Operating ITER Robustly without Disruptions

by

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with

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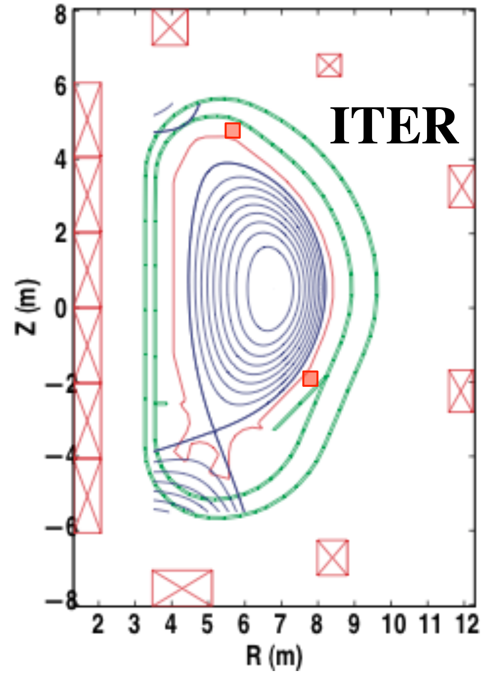

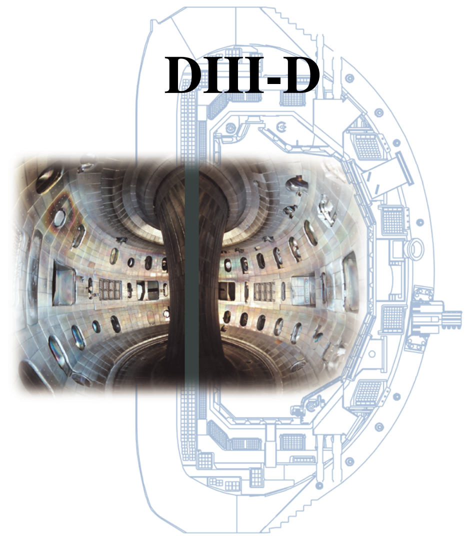

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Operating ITER Robustly without Disruptions

Physics view | Engineering view

T. Todd, in R. Dendy Plasma Physics p. 448 (1993)

Physics view | **Control design view**

T. Todd, in R. Dendy Plasma Physics p. 448 (1993)

Overview

It's all about the control

Overview

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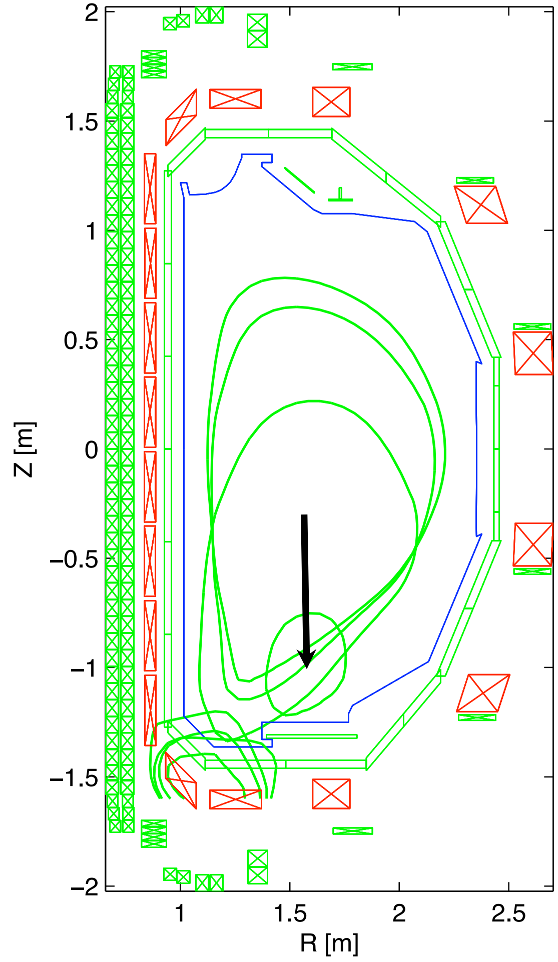
➡Focused effort on control has the potential for enabling disruption-free operation in ITER (or nearly…)

Disruptions are Plasma-Terminating Events that Result from Uncontrolled Instability Growth

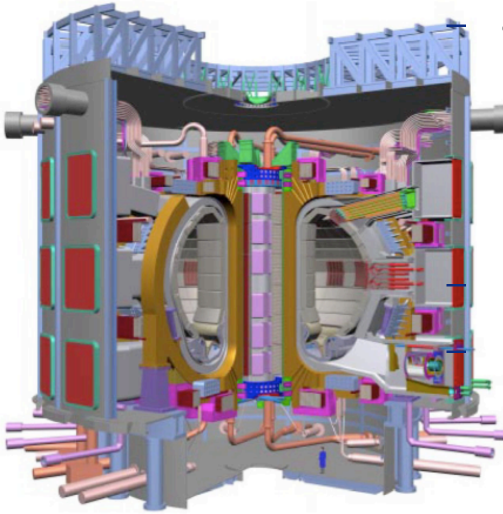
- **Examples of instabilities that can grow and cause disruption:**
  - Vertical instability
  - Tearing mode
- **Vertical Displacement Event (VDE): loss of vertical control leads to global MHD instability and thermal quench**
- **Major Disruption: absence of profile control allows unstable profiles to evolve, triggering global MHD instability and thermal quench**

Intentional VDE in DIII-D



Success of ITER Requires Sufficiently Low Disruption Rate

- Mid-pulse disruptions eliminate planned discharge time following disruption, reducing physics productivity
- Disruptions may require long recovery time, reducing overall shot frequency
- Disruption heat fluxes can reduce component lifetime (e.g. divertor target ablation)
- Damage to in-vessel components can require shutdown for repair



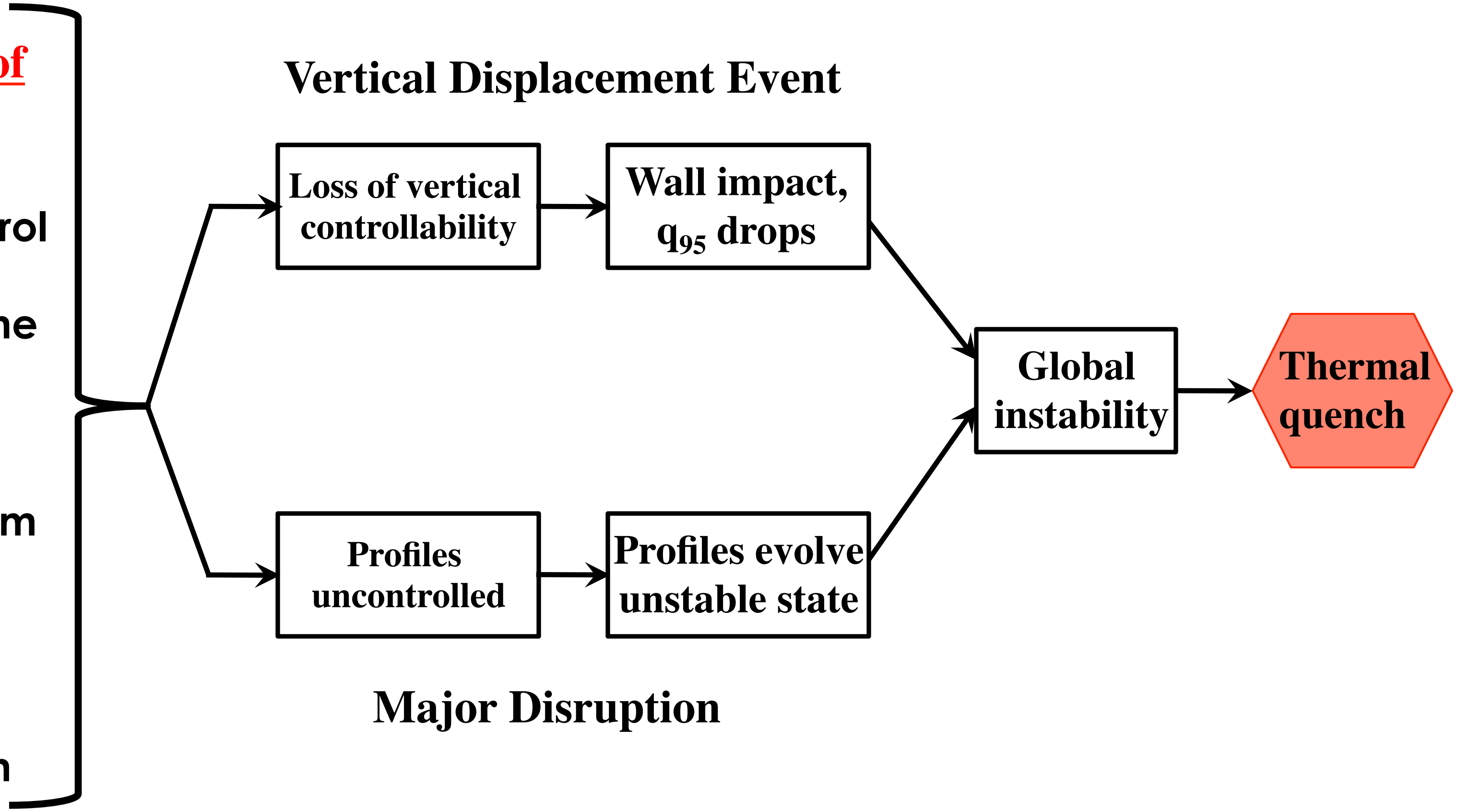
80% availability (during operation periods)

Design target: <10% disruptivity

Disruptions are a Result of Insufficient Controllability of Operating Regime and Associated Instabilities

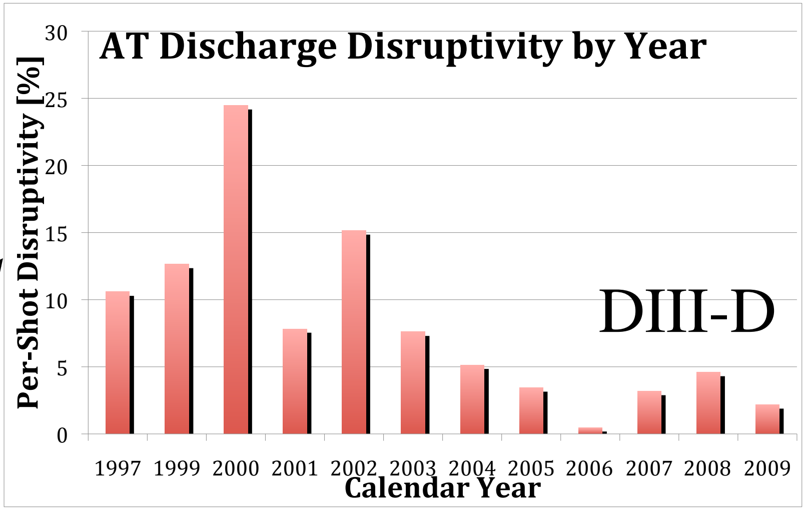
Primary Causes of Control Loss

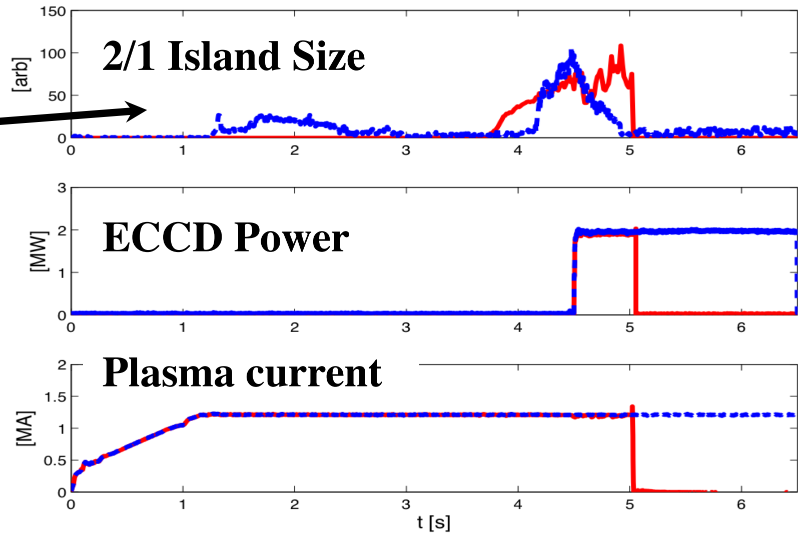
- Insufficient control capability for operating regime
- Design choice
- Hardware/system failure
- Human error
- Human intention



Improved Control Leads to Reduced Disruption Rate

- **JET disruptivity analysis [deVries, 2009]**
  - "…lower disruption rates [over time]… primarily due to improvement in technical ability to operate JET"
- **DIII-D steady-state scenario disruption rate analysis 1997-2009**
  - Experience, improved control reduce per-shot disruptivity from ~15% to <5%
- **ECCD at rational surface controls NTM**
  - Replaces missing bootstrap current
  - Prevents disruption
- **Improved vertical control prevents VDE**
  - Routinely robust in operating devices
  - High confidence extrapolation to ITER design





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Integrated Control Research is Required In Order to Operate ITER Robustly Without Disruptions

- **Identify robust operating scenarios**
  - Passively stable
  - Actively controllable
  - Demonstration on operating machines

- **Develop robust controllability for scenarios**
  - Validated models of instabilities, actuators, plasma
  - Quantified controllability with noise, disturbances
  - Real-time monitoring of controllability boundaries

- **Develop provable algorithms to avoid or recover from impending fault trajectories**
  - Prediction with Faster Than Real-Time simulation
  - Algorithms for off-normal responses
  - Soft shutdown if required
  - Hard shutdown (mitigated disruption effects) as rare last resort

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Corresponding Research Needs Workshop Thrusts

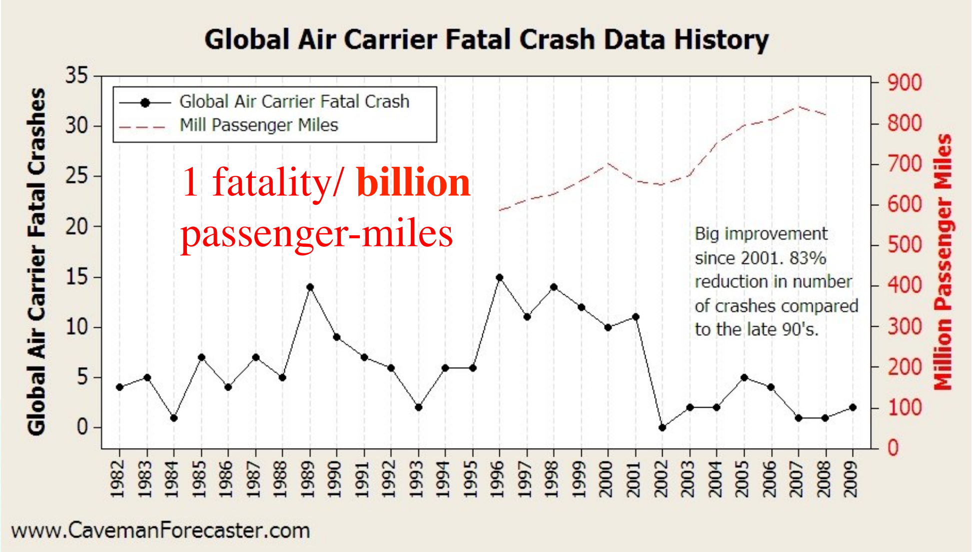
ReNeW Thrust 8
(~Scenarios in burning plasmas)

ReNeW Thrust 5
(~Disruption-free control)

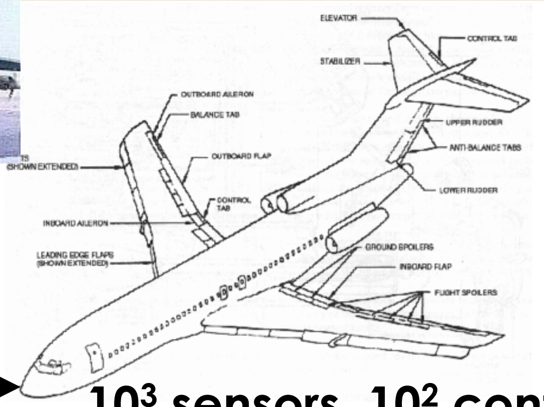
ReNeW Thrust 2
(~Control transient events)

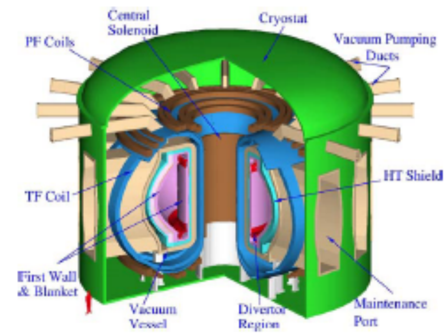
How Do We Know Robust Control Approach Works? High Reliability Aircraft Design Works…

- Commercial aircraft achieve very high reliability and performance



- Military aircraft achieve extreme robustness near operating limits using modern control methods





- ITER has similar levels of control complexity and requirements on reliability and performance →

10^3 sensors, 10^2 controlled parameters, ~10 key instabilities, 10^2 actuators

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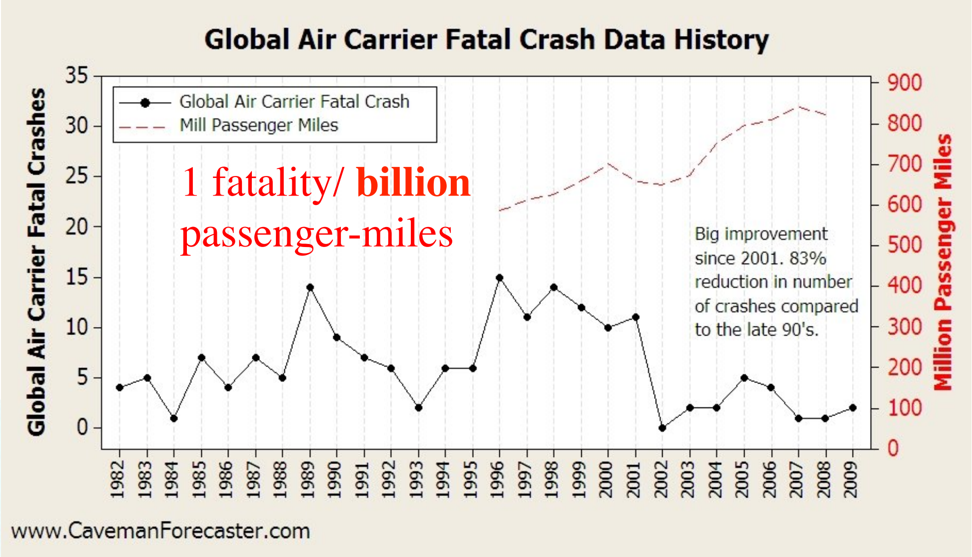

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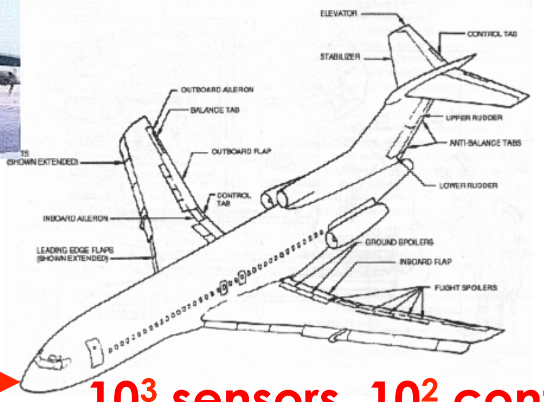

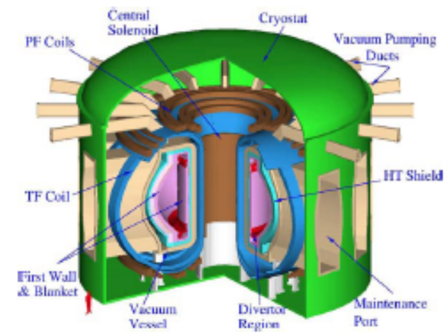

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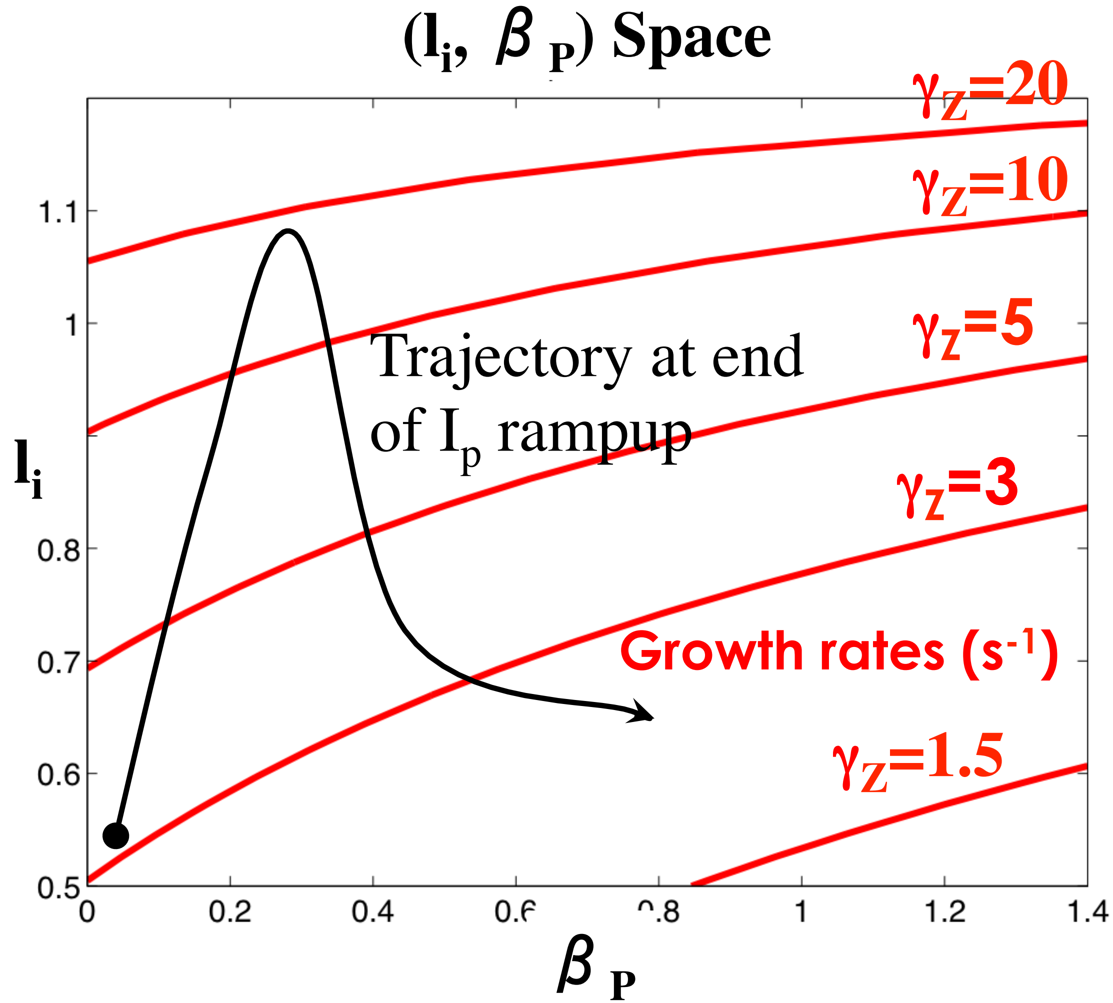
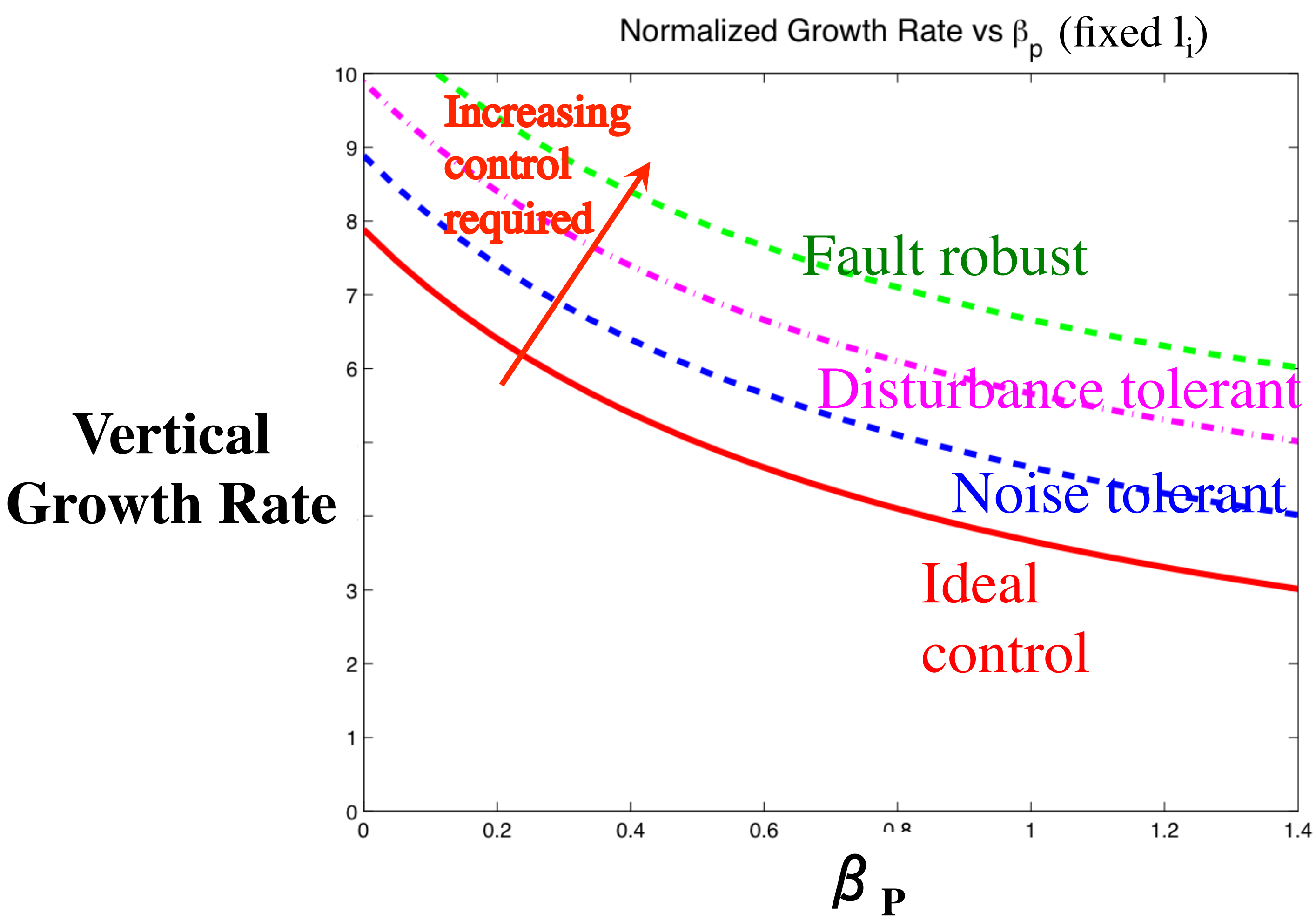
Robust Control Requires Systematic Analysis: Control Operating Space

- Plot of controllability in ITER operating space
  - Trajectory in (l_i, β_P) space as discharge evolves
  - Vertical growth rate indicates controllability required
  - Ensuring sufficient controllability ensures NO LOSS OF CONTROL



Control Operating Space Can Quantify Need for More Control Capability for Greater Robustness



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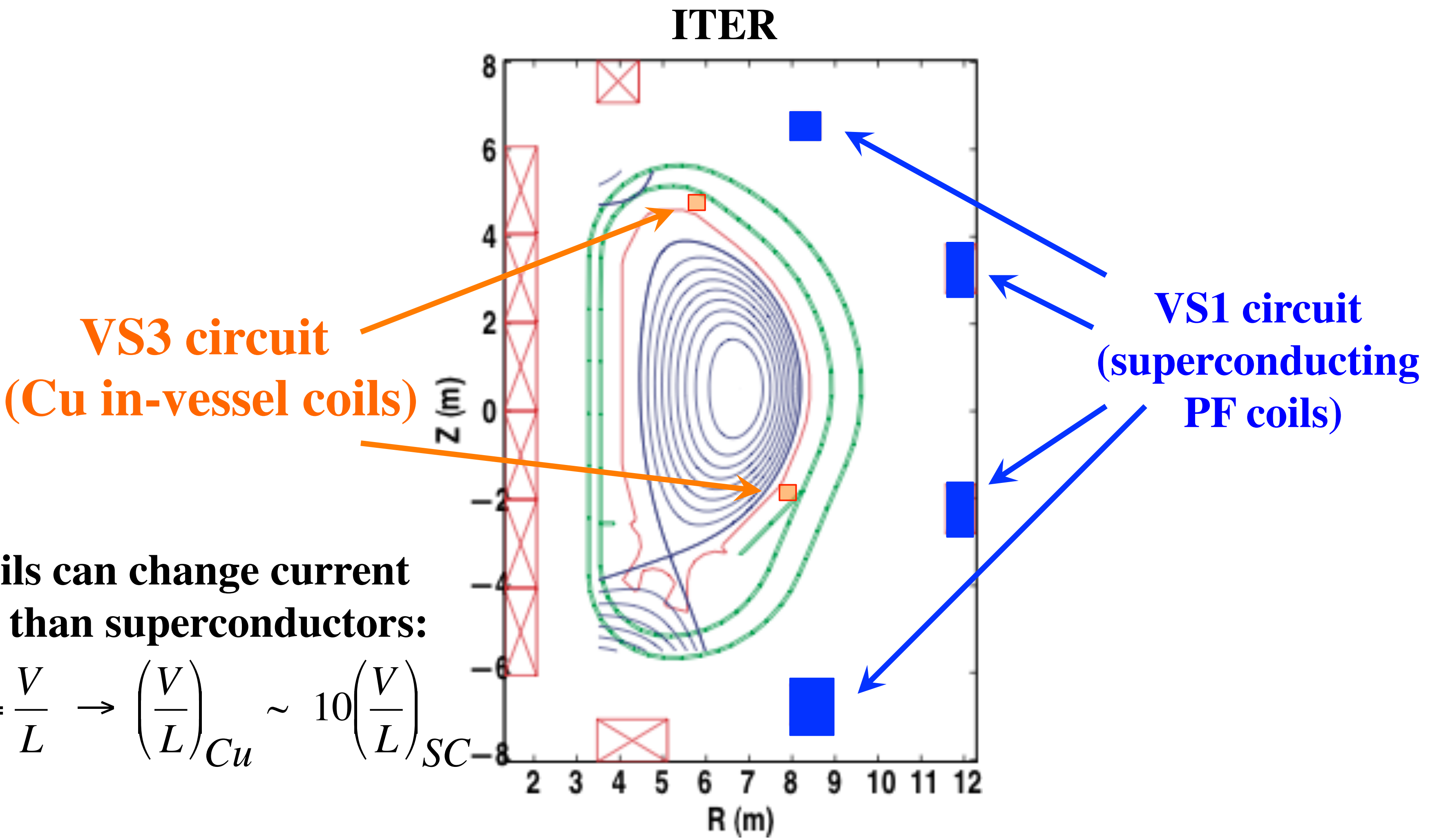
ITER Vertical Control System Includes Mix of Superconducting and Copper Coils



Cu coils can change current faster than superconductors:

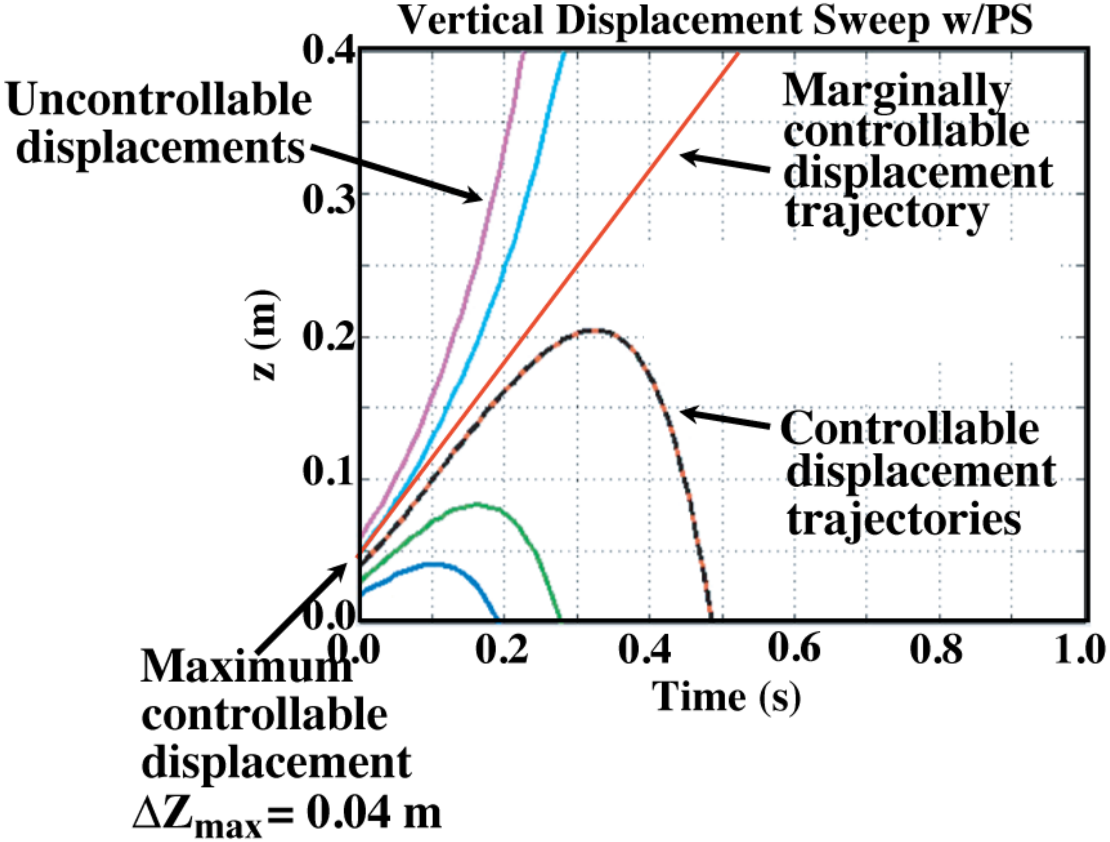
$$\frac{dI_C}{dt} = \frac{V}{L} \rightarrow \left(\frac{V}{L}\right)_{Cu} \sim 10\left(\frac{V}{L}\right)_{SC}$$

Robust Control Metric for Vertical Disturbance Rejection: ΔZ_{MAX}

- All disturbances result in sudden jump in vertical position Z_P
- ΔZ_{MAX} = maximum ΔZ_P beyond which motion can't be reversed with saturated voltage
- Normalizing by minor radius produces machine-independent metric $\Delta Z_{MAX}/a$

VS1: $\Delta Z_{MAX}/a \sim 2\%$
VS3: $\Delta Z_{MAX}/a \sim 9\%$

Example of Analysis and Gedanken Experiment to Calculate ΔZ_{max}



ΔZ_{max} Quantifies Effects of Physics and Machine Characteristics on Controllability

- **Good controllability metrics relate**
  - Physics characteristics of instability
  - Actuator capabilities
  - Machine/configuration constraints
  - Cost drivers

$$\Delta Z_{MAX} \approx \frac{\left(\frac{\partial B_R}{\partial I_C} \frac{R_0}{n B_{Z0}} \Delta I_{MAX} \right) e^{-\gamma \left(T_{PS} + \tau_w \right)}}{\left(1 + \gamma \frac{L_C}{V_{SAT}} \Delta I_{MAX} \right)}$$

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Equilibrium, growth rate

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Power supplies, coils

$$\Delta Z_{MAX} \approx \frac{\left(\frac{\partial B_R}{\partial I_C}\frac{R_0}{nB_{Z0}}\Delta I_{MAX}\right)e^{-\gamma\left(T_{PS}+\tau_w\right)}}{\left(1+\gamma\frac{L_C}{V_{SAT}}\Delta I_{MAX}\right)}$$

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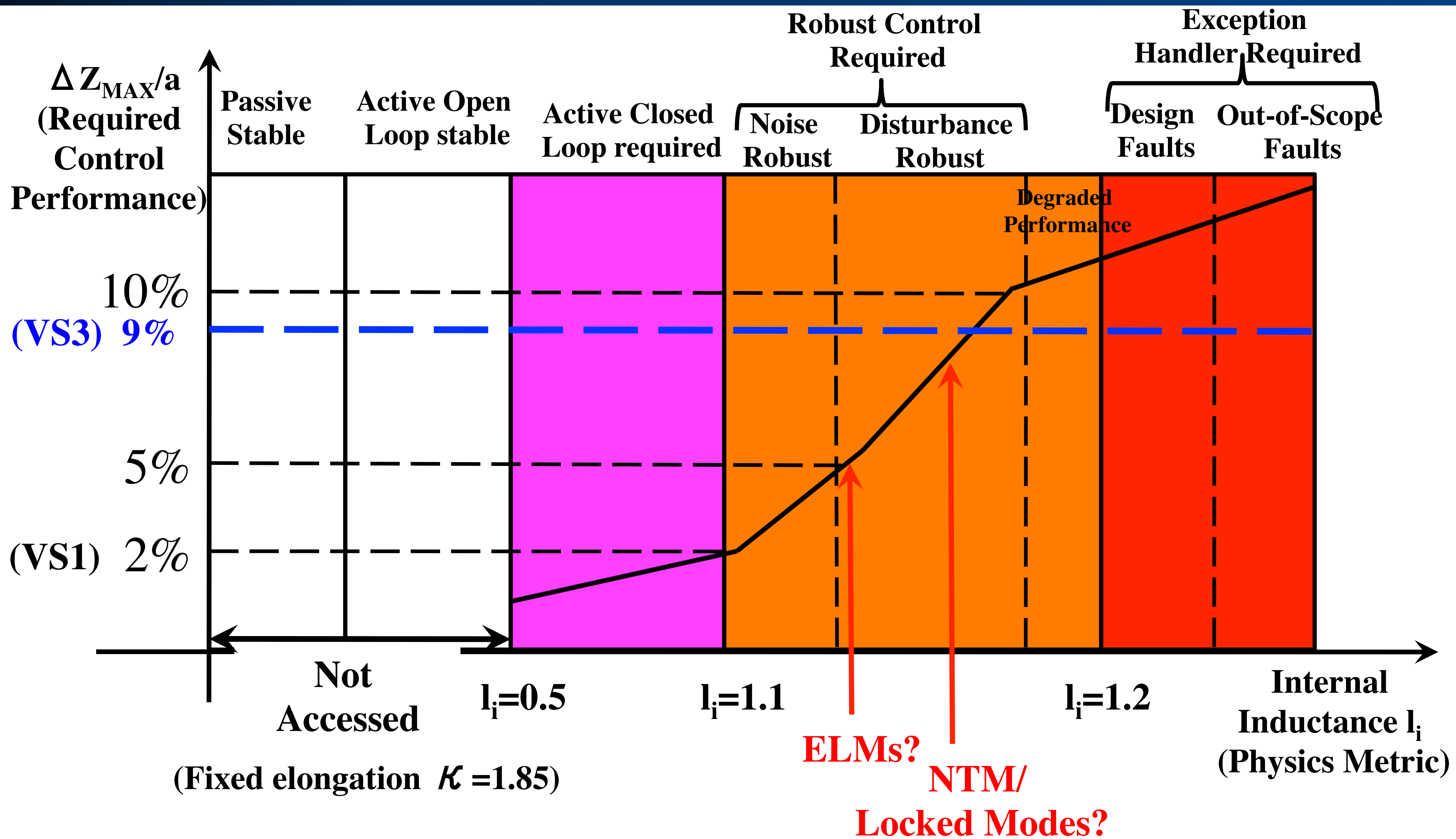
Machine constraints

$$\Delta Z_{MAX} \approx \frac{\left(\frac{\partial B_R}{\partial I_C}\frac{R_0}{nB_{Z0}}\Delta I_{MAX}\right)e^{-\gamma\left(T_{PS}-\tau_w\right)}}{\left(1+\gamma\frac{L_C}{V_{SAT}}\Delta I_{MAX}\right)}$$

Control Operating Space for ΔZ_{MAX} Performance in ITER Shows VS3 Coils Provide Robustness to Disturbances

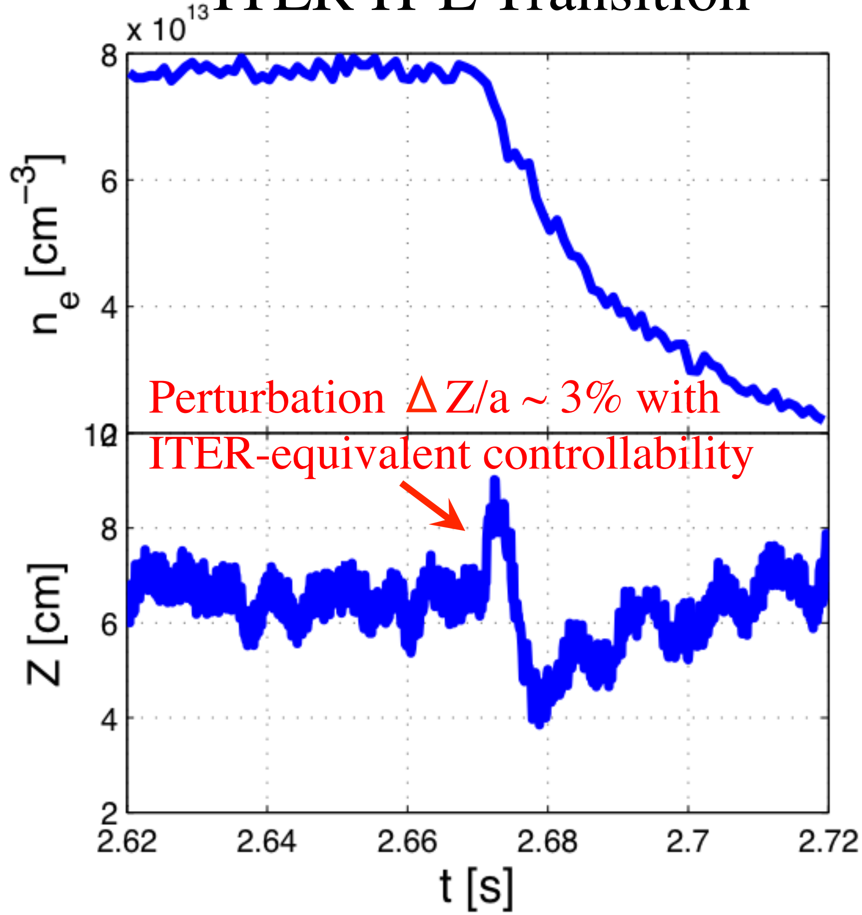


Experiments Are Essential in Characterizing Control Disturbances

- **Typical disturbances that set controllability limits**
  - ELM's
  - H-L transitions (less so for L-H)
  - Loss of Internal Transport Barrier (ITB)
  - NTM/Locked Modes

- **Limited predictive theories for effect of complex transient phenomena on equilibrium**
  - Empirical ELM model: $\Delta l_i \sim +0.05$, $\Delta \beta_p \sim -0.05$
  - Control analysis can be forgiving, but extra design margin = cost, so accuracy in disturbance models is important…

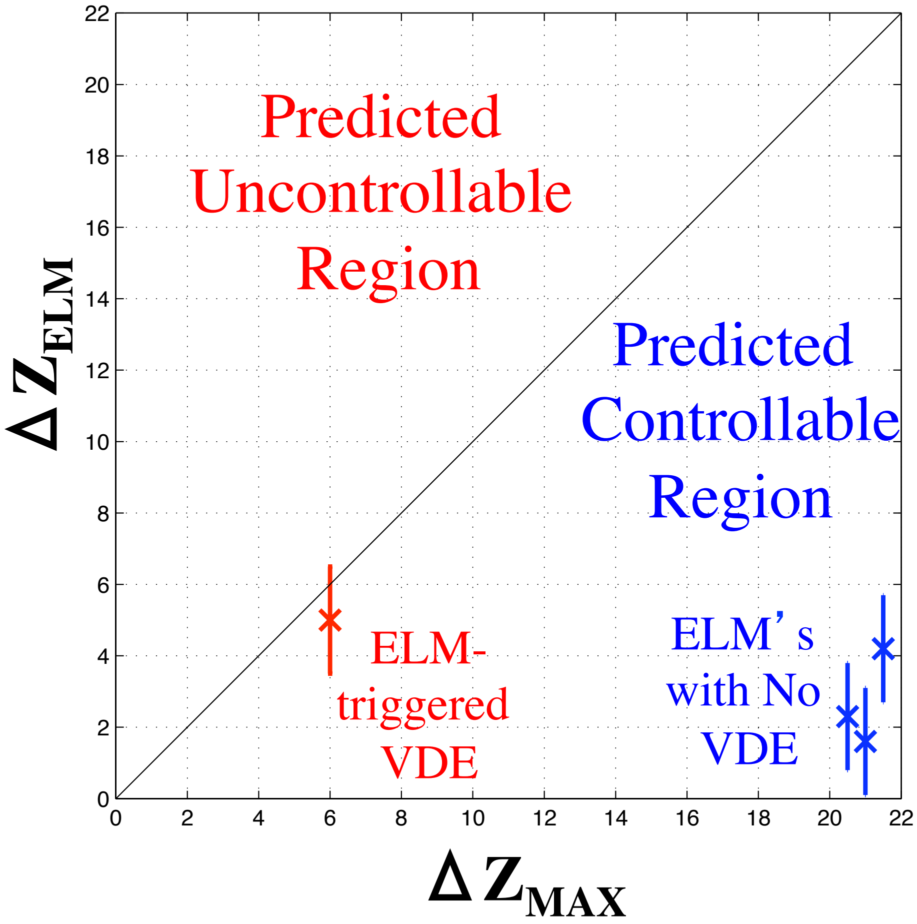
DIII-D Simulation of ITER H-L Transition



ITER Scenario ELM Disturbance Experiments in DIII-D Show ΔZ_{MAX} is Good Predictor for ELM Controllability

- **Experiment**
  - ELMy H-mode ITER baseline scenario in DIII-D
  - ΔZ_{MAX} varied by varying vertical control maximum voltage

- **Results**
  - ELM's in discharges with high ΔZ_{MAX} were well-controlled
  - Discharge with ΔZ_{MAX} near predicted marginal value produced VDE
  - ΔZ_{MAX} is a good predictor for uncontrollable ELM perturbation



Summary

- **Disruptions are the result of insufficient control capability**
  - Consequence of design choices
  - Hardware/system faults
  - Human error or human intention
- **Focused efforts on robust control hold the promise of reducing ITER disruptivity to well below present design requirements (caveat: what cost trade-offs and design choices must ITER make?)**
- **Recent theoretical and experimental studies of ITER vertical controllability provide examples of the robust control analysis/design approach**
  - Analytic formulation of maximum controllable displacement
  - Quantified control operating space for ITER
  - Assessment of ELM disturbances in ITER baseline scenario simulated in DIII-D