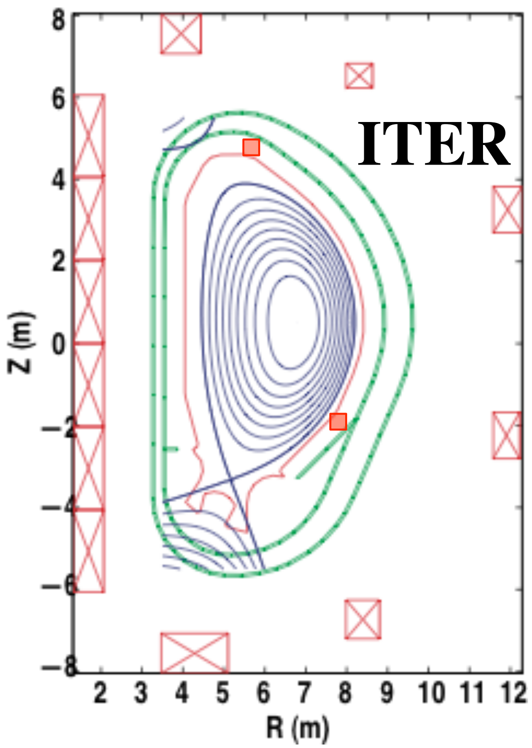
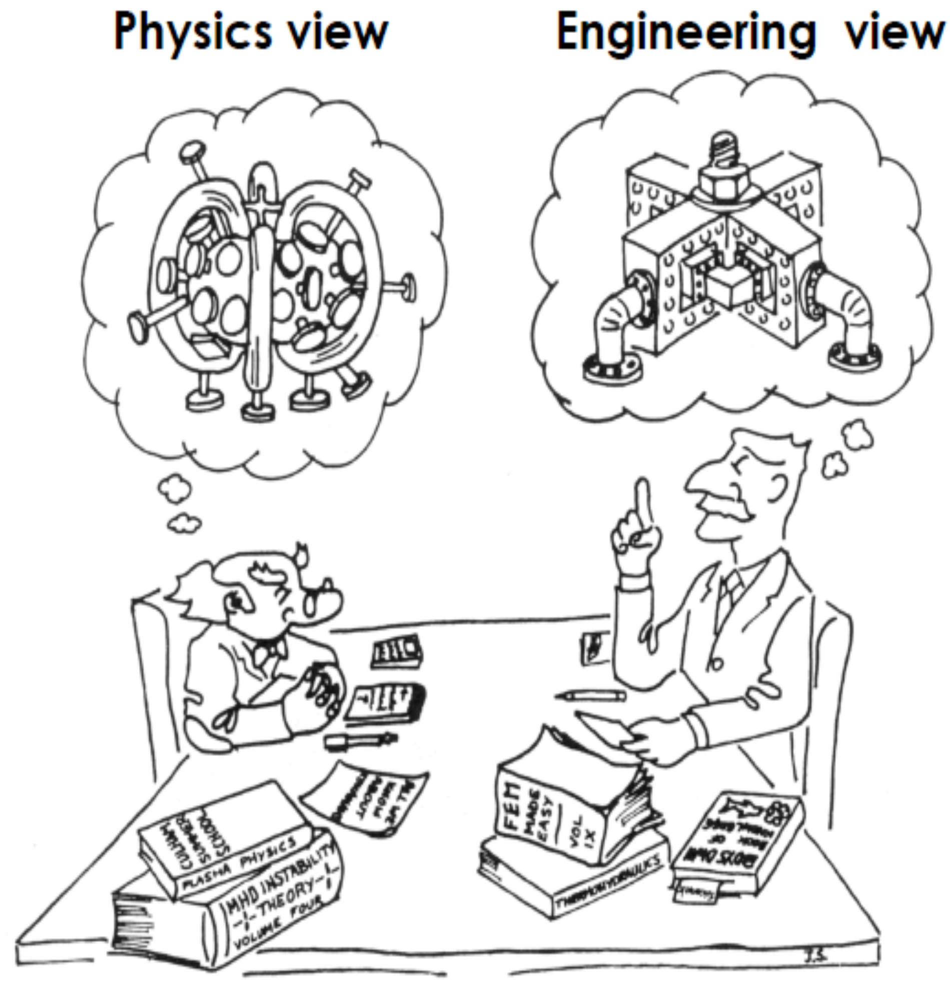
High Reliability Operation and Disruption Control in Tokamaks

D.A. Humphreys
General Atomics, San Diego, California





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

4th ITER International Summer School
MHD and Plasma Control
in Magnetic Fusion Devices
May 31 – June 4, 2010

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GENERAL ATOMICS

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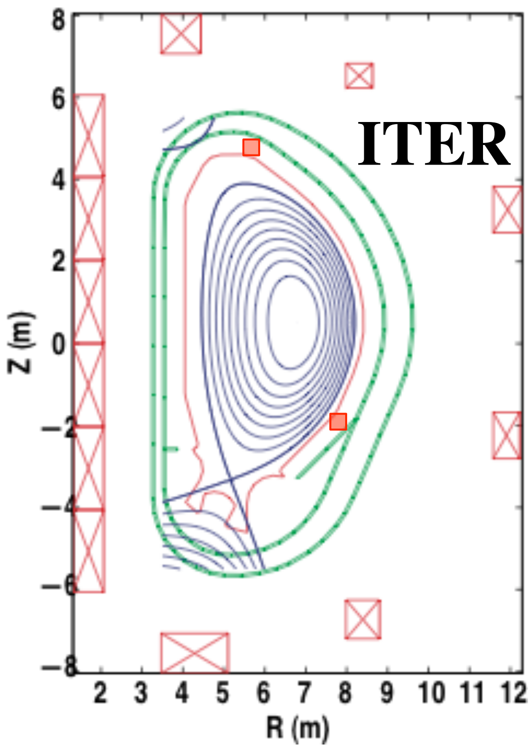

Physics view **Control design view**

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

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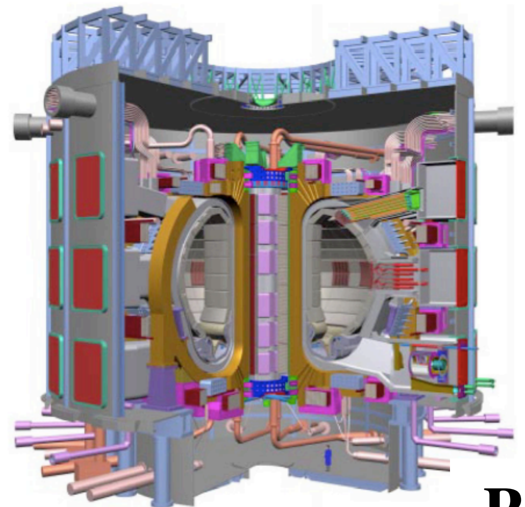
Motivation: ITER and Fusion Power Plants Require High Reliability and High Performance

- **High Reliability:**
  - High probability of sustained operation
  - High availability (time fraction operating)
  - High confidence in design performance

- **High Performance:**
  - High values of physical performance metrics (beta, power output, efficiency, etc…)

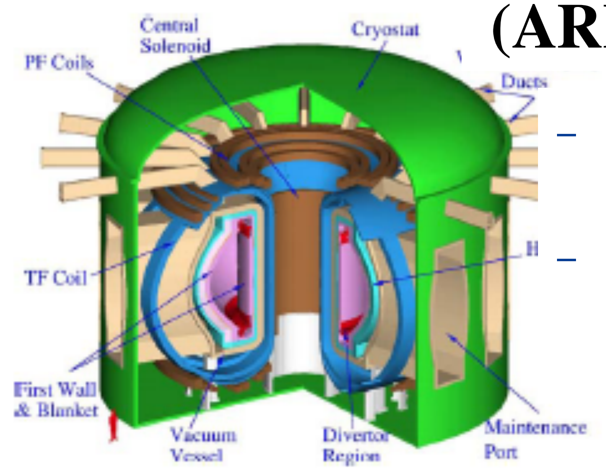
- **Both aspects require and are enabled by control performance:**
  - Design of controllers based on accurate models enables quantifiable reliability
  - Verification of algorithms in simulations confirms implementation and function



ITER

- **80% availability (during operation periods)**
- **< 10% disruptivity**

Power Plant (ARIES-AT)



- **80% availability (out of full year)**
- **~ 0% disruptivity**

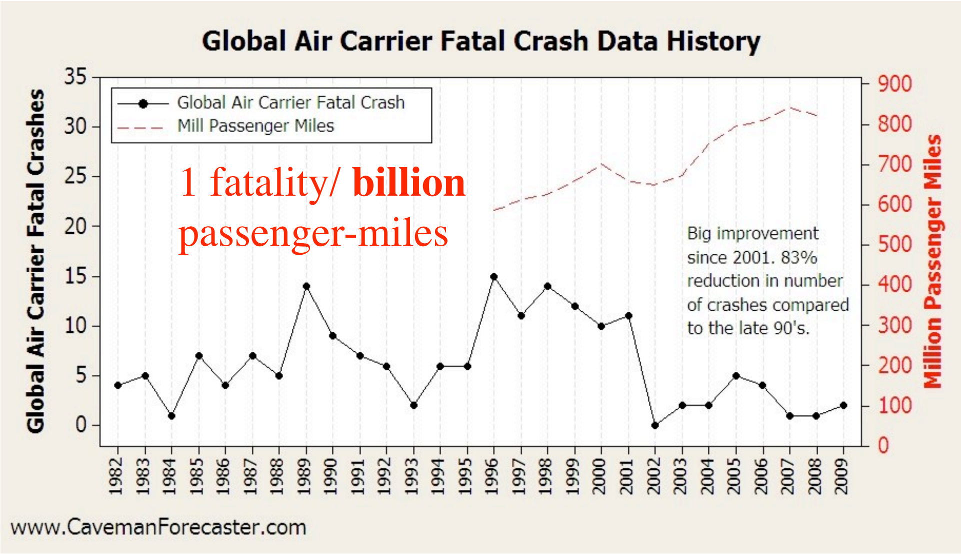
Najmabadi et al, FED 80 (2006) 3

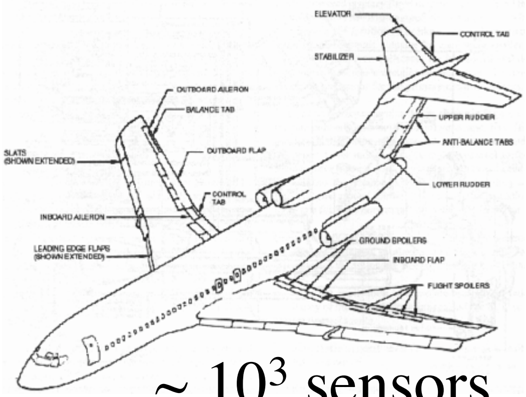
Aircraft Control Provides a Good Example of High Reliability, High Performance Control

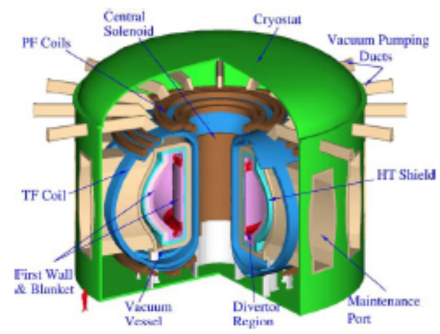
- **Commercial attractiveness requires high reliability:**
  - High availability needed for economics
  - High reliability (safety) required for passenger acceptance

- **Missions of commercial/military aircraft demand high performance:**
  - High availability/reliability/efficiency
  - High maneuverability
  - High speed (in many cases)

- **Fusion power plants have comparable potential for reliability:**
  - Similar level of control complexity, requirements on performance…







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

Najmabadi et al, FED 80 (2006) 3

Aircraft and Fusion Power Plant Designs Are Driven by Mission Requirements

- **Passive vs Active Control in Aircraft:**
  - 1910: many aircraft designed intrinsically unstable; strong pilot-in-loop control role
  - 1930's: long flight times led to reduced control burden on pilot, passively stable designs
  - Present day: many aircraft designed passively stable to limit cost; many designed unstable to exploit fast response for maneuverability

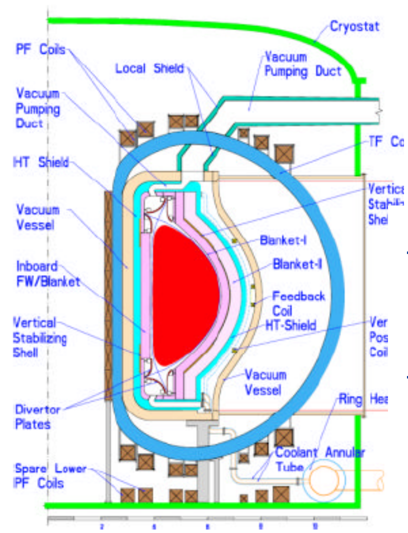
Unstable Sopwith Camel

A320: "relaxed stability"

Stable Cessna 172

Unstable F-117A

- **Mission determines design requirements for tokamak power plants as well:**
  - High plasma pressure required for efficiency, economic attractiveness
  - Blankets require space: increases distance from plasma to wall
  - Increased pressure and plasma-wall distance bring plasma closer to stability boundaries



Power Plant (ARIES-AT)

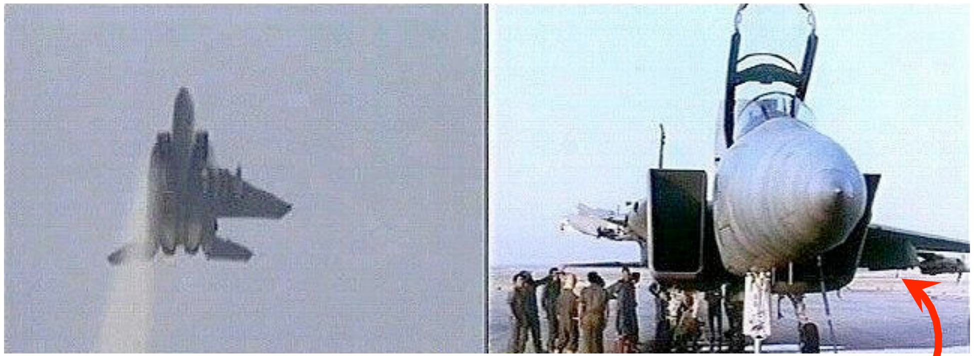
- **High plasma pressure**
- **Operates above passive stability limits**

Jardin et al, FED 80 (2006) 25

High Performance Aircraft and Fusion Power Plants Require a High Degree of Robustness

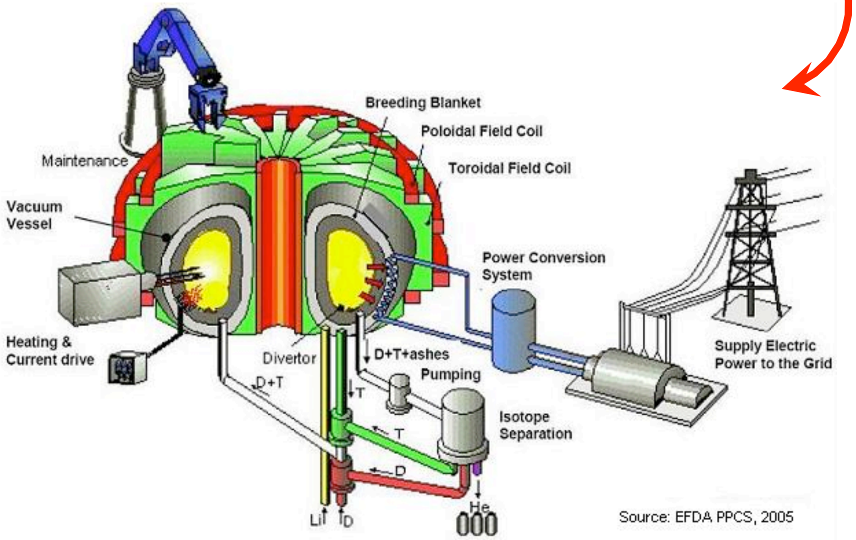
- **High performance aircraft:**
  - Intrinsically unstable (closed loop stable)
  - Operate near edge of performance envelope provided by technology
  - High speed, high airframe stress, high maneuverability…
  - High robustness to off-normal and even damage events!

Israeli Air Force F-15:



High performance, extreme robustness…

- **High performance fusion power plant:**
  - Operates beyond many stability boundaries, depending heavily on robust active control
  - High plasma pressure, neutron fluence
  - Low incidence of lost-time faults
  - High robustness to off-normal events



With thanks to T. Weaver, Boeing Corp.

Key Questions Considered in This Lecture

- **General control issues in high reliability operations:**
  - How do control considerations impact machine design for high reliability?
  - How do requirements on reliability impact choices of operating regimes, scenarios?
- **Control design approaches:**
  - How do we design control algorithms for high reliability, robustness?
  - How do we design for noise and disturbance rejection?
- **Exception handling and disruption control:**
  - What is exception handling, and how does it relate to high reliability?
  - How can we reduce disruptivity to near zero?
  - How do control methods apply to responses to rare impending disruptions?
- **What role does control play in the vision for a high performance, high reliability fusion reactor?**

High Reliability Requires Systematic Application of Control Design to Scenarios, Algorithms, Fault Response

- **Scenarios:**
  - Physics and control perspectives
  - Issues in scenario design

- **Integrated Plasma Control and Algorithm Design:**
  - Elements of algorithm design
  - Illustrations/Examples

- **Exception/Fault Handling and Disruption Control**
  - What are exceptions?
  - Design approaches to exception handling and disruption control

- **Research Needs and Opportunities**

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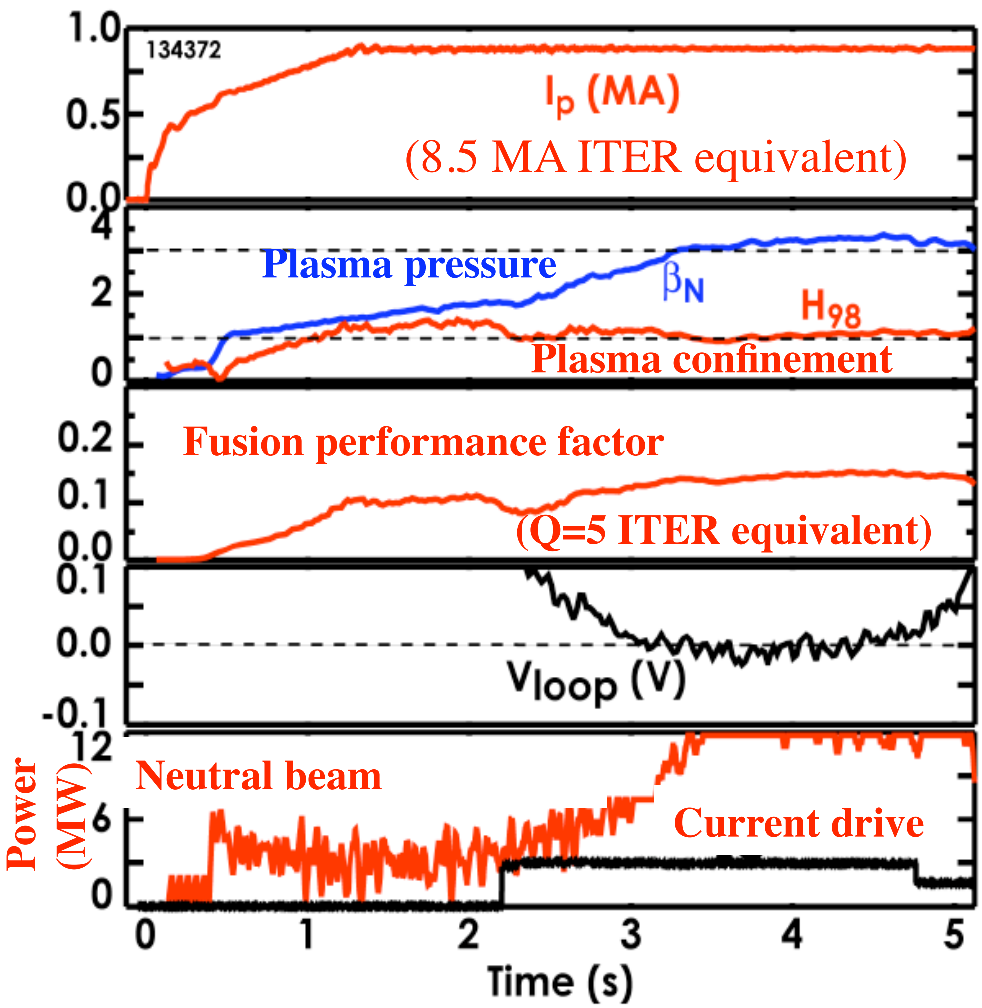
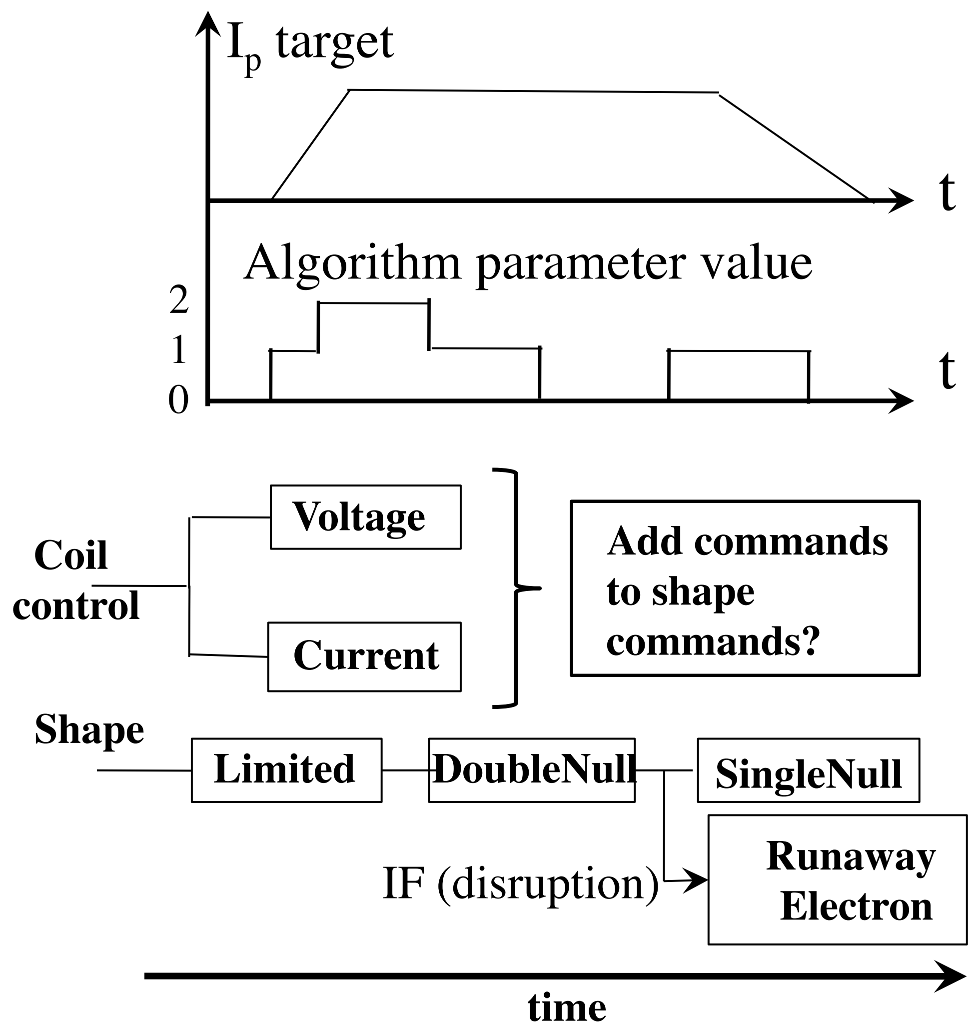
Physics Interpretation of "Scenario" Includes Plasma Regime and Use of Actuators

- **"Scenario" has different meaning to different communities:**
  - Physics scenario vs control scenario
- **Plasma regimes:**
  - Key plasma characteristics…
  - Confinement, profiles, stability to various instabilities or proximity to stability boundaries
  - (Reactor) Burn state, fusion gain, thermal stability properties
- **Use of Actuators:**
  - Sequence of application for access to regime (avoid instability boundaries, establish profiles, etc…)
  - Application to sustain regime (sustain profiles, etc…)



Control Interpretation of "Scenario" Includes Target Waveforms and Feedback Algorithms

- **Feedforward target waveforms**
  - Related to use of actuators, but actual waveforms of interest for control
- **Choice of feedback algorithms:**
  - What types of control algorithms
  - Choice of controlled variables, how algorithms interact
- **Programmed vs Asynchronous switching (of regimes/algorithms)**
  - Gain scheduled vs robust algorithms
  - Possibility of change in plasma regime
- **Put these two aspects of scenario together in one picture…**

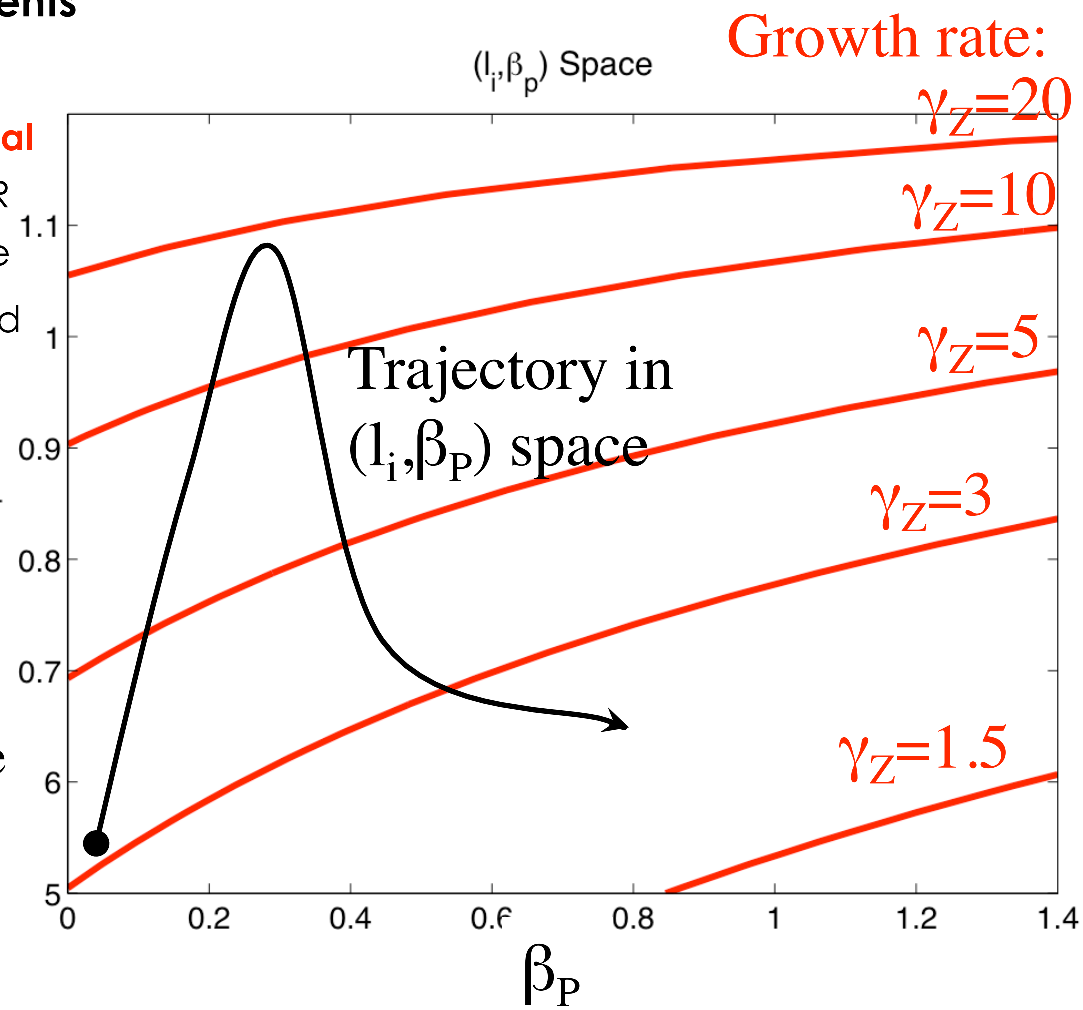


Control Operating Space: Unifying Physics and Control Scenarios

- **Start by showing control requirements in physics operating space:**
  - Trajectory shows variation in **vertical growth rate** in (l_i, β_P) space as ITER discharge scenario evolves in time
  - Growth rate that must be stabilized peaks in mid-scenario
  - Maximum control demand sets requirement on control system capabilities...

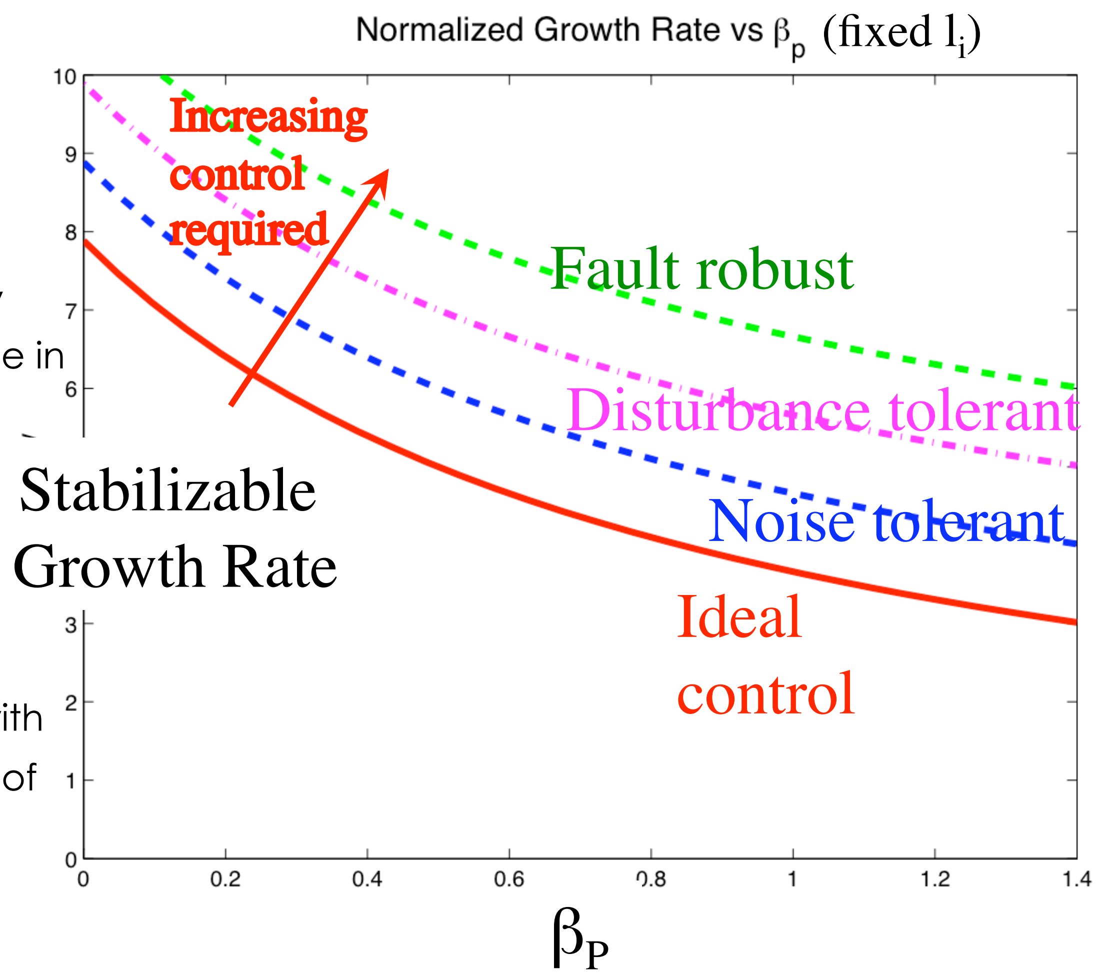
l_i = measure of internal inductance (peaking of current distribution)

β_P = measure of plasma pressure

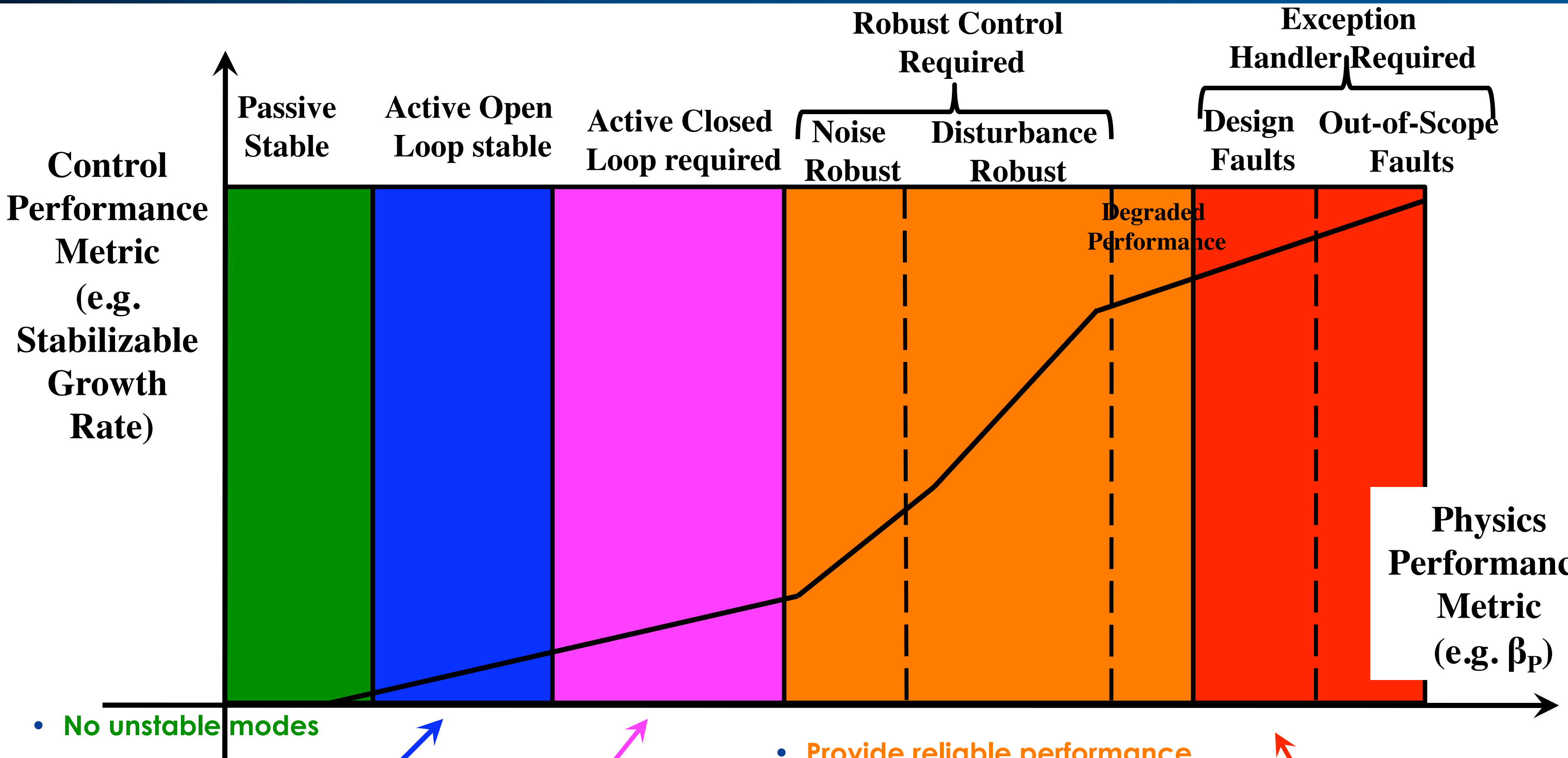


Control Operating Space: Unifying Physics and Control Scenarios

- **Evaluating design contours for varying levels of robustness:**
  - **Ideal control**: stabilizes mode in absence of noise, disturbances, faults
  - **Noise tolerant**: maintains stability and good dynamic performance in presence of expected noise
  - **Disturbance tolerant**: maintains stability and good dynamic performance in presence of expected disturbances
  - **Fault robust**: maintains stability with certain specified faults (e.g. loss of single sensor or actuator)



Control Operating Space: Unifying Physics and Control Scenarios



- No unstable modes
- Low performance

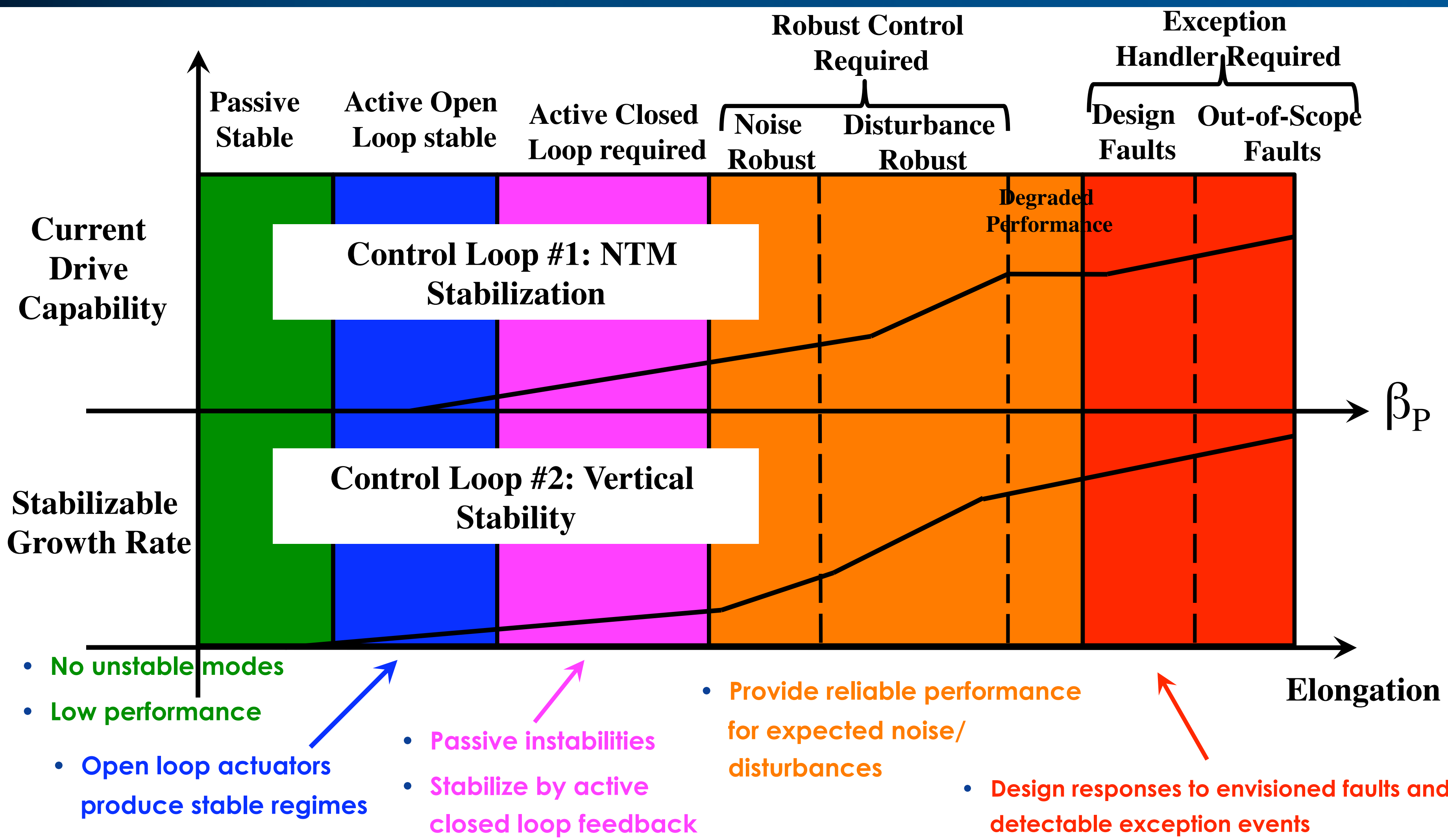
- Open loop actuators produce stable regimes

- Passive instabilities
- Stabilize by active closed loop feedback

- Provide reliable performance for expected noise/ disturbances

- Design responses to envisioned faults and detectable exception events

Control Operating Space Can Be Used to Assess and Specify Performance Needed for Many Control Loops



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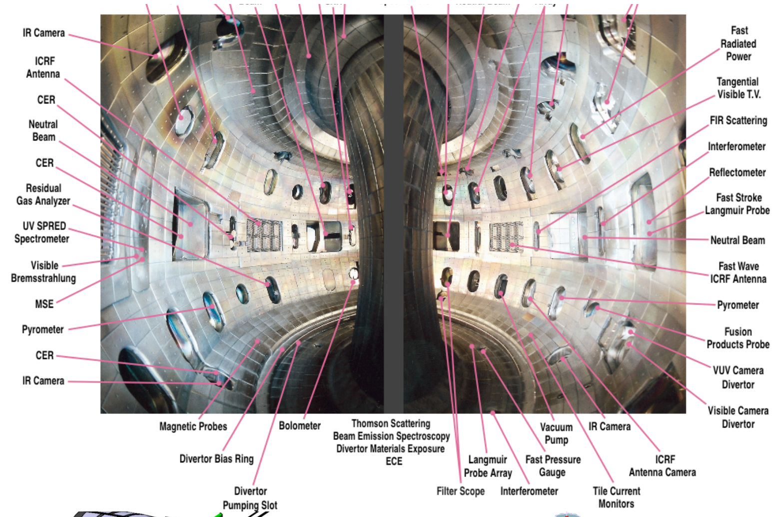
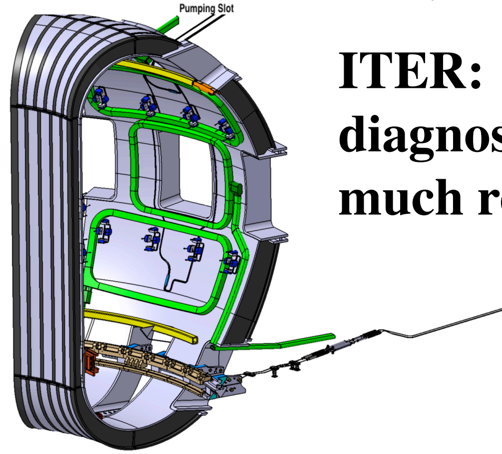
Control Operating Space and Design Issues for Fusion Reactors

- **Additional constraints on regimes:**
  - Specific plasma target for high performance power production
- **Additional constraints on control:**
  - Reduced numbers of diagnostics
  - Strong constraints on actuator capability, recirculating power
  - Tradeoff between desired robustness and cost of actuator capabilities
- **How do we make it happen:**
  - Design of Plasma Control System including architecture and algorithms is a critical research topic
  - Solutions not yet available even for ITER

DIII-D: high diagnostic access





ITER: diagnostic access much reduced

High Reliability Requires Systematic Application of Control Design to Scenarios, Algorithms, Fault Response

- **Scenarios:**
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  - Issues in scenario design
- **Integrated Plasma Control and Algorithm Design:**
  - **Elements of algorithm design** ←
  - Illustrations/Examples
- **Exception/Fault Handling and Disruption Control**
  - What are exceptions?
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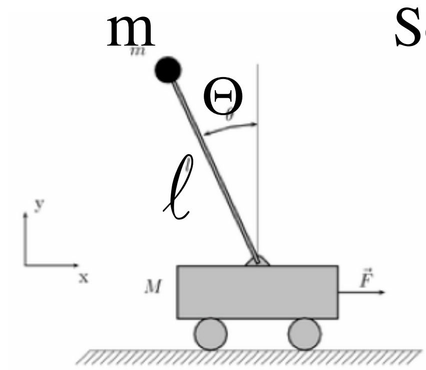
Classroom Demo: Basic Control Design Issues

- **Inverted Pendulum:**
  - Classic example of single-variable, approximately linear unstable system
  - Equation of motion: $\ddot{\Theta} = \frac{g}{\ell}\sin\Theta \approx \frac{g}{\ell}\Theta$



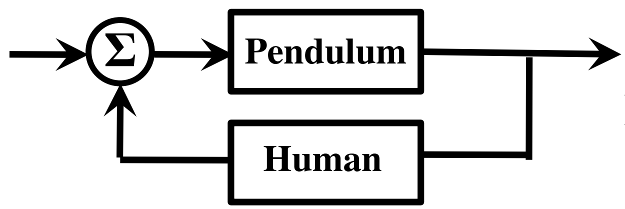
Solutions : $\Theta = e^{\pm\gamma_P t}$

$$\gamma_P = \sqrt{\frac{g}{\ell}}$$

[m]	γ_P [rad/s]	$1/\gamma_P$ [ms]
0.1	10	100
0.2	7	150
0.4	5	200

- **"Regime" choice:**
  - Length ➔ Growth rate

Human-in-Loop:

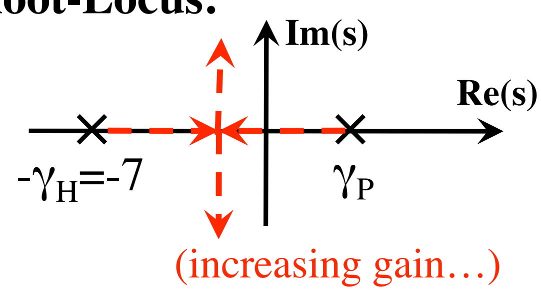


$$\text{Human} \approx \frac{1}{1+\tau_H s} \approx \frac{1}{1+0.15s}$$

$$\tau_H \approx 150\ \text{ms} \Rightarrow \gamma_H \approx 7\ \text{rad/s}$$

- **"Controller" choice:**
  - Human response time
    ~ 150-200 ms

Root-Locus:

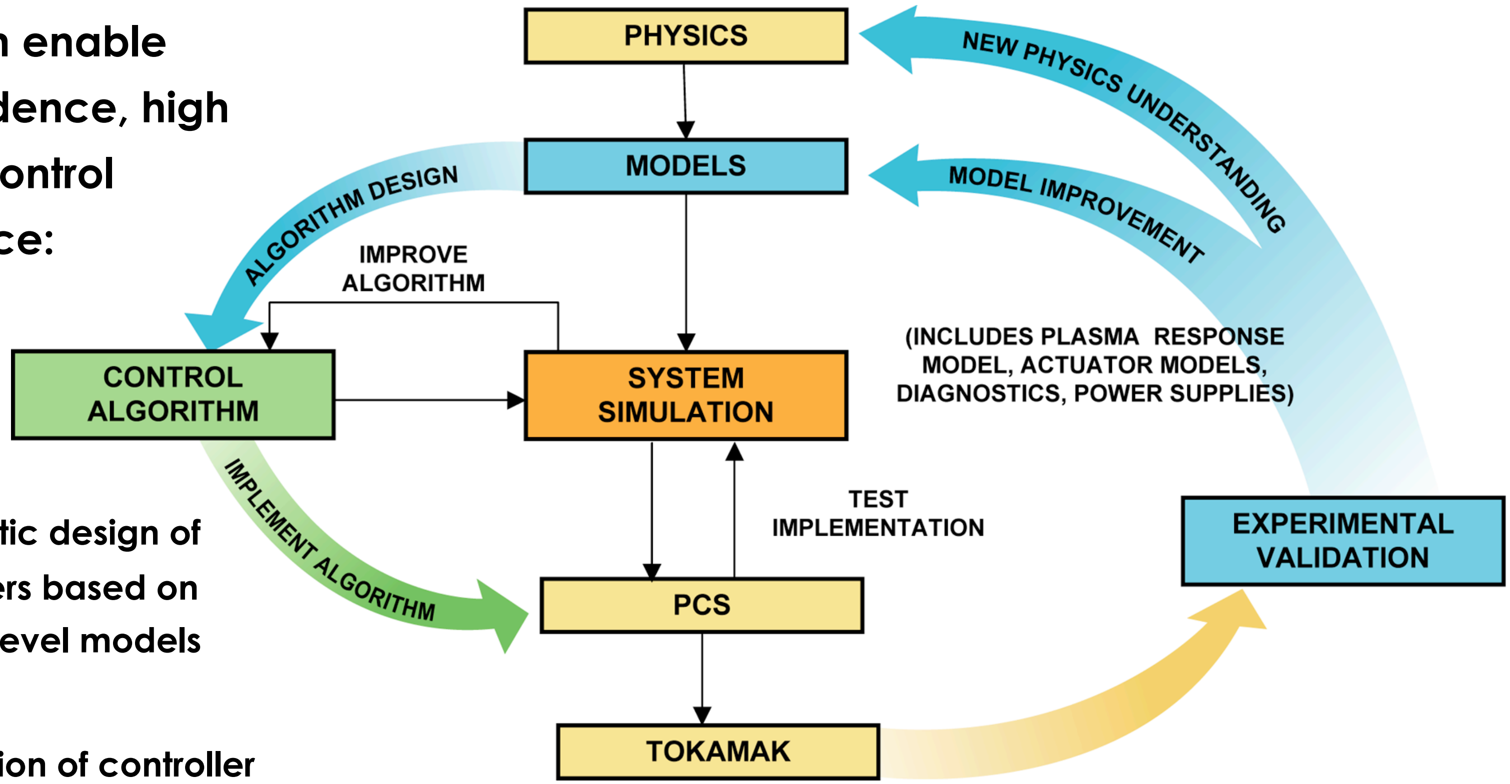


Need $\gamma_H > \gamma_P$ to stabilize
$\gamma_H >> \gamma_P$ for robustness

- **Robustness issues:**
  - Disturbance tolerance
  - Requires lower growth rate…

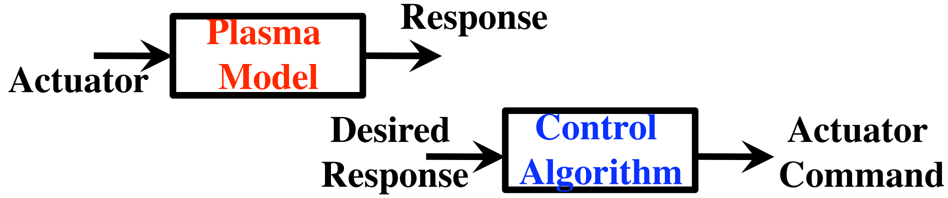
High Performance Control Requires Systematic Model-Based Design: Integrated Plasma Control

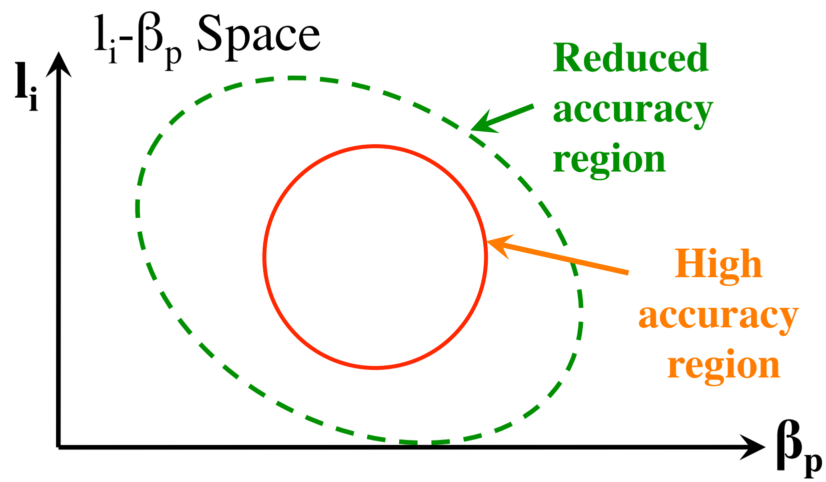
- Integrated plasma control can enable high-confidence, high reliability control performance:
  - Systematic design of controllers based on control-level models
  - Verification of controller implementation in simulations before experimental use



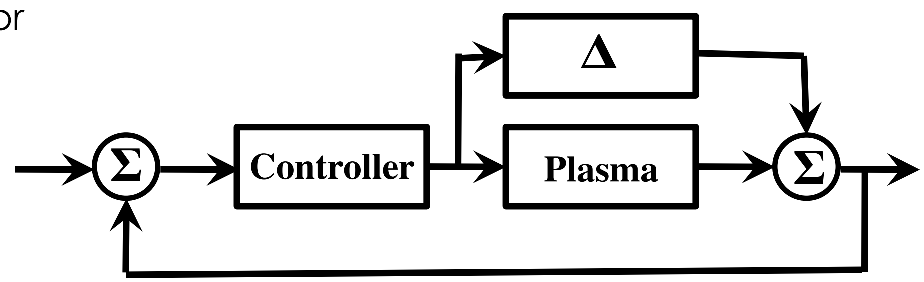
Robust Control Requires Sufficiently Accurate Models

- **Design of algorithms requires models:**
  - Model describes response of system to actuators
  - Control algorithm "inverts" model to derive actuator command needed for desired system response…



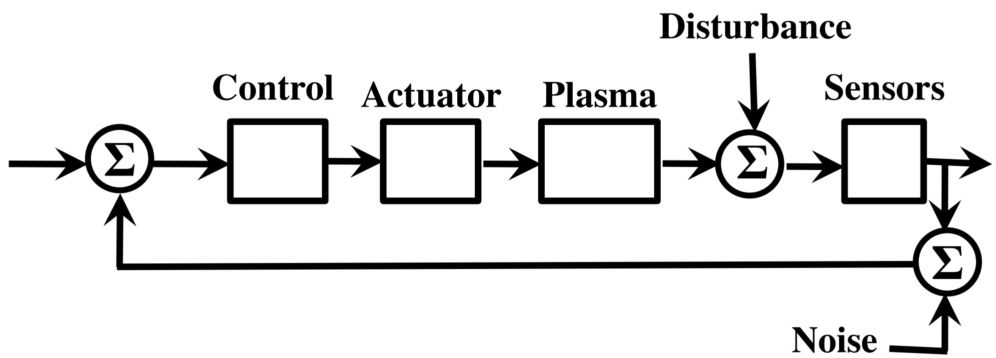


- **Robust design methods can handle some degree of inaccuracy in models:**
  - Design controller to guarantee stability with specified uncertainty Δ
  - Greater uncertainty requires higher cost for actuators
  - Can also treat model error as disturbance



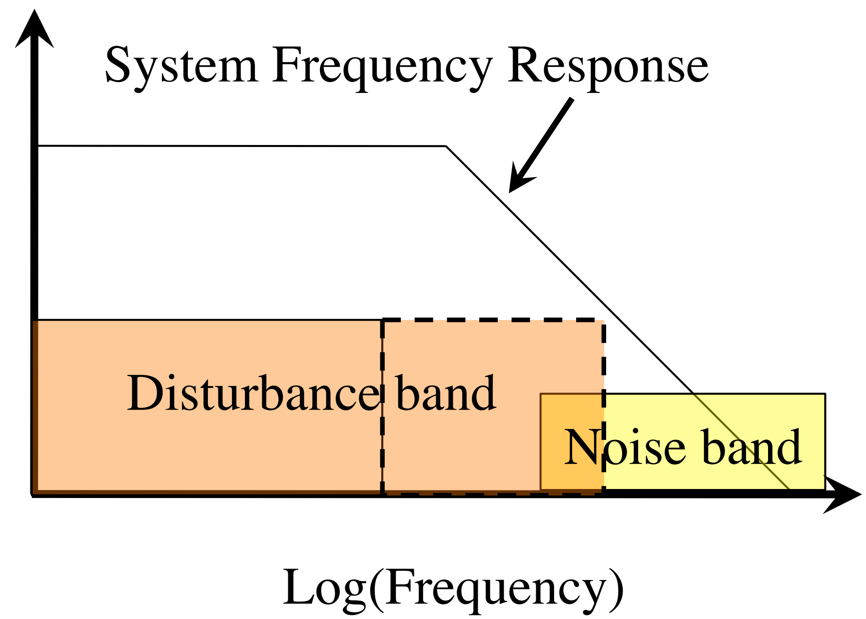
High Performance Control Requires Good Noise and Disturbance Rejection

- **High performance:**
  - High accuracy in matching command
  - Good dynamic response: small levels of fluctuation, small overshoots…



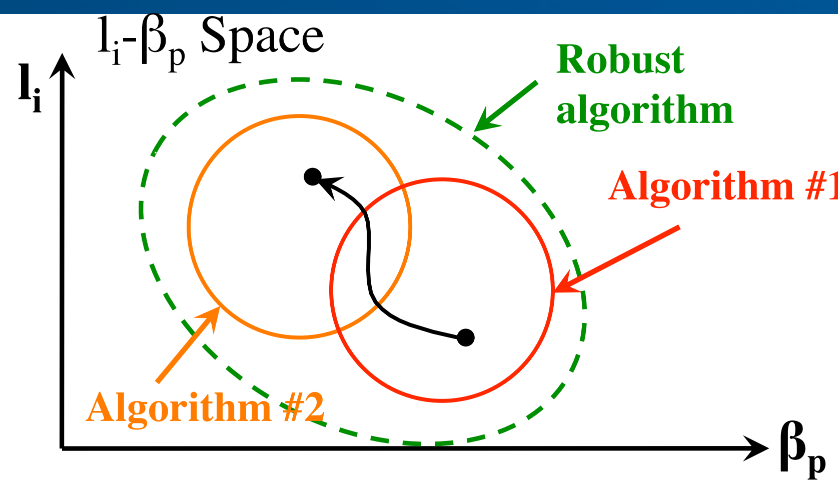
- **Noise rejection:**
  - Don't respond to noise signals (typically high frequency, but not always…)

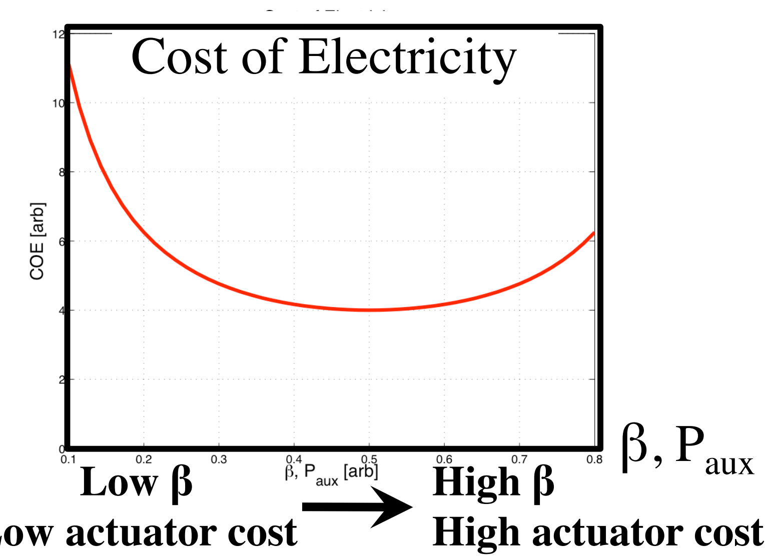
- **Disturbance rejection:**
  - Respond to disturbance so as to suppress (typically lower frequency than noise, but not always…)
  - If frequencies overlap, must discriminate in other ways, e.g. mode discrimination, Poisson (√N) reduction



Control Designers are Faced with Many Choices and Tradeoffs for Robustness

- **Gain scheduling vs robust:**
  - Switch from **algorithm #1** to **algorithm #2** based on changes in plasma state ("gain scheduling")?
  - Use **single robust algorithm** over large operating space?
- **Where to use each with what balance:**
  - High accuracy often requires accurate models, gain scheduled multiple algorithms (e.g. vertical stability)
  - Control with intrinsic uncertainty often requires use of robust, lower accuracy algorithms (e.g. NTM suppression)
  - Power plant: balance cost of high control (actuator) capability vs need for high plasma performance
- **Scenarios: what regimes to operate in?**



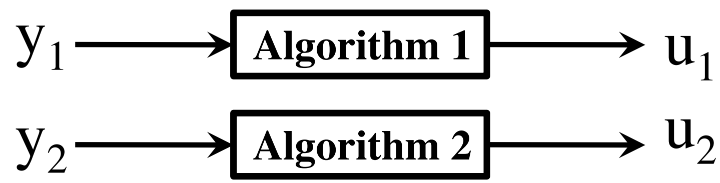


Scenarios are Directed by Plasma Control Systems

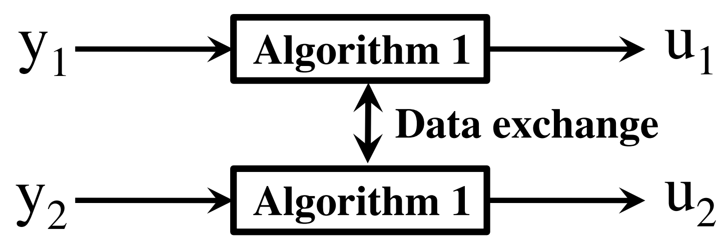
- **Plasma control systems must have:**
  - Operator interface
  - Sensor/data acquisition (inputs)
  - Actuator commands (outputs)
  - Scheduling manager (what happens when)
  - Feedforward command generators
  - Feedback algorithms
  - (Often) Algorithms to interpret inputs

- **Design alternatives choices:**
  - Highly parallel/independent vs highly coupled or fully integrated algorithms
  - PID controllers: $u = G_p y + G_d \dot{y} + G_i \int y dt$
  - State space/matrix: $\begin{cases} \dot{x} = Ex + Fy \\ u = Gx + Ky \end{cases}$
  - Logic, nonlinear
  - Degree of asynchronous intelligence/authority

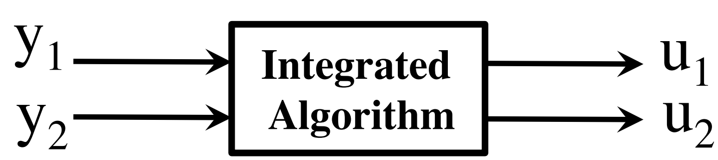
Parallel algorithm structure:



Coupled algorithm structure:



Fully integrated algorithm structure:



EAST Tokamak PCS Derived from DIII-D PCS Illustrates Key Features Common to Most Plasma Control Systems

- **Plasma control systems must have:**
  - Operator interface
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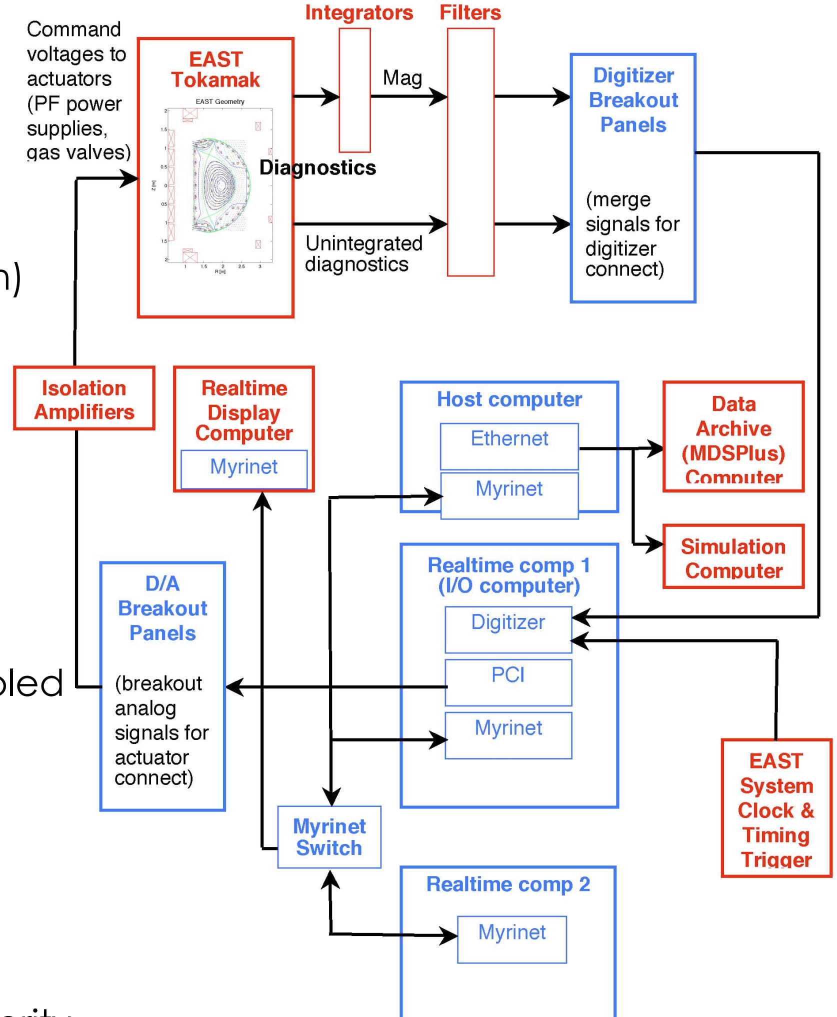

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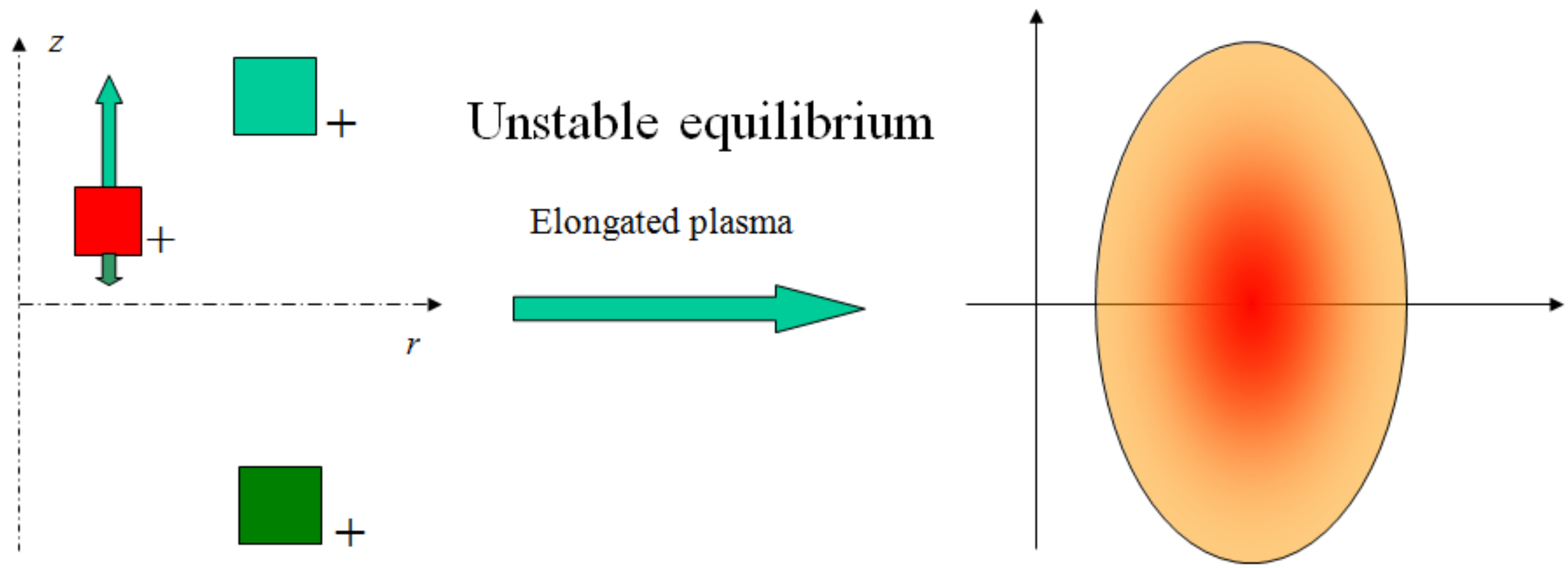
Introduction to Vertical Stability

- **Vertically elongated plasma equilibrium:**
  - Requires upper/lower coils to pull plasma: produced by positive coil currents pulling on positive plasma current
  - Vertical displacements are **unstable** (**pulling** force increases as **plasma** moves closer to pulling **coils**)



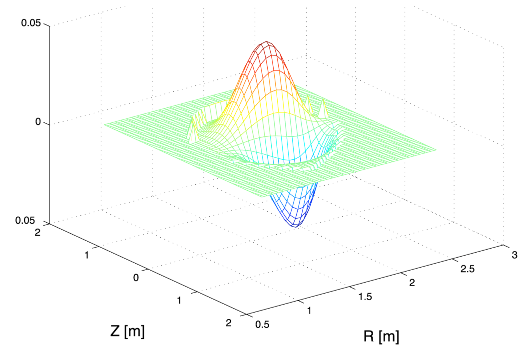
Figures courtesy of G. De Tommasi

Introduction to Vertical Stability

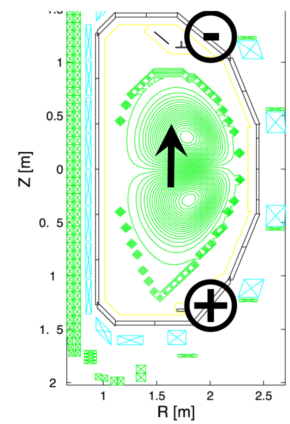
- **Vertical instability is n=0 (axisymmetric):**
  - Vertical plasma motion typically ~rigid
  - Motion induces currents in conductors (wall and coils) that slow mode growth
  - Linear dynamic equations are derived from force balance on plasma and Faraday's law circuit equations

- **Basic control representation is similar to inverted pendulum:**
  - Single unstable mode (γ_Z), single power supply mode (γ_{PS})
  - ALSO a conductor mode corresponding to penetration rate through wall (γ_V)

Perturbed Current Density



Plasma Motion, Induced Current

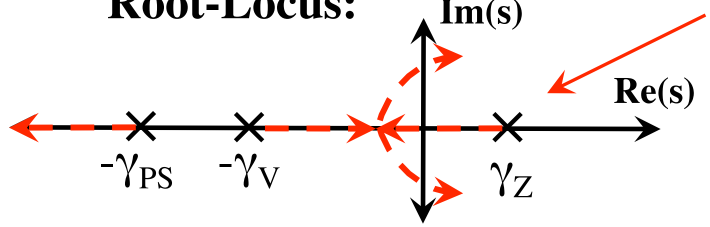


Vessel Flux Change from Plasma Motion

$$M_{VV}\dot{I}_V + R_{VV}I_V + \boxed{\frac{\partial \psi_{PV}}{\partial z_P}\dot{z}_P} = 0 \;\Rightarrow\; \underbrace{\dot{I}_V = AI_V}$$

Solution: many eigenmodes, one unstable (γ_Z)

Root-Locus:

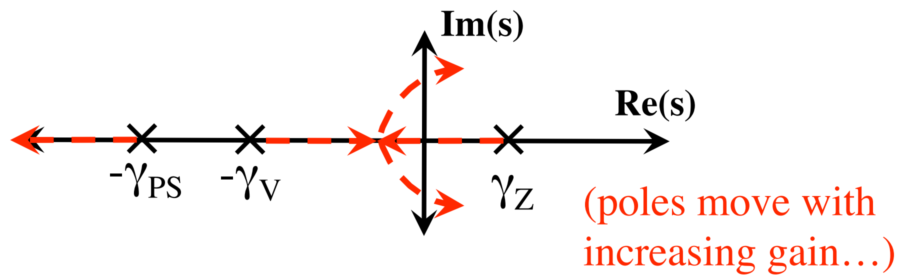


(increasing gain…)

Stabilizing the Vertical Instability Depends on Plasma, Conductor, and Power Supply Characteristics

- **Root-locus shows rough requirements for stabilization:**
  - Like inverted pendulum: power supply response bandwidth (γ_{PS}) sufficiently larger than γ_Z
  - Vessel penetration rate sufficiently large relative to growth rate
  - Actual dynamic response more complex…
  - Thick vessel or In-vessel passive structure produces system "zeros" that can require velocity feedback
- **Nonideal characteristics limit control capability significantly:**
  - Voltage saturation limits effectiveness of high gain…

Root-Locus:



Root-locus interpretation: centroid of poles constant as gain increases…

➔ Once $\gamma_{PS} >> \gamma_Z$ stability depends on sufficiently large γ_V/γ_Z

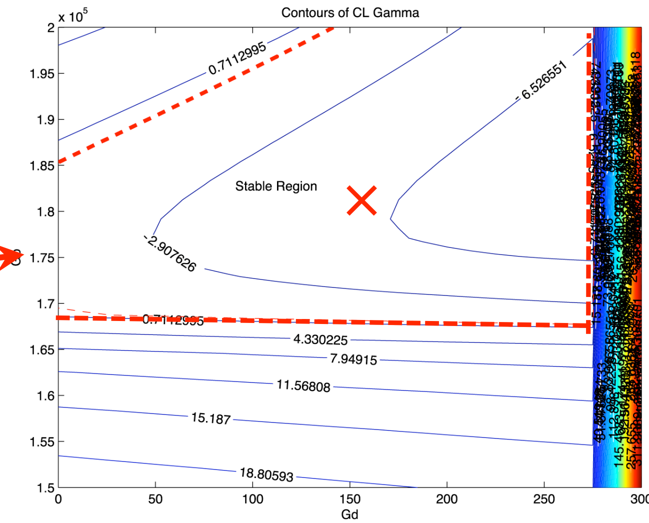
➔ Larger γ_V moves centroid to left, improves ability to stabilize…

Stability margin: $$m_S \approx \frac{\gamma_V}{\gamma_Z}$$

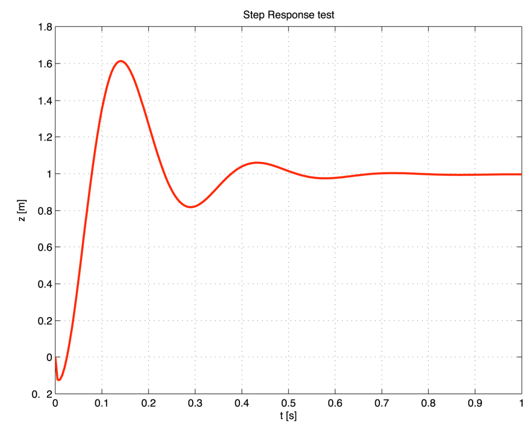
➔ Measure of gain (voltage) needed to stabilize and robustness of stabilization

Example of Robust Design with PID: Large Stable Gain Space

- **Single variable PID control lends itself to brute-force scan of gains:**
  - Sweep proportional gain (G_p) and derivative gain (G_d)
  - Typically select center of stable region for maximum robustness
  - Tradeoff with response/settling time performance…



- **Designing for large stable gain space:**
  - Increases probability of stable performance
  - Tolerant to uncertainties in most system aspects
  - Does not directly address noise and disturbance effects, or many nonlinearities…



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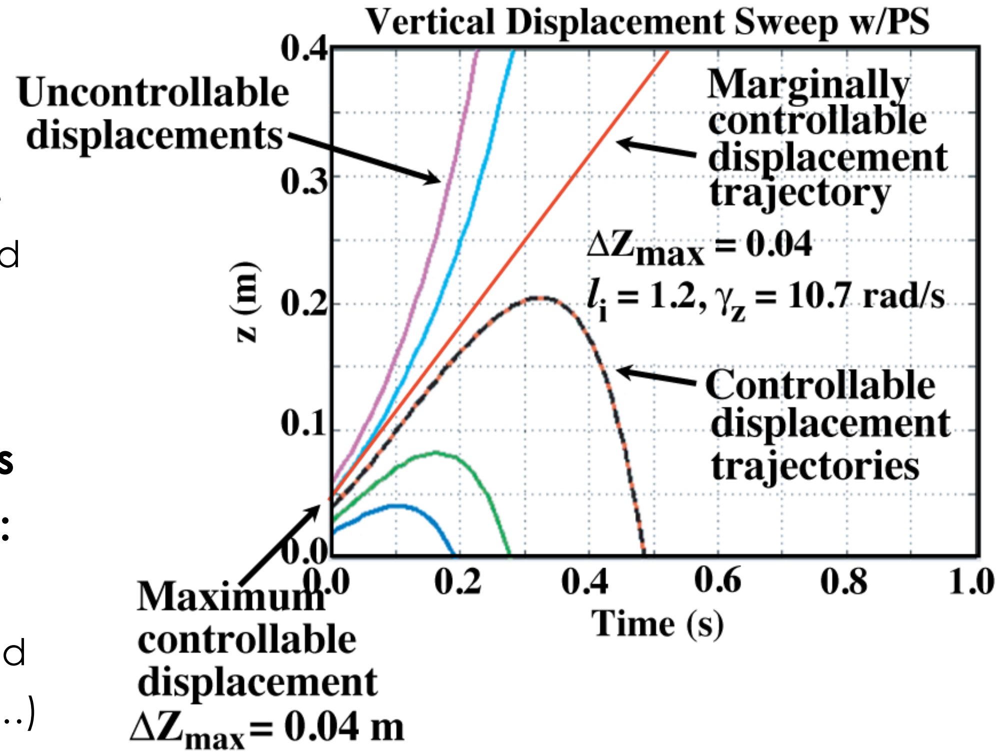
Vertical Control Disturbance Rejection and Robustness Issues for ITER

- **Many disturbances result in sudden jump in vertical position Z_P:**
  - ELM: rapid loss of edge current shifts current centroid
  - Locked mode: growth of tearing mode and loss of rotation shift current centroid
  - Must design to reject ΔZ_P expected
- **Maximum controllable displacement is useful metric to quantify robust control:**
  - ΔZ_{MAX} = maximum ΔZ_P beyond which motion can't be reversed with saturated voltage (also reflects γ_{PS}, current limit,…)
  - Not true control demonstration, but measure of "best possible"
  - $\Delta Z_{MAX}/a$ is machine-independent metric

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



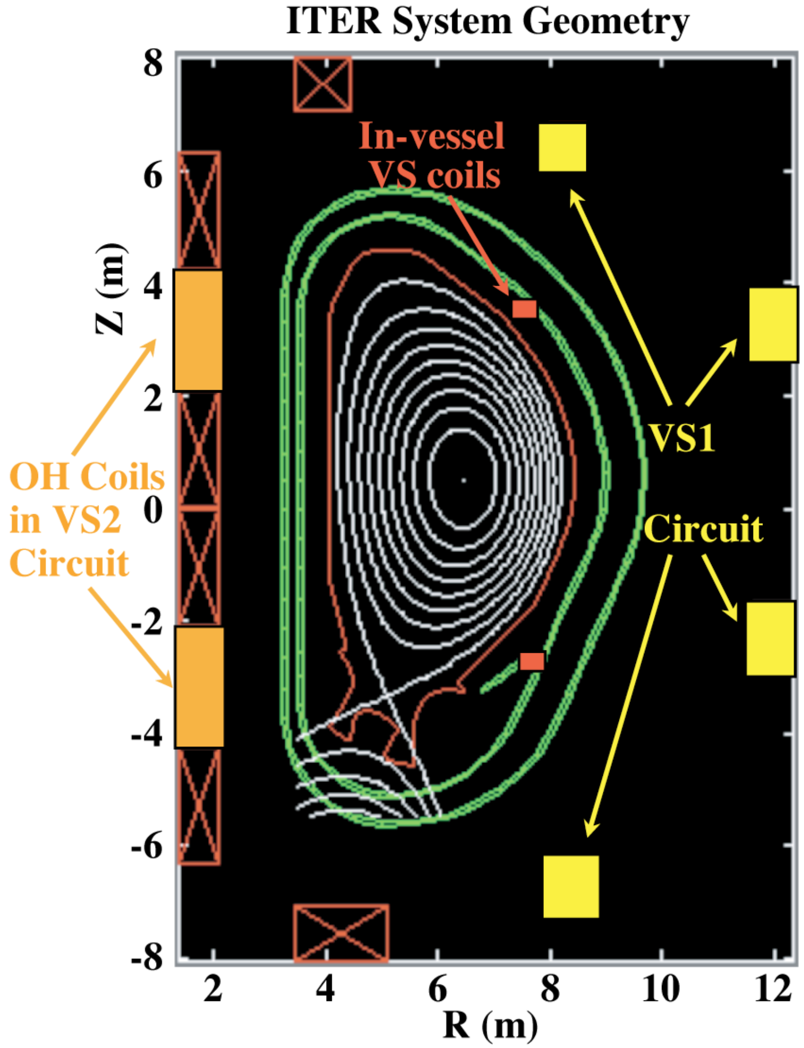
(ITER VS1: Outboard PF coils only)

New In-Vessel Vertical Control Coils Greatly Increase the ΔZ_{MAX} Performance of ITER

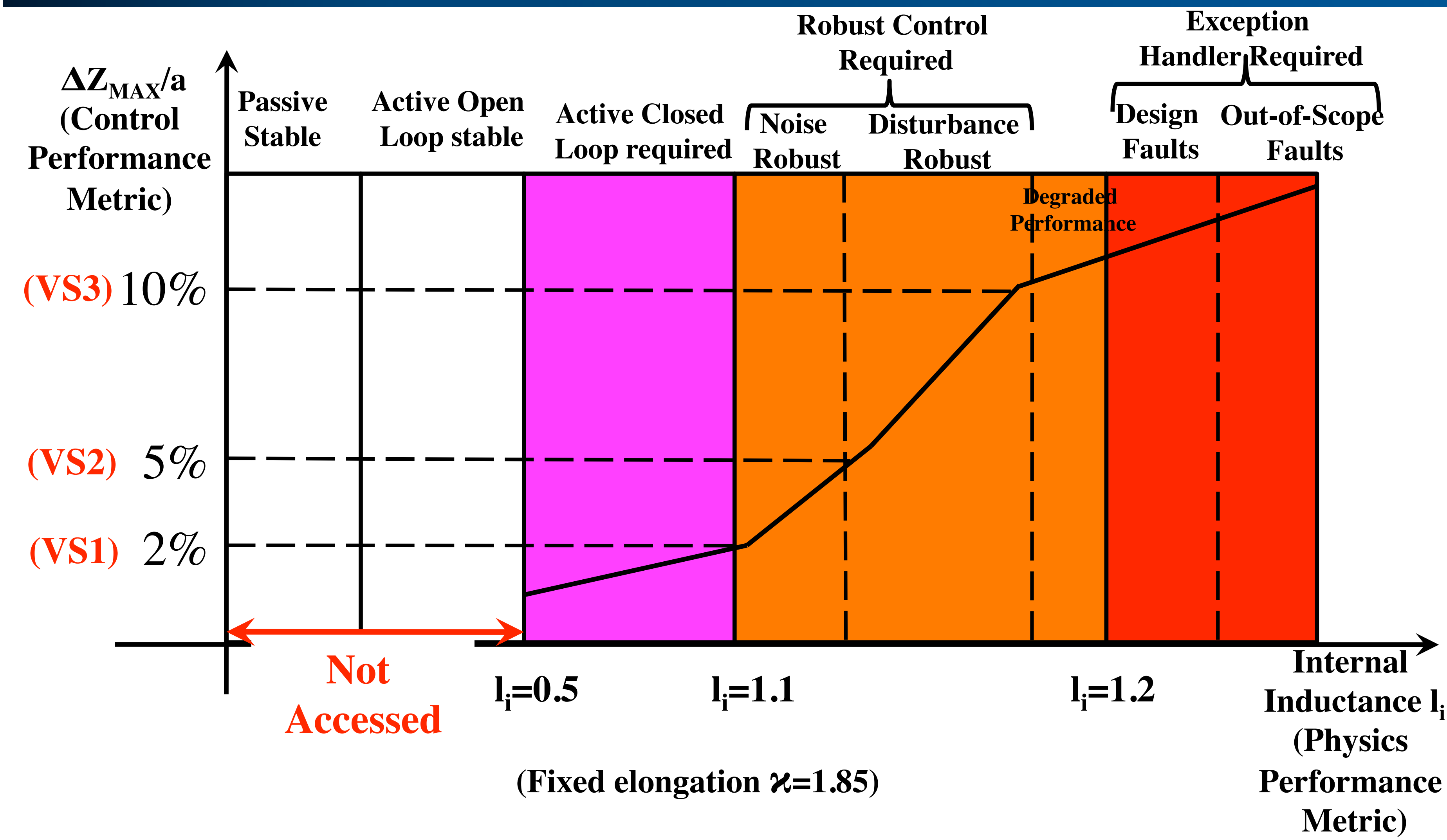
- **Operating devices provide guidance on requirement (assuming noise levels scaling with minor radius):**
  - $\Delta Z_{MAX}/a > 5\%$ required for marginal control
  - $\Delta Z_{MAX}/a \sim 10\%$ required for robust control

- **VS1 System (ITER baseline design):**
  - All outboard PF coils (PF2-5) used for vertical control, 6 kV maximum voltage
  - Provides $\Delta Z_{MAX}/a \sim 2\%$ (guaranteed VDE in DIII-D, C-Mod, JET, …)

- **In-vessel VS3 (Cu) coil system:**
  - Provides $\Delta Z_{MAX}/a \sim 10\%$
  - Severe constraints on operating scenario due to cooling limitations…

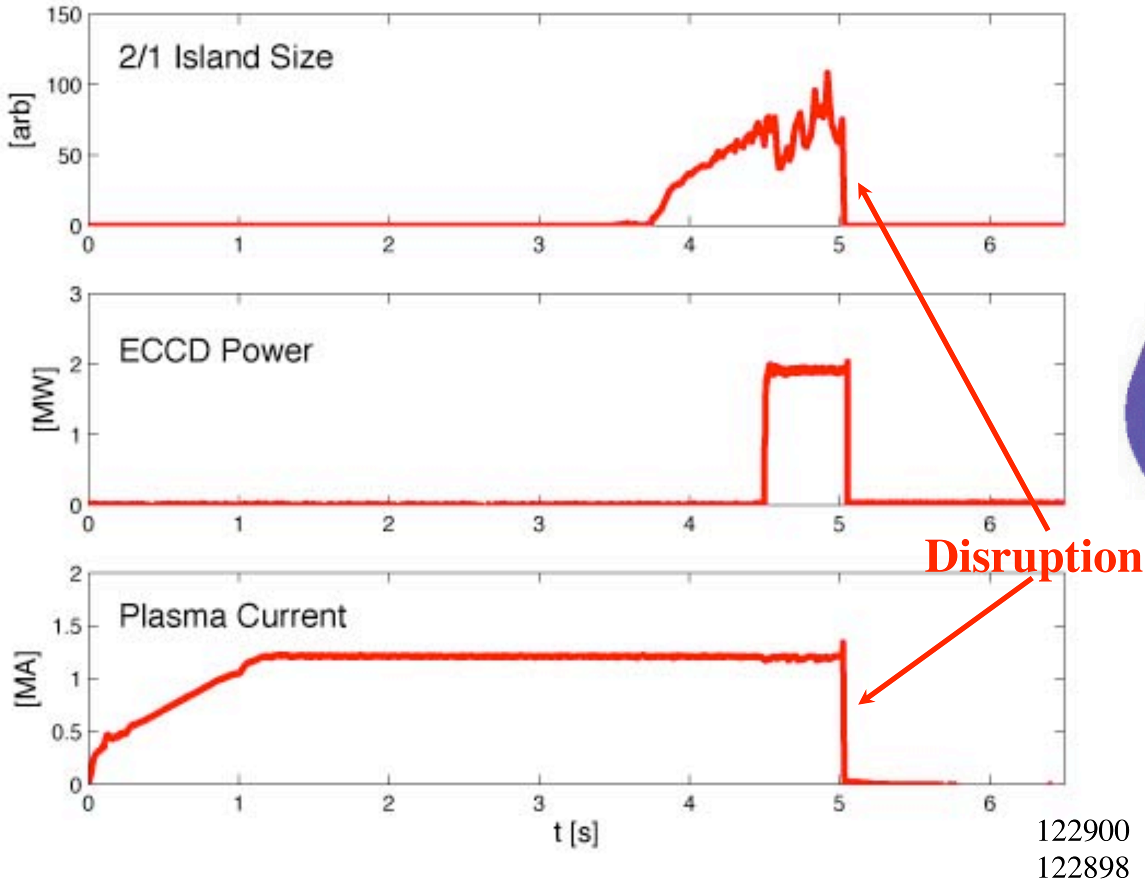


Control Operating Space for ΔZ_{MAX} Performance in ITER



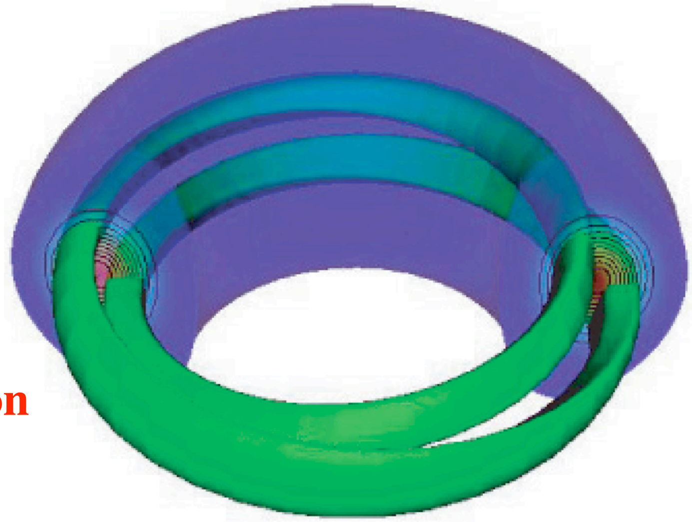
Tokamaks Operating in High Performance (high β) Can Be Unstable to Neoclassical Tearing Mode

2/1 NTM can disrupt plasma if not stabilized



m/n=2/1 NTM:

Poloidal periodicity = 2
Toroidal periodicity = 1



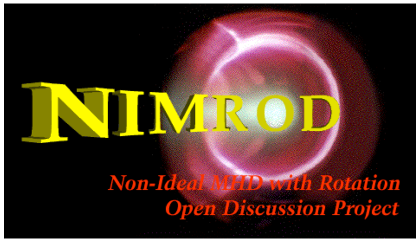
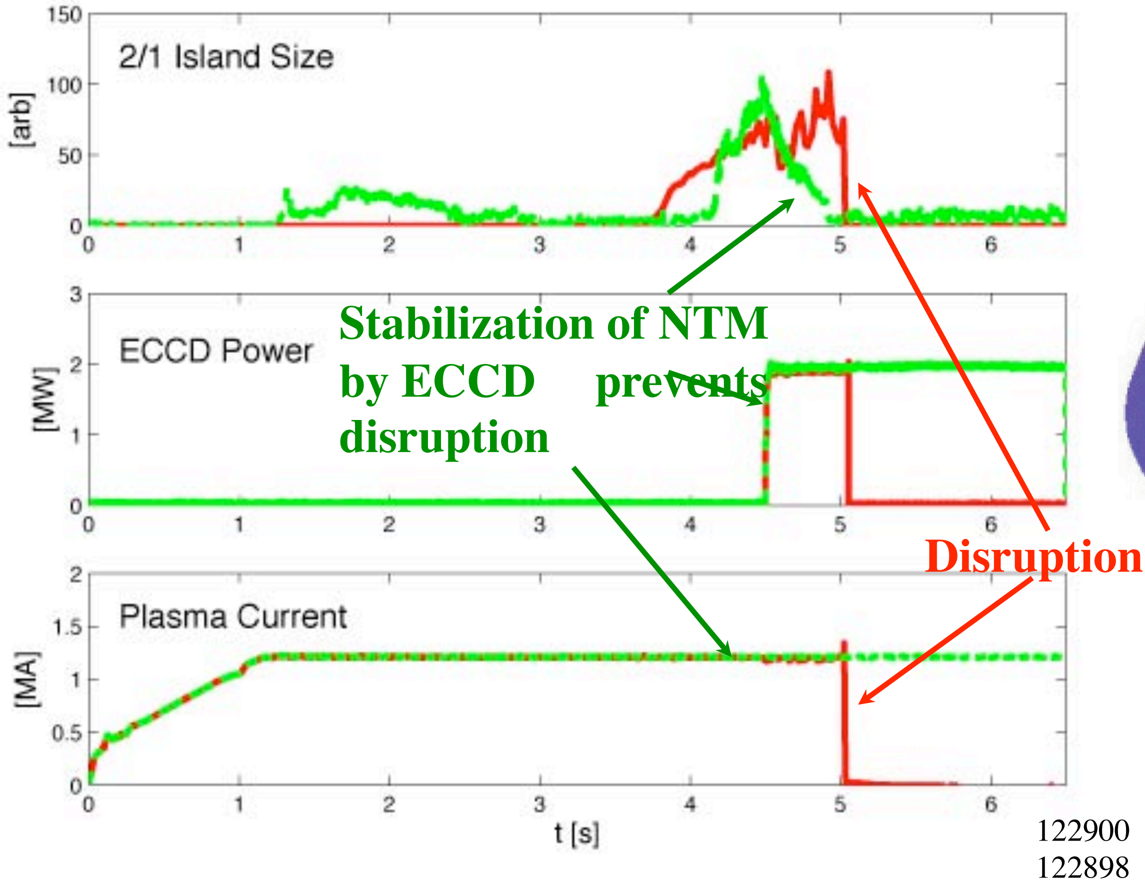


Figure courtesy of D. Brennan

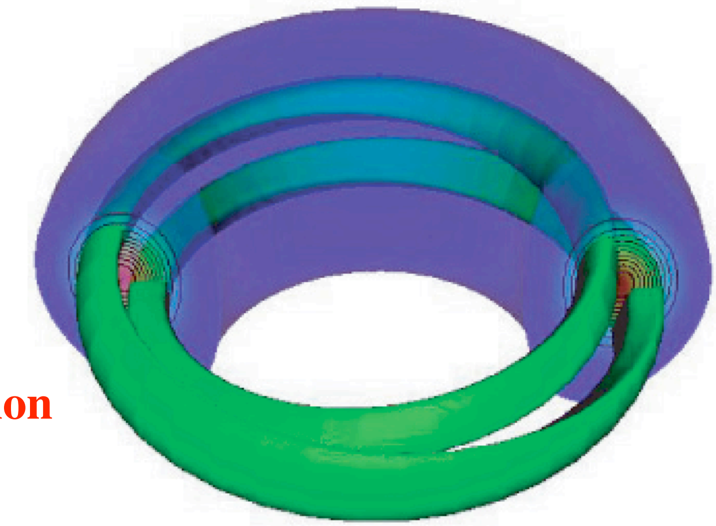
Electron Cyclotron Current Drive (ECCD) Can Stabilizr the Neoclassical Tearing Mode

2/1 NTM can disrupt plasma if not stabilized



m/n=2/1 NTM:

Poloidal periodicity = 2
Toroidal periodicity = 1



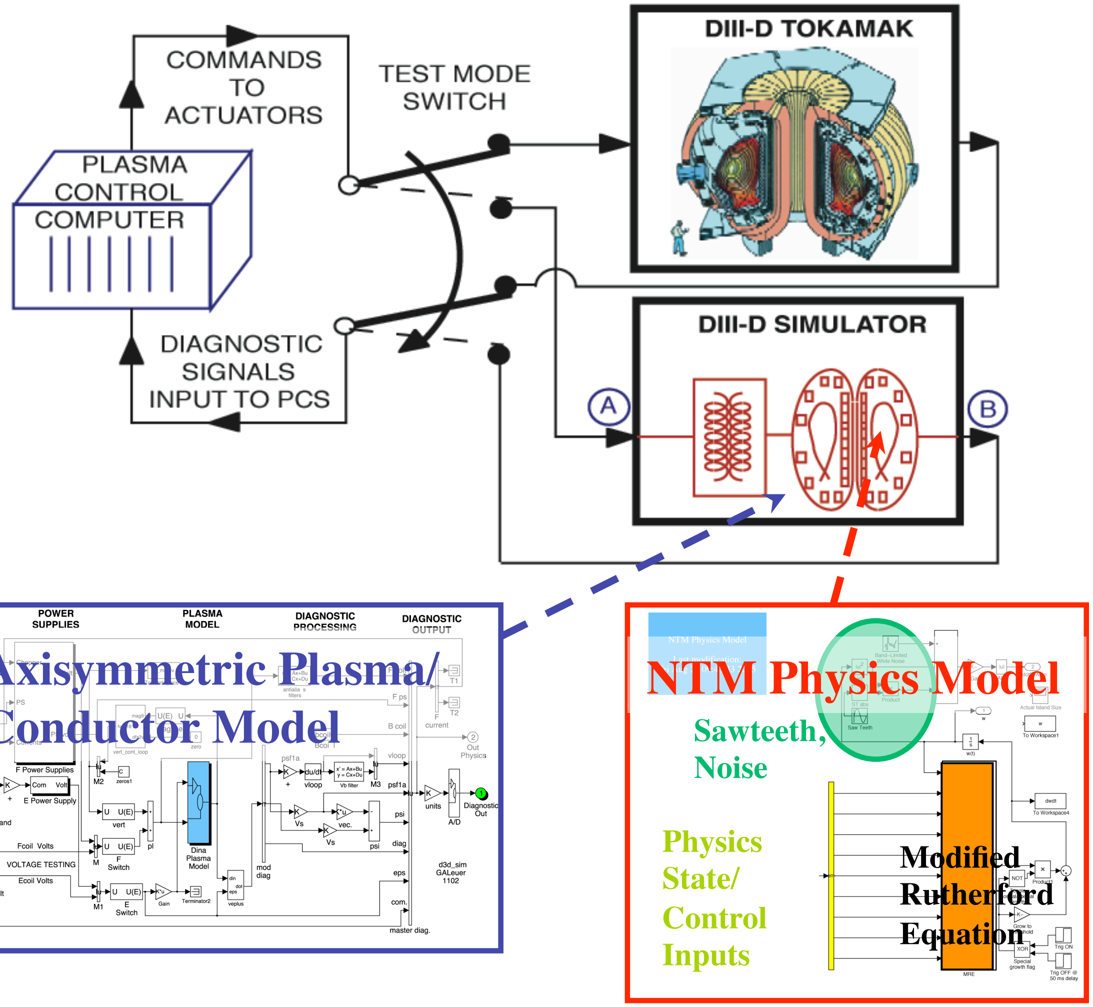
NIMROD
Non-Ideal MHD with Rotation Open Discussion Project

Integrated Plasma Control Simulations Allow Systematic Design and Testing of NTM Controllers

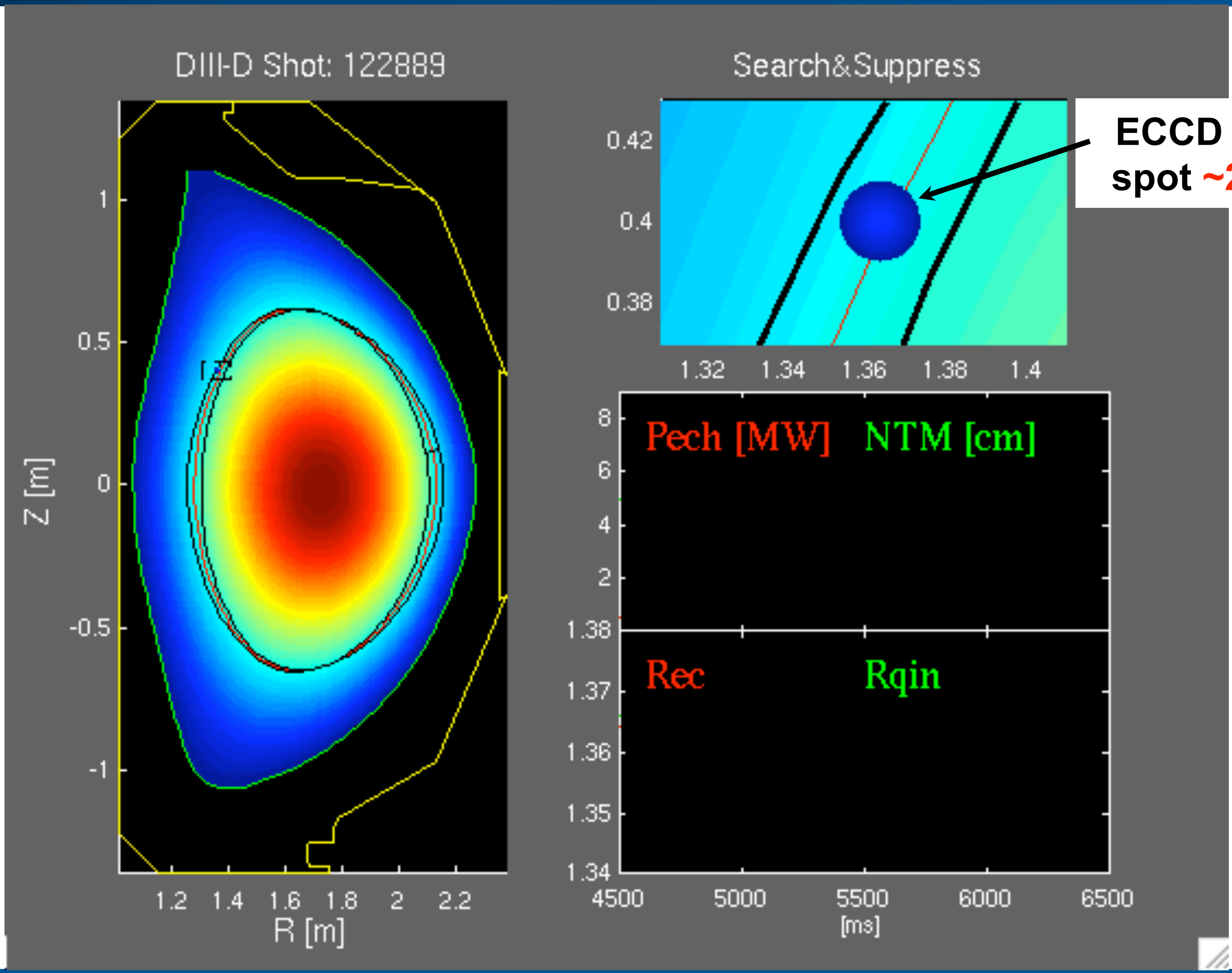
- **Control-level simulations: sufficient detail to describe relevant elements of control action**

- **Simulations connect to actual DIII-D Plasma Control System to allow verification of implementation, performance**

- **Allows development and testing without consuming experimental time**



Active Control Robustly Suppresses NTM and Maintains Alignment of ECCD with Island



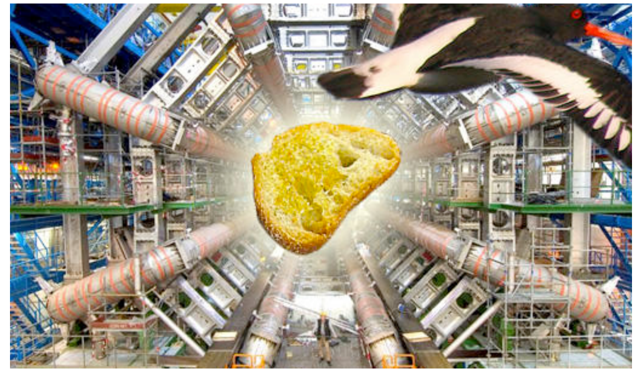
ECCD deposition spot ~2 cm FWHM

High Reliability Requires Systematic Application of Control Design to Scenarios, Algorithms, Fault Response

- **Scenarios:**
  - Physics and control perspectives
  - Issues in scenario design
- **Integrated Plasma Control and Algorithm Design:**
  - Elements of algorithm design
  - Illustrations/Examples
- **Exception/Fault Handling and Disruption Control**
  - What are exceptions?
  - Design approaches to exception handling and disruption control
- **Research Needs and Opportunities**

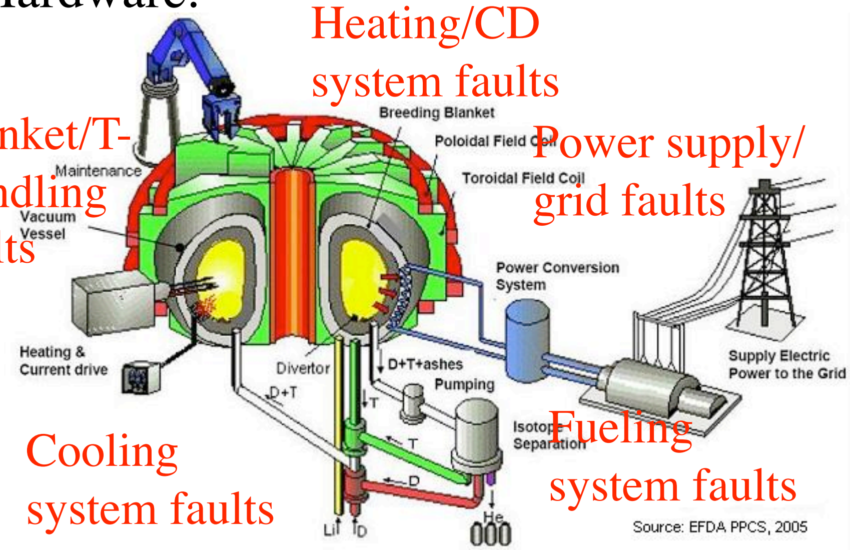
Exception Handling: Minimizing Probability and Impact of Fault Events

- **Exceptions:**
  - Not well-defined yet; subject of discussion and design…
  - Possible definition: events not planned or desired, outside the normal-function envelope of the pulse program
  - Include Design Faults (system faults envisioned and designed for) and Out-of-Scope Faults…
  - DO NOT include design disturbances (perturbations to control within design envelope)
- **Examples:**
  - Failure of a few probes (Design Fault)
  - Baguette-dropping bird (LHC Out-of-Scope fault)



LHC Bombed by Bird

Design Should Ensure Most Faults Are Hardware:



Heating/CD system faults

Blanket/T-Handling faults

Power supply/ grid faults

Cooling system faults

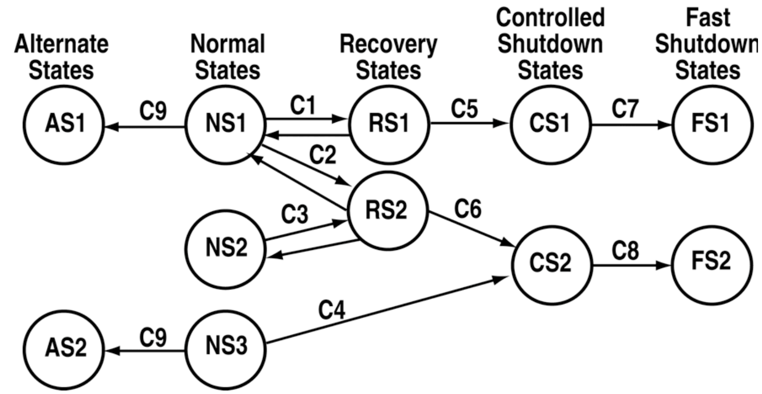
Fueling system faults

Exception Handling: Basic Design Requirements and Approaches

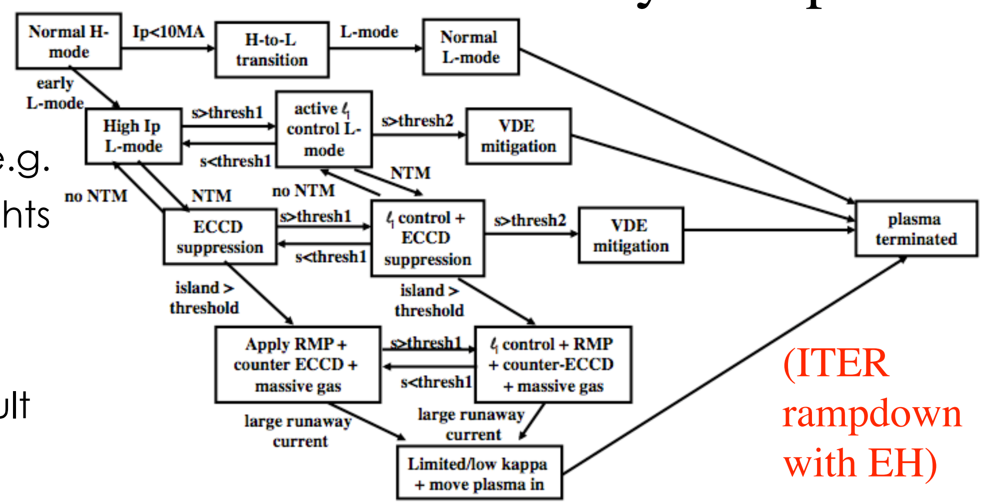
- **Basic design requirements for EH:**
  - Reduce probability to below threshold
  - Sufficient robustness of normal control
  - Effective responses to Design Faults
  - Effective responses to Out-of-Scope events
  - Avoidance, recovery, alternate regimes, soft rapid shutdown, hard rapid shutdown (effects mitigation)

- **Many Possible Approaches:**
  - Algorithms robust to hardware failures (e.g. equilibrium reconstruction with low weights on magnetics)
  - General approaches to classes of faults
  - Specific planned actions to adjust to fault
  - Finite state machine (FSM) structure

General FSM Architecture:



FSM Can Become Very Complex:



(ITER rampdown with EH)

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Disruptions Represent a Particular Kind of Exception Event in Which Plasma is Terminated

- **Disruptions are:**
  - Plasma instability-driven complete loss of thermal energy (thermal quench, TQ)
  - Rapid loss of plasma current, shape, position (current quench, CQ)
- **Possible Damaging Effects:**
  - High heat load to wall, divertor
  - Large electromagnetic forces on conducting structures
  - Damage from relativistic electrons
- **Control Requirements:**
  - Prediction of impending unrecoverable instability
  - Avoidance of disruption
  - Control of effects (e.g. relativistic electrons)

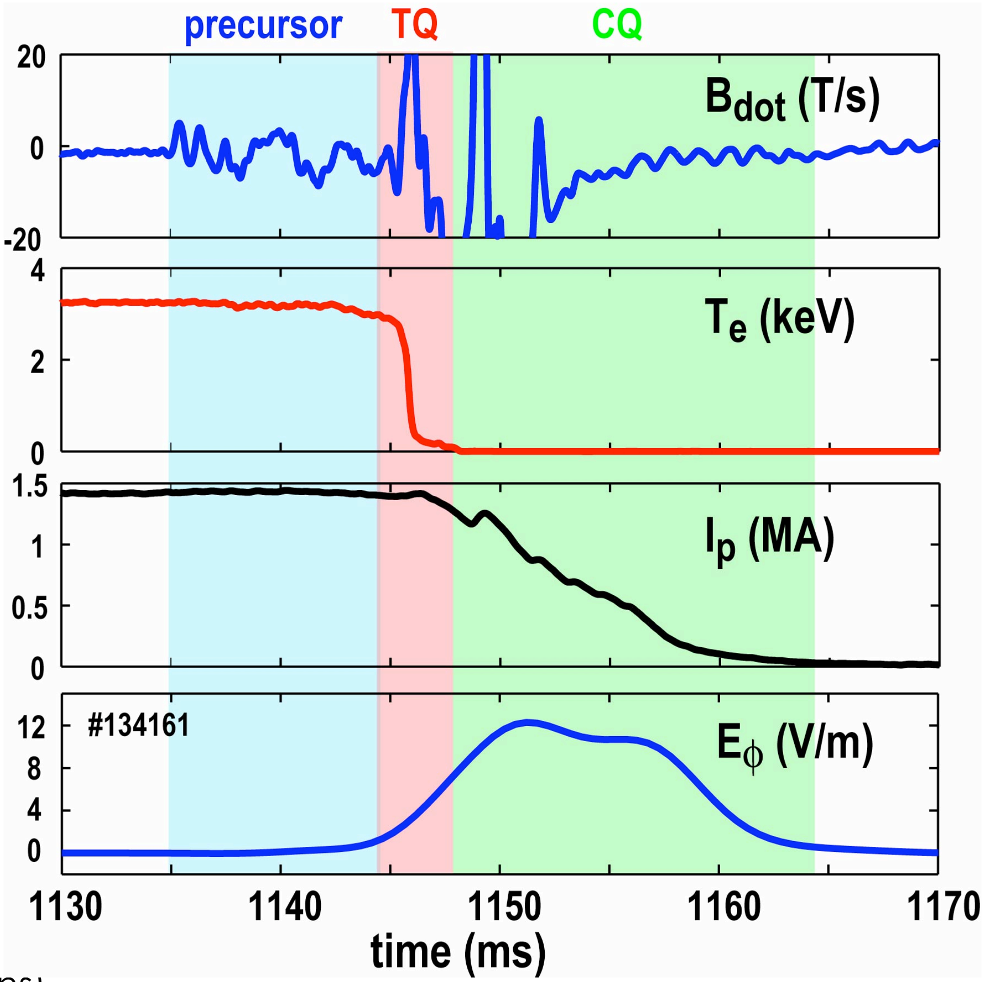

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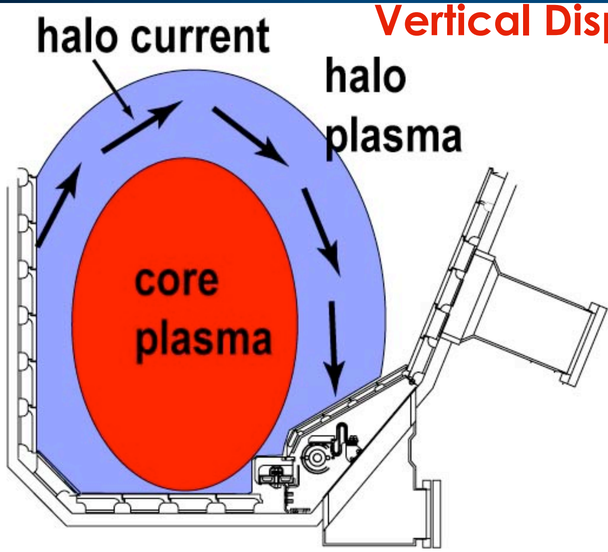
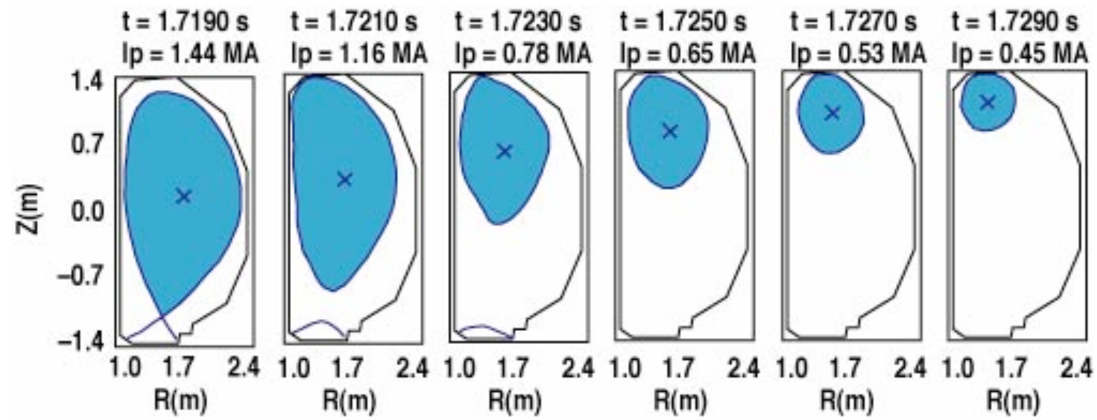
Figure courtesy of E. Hollmann

Unmitigated Disruptions Can Damage First Wall with High Heat Loads, Forces, and Runaway Electrons

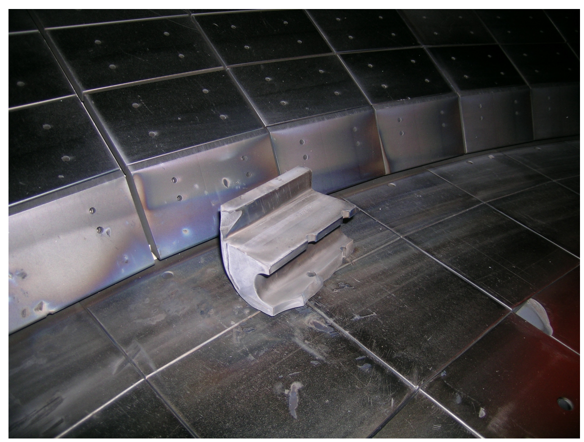


Vertical Displacement Event Applies High Local Halo Current Forces

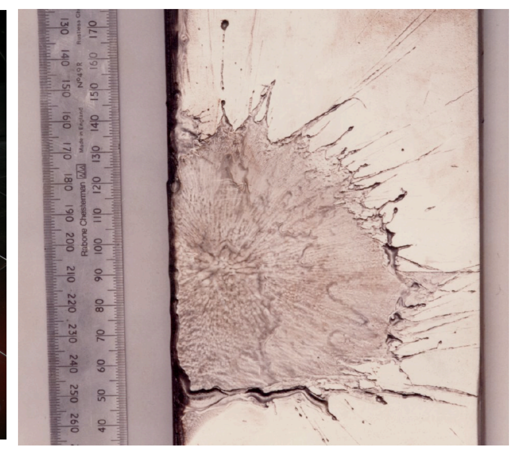


- **Possible Damaging Effects:**
  - High heat load to wall, divertor
  - Large electromagnetic forces on conducting structures
  - Damage from runaway electrons (electrons accelerated to relativistic speeds by high post-disruption voltage)

Tile broken by disruption forces in DIII-D



Tile damage due to RE beam on JET



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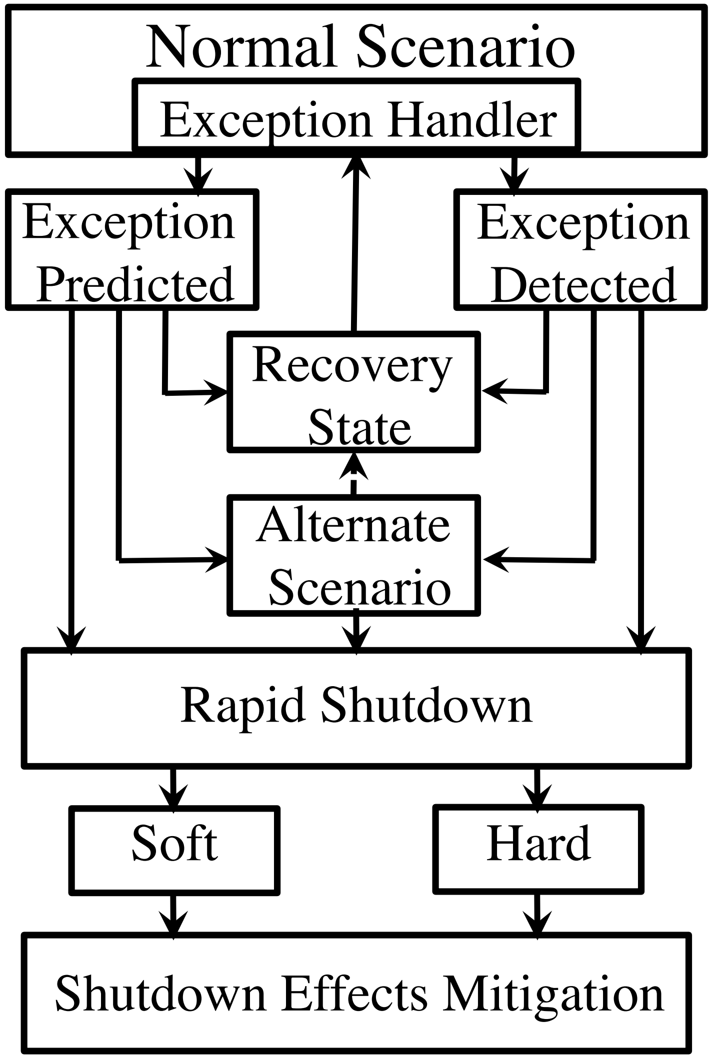
Figures courtesy of E. Hollmann, A. Kellman, G. Martin

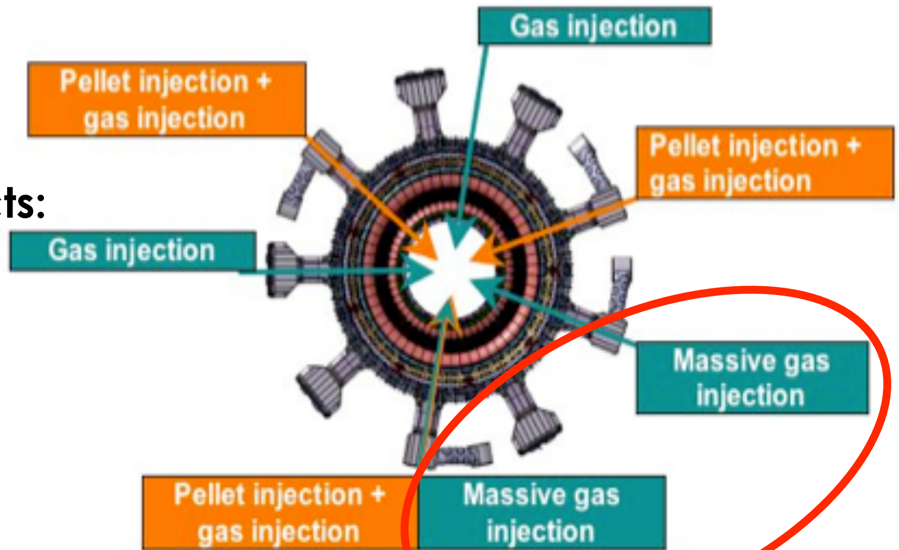
Disruption Control is Part of a Well-Designed Exception Handling System

- **Minimizing incidence of disruptions:**
  - Provable normal scenario control performance
  - Virtually all disruptions should result from machine failure, not initiate with plasma
  - Power supply faults, computer faults, etc…
- **Predicting chain of events leading to disruption:**
  - High accuracy real-time plasma stability assessment
  - System health monitoring, prediction, detection
- **Response to impending disruptions:**
  - Alternate regime, sustained or recovery
  - Alternate control scenario (activate specialized actuators, algorithms)
  - Soft rapid shutdown
- **Mitigating damaging disruption effects:**
  - Hard rapid shutdown with mitigation



Disruption Mitigation Methods

- **Final machine protection action:**
  - Extremely rare event by design
  - Analogous to crash survival
- **Partial success in mitigating disruption effects:**
  - Massive gas injection: 75% reduction of heat load/forces
  - Control of runaway channel position
- **Active area of research:**
  - Large cryogenic pellets, more massive gas…
  - Exceed Rosenbluth density to suppress runaways
- **Reactors including ITER have unique needs:**
  - Provable/quantifiable mitigation
  - Need for coordinated response, not just individual hardware interlocks for subsystems



ITER plans 2 ports for Massive Gas Injection

Bringing It All Together

The Full Vision

- **High reliability fusion reactors are achievable with integrated plasma control design:**
  - Control design based on validated models
  - Verification of implementation and function with simulations
  - Provable exception handling algorithms and response systems

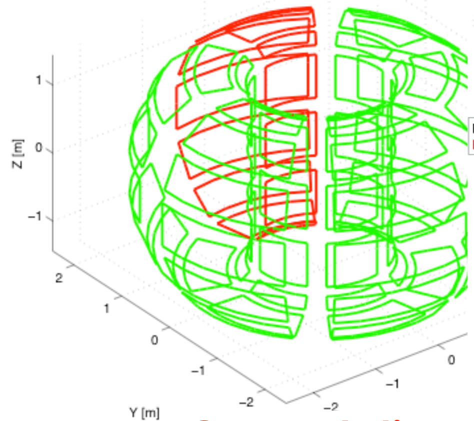
- **Control design that takes into account the Control Operating Space is critical to many aspects of reactor development:**
  - Machine design
  - Scenario design and operation
  - Control algorithms
  - PCS design
  - Exception handling

- **Strong analogy between fusion reactor control and high performance aircraft control:**
  - Mature control design approaches have demonstrated the capability of high reliability
  - BUT substantial fusion control research is needed to provide solutions for ITER and beyond
  - Key question: can fusion reactors be economical at the cost of the required control reliability?

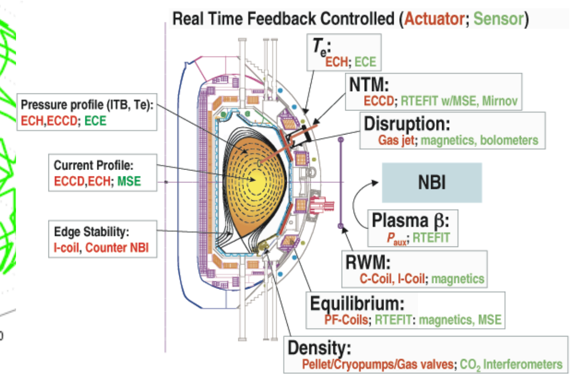
Path to Control of ITER and Operational Fusion Reactors is Rich with Research Opportunities

- **Control physics:**
  - Plasma response models **for control**
  - Heating, current drive effects models
  - Instability physics models
- **Control mathematics:**
  - Integrated multivariable algorithms
  - Robust design methods
  - Design solutions for nonlinearities (saturation, plasma nonlinearity, etc…)
  - Provable architectures and algorithms for exception handling
- **Tool development:**
  - Modeling/simulation/validation/verification
  - Computational solutions: real-time and offline

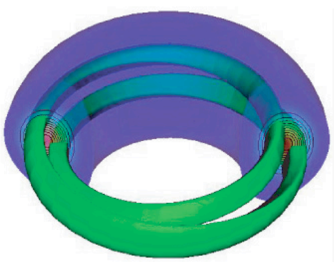
Physics models

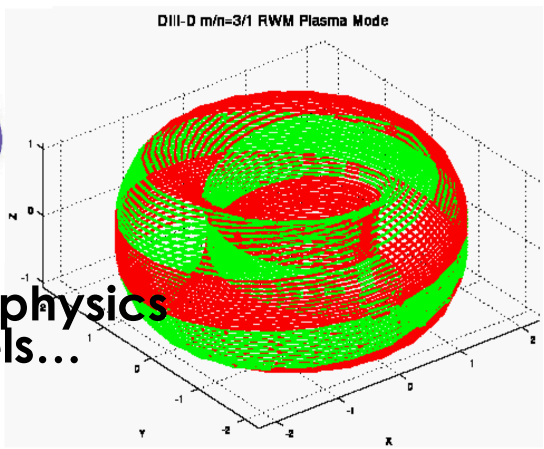


High performance experiments



Computational tools





More physics models…

Some References

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