Computational Modeling for Disruption Avoidance

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J. Menard, PPPL

Acknowledge discussions with
A. Pankin, D. Humphreys, V. Chan, A. Reiman, 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Caveat: Many slides come from 2010 so some experimental data may be out of date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

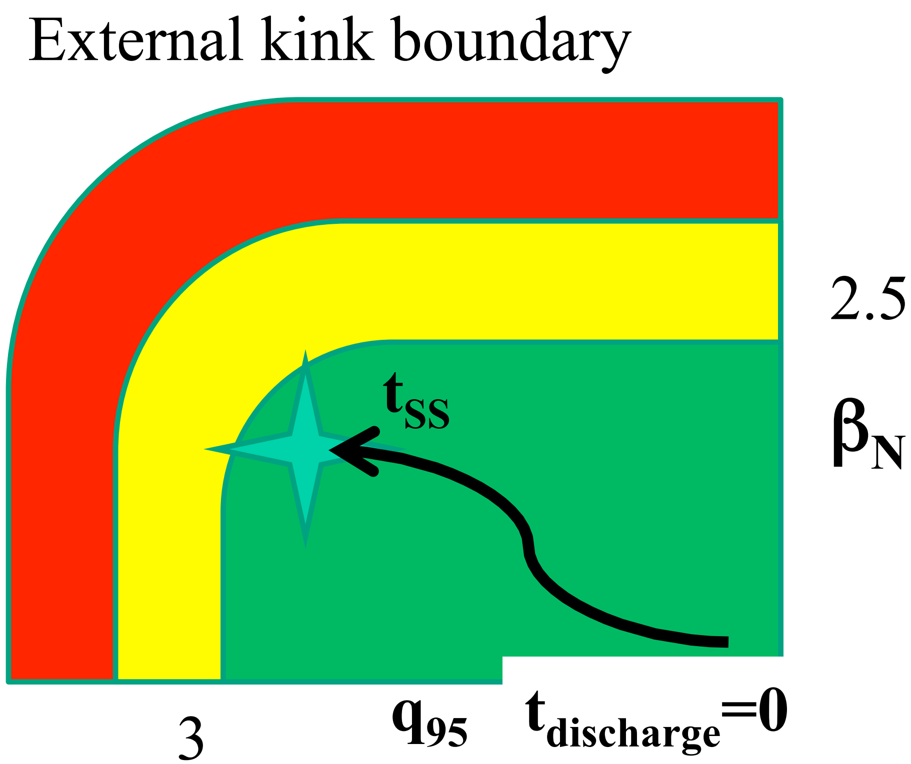
+

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**

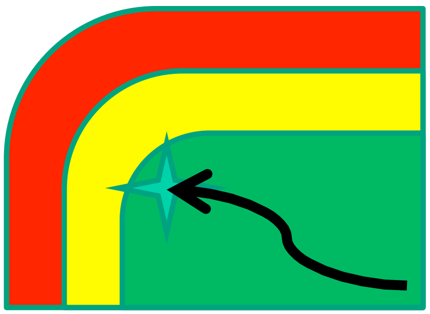


- **Boundaries are fuzzy because of profile effects**
- **Steady-state is fuzzy because profile is constantly changing**

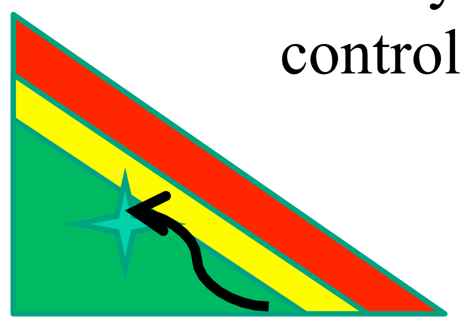
Many causes of disruptions: stable trajectory needed for all causes

Ideal modes

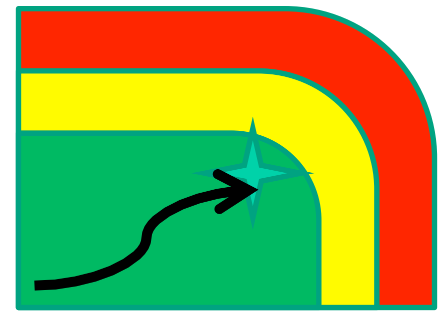
External kink



Vertical instability control

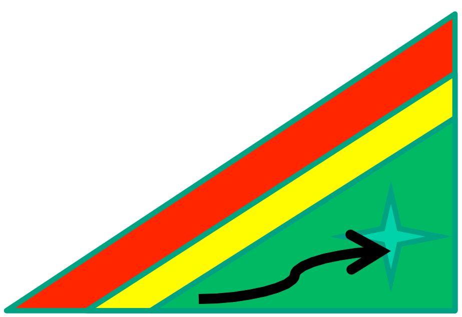


Internal kink (sawtooth)

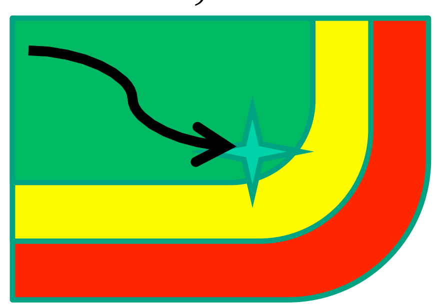


Non-ideal modes

n=1 locked-mode

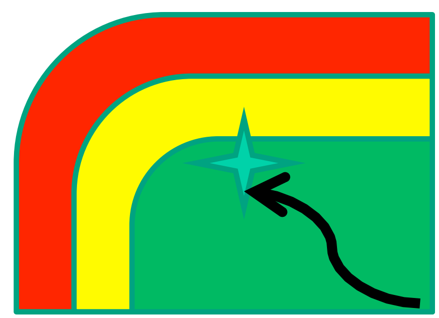


TM, NTM



Δ′, triggering by ELM/ST/EPM/EF

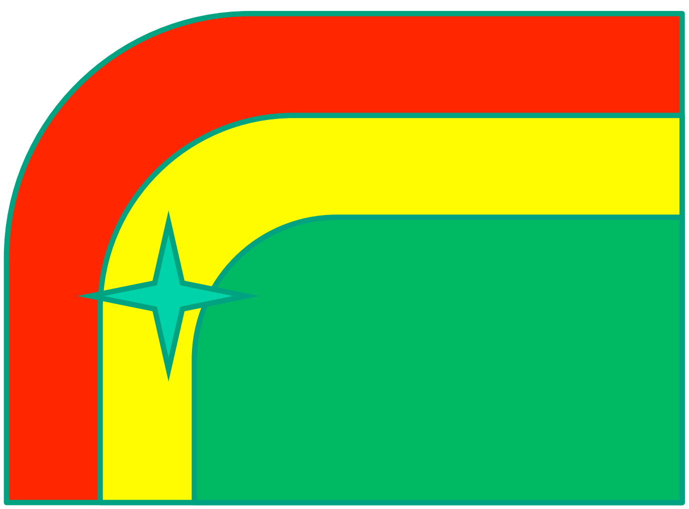
n=1 RWM (Scenario 4)



Feedback, rotation, kinetic stabilization

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

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

CannasB.*etal* NF ***47,****1559* ***(****2007)*

Windsor *etal* NF ***45,*** *337 (2005)*

- **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

Gerhardt *etal* 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

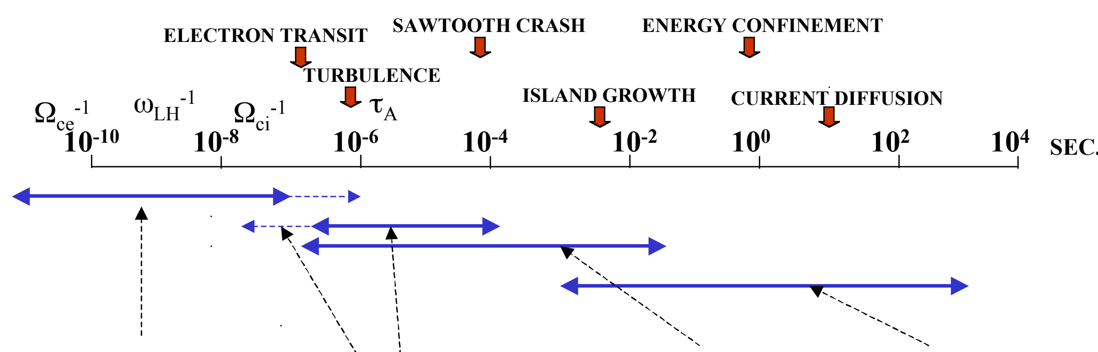
  Fission reactor fuel physics != Heated fuel rod

- 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 $B = 10$ T, $R = 2$ m, $n_e = 10^{14}$ cm^{-3}, $T = 10$ keV

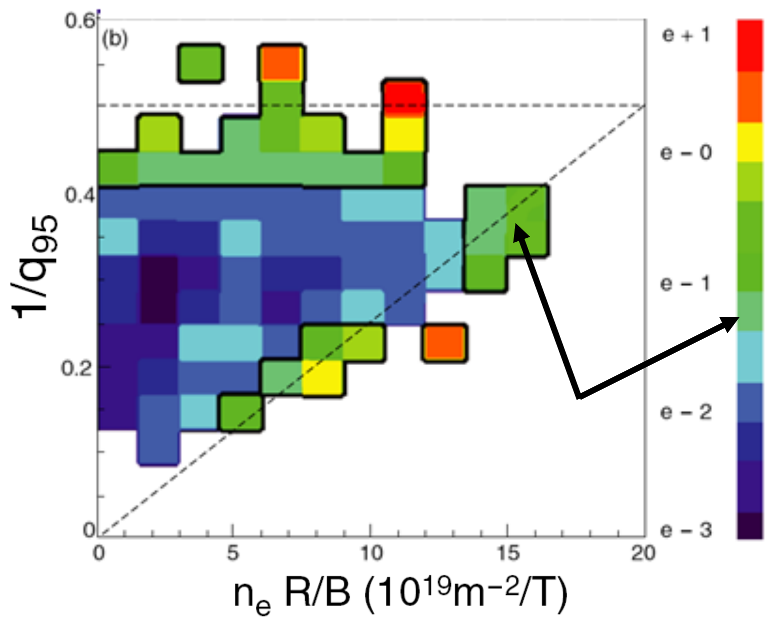


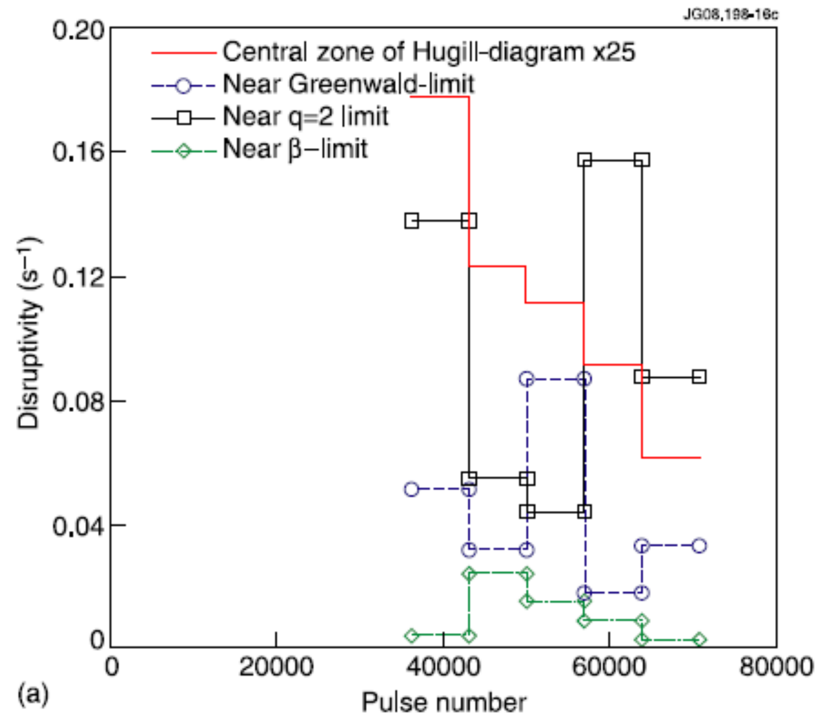
Single frequency and prescribed plasma background	Neglect displacement current, average over gyroangle, (some) with electrons	Neglect displacement current, integrate over velocity space, neglect electron inertia	Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia
RF Codes	Gyrokinetics Codes	Extended MHD Codes	Transport Codes
wave-heating and current-drive	turbulent transport	device scale stability	discharge time-scale
6D	5D	3D	1.5D

Jardin

Identification of states with acceptable MHD stability

P.C. de Vries Nucl. Fusion **49** (2009) 055011





- **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, l_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 → pressure-driven MHD instabilities near q-min → possible disruption
  - Control of q profile (aka parallel current density profile) is likely essential for disruption avoidance

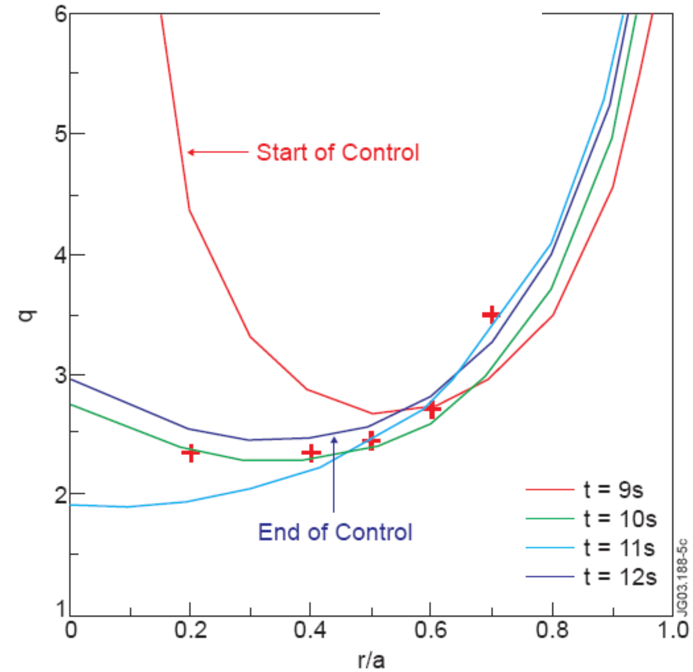


Figure 1(b): Real-time control of the q-profile using LHCD, NBI and ICRH (Pulse No: 58474, B_T = 3T, I_p = 1.8/1.5MA). The profile is shown at four different times between 7s and 12s. Pluses represent the 5 q-setpoints at r/a = [0.2 0.4 0.5 0.6 0.7].

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

$$\mu_0 \frac{\partial j}{\partial t} = -\nabla \times \nabla \times E \qquad \frac{\partial n}{\partial t} = -\nabla . \Gamma + S_n \qquad \frac{3}{2}\frac{\partial (nT)}{\partial t} = -\nabla . Q + S_T$$

$$\partial \Psi / \partial t = A_{11}\Psi(t) + A_{12} T(t) + B_{11} P(t) + B_{12} n(t) + U.V_{ext}(t)$$

$$\varepsilon\, \partial T / \partial t = A_{21}\Psi(t) + A_{22} T(t) + B_{21} P(t) + B_{22} n(t)$$

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

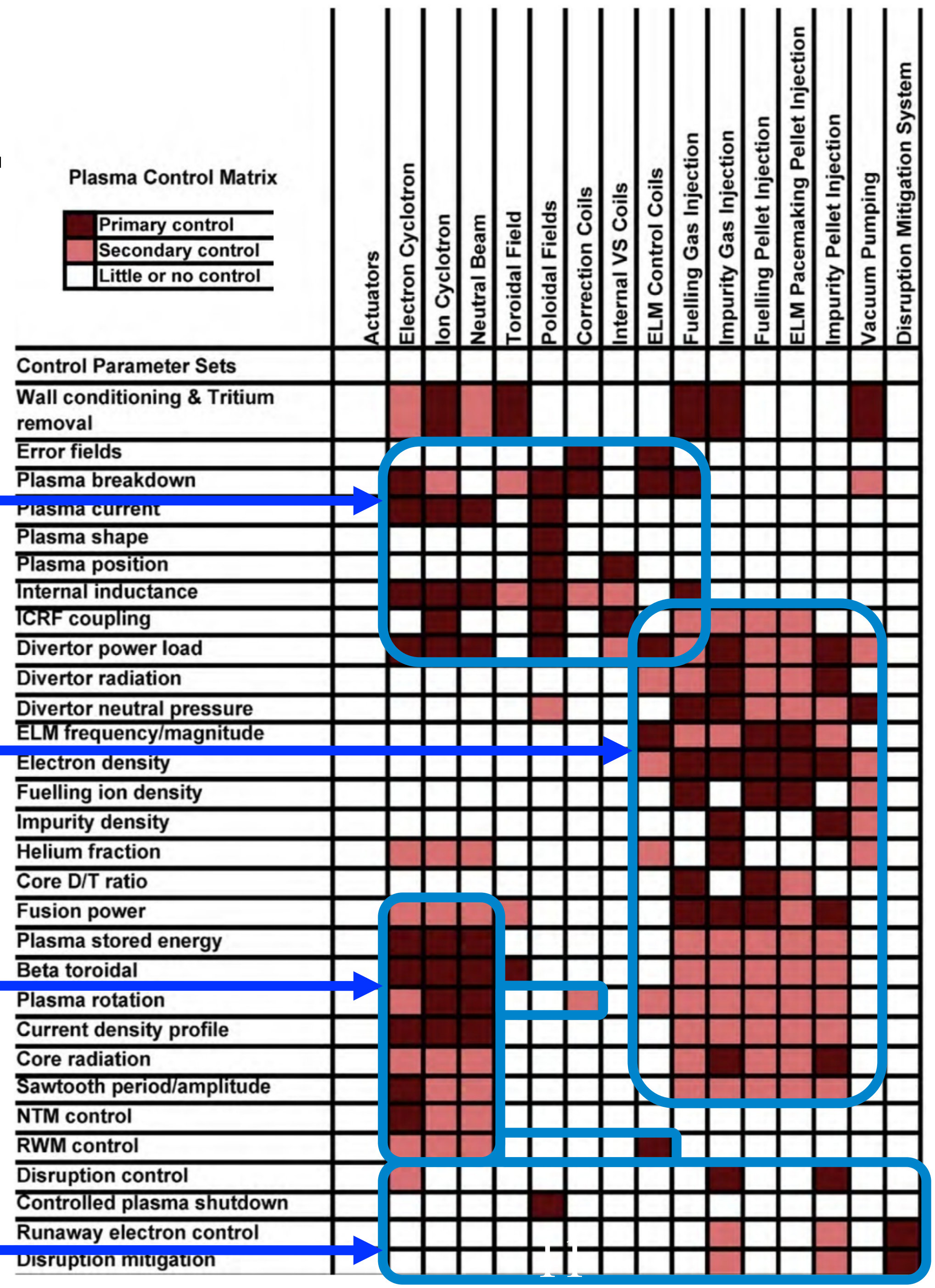
J.A. Snipes et al. / Fusion Engineering and Design 85 (2010) 461–465

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

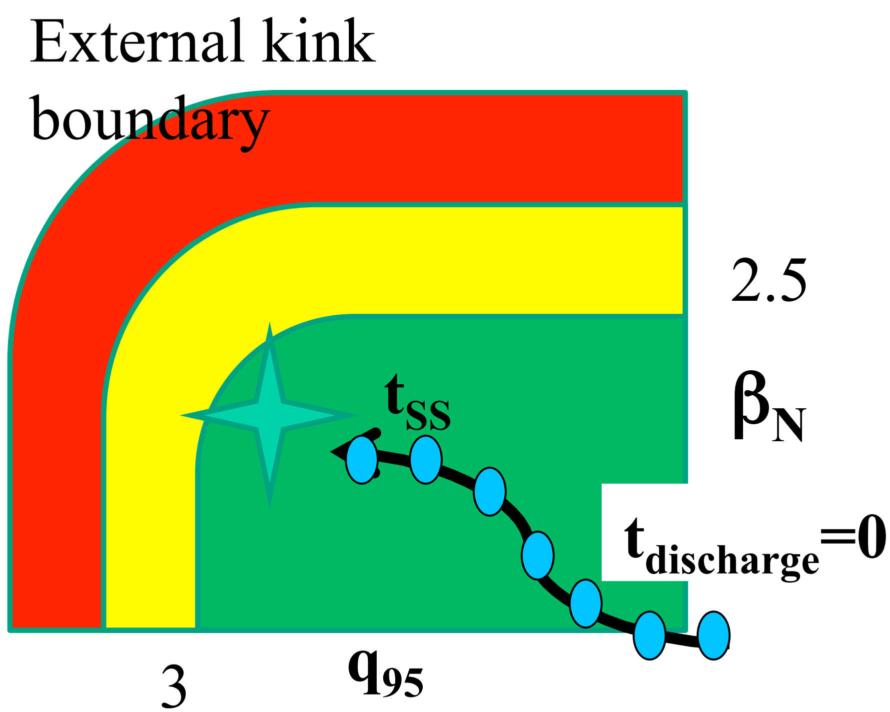
Pedestal/ELMs, fueling, impurities strongly influence fusion performance

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:

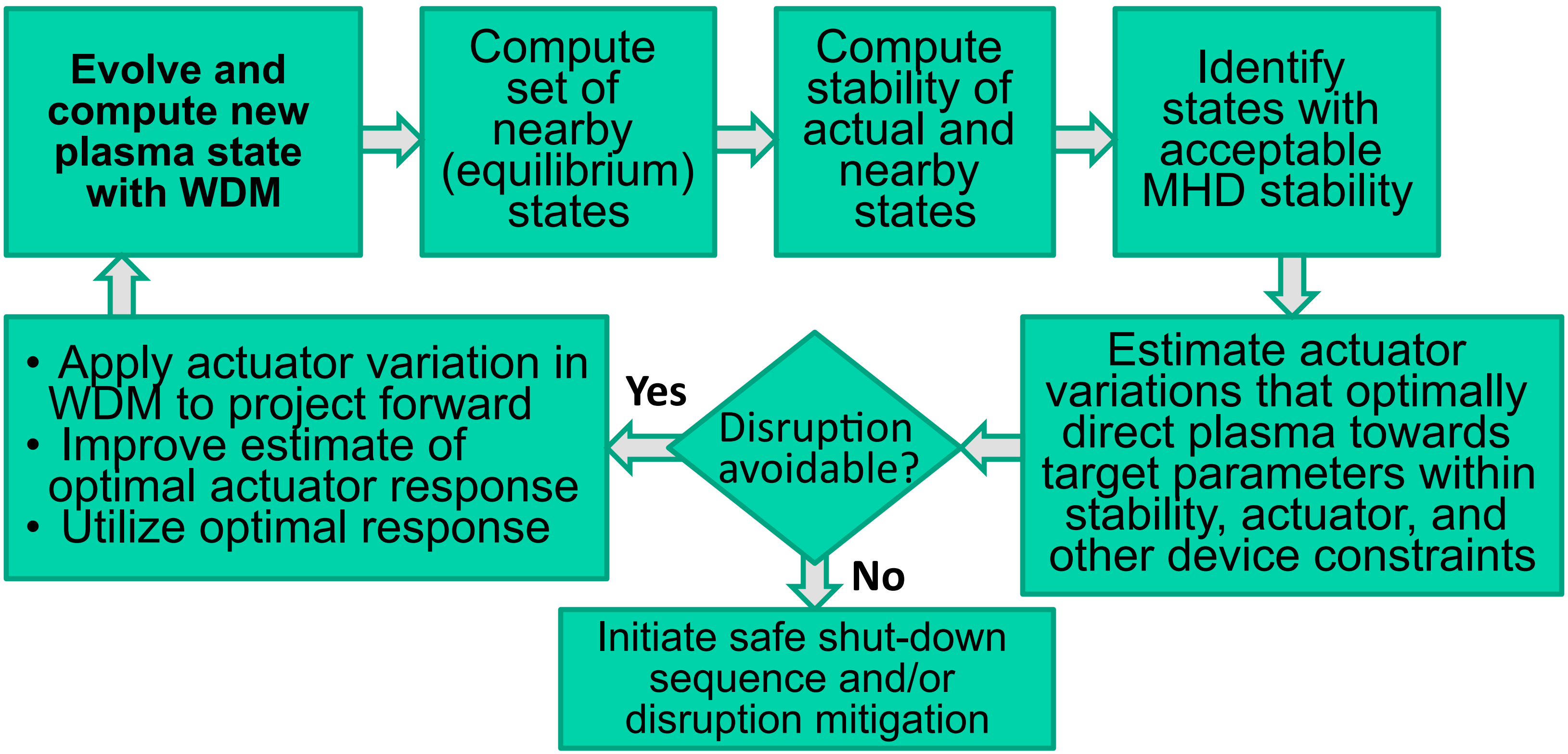
- **Evaluate nearness to disruption boundaries**
- **Based on nearness to boundary, use actuators appropriately to move in desired direction**

- **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

Flow-chart for WDM-based stability forecasting:



- **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

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

Reality check

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From A. Siegel on nuclear engineering modeling

Fundamental insight

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

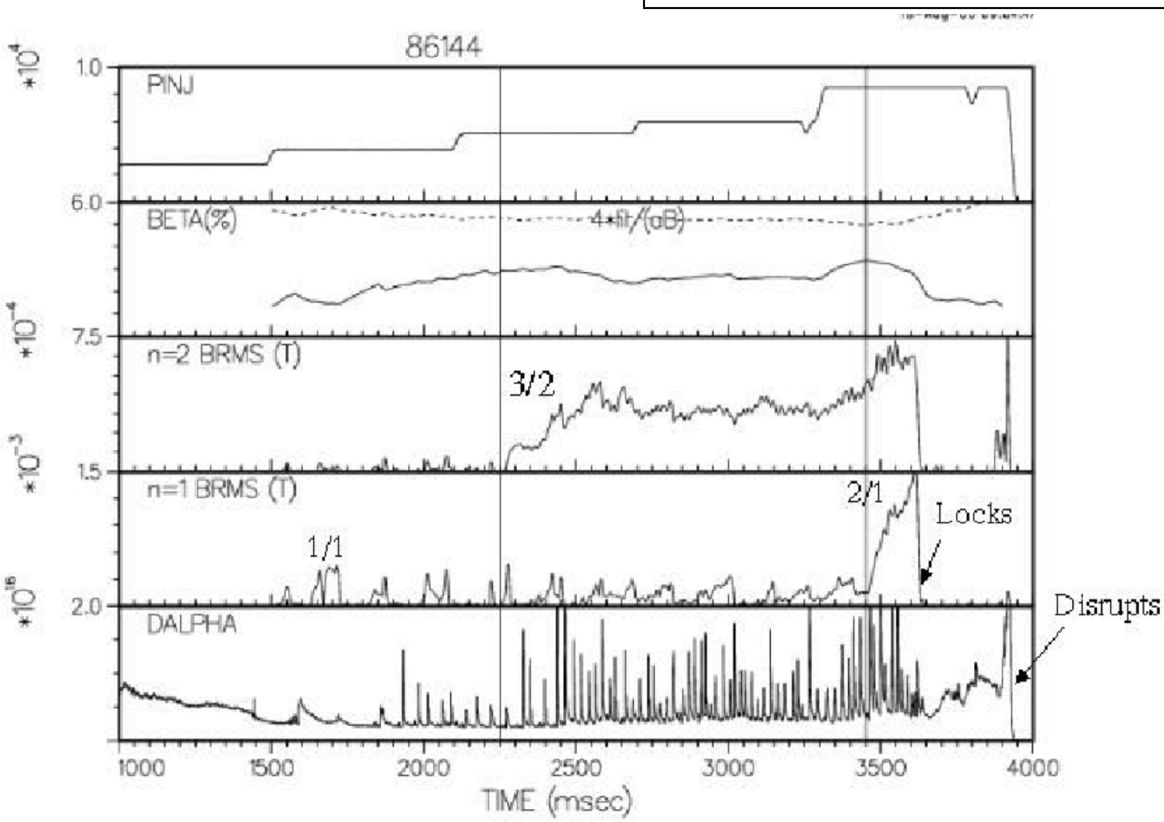
- Based on experimental data
- Simple e.g. 1d physics

Can we predict tearing modes?

- Resistive MHD: $\tilde{B} \bullet \nabla \frac{J_{\parallel 0}}{B_0}$

$$\sim m\tilde{\psi}\frac{\partial^3}{\partial r^3}\psi_0$$

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 Te , Ti , and vphi , 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 xexp, xsim:**

$$x = [n, Te, Ti, \Omega, \Psi]$$

- **Flux and sources tensors explicitly separated**

$$\Gamma_x(\rho) = \Gamma_{predict}(\rho) + \Gamma_{interp}(\rho; p_1, p_2, \ldots) = \Gamma_{GLF23} + \Gamma_{neo} + \ldots + \Gamma_{interp}$$
$$S_x(\rho) = S_{predict}(\rho) + S_{interp}(\rho; p_1, p_2, \ldots) = S_{RF} + S_{NB} + S_{\ldots} + S_{interp}$$

- **Choose optimization metric; e.g.,**

$$M = \left\| x_{sim} - x_{\mathrm{mod}} \right\|; \quad M = \left| x_{sim}(\rho_s) - x_{\mathrm{mod}}(\rho_s) \right|; \quad \ldots$$

- **Find parameters p1, p2, … which optimize metric**
  Γ_{inter} , S_{interp} -> 0 => predictive
  $\Gamma_{predict}$, $S_{predict}$ -> 0 => interpretive

Additive flux minimization technique has been used for JRT

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- **Want to understand extent to which paleoclassical model explains observations**
- **Using *x=[n]* and:**

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

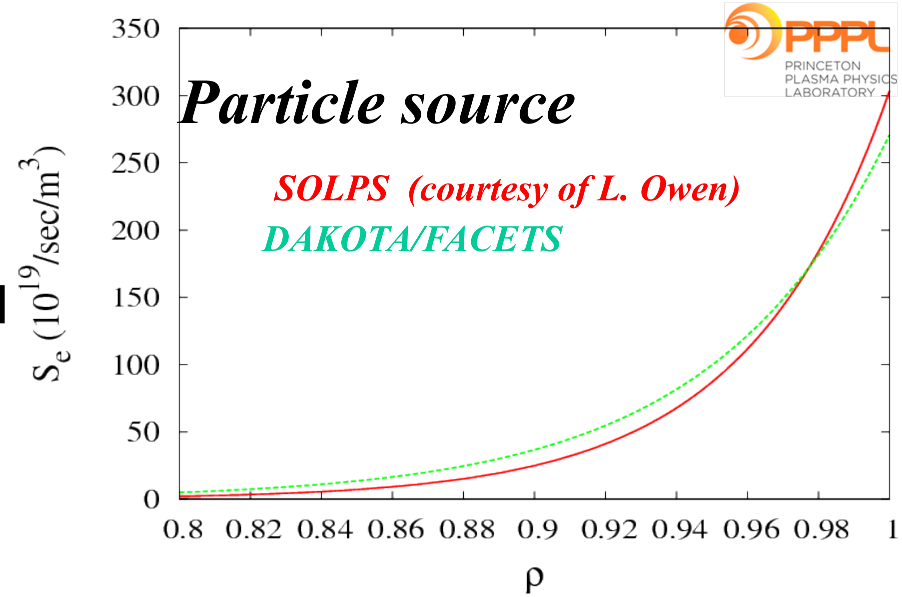
$$S_{diff}(\rho; S_0^{\exp}, \delta) = S_0^{\exp}\exp\left[-\frac{|\rho - \rho_a|}{\delta}\right]$$

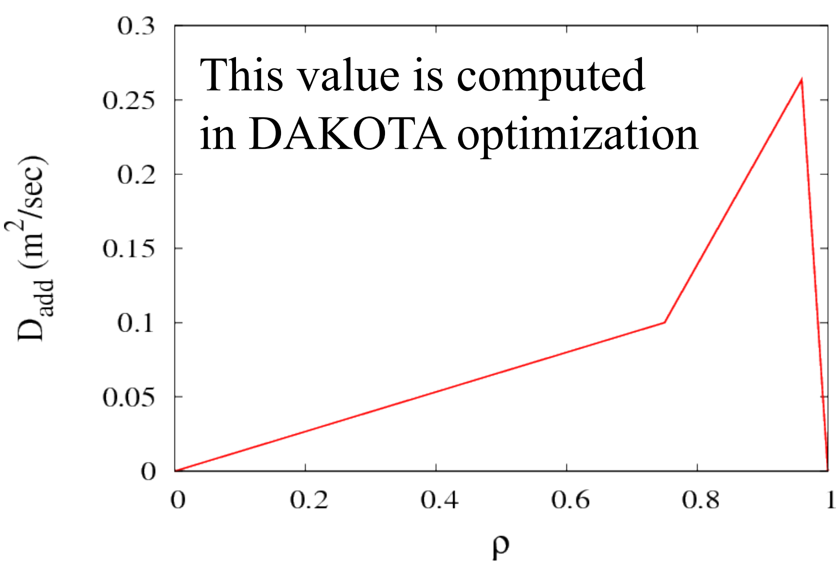
- **Optimization metric:** $M = \left\| n_{sim}(\rho_{ped}) - n_{\exp}(\rho_{ped}) \right\| / n_{\exp}$

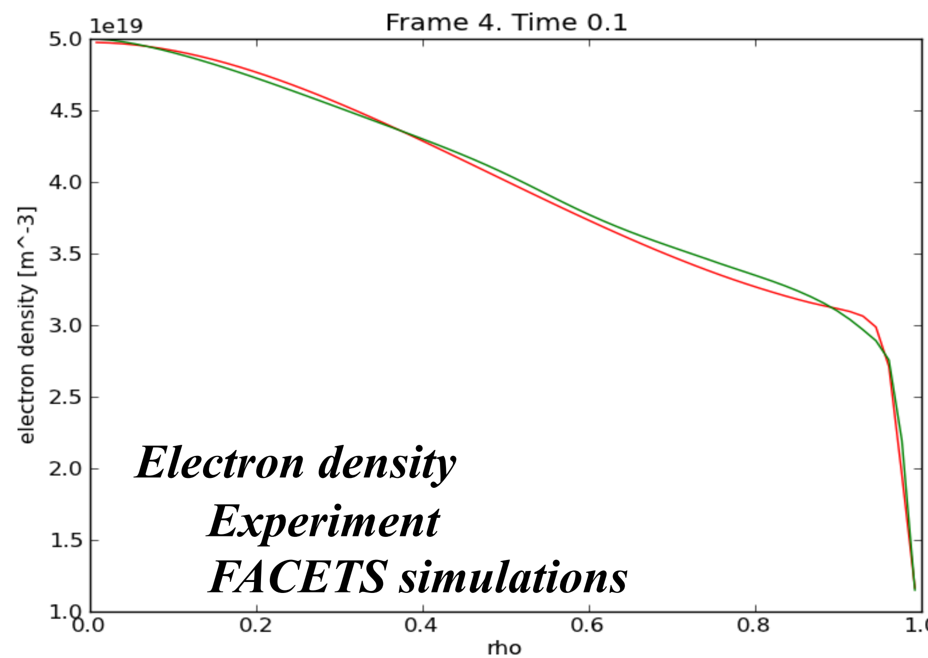
- **Use DAKOTA Project software from Sandia**
  - **"Large Scale Enginering and Uncertainty Analysis Software"**
  - **Least-squares, Gradient-based unconstrained optimization**

Results of optimization study

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







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 equilbrium -> delta-W (Cowley)
  - Delta-W is very stiff so small radius of convergence
  - … but routinely done by EFIT for peeling-ballooning 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

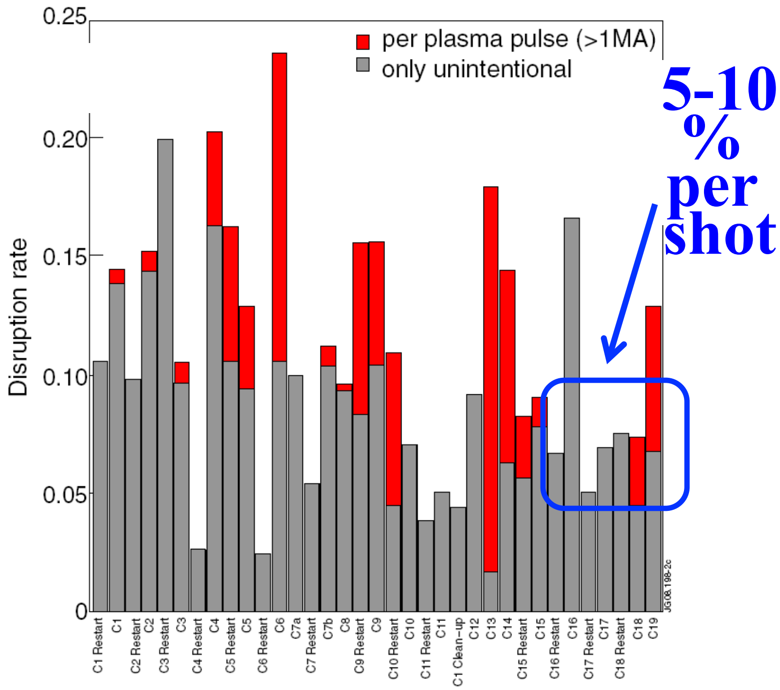


Figure 2. The total disruption rate per plasma pulse (red) and the rate for only unintentional disruptions (grey) for the various commissioning and experimental campaigns from 2000 to 2007. Note that the duration and number of plasmas produced in each campaign can vary considerably.

P.C. de Vries Nucl. Fusion **49** (2009) 055011

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.

	All disruptions (I_p > 1 MA)		Unintentional disruptions	
Total	1707		1301	
Type of shutdown				
Mode Lock	736	43.1%	630	48.4%
Technical (PPCC, SC, etc.)	304	17.8%	304	23.4%
MHD mode	40	2.3%	40	3.1%
None	627	36.7%	327	25.1%

Nearly ½ caused by locked TM/NTM

- **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) probablistically to determine safe operating conditions, improve performance**

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*, <JxB>, …
  - Also need a range of constraints: I_P, β_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

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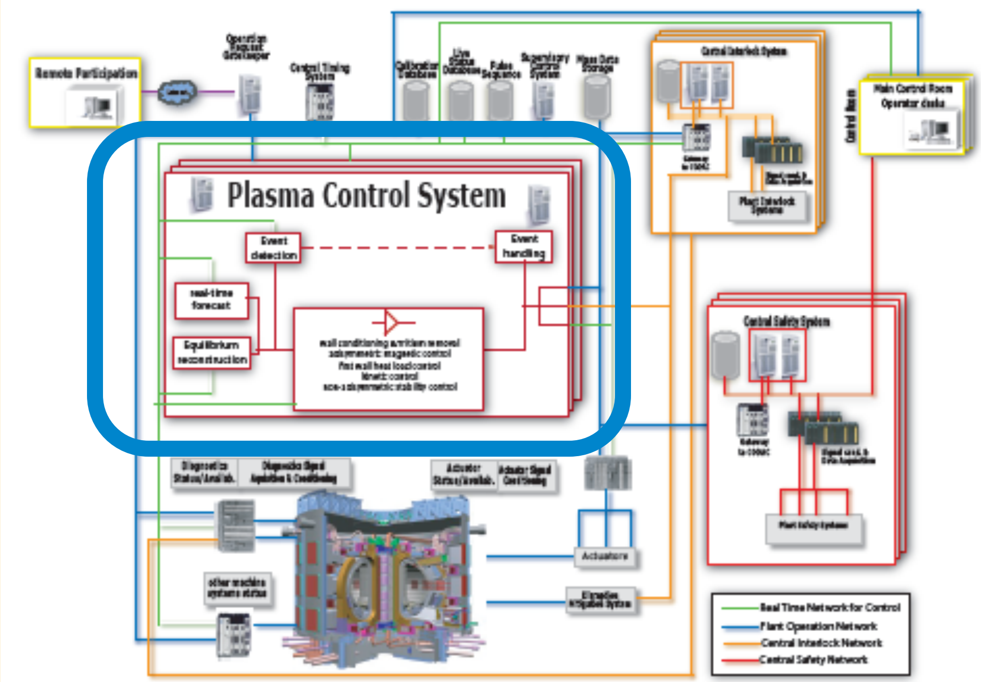
PCS Interfaces



- 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

- α-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 fuelling
  - non-linear interactions between α and auxiliary heating, plasma pressure, rotation and current density profiles

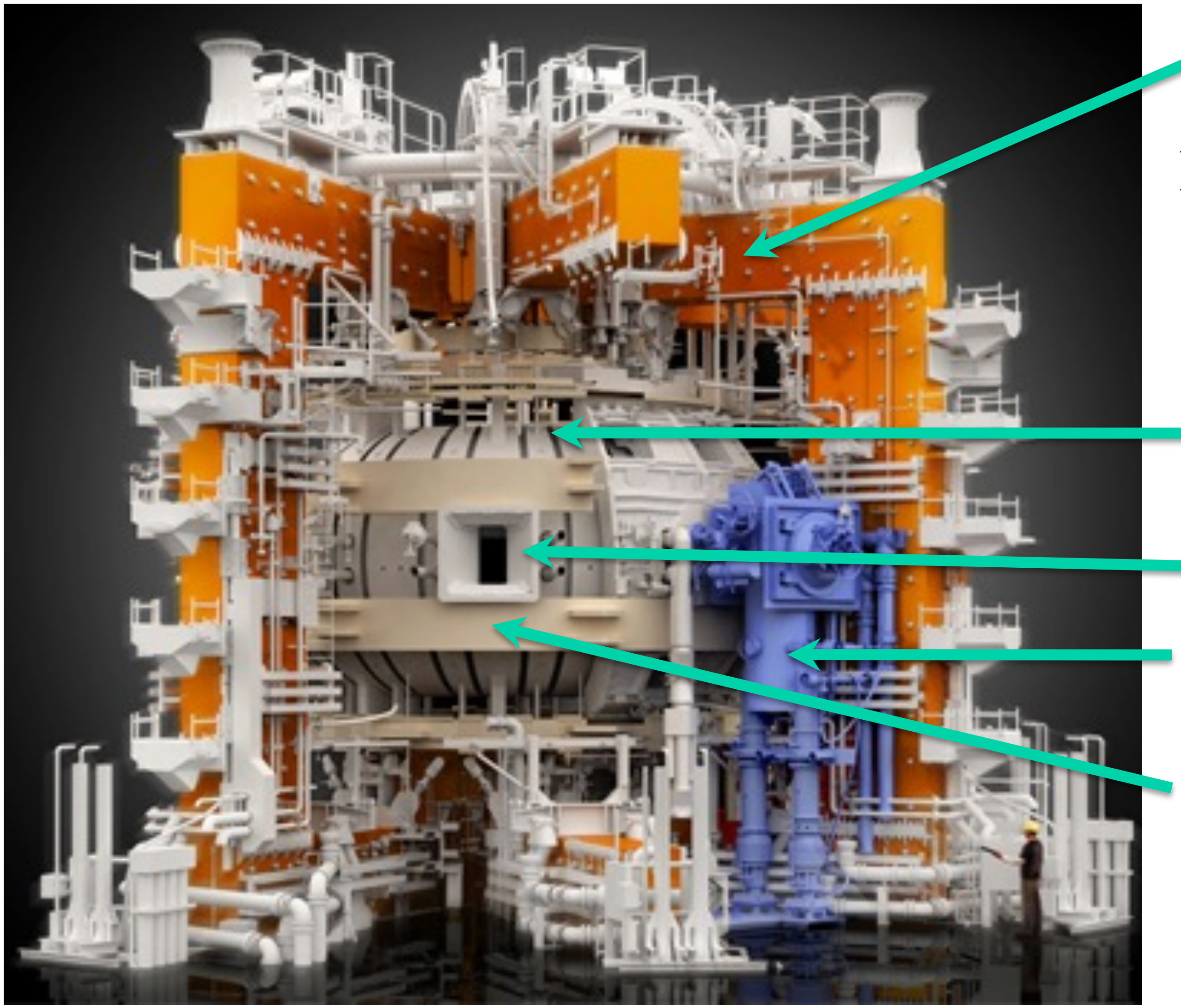
2) multiple coupled control

- Number of actuators per control functions
- Example: Electron Cyclotron Heating used for heating, NTM stabilization, sawtooth contol, 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

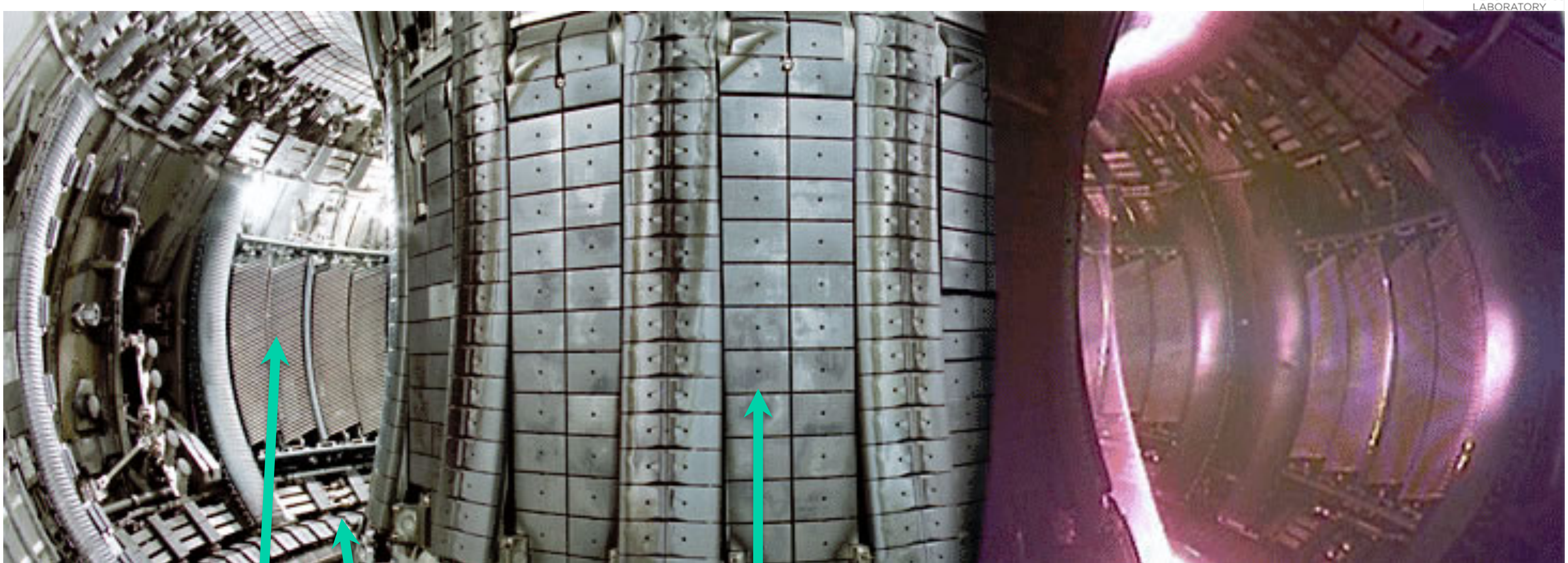
3) event handling

- 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)



Modern tokamaks are rather complex (II)



RF Antennas

Divertors

Plasma Facing Materials

Diagnostic Ports

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 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
$$\left[\frac{1}{V'}\frac{\partial}{\partial t}V' + \dot{\rho}\frac{\partial}{\partial \rho}\right] n \quad + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \ \Gamma_n\right] = \left\langle S_n \right\rangle$$
N_i equations
(N_i=# of ion species)

Species energy
$$\left[\frac{1}{V'^{5/3}}\frac{\partial}{\partial t}V'^{5/3} + \dot{\rho}\frac{\partial}{\partial \rho}\right]\frac{nT}{\gamma - 1} + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \ \Gamma_E\right] = \left\langle Q_{net} \right\rangle$$
N_i +1 equations

Total angular momentum
$$\left[\frac{1}{V'}\frac{\partial}{\partial t}V' + \dot{\rho}\frac{\partial}{\partial \rho}\right] L_T \quad + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \ \Gamma_\Omega\right] = \left\langle S_\Omega \right\rangle$$
1 equation

Poloidal flux
$$\frac{\partial}{\partial t}\psi_p \quad - \frac{\eta_\parallel^{nc}}{\mu_0}\Delta^+\psi_p = \left\langle S_\psi \right\rangle$$
1 equation

3 + N_i equations

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

$$\left[\frac{1}{V'}\frac{\partial}{\partial t}V' + \dot{\rho}\frac{\partial}{\partial \rho}\right] n + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \ \Gamma_n\right] = \langle S_n \rangle$$

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

$$\left[\frac{1}{V'}\frac{\partial}{\partial t}V' + \dot{\rho}\frac{\partial}{\partial \rho}\right] L_T + \frac{1}{V'}\frac{\partial}{\partial \rho}\left[V' \ \Gamma_\Omega\right] = \langle S_\Omega \rangle$$

$$\frac{\partial}{\partial t}\psi_p - \frac{\eta_{\parallel}^{nc}}{\mu_0}\Delta^{+}\psi_p = \langle S_\psi \rangle$$

Sources

Equilibrium

Core Profiles (dependent variables)

Transport

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

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

Increasing computational cost

SOURCES

NEUTRAL BEAM INJECTION,…
- NBEAM
- NUBEAM

RF HEATING AND CURRENT DRIVE
- GENRAY, TORAY
- TORIC
- AORSA

FUSION HEATING

PELLET INJECTION

GLAQUELC,…

2D EQUILIBRIA (Includes coils)

TEQ, VMEC, EFIT, ..

MHD Linear Stability

DCON, ELITE, MARS, …

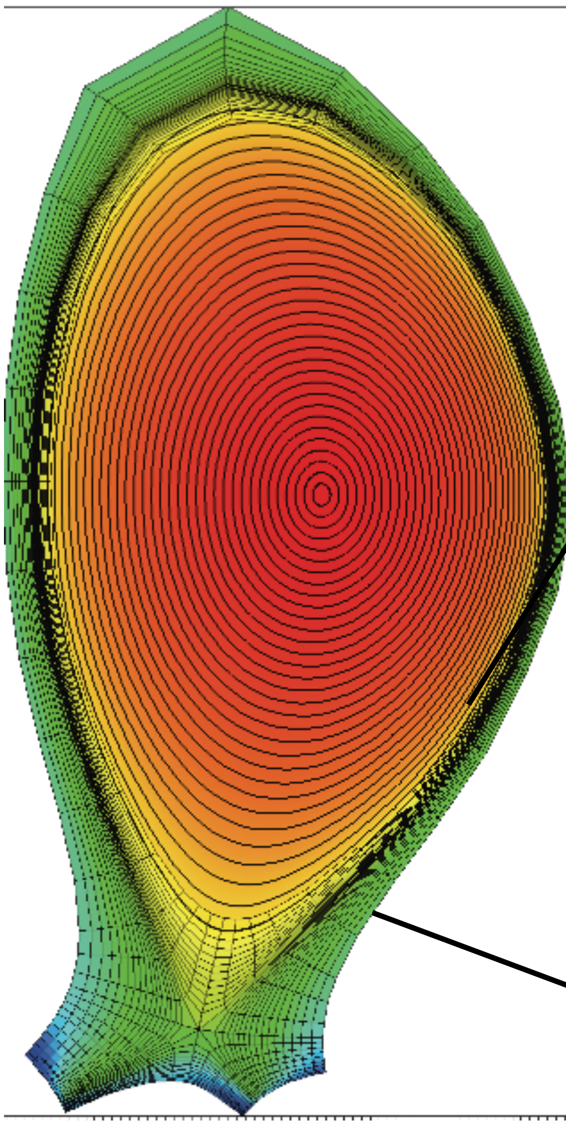
MHD Transport Models

ISLAND, ELM, Sawtooth, …

Kinetic Stability

GS2, …

“Edge region” acts as boundary condition for core region



2D TRANSPORT
UEDGE,
TEMPEST,XGC0

NEUTRAL MODEL
UEDGE, DEGAS, …

RADIATION
CRETIN, …

WALL MODELING
WALLPSI, REDEP, …

3D TRANSPORT
BOUT++, XGC1, …

Many ways harder than core plasmas

FACETS goal: WDM for core-edge-wall using HPC resources

	Profile advance	Dynamic Eq.	Parallel NB	Parallel RF	Parallel reduced flux calcs	Embed Turb.	2D Edge Transprt	Wall modeling
pTRANSP	YES	YES	YES	YES	NO	NO	NO	NO
TSC	YES	YES	YES	NO	YES	NO	NO	NO
XPTOR	YES	YES	NO	NO	NO	NO	NO	NO
CORSICA	YES	YES	NO	NO	NO	NO	NO	NO
TRINITY	NO	NO	NO	NO	NO	YES	NO	NO
TGYRO	NO	NO	NO	NO	YES	YES	NO	NO
IPS/TSC	YES	YES	YES	YES	YES	NO	NO	NO
FACETS	YES	~6 months	YES	~6 mo. w/ IPS	YES	YES	YES	~6 months

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:**

$$\tilde{B}\bullet\nabla\frac{J_{\|0}}{B_0} \sim m\tilde{\psi}\frac{\partial^3}{\partial r^3}\psi_0$$

  - **Kinetic effects: rotation, ion banana orbits, electron kinetics, energetic particles, …**