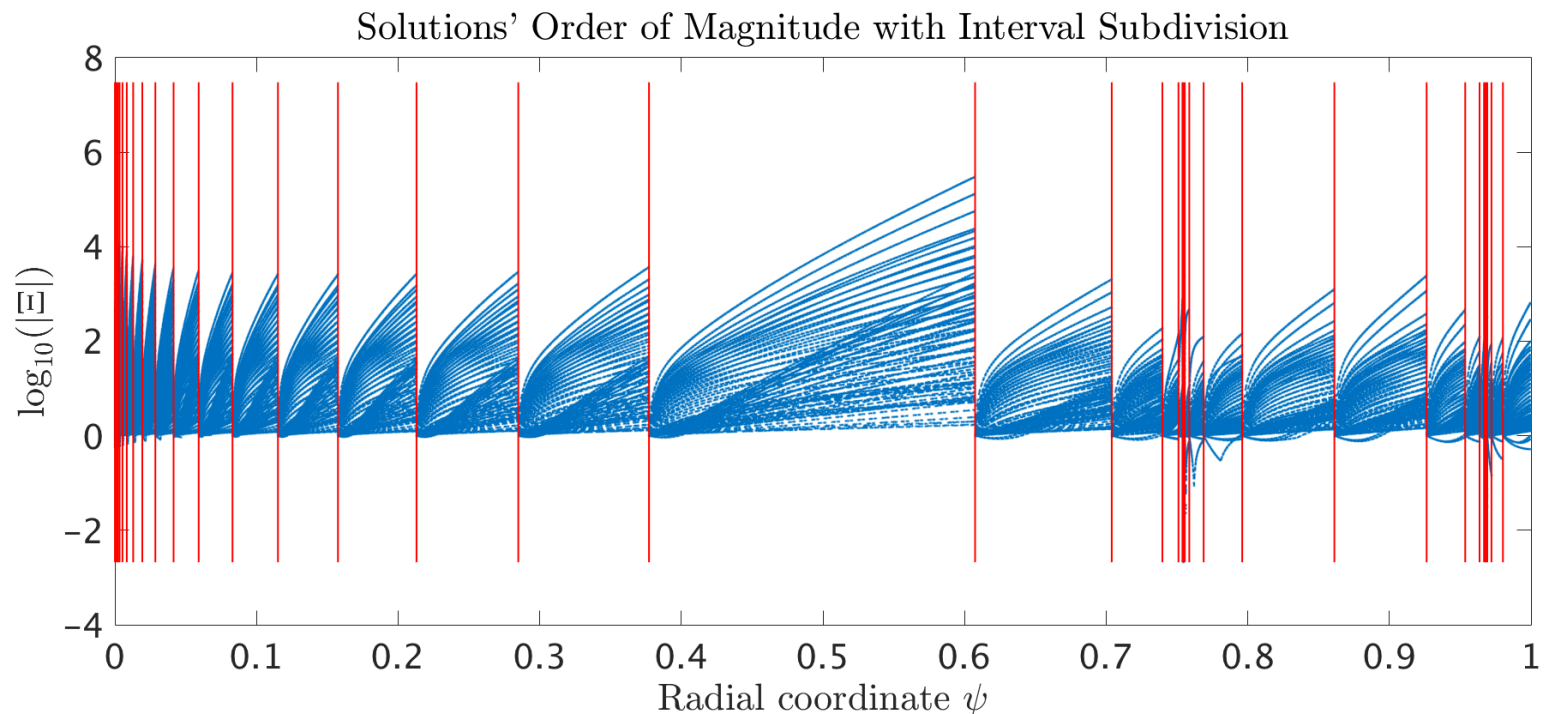
- Convert the problem to a **2-point BVP** (with analyticity condition at singular points) because it allows fast computation methods

$$\begin{pmatrix} \dot{\mathbf{q}} \\ \dot{\mathbf{p}} \end{pmatrix} = \mathbf{A}(\psi) \begin{pmatrix} \mathbf{q} \\ \mathbf{p} \end{pmatrix} \text{ with } \mathbf{q}(0) = 0, \mathbf{p}(1) = 0, \text{ and } \mathbf{K}^{\dagger}\mathbf{F}^{-1}\mathbf{K}\mathbf{q} \Big|_{m_s} = 0$$

Parallelize integration for multiple cores with state transition matrix and domain decomposition

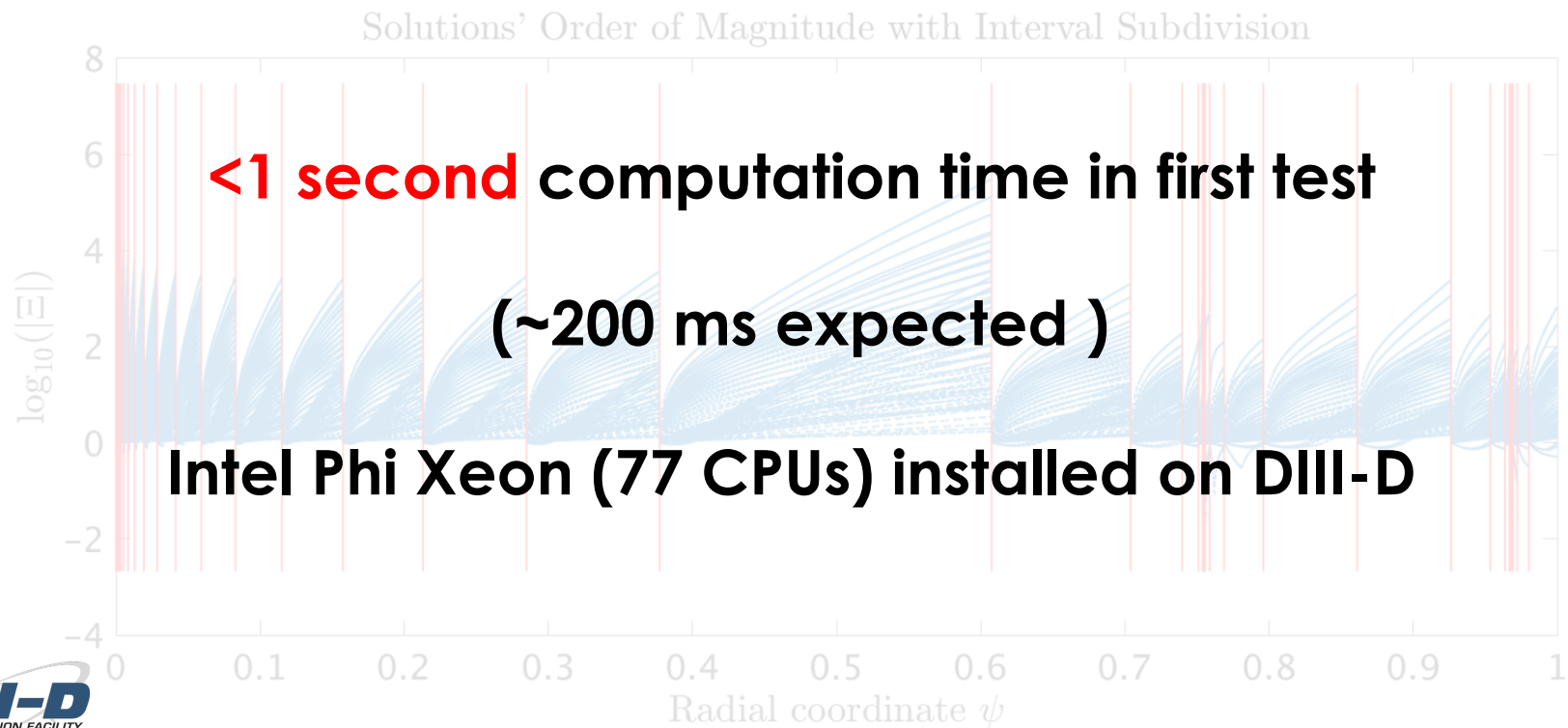
$$\dot{\Phi}(\psi) = \mathbf{A}(\psi)\Phi(\psi) \quad \text{with} \quad \Phi(\psi_0) = \mathbb{1}$$

$$\begin{pmatrix} \mathbf{q}_1 \\ 0 \end{pmatrix} = \Phi(\psi_n, \psi_{n-1}) \cdots \Phi(\psi_2, \psi_1) \Phi(\psi_1, \psi_0) \begin{pmatrix} 0 \\ \mathbf{p}_0 \end{pmatrix}$$



Parallelize integration for multiple cores with state transition matrix and domain decomposition

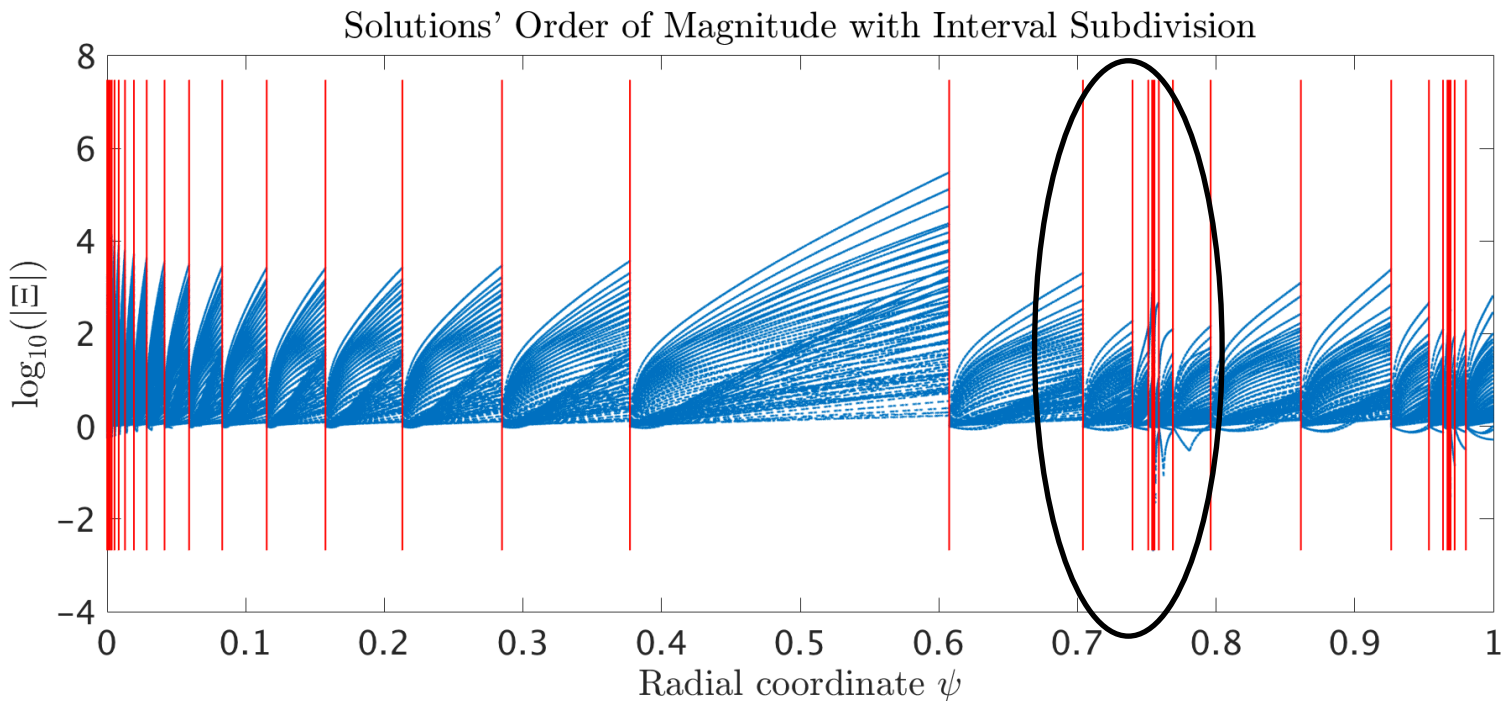
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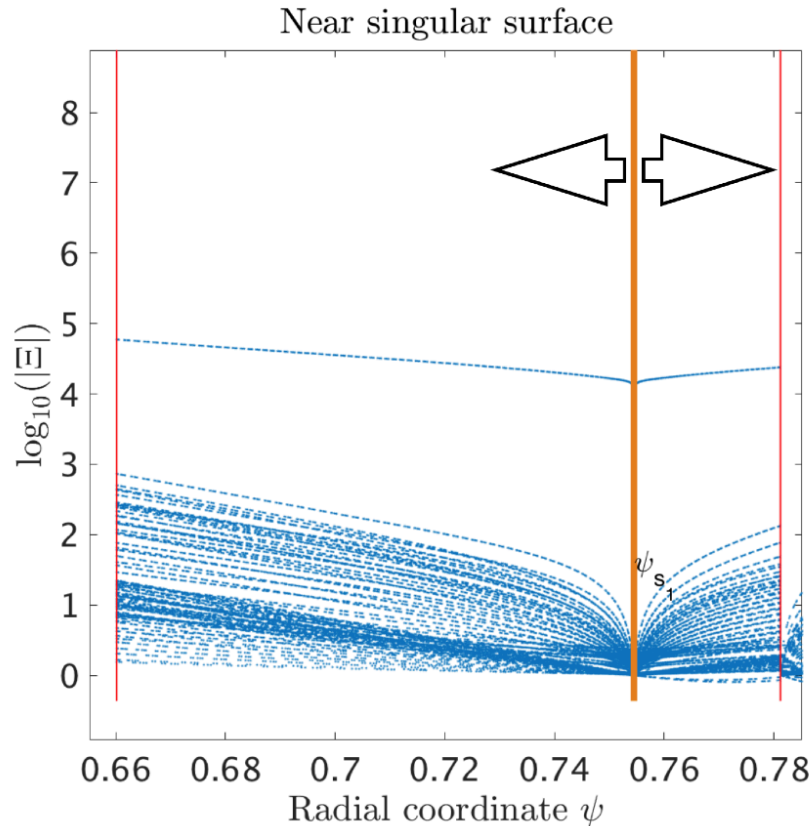
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Integration at singular surface (1)

- State transition matrices may be **inverted** to integrate **out** from singular surfaces rather than **in**, ensuring only analytic solutions are integrated

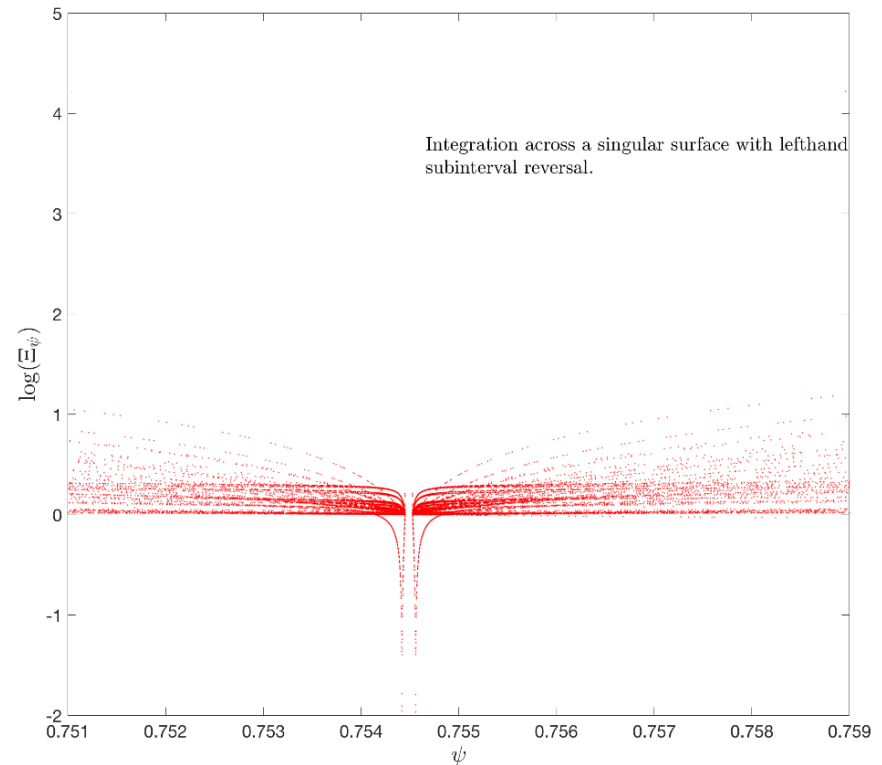
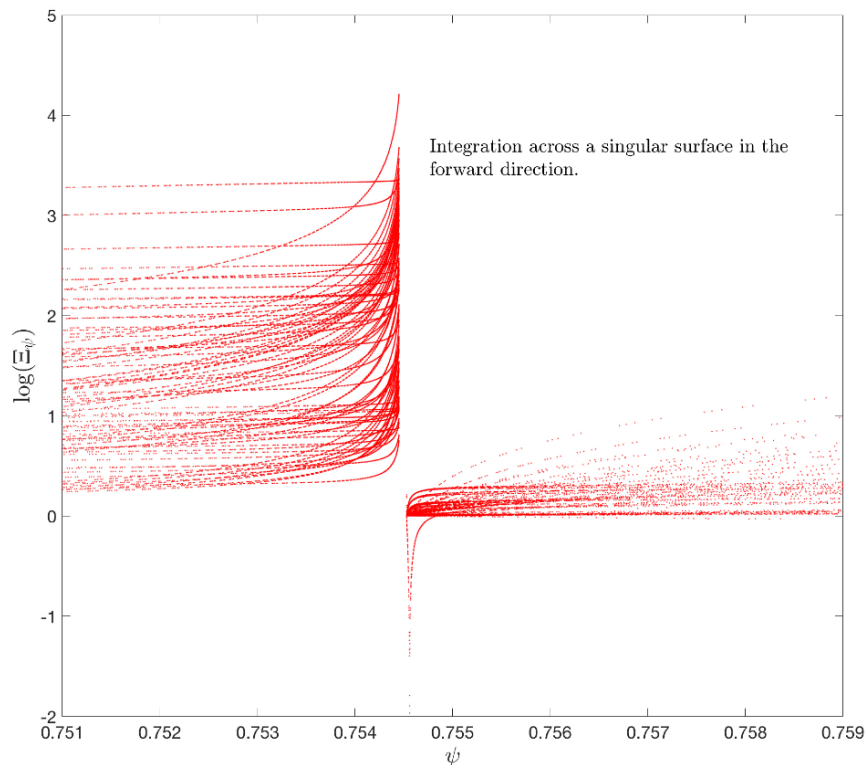
$$\Phi^{-1}(\psi_1, \psi_2) = \Phi(\psi_2, \psi_1)$$



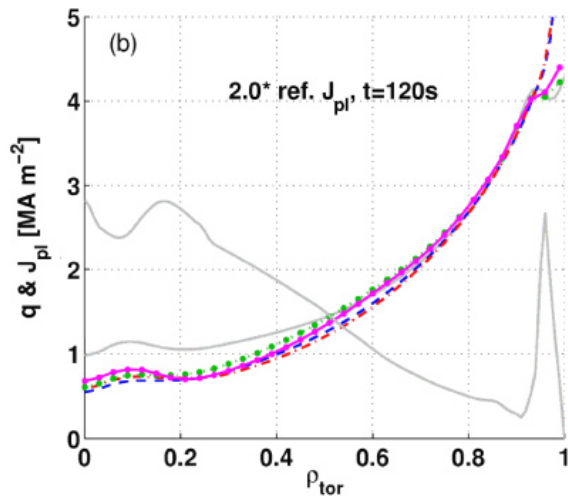
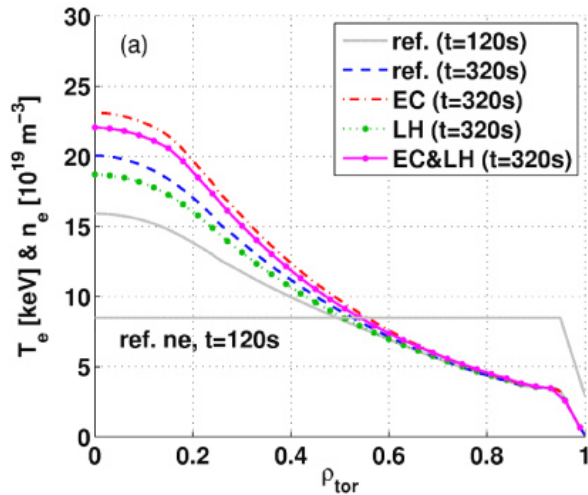
Integration at singular surface (2)

- State transition matrices may be **inverted** to integrate **out** from singular surfaces rather than **in**, ensuring only analytic solutions are integrated

$$\Phi^{-1}(\psi_1, \psi_2) = \Phi(\psi_2, \psi_1)$$



Vision: Real-time Stability Calculations for Plasma Control and Disruption Avoidance



- **Develop the system for ITER on current machines**
- Each server will run a different **variation of a profile** parameter (e.g. increase NBI power, reduce edge current etc.)
- **Project the stability** in the future.
- **If approaching stability boundary change/control the profiles**
 - Calculate multiple profile variations
 - choose the best path

Conclusions

- **Automated kinetic equilibrium reconstructions is implemented at DIII-D → Real-time under development**
- **Real-time methods for ideal stability calculations based on DCON are under development at DIII-D**
- **Aim: Control profiles evolution to keep the plasma away from the stability boundaries**
 - **First to be tested at DIII-D**
 - **Then, implemented at ITER**

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