Computational Modeling for Disruption Avoidance

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Acknowledge discussions with
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M. Greenwald

Caveat: Many slides come from 2010 so some experimental data may be out of date
Much of the conference has focused on consequences

- Halo/Hiro currents
- Runaway electrons

Consequences

How to mitigate the consequences

Important, but need to worry about avoiding disruptions
Consider avoiding disruptions from external kinks

- Goal is to safely traverse to safe, but highly performant, operating point

External kink boundary

- Boundaries are fuzzy because of profile effects
- Steady-state is fuzzy because profile is constantly changing

3

β_N

q_{95}  \quad t_{\text{discharge}} = 0

2.5

\text{External kink boundary}
Many causes of disruptions: stable trajectory needed for all causes

**Ideal modes**
- External kink
  - $q_{95}$ = 3
  - $\beta_N$ = 2.5
- Vertical instability control
  - $\kappa$ = 2
  - $l_i$ = 0.9
- Internal kink (sawtooth)
  - $\rho_{q=1}$ = 0.5

**Non-ideal modes**
- n=1 locked-mode
  - $10^{19}$ m$^{-3}$ $n_e$
  - $\frac{\delta B_r}{B_T}$ = $10^{-3}$
  - $J_{\text{ECCD}} / J_{\text{BS}}$ = 1.2
- TM, NTM
  - $\Delta'$, triggering by ELM/ST/EPM/EF
- n=1 RWM (Scenario 4)
  - $3$ $\beta_N$
  - Feedback, rotation, kinetic stabilization

Feedback, rotation, kinetic stabilization

External kink

Internal kink (sawtooth)
Avoidance is closely tied to disruption prediction

- During a disruptive discharge, the stability limits are reached and then crossed
- As it crosses boundaries, time to detect precursors
  - Callen: Detection time for ideal modes tied to transport time scale
- Experimental detection of precursors tells us how well we understand stability boundaries

Two approaches:
- Detect precursor, mitigate
- Detect boundary, use actuators to nudge back to stable region

External kink boundary
NSTX studies: Multiple cause, physics-based approach is effective

- **Neural network approach:**
  - JET: 23% Miss rate
  - Neural net trained on JET applied to ASDEX: 67% success rate within 10 ms
  - ASDEX trained on JET: 69% success rate within 40 ms

- **Multi-diagnostic, hand-tuned approach (NSTX):**
  - Missed rate: 3.7%
  - False-positive rate: 2.8%
  - Uses: Magnetic signals, neutron emission, loop voltage, rotation measurements, EFIT-derived measurements

CannasB. et al. NF 47, 1559 (2007)
Windsor et al. NF 45, 337 (2005)
Gerhardt et al. NF 53, 063021 (2013)
Burning plasma is a new regime: Fundamentally different physics

- Endothermic regime => exothermic regime
  - Self-heated, not externally heated
  - Significant isotropic 3.5 MeV alpha population
  - Larger device scale
- We will have *less control* of plasma
  Combustion science != locally heated gas dynamics
  Fission reactor fuel physics != Heated fuel rod
- Use simulation to reduce uncertainties
Why Whole Device Model?

- Only model that operates on the long time scale needed for disruption avoidance
- Has synthetic plasma control systems for modeling the actuators
- Many of the problems are really transport problems:
  - Impurities entering the core on JET
  - Inadequate control systems
  - How a plasma reaches an MHD unstable state

Typical Time Scales in a next step experiment with \( B = 10 \text{T}, R = 2 \text{m}, n_e = 10^{14} \text{cm}^{-3}, T = 10 \text{keV} \)

- Single frequency and prescribed plasma background
  - RF Codes: wave-heating and current-drive
- Neglect displacement current, average over gyroangle, (some) with electrons
  - Gyrokinetics Codes: turbulent transport
- Neglect displacement current, integrate over velocity space, neglect electron inertia
  - Extended MHD Codes: device scale stability
- Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia
  - Transport Codes: discharge time-scale

\[ \begin{align*}
\Omega_{ce}^{-1} & \quad 10^{-10} \\
\Omega_{LH}^{-1} & \quad 10^{-8} \\
\Omega_{ci}^{-1} & \quad 10^{-6} \\
\tau_A & \quad 10^{-4} \\
100 & \quad 10^2 \\
10^4 & \quad 10^6 \\
10^8 & \quad 10^10 \\
10^12 & \quad 10^14 \\
\end{align*} \]
Identification of states with acceptable MHD stability

- Need WDM + expt to understand chains of events that lead to disruption
- Example chain: from PFC to plasma core and back:
  - Tile over-temperature → tile melting or ablation → impurity influx → radiated power increase leading to H→L back-transition → p profile peaks, I_i increases → internal kink mode → thermal collapse and/or VDE → possible damage to PFCs
- Need to determine probability of each event to determine overall risk
WDM will be essential for determining optimal actuator and transport response to avoid disruption

- Transport + sources determine profiles
- Profiles determine turbulent transport
  - Can have strongly non-linear responses and/or positive feedback loops (can lead to disruption)
  - Reversed shear (RS) q profile can reduce core transport, re-enforcing RS profile $\rightarrow$ pressure-driven MHD instabilities near $q$-min $\rightarrow$ possible disruption
  - Control of q profile (aka parallel current density profile) is likely essential for disruption avoidance

- WDM vital to designing/validifying controllers for real-time current profile control
  - Same actuators must respond to many other control requests and constraints
  - Example: reduced model evolving: $\psi$, $n$, $T$, $P$, $V_{\text{Loop}}$

\[
\begin{align*}
\mu_0 \frac{\partial j}{\partial t} &= -\nabla \times \nabla \times E \\
\frac{\partial n}{\partial t} &= -\nabla \cdot \Gamma + S_n \\
\frac{3}{2} \frac{\partial (nT)}{\partial t} &= -\nabla \cdot \mathbf{Q} + S_T \\
\frac{\partial \Psi}{\partial t} &= A_{11} \Psi(t) + A_{12} T(t) + B_{11} P(t) + B_{12} n(t) + U \cdot V_{\text{ext}}(t) \\
\varepsilon \frac{\partial T}{\partial t} &= A_{21} \Psi(t) + A_{22} T(t) + B_{21} P(t) + B_{22} n(t)
\end{align*}
\]

Figure 1(b): Real-time control of the $q$-profile using LHCD, NBI and ICRH (Pulse No: 58474, $B_T = 3T$, $I_p = 1.8/1.5M4$). The profile is shown at four different times between 7s and 12s. Pluses represent the 5 $q$-setpoints at $r/a = [0.2 \ 0.4 \ 0.5 \ 0.6 \ 0.7]$.

D. Moreau
Development of Integrated Real-Time Control of Internal Transport Barriers in Advanced Operation Scenarios on JET - EFDA–JET–CP (04)07-29
ITER actuator plasma control matrix is large

Magnetic field coils, heating and current drive sources, and plasma transport properties determine equilibrium shape and profiles.

Pedestal/ELMs, fueling, impurities strongly influence fusion performance.

Heating, current drive, fueling, and 3D field actuators strongly influence plasma MHD stability and thus disruption avoidance.

Disruption mitigation is required when disruption is unavoidable.
Basic picture of simulations for disruption avoidance

At each point:
• Evaluate nearness to disruption boundaries
• Based on nearness to boundary, use actuators appropriately to move in desired direction

Evaluate for each cause: “Curse of many dimensions”

Two main accuracy issues:
1. How accurately can we predict trajectory through parameter space? (reduced models of RF and GK)
2. How accurately can we predict nearness to boundary? (reduced models of MHD)
How can we use modeling to help? Consider disruptions caused by MHD instabilities

- Enables calculation of both safe and best-possible performance of ITER
- Same process can also model performance of real-time controllers
- Longer term: “reduced WDM” + stability forecasting in real-time/PCS
- Each box above represents an extensive validation campaign!!
**Considering just the MHD unknowns**

<table>
<thead>
<tr>
<th>MHD Type</th>
<th>Experimental Understanding</th>
<th>ITER relevance</th>
<th>Theoretical/Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDE</td>
<td>High</td>
<td>Most dangerous, but best controls in place</td>
<td>Reasonably well understood for initial dynamics</td>
</tr>
<tr>
<td>External kink</td>
<td>High</td>
<td>Dangerous, but limits well understood</td>
<td>Reasonably well understood for onset</td>
</tr>
<tr>
<td>Sawtooth</td>
<td>High</td>
<td>Can probably live with?</td>
<td>Reasonably well understood</td>
</tr>
<tr>
<td>NTM</td>
<td>Medium</td>
<td>High: Most frequent cause of disruptions on JET</td>
<td>Need work on locked mode -&gt; disruption</td>
</tr>
<tr>
<td>RWM</td>
<td>Medium</td>
<td>Depends on operating regime</td>
<td>Improving - drift-kinetic effects shown to be important</td>
</tr>
</tbody>
</table>
Reality check

*From A. Siegel on nuclear engineering modeling*

**SciFi**
- "Virtual Experimental Facility"
  - (run a reactor to study anything of interest)
  - First-principles physics
  - Replace experiment
  - Virtual prototyping

**Future**
- Predict Specific Global Properties
  - (mixing, mean temp profile)
  - Some modeling required
  - Imperfect physics
  - Huge range in scales

**Traditional**
- Extrapolate Empirical Correlations
  - Based on experimental data
  - Simple e.g. 1d physics
Can we predict tearing modes?

- Resistive MHD: \( \tilde{B} \cdot \nabla \frac{J_{\parallel 0}}{B_0} \)
  \[ \sim m\tilde{\psi} \frac{\partial^3}{\partial r^3} \psi_0 \]

Kinetic effects: rotation, ion banana orbits, electron kinetics, energetic particles, …
What do we mean by “predictive simulations”

- We are not predictive without significant caveats, and this is likely to be the case for decades to come
  - Historical reasons for using the word “predictive”:
    Predictive WDM was used to distinguish between interpretive WDM
  - But “predictive” carries mental baggage that conveys the wrong idea to people both within and without the fusion community

- Why do simulations?
  - Weather simulations are not predictive either, but they still do them for forecasts
  - Can we forecast disruption probabilities?
    - Hurricane simulations have saved lives.
    - Can disruption WDM save machines?

Validation is crucial to accurate forecasting
WDM has unique challenges for validation

Example from Kinsey, PP 9, 1676 (2002):

The average rms error for all 22 discharges is 18.4%, 13.1%, and 16.7% for $T_e$, $T_i$, and $\nu_{\phi}$, respectively.

... For the entire 125 discharge dataset, the model has an rms error of 12.4% in the core thermal stored energy. The corresponding rms error in the incremental thermal stored energy is 17.4%.

But, this is taking from the experiment:

- Sources
- Sinks
- Magnetic geometry
- Boundary condition
- Free parameter to get best fit for velocity profile
Spirit of UQ: Formalize all inputs and assumptions

- Define experimental and simulation vectors \( x_{\text{exp}}, \ x_{\text{sim}} \):
  \[
  x = [n, Te, Ti, \Omega, \Psi]
  \]

- Flux and sources tensors explicitly separated
  \[
  \Gamma_x(\rho) = \Gamma_{\text{predict}}(\rho) + \Gamma_{\text{interp}}(\rho; p_1, p_2, \ldots) = \Gamma_{\text{GLF23}} + \Gamma_{\text{neo}} + \ldots + \Gamma_{\text{interp}}
  \]
  \[
  S_x(\rho) = S_{\text{predict}}(\rho) + S_{\text{interp}}(\rho; p_1, p_2, \ldots) = S_{\text{RF}} + S_{\text{NB}} + S_{\ldots} + S_{\text{interp}}
  \]

- Choose optimization metric; e.g.,
  \[
  M = \| x_{\text{sim}} - x_{\text{mod}} \|; \quad M = \| x_{\text{sim}}(\rho_s) - x_{\text{mod}}(\rho_s) \|; \quad \ldots
  \]

- Find parameters \( p_1, p_2, \ldots \) which optimize metric
  \[
  \Gamma_{\text{inter}}, S_{\text{interp}} \rightarrow 0 \quad \Rightarrow \text{predictive}
  \]
  \[
  \Gamma_{\text{predict}}, S_{\text{predict}} \rightarrow 0 \quad \Rightarrow \text{interpretive}
  \]
Additive flux minimization technique has been used for JRT

● Want to understand extent to which paleoclassical model explains observations

● Using $x=[n]$ and:

$$\Gamma_{\text{predict}}(\rho) = \Gamma_{\text{Paleo}}(\rho); \quad \Gamma_{\text{interp}}(\rho; D_{\text{add}}) = -D_{\text{add}} \frac{dn}{d\rho};$$

$$S_{\text{diff}}(\rho; S_{0}^{\text{exp}}, \delta) = S_{0}^{\text{exp}} \exp \left[ -\frac{|\rho - \rho_a|}{\delta} \right];$$

● Optimization metric: $$M = \left\| n_{\text{sim}}(\rho_{\text{ped}}) - n_{\text{exp}}(\rho_{\text{ped}}) \right\| / n_{\text{exp}}$$

● Use DAKOTA Project software from Sandia
  ● “Large Scale Engineering and Uncertainty Analysis Software”
  ● Least-squares, Gradient-based unconstrained optimization
Results of optimization study

- Paleoclassical theory requires additional contributions to describe pedestal profiles
  - $\Gamma_{\text{interp}} \gg \Gamma_{\text{paleo}}$
  - But simplified form is implemented
  - ~400 runs in optimization study

Particle source

- SOLPS (courtesy of L. Owen)
- DAKOTA/FACETS

This value is computed in DAKOTA optimization

Electron density

- Experiment
- FACETS simulations
Applying optimization technique to disruption avoidance

- Lessons learned: Automate as much as possible. Use modern architecture to brute force everything.

- Multiple runs allow for statistical measures:
  - Move from “prediction” to “forecasting”

- Automating equilibrium generation has many challenges:
  - Perturbations to for optimizing equilibrium -> delta-W (Cowley)
  - Delta-W is very stiff so small radius of convergence
  - … but routinely done by EFIT for peeling-balloononing studies, currently being done by Pankin with more constrained eq codes.
Conclusions

- Avoidance on ITER might be easier because of the long pulses -> More time to respond
- Scaling current methods to ITER needs computational modeling.

- For disruption avoidance, WDM can be used to:
  - Provide mechanism for reducing complex physics from MHD/GK/… codes to something closer to the boundaries
  - Optimize the plasma control system
  - Provide statistical measure of nearness of stability boundaries
  - Explore the large parameter space more efficiently
- Development of this capability requires extensive validation
- Tools from the applied math community are useful in performing this validation and point to the future of how to use and validate WDM models
Extra Slides
WDM needed for disruption probability validation

- WDM can provide the foundation for understanding coupled plasma processes that can lead to plasma instabilities and disruptions
- Need to treat disruptions (WDM and expt) probabilistically to determine safe operating conditions, improve performance

Table 2. The number of shutdown triggers observed prior to disruptions over the operational period from 2000 to 2007. The first two columns give the numbers for all the disruptions, while in the last two columns intentional disruptions are excluded. The technical shutdowns combine all possible stops triggered by PPCC, shape controller (SC), power supply protection systems and even manual stop buttons.

<table>
<thead>
<tr>
<th>Type of shutdown</th>
<th>All disruptions ($I_p &gt; 1$MA)</th>
<th>Unintentional disruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1707</td>
<td>1301</td>
</tr>
<tr>
<td>Mode Lock</td>
<td>736</td>
<td>43.1%</td>
</tr>
<tr>
<td>Technical (PPCC, SC, etc.)</td>
<td>304</td>
<td>17.8%</td>
</tr>
<tr>
<td>MHD mode</td>
<td>40</td>
<td>2.3%</td>
</tr>
<tr>
<td>None</td>
<td>627</td>
<td>36.7%</td>
</tr>
</tbody>
</table>

Nearly $\frac{1}{2}$ caused by locked TM/NTM
Computation set of nearby (equilibrium) states

- MHD stability quite sensitive to underlying equilibrium
  - Need well resolved, converged equilibrium - fixed and free
  - WDM needs increased spatial resolution (mesh refinement)
  - Uncertainty quantification methods for equilibrium generation need to be more robustly developed
- Above issues also apply to equilibrium reconstruction
- Need ability to easily and rapidly vary/scale $p$, $q$, $<\mathbf{J} \times \mathbf{B}>$, ...
  - Also need a range of constraints: $I_p$, $\beta_N$, $q_{95}$, ...
- 3D effects also important in tokamak equilibrium solutions
  - Error fields, TBM/TF ripple: impacts transport, stability
  - RMP coils: Islands in pedestal(?), divertor strike-pt splitting
  - Need 3D equil. solvers (perturbed ideal, with islands, ...)
  - Actual & synthetic diagnostics to measure/constrain in 3D
  - Resolution, convergence requirements also apply to 3D
ITER needs WDM for plasma control system (PCS) development to achieve $Q=10$ while avoiding disruptions.

**PCS Interfaces**

- 55 diagnostic systems, 20 actuator systems connected with real-time networks
- PCS connected to other CODAC systems: live databases, mass data storage, supervisory control system ...
- PCS and Interlock Systems together provide ITER investment protection

**PCS novel features/challenges**

1) novel control schemes - e.g. Fusion burn control
   - $\alpha$-particle/energetic particle physics
   - energetic particle confinement, influence of self-heating, enhanced heat loads

   - Burning plasma control scenarios
   - burn control (D/T mix profile), transport barriers, dominant core pellet fueling
   - non-linear interactions between $\alpha$ and auxiliary heating, plasma pressure, rotation and current density profiles

2) Multiple coupled control
   - Number of actuators per control functions
   - Example: Electron Cyclotron Heating used for heating, NTM stabilization, sawtooth control, temperature profile control
   - For high performance discharges, most of the above need to be controlled.
   - Most present day tokamaks use designated shots where only few coupled parameters are routinely controlled simultaneously (apart from equilibrium).
   - Active R&D topic with major impact on PCS design

3) Event handling
   - Keep discharges available for physics exploitation
   - Optimize discharge time, enable event-driven multiple experiments per discharge
   - Avoid disruptions and continue discharge if possible
     - Mitigate plasma-driven effects and component failure & problems
     - Switch to backup heating systems or scenario, suppress MHD instabilities, cope with sensor & actuator failure
     - Event forecasting
     - Implement real-time modeling if applicable, avoid undesired plasma regimes
   - Provide dynamic ramp down scenarios (limit use of disruption mitigation system)

   - Most demanding, practically not implemented anywhere, presently with complexity close to ITER needs
Modern tokamaks are rather complex (I)

- Transformer
- Pellet injectors
- Gas injections system
- Vacuum vessel
- Neutral beam
- Pumps
- Coils
Modern tokamaks are rather complex (II)

Each method for controlling the plasma needs to be included in modeling (to varying levels of degrees)
WDM codes answer the broadest tokamak operational questions

- How can we best operate current experiments?
  - How do we understand interpret experimental data in terms of physically intuitive quantities?
  - How do we predict the behavior of the next discharge based on our current knowledge?
  - How do we achieve higher performance given our available actuators?

- How do we extend our knowledge to ITER?
  - E.g., how do we avoid disruptions?

- How do we extend our knowledge to DEMO?
  - What materials should we use? What sources are optimal?
Core Transport Equations

Ion species density

\[
\begin{align*}
\left[ \frac{1}{V'} \frac{\partial}{\partial t} V' + \dot{\rho} \frac{\partial}{\partial \rho} \right] n + \frac{1}{V'} \frac{\partial}{\partial \rho} [V' \Gamma_n] &= \langle S_n \rangle \\
\end{align*}
\]

\( N_i \) equations

\( (N_i=\# \text{ of ion species}) \)

Species energy

\[
\begin{align*}
\left[ \frac{1}{V'^{5/3}} \frac{\partial}{\partial t} V'^{5/3} + \dot{\rho} \frac{\partial}{\partial \rho} \right] \frac{nT}{\gamma - 1} + \frac{1}{V'} \frac{\partial}{\partial \rho} [V' \Gamma_E] &= \langle Q_{net} \rangle \\
\end{align*}
\]

\( N_i + 1 \) equations

Total angular momentum

\[
\begin{align*}
\left[ \frac{1}{V'} \frac{\partial}{\partial t} V' + \dot{\rho} \frac{\partial}{\partial \rho} \right] L_T + \frac{1}{V'} \frac{\partial}{\partial \rho} [V' \Gamma_\Omega] &= \langle S_\Omega \rangle \\
\end{align*}
\]

1 equation

Poloidal flux

\[
\frac{\partial}{\partial t} \psi_p - \frac{\eta_{nc}^{\psi}}{\mu_0} \Delta^* \psi_p &= \langle S_\psi \rangle \\
\]

1 equation

Together with separate 2D equilibria equation:

\[
\Delta^* \psi = -R^2 \mu_0 \frac{\partial p}{\partial \psi} - F \frac{\partial F}{\partial \psi} \\
\]

And neutrals equation which is not shown (potentially 2D)
1D Core Transport Equations

\[
\begin{align*}
\frac{1}{V'} \frac{\partial}{\partial t} V' + \dot{\rho} \frac{\partial}{\partial \rho} V' + \frac{1}{V'} \frac{\partial}{\partial \rho} \left[ V' \right] n &= \left\langle S_n \right\rangle \\
\frac{1}{V'^{5/3}} \frac{\partial}{\partial t} V'^{5/3} + \dot{\rho} \frac{\partial}{\partial \rho} V'^{5/3} &= \left\langle Q_{\text{net}} \right\rangle \\
\frac{1}{V'} \frac{\partial}{\partial \rho} \left[ V' \right] L_T + \frac{1}{V'} \frac{\partial}{\partial \rho} \left[ V' \right] \Gamma_S &= \left\langle S_\Omega \right\rangle \\
\frac{\partial}{\partial t} \psi_p &= \left\langle S_\psi \right\rangle
\end{align*}
\]
Component often classified by how they fit into WDM paradigm

Component list at:
http://fspcomp.web.lehigh.edu/index.php/Existing_components

Lists 67 components

<table>
<thead>
<tr>
<th>Plasma Transport</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent:</td>
<td>Neoclassical</td>
</tr>
<tr>
<td>Coppi-Tang,…</td>
<td>Chang-Hinton,…</td>
</tr>
<tr>
<td>GLF23, MMM95</td>
<td>NCLASS</td>
</tr>
<tr>
<td>TGLF, MMM08</td>
<td>NEO</td>
</tr>
</tbody>
</table>

| Turbulent:       | Neoclassical |
| Coppi-Tang,…    | Chang-Hinton,… |
| GLF23, MMM95    | NCLASS       |
| TGLF, MMM08     | NEO          |
| GYRO, GEM, …    |             |

PLASMA TRANSPORT | SOURCES

NEUTRAL BEAM INJECTION,…
NBEAM
NUBEAM
RF HEATING AND CURRENT DRIVE
GENRAY, TORAY
TORIC
AORSA

Increasing computational cost

2D EQUILIBRIA (Includes coils)
TEQ, VMEC, EFIT, ..

MHD Linear Stability
DCON, ELITE, MARS, …

MHD Transport Models
ISLAND, ELM, Sawtooth, …

Kinetic Stability
GS2, …

FUSION HEATING

PELLET INJECTION
GLAQUELC,…
“Edge region” acts as boundary condition for core region

Many ways harder than core plasmas
## FACETS goal: WDM for core-edge-wall using HPC resources

<table>
<thead>
<tr>
<th>FACETS</th>
<th>Profile advance</th>
<th>Dynamic Eq.</th>
<th>Parallel NB</th>
<th>Parallel RF</th>
<th>Parallel reduced flux calcs</th>
<th>Embed Turb.</th>
<th>2D Edge Transp.</th>
<th>Wall modeling</th>
</tr>
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<tr>
<td>pTRANSP</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
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<td>TSC</td>
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<td>IPS/TSC</td>
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<td>YES</td>
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<td>YES</td>
<td>YES</td>
<td>NO</td>
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</tr>
<tr>
<td>FACETS</td>
<td>YES</td>
<td>~6 months</td>
<td>YES</td>
<td>~6 mo. w/ IPS</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>~6 months</td>
</tr>
</tbody>
</table>

Note: "YES" means the feature is supported, "NO" means the feature is not supported.
Possible examples of SciFi

● Sovinec: Can we predict that tile 539 will fall into the plasma and cause it to disrupt?
● L-H transition (predator prey model canonical chaotic system.

● Can we predict tearing mode onset?
  ◆ Resistive MHD: 
  \[ \tilde{B} \cdot \nabla \frac{J_{||0}}{B_0} \]
  \[ \sim m\tilde{\psi} \frac{\partial^3}{\partial r^3}\psi_0 \]
  ◆ Kinetic effects: rotation, ion banana orbits, electron kinetics, energetic particles, …