Prospects for Disruption Handling in a Commercial Tokamak Fusion Reactor

by

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General Atomics

Presented at

DIII-D Friday Science Meeting

July 19, 2021

GENERAL ATOMICS

If you remember nothing else…

1. Disruptions are among greatest challenges to achieving an economically viable tokamak-based fusion reactor

2. Disruption handling must be incorporated into tokamak reactor design at the same priority as core performance and steady state heat flux removal

3. ITER ≠ Commercial Reactor

Outline

1. What are disruptions & why/how do we handle them?
2. Evolution of disruption handling requirements: Research → Commercial Reactor
3. Contemporary state of disruption handling
4. Challenges to disruption prevention posed by a commercial reactor
5. Resilient design

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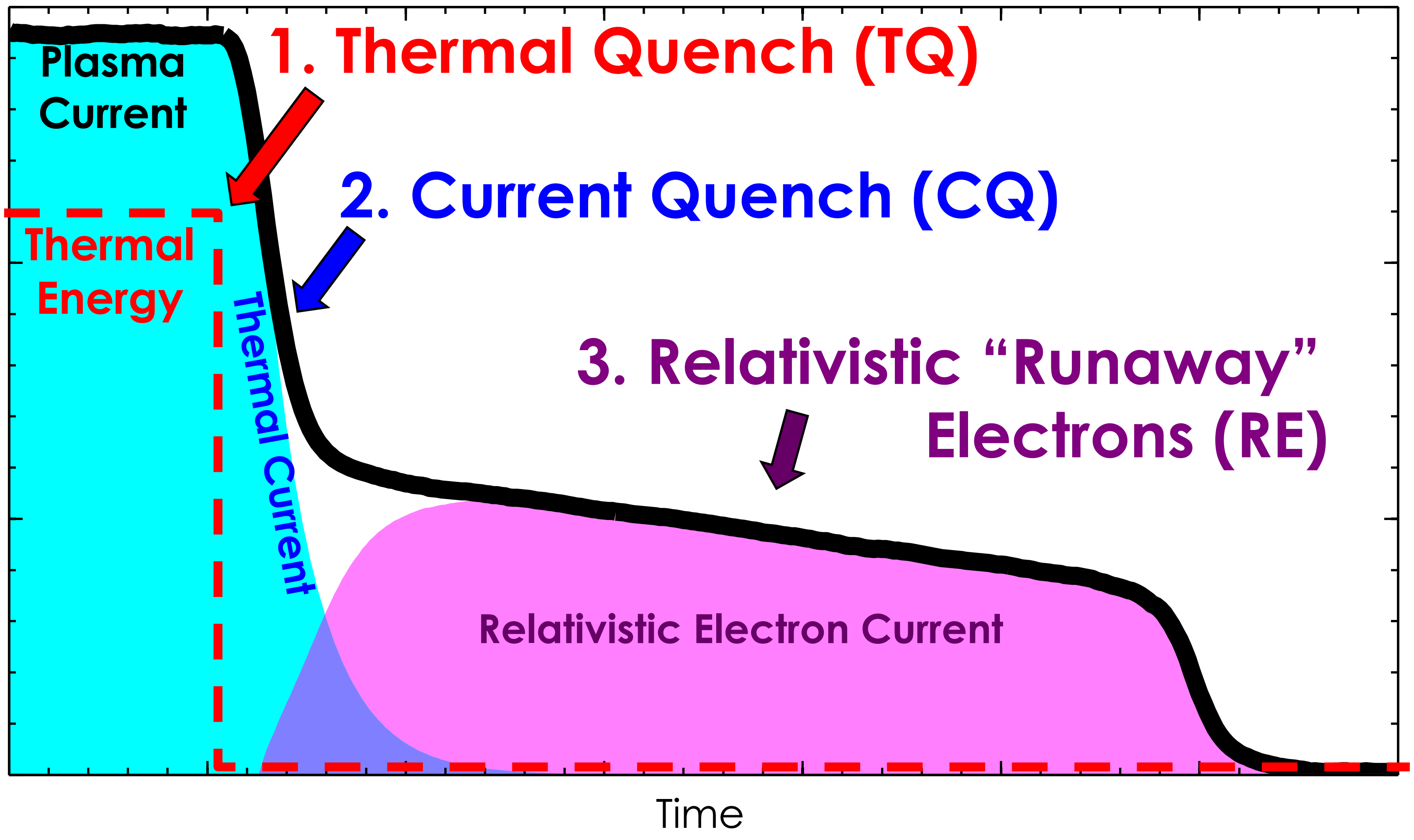
Disruption =
Rapid termination of a discharge due to plasma instability

3 Stages of Tokamak Disruption

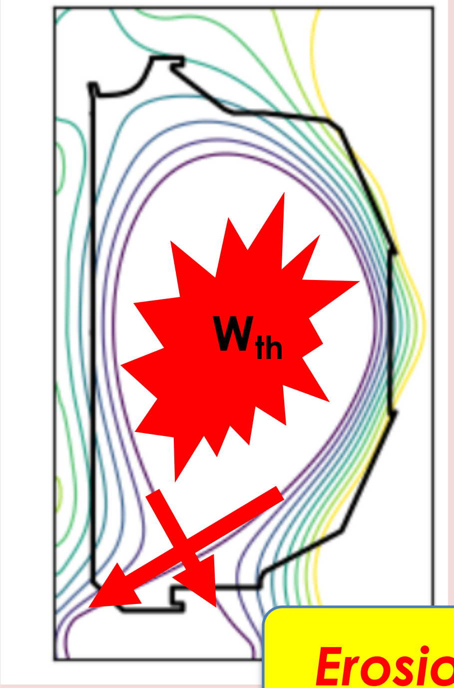


Result: Complete transfer of plasma thermal & magnetic energy to vessel & in-vessel components on a very rapid timescale

Each stage of disruption poses unique threats to device

TQ

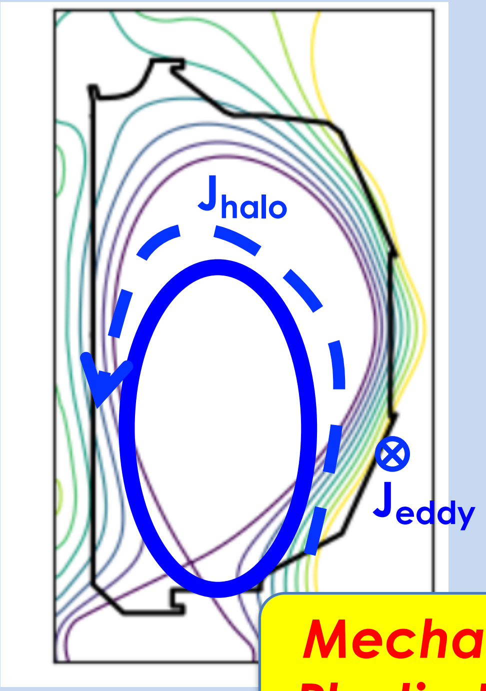
Conduction of stored thermal energy to the divertor



Erosion

CQ

Large vessel forces from halo or eddy currents



Mechanical Stress, Plastic Deformation

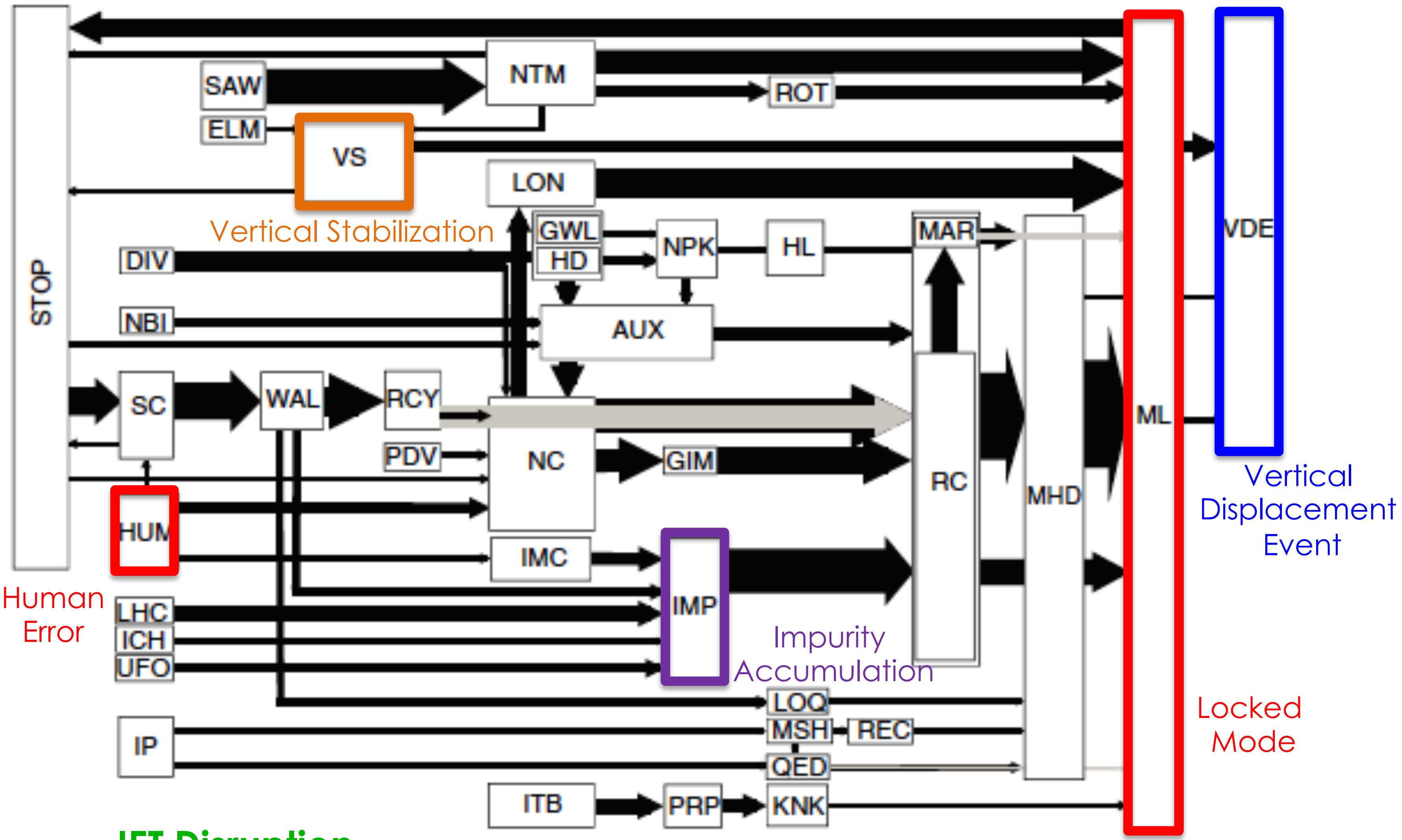
RE

Large population of high energy (MeV) electrons

PFC Melting, H_20 Leaks, Tile Failure, Coil quench

All purpose references: M. Lehnen JNM 2015
R. Sweeney JPP 2020

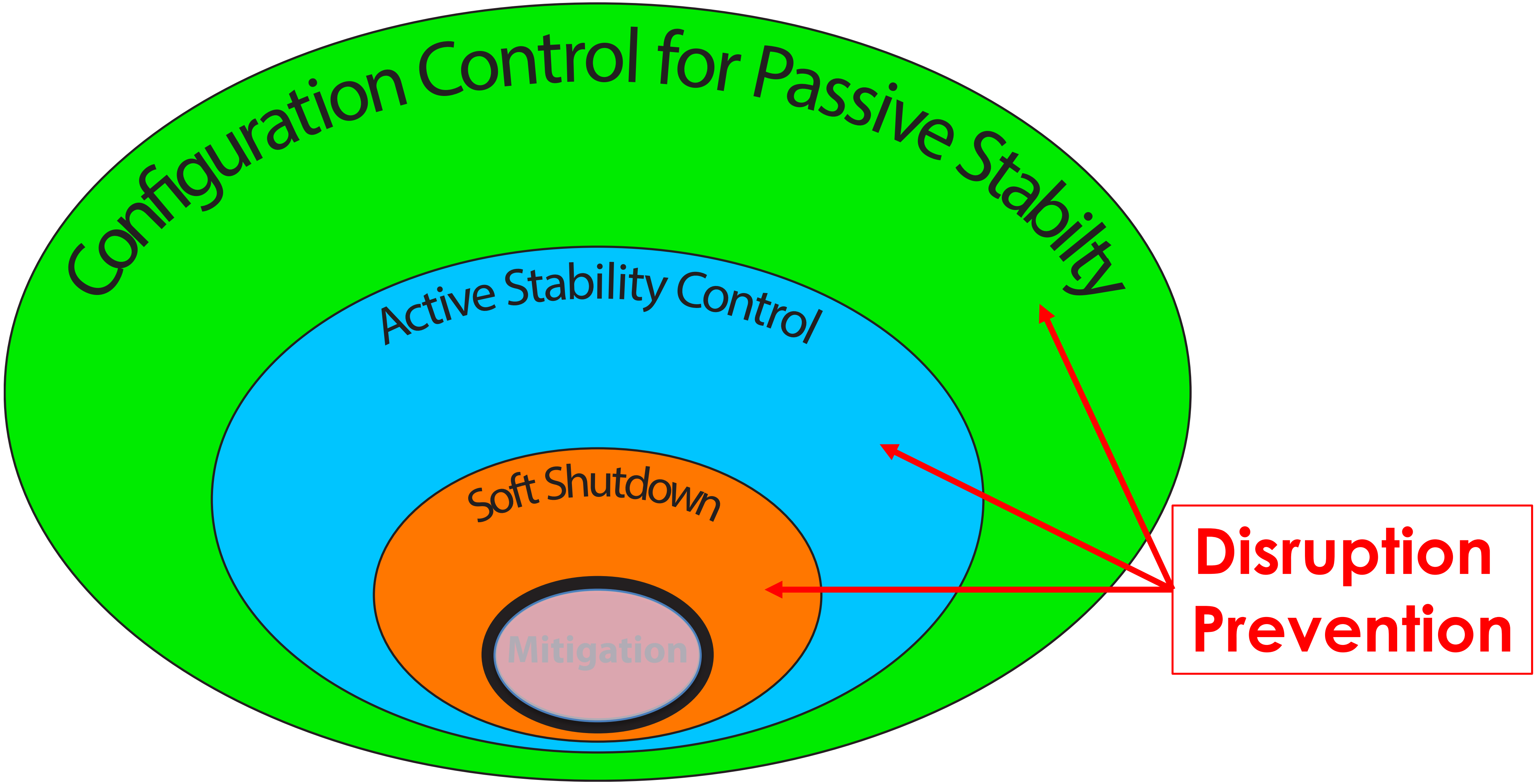
Root causes of disruptions in tokamaks are widely varied *(so we will not go into them)*



JET Disruption Chain of Events

P.C. de Vries et al, Nucl. Fusion **51** (2011) 053018

Disruption handling is a multi-stage process



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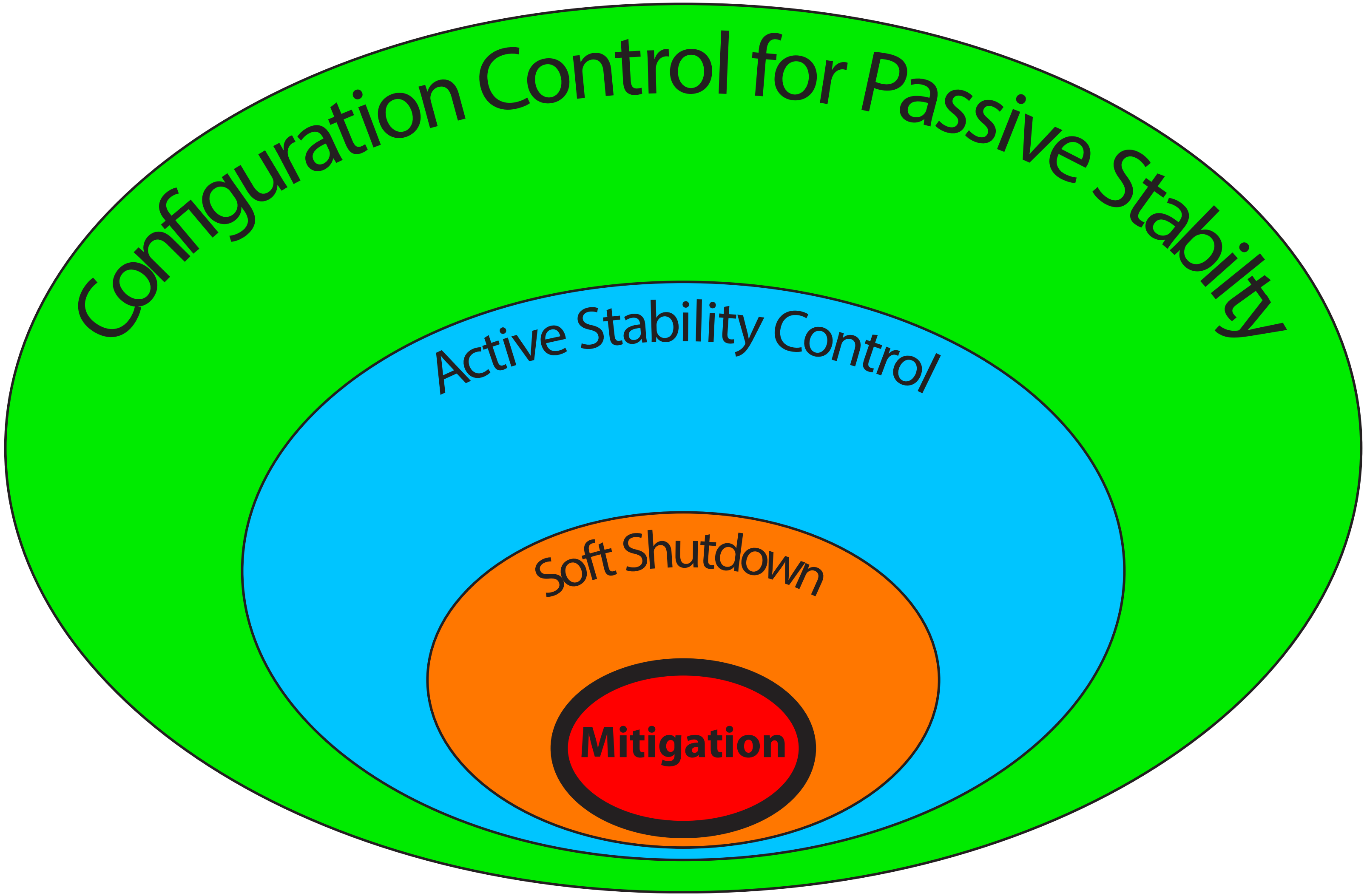

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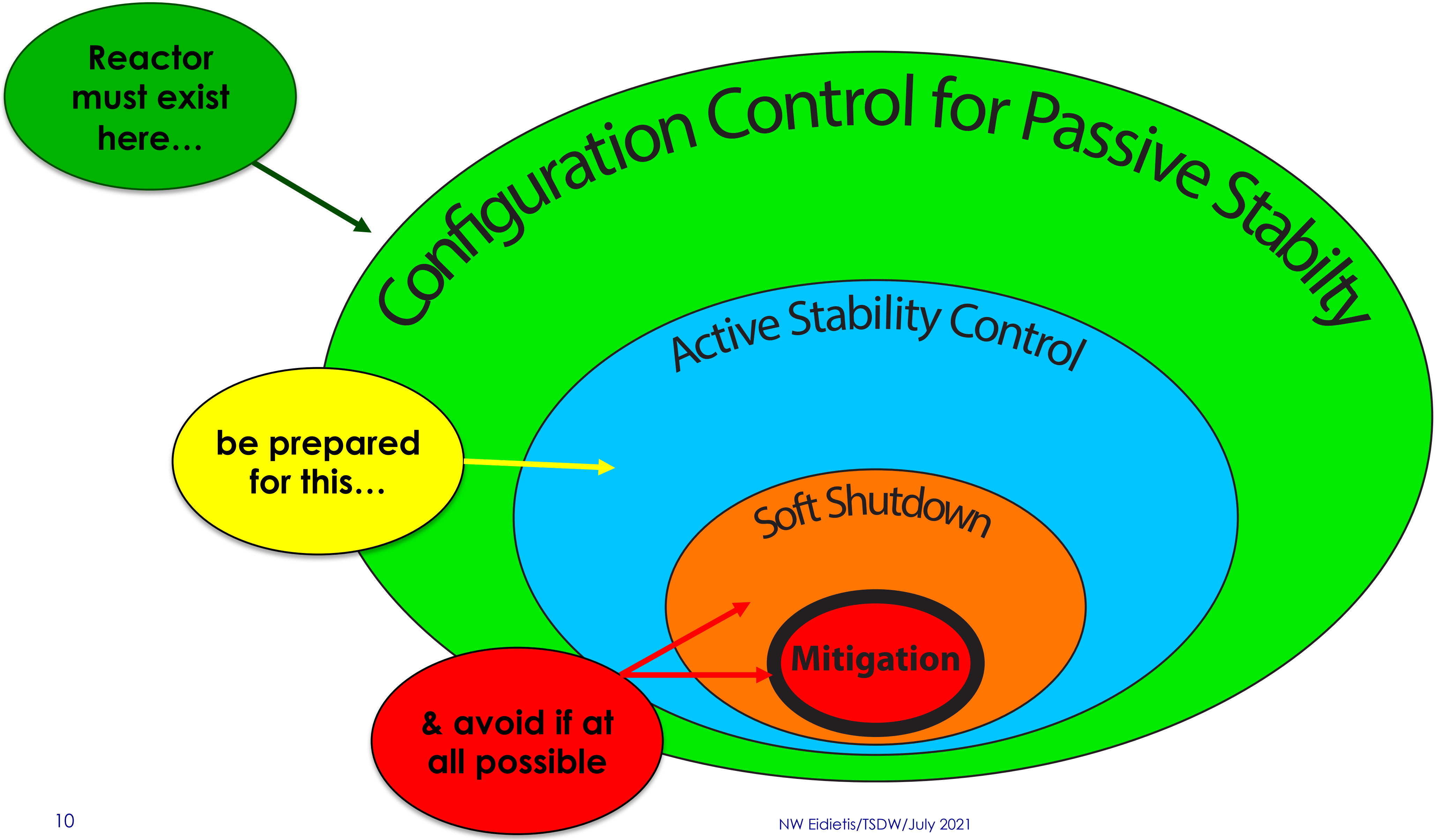

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Disruption handling requirements change drastically with tokamak mission and size: Contemporary Research Tokamak

- **Mission:** Research physics/tech basis for burning plasma
- **Lifetime:** Indeterminant
- **Duty Factor:** Short pulse
- **Energy Density:** Low

Soft Shutdown Acceptable
YES

Disruption Acceptable?
YES

Mitigation Required?
NO*

* Notable exceptions are metal-wall JET[1], which utilizes closed-loop mitigation at times

[1] C. Reux FED 2013

Disruption handling requirements change drastically with tokamak mission and size: ITER

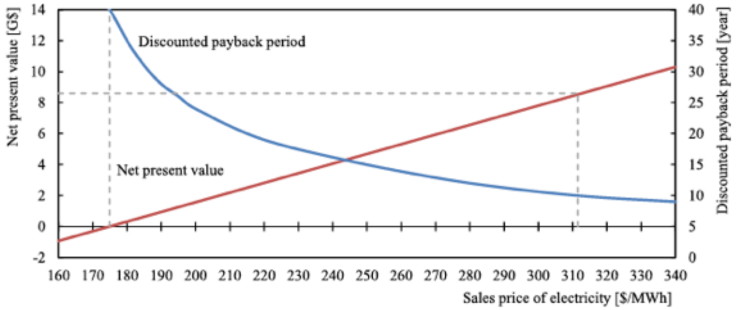
- **Mission:** Research[1]. $Q=10$ pulse & $Q \geq 5$ non-inductive + tech
- **Lifetime:** 10+6 years
- **Duty Factor:** Short pulse → Soft Shutdown Acceptable YES
- **Energy Density:** High → Disruption Acceptable? NO; Mitigation Required? YES

ITER must operate within **Disruption Prevention** regime

[1] ITER Research Plan ITR-18-003 2018

Disruption handling requirements change drastically with tokamak mission and size: Commercial Reactor

- **Mission:** Stable energy production & capital return



- **Lifetime:** 40+ years[1]

Commercial reactor outlook sensitive to low probability, high impact events

- **Duty Factor:** 18+ months continuous
- **Energy Density:** High

Soft Shutdown Acceptable
NO

Disruption Acceptable?
NO

Mitigation Required?
YES

Commercial reactor must operate within **Passive Stability & Active Stabilization** stages of Disruption Prevention

[1] S. Entler *Energy* 2018

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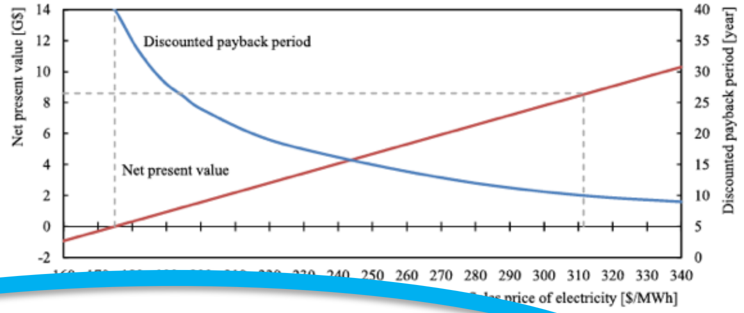

Unless reactor designed with excess thermal reservoir to allow restarts without massive loss of generating capacity (i.e. pulsed design[2])

Soft Shutdown Acceptable
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Disruption Acceptable?
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[1] S. Entler *Energy* 2018
2. Segal NF 2021

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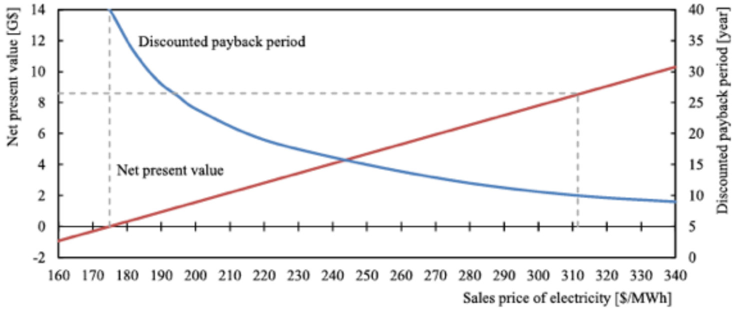

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DEMO/FPP straddle the ITER←→Commercial line

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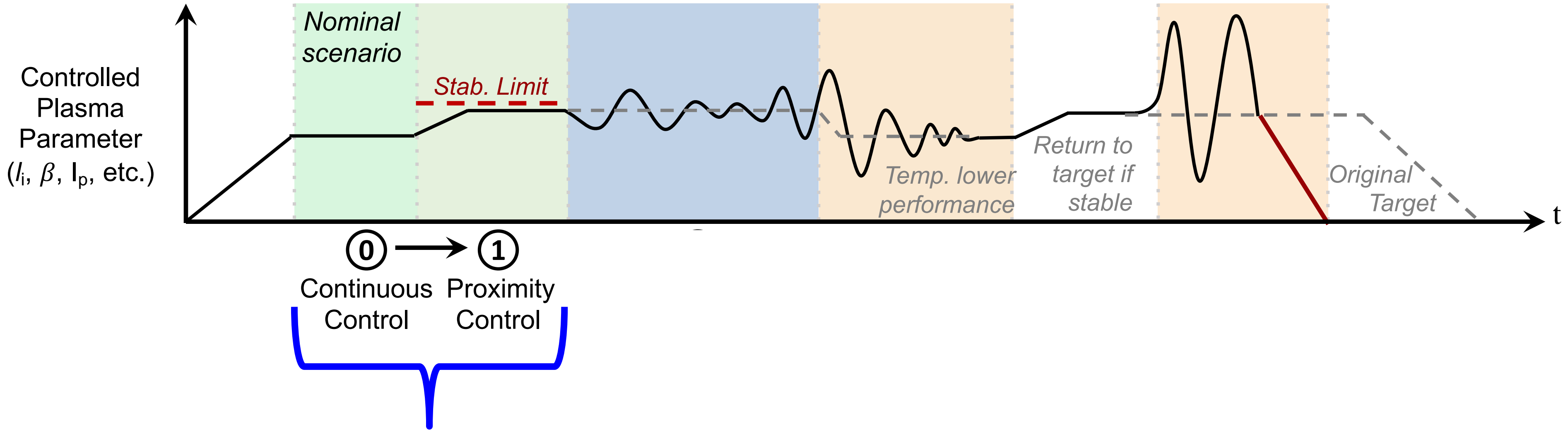
Excellent overviews in ITER context:
Prevention: E. Strait NF 2019
Mitigation: M. Lehnen JNM 2015

Functional view of disruption handling



Stage 0 & 1: Avoid unstable regimes

Stage 0: Nominal scenario

Goals
1.High pressure
2. Passive Stability

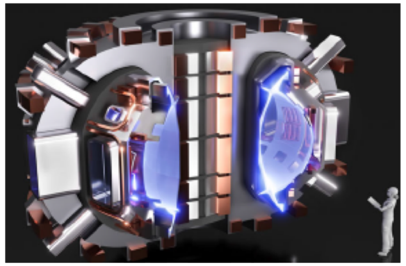
"Engineering" route

High Field

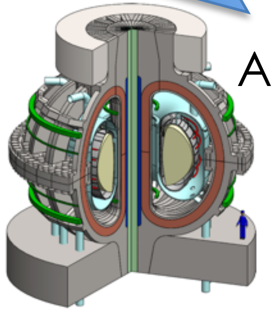
"Physics" route

Advanced Tokamak

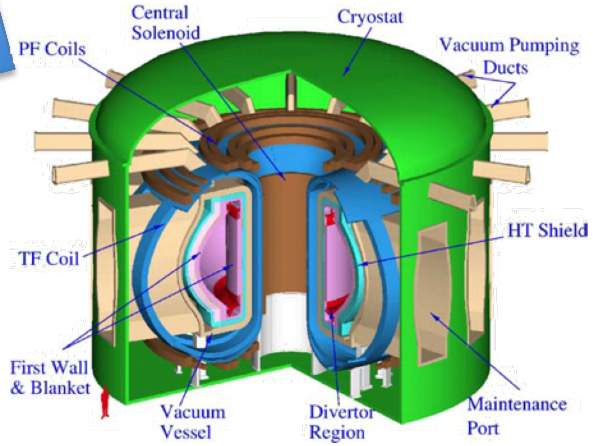
SPARC



ARC



ARIES-AT



- Well-established physics
- Strong toroidal field key

- Advanced physics
- Plasma profile manipulation key

Key Enabling Tech:
High Temperature Superconductors

Key Enabling Tech:
Advanced Current Drive

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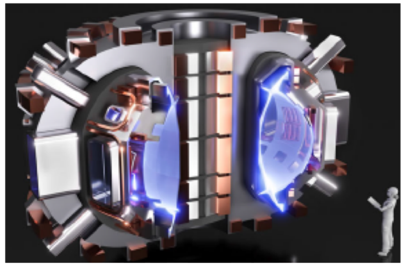

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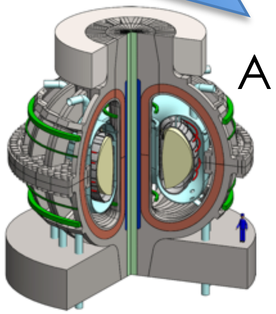

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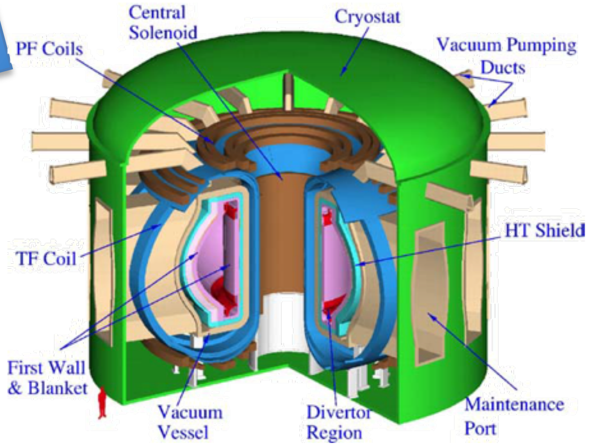

Continuum of designs in between

- Well-established physics
- Strong toroidal field key

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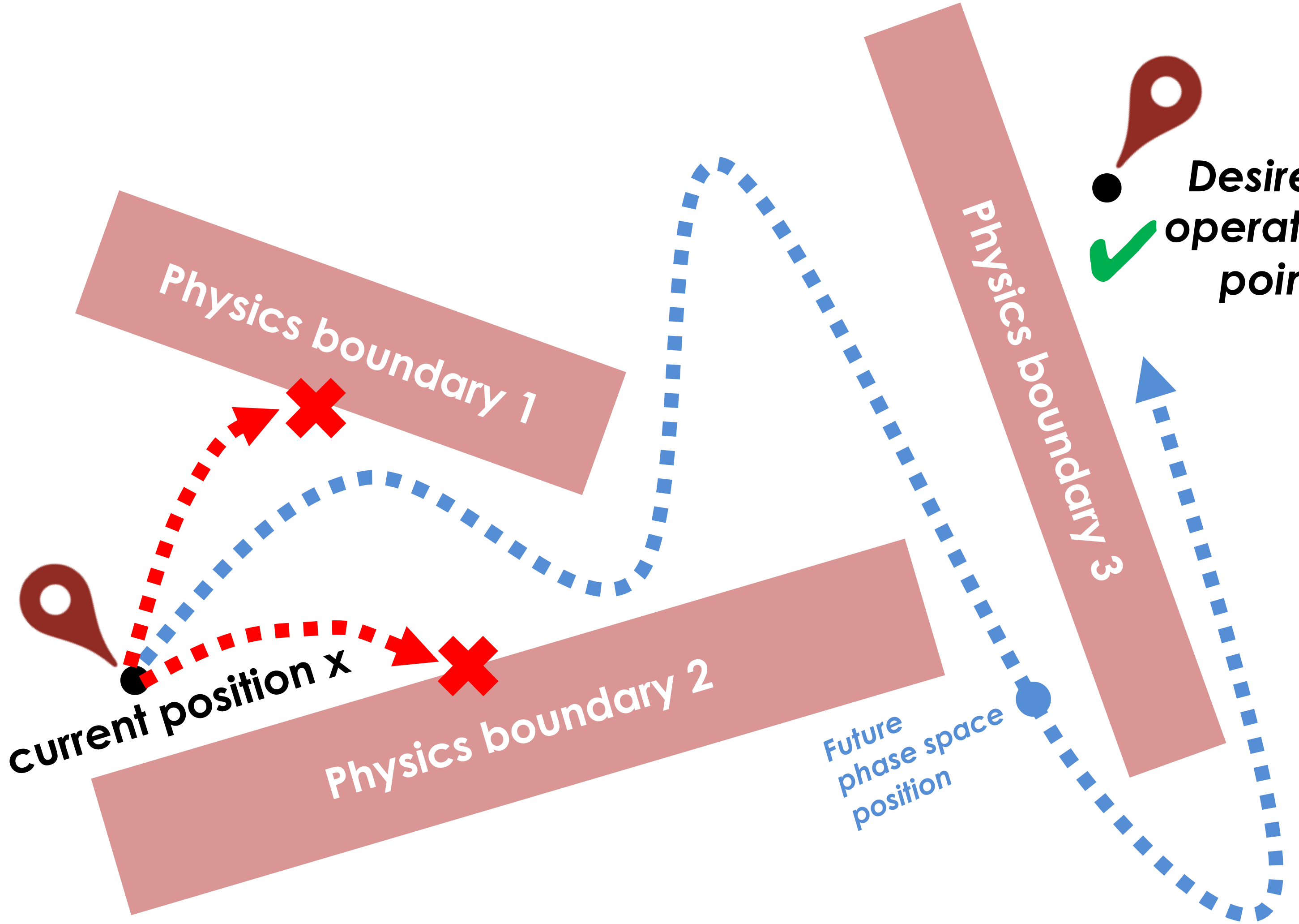
Stage 1. Regulated passive stability / proximity control (avoidance of unstable areas)



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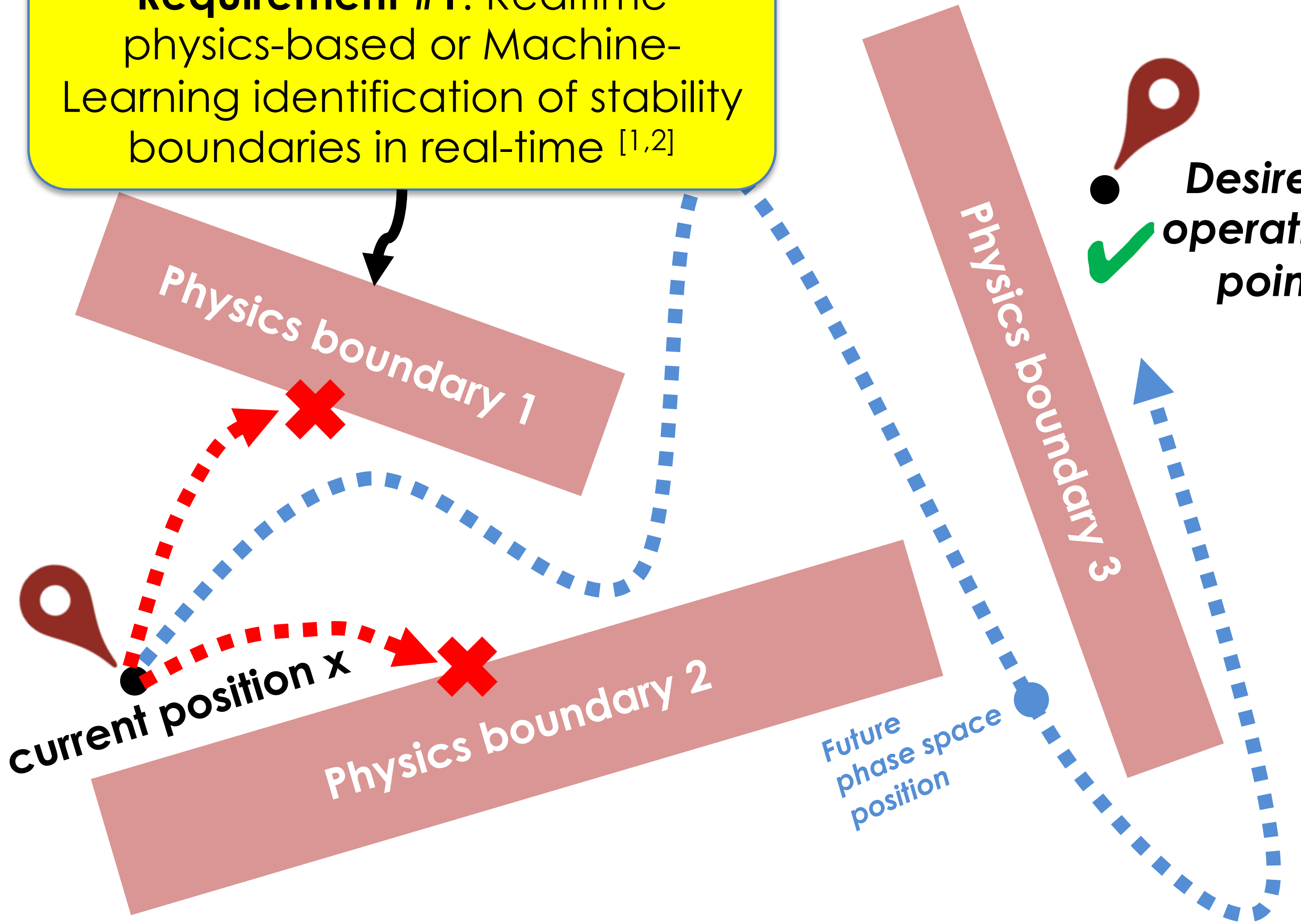
Requirement #1: Realtime physics-based or Machine-Learning identification of stability boundaries in real-time [1,2]



[1] KEJ Olofsson PPCF 2018
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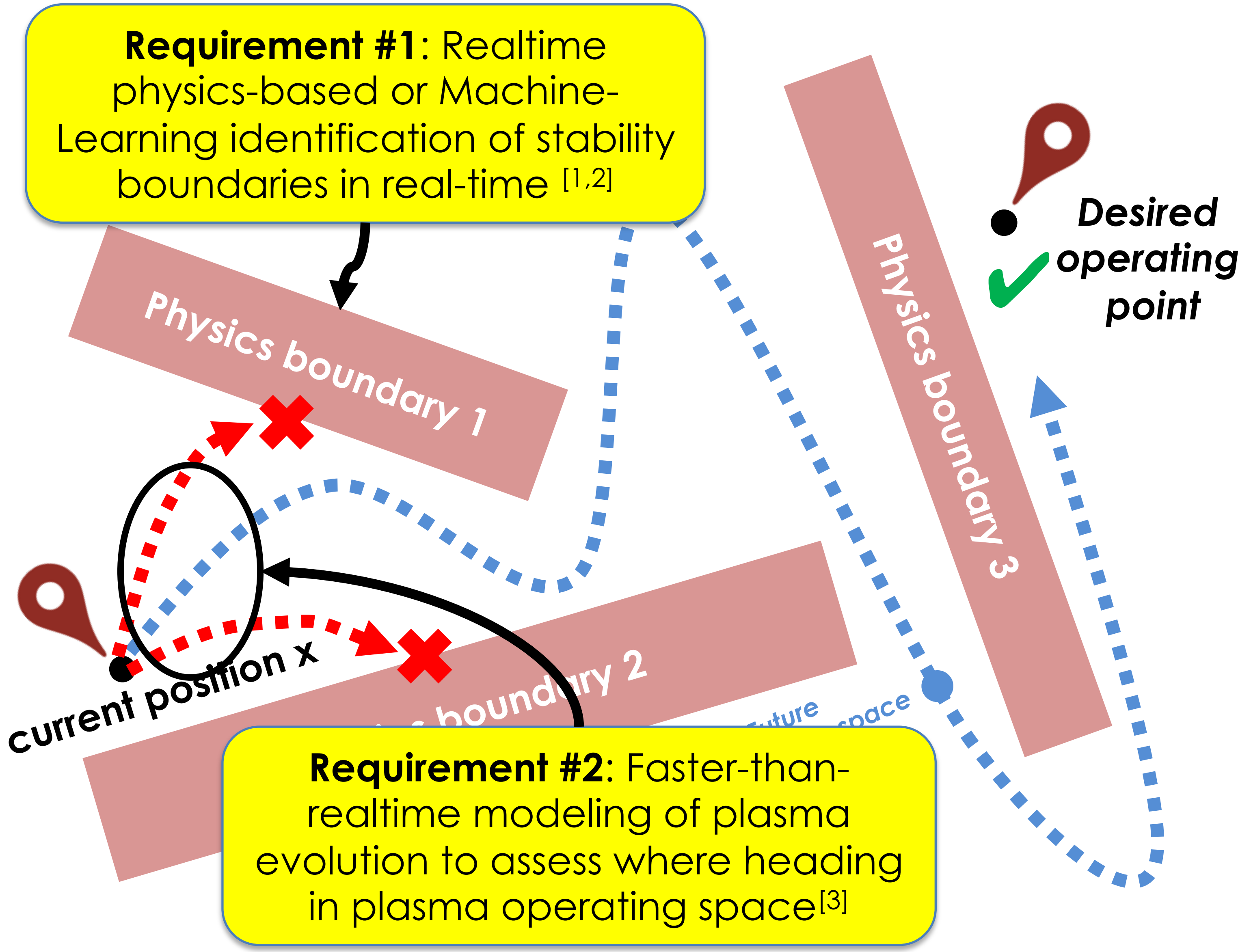

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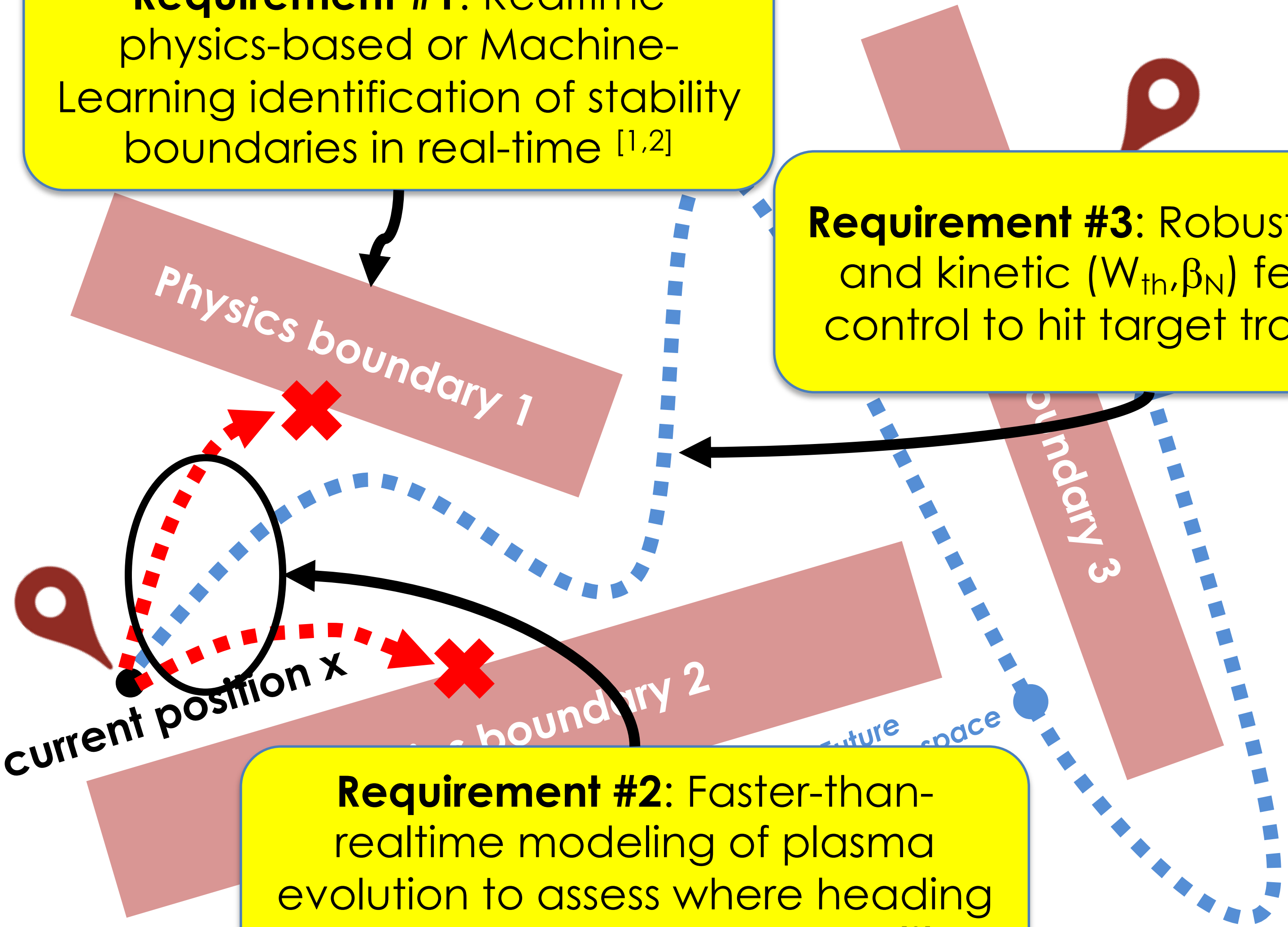
[3] F. Felici NF 2018

Stage 1. Regulated passive stability / proximity control (avoidance of unstable areas)

Requirement #1: Realtime physics-based or Machine-Learning identification of stability boundaries in real-time [1,2]

Requirement #3: Robust profile (j) and kinetic (W_{th},β_N) feedback control to hit target trajectory[4]

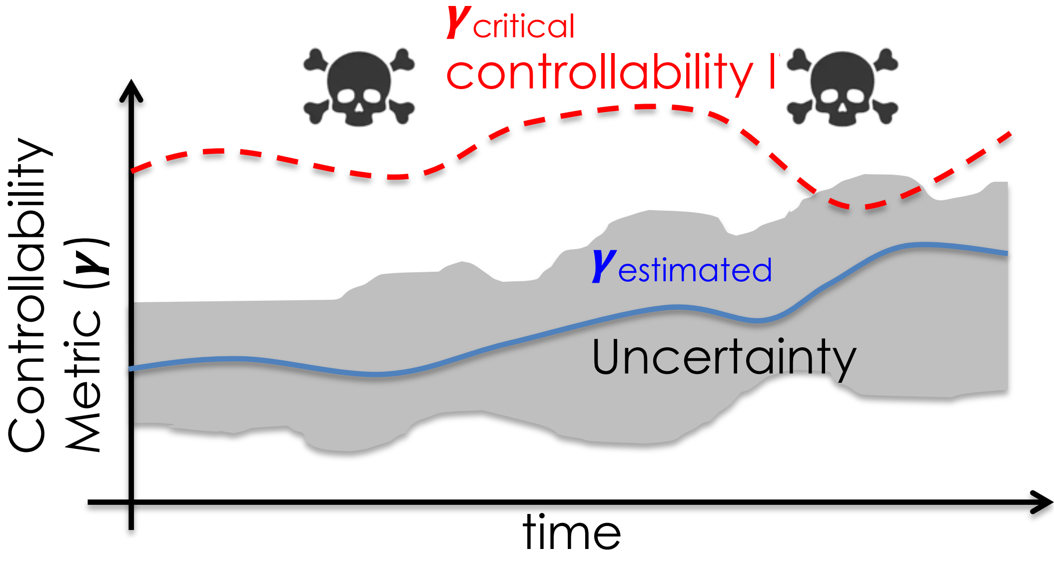


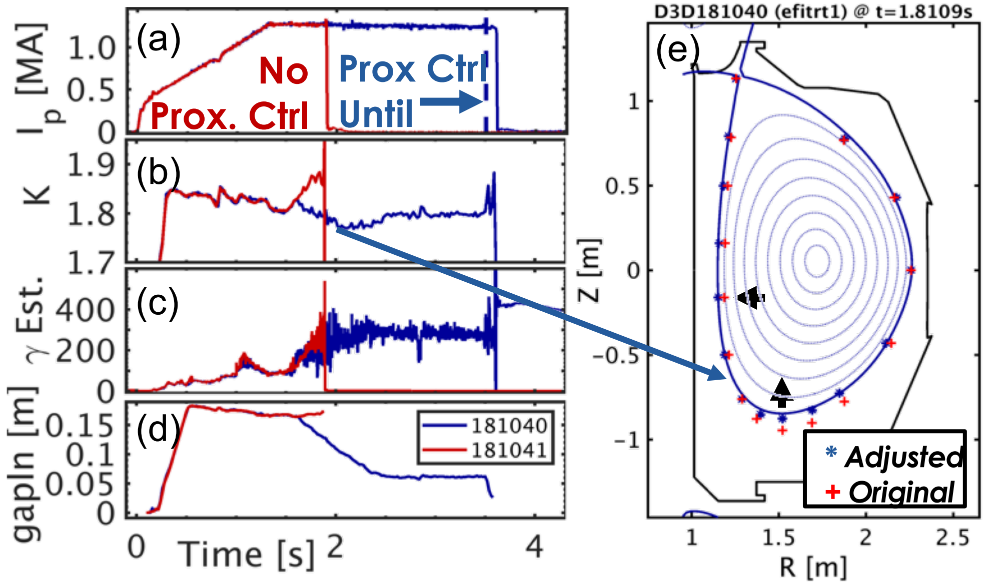
Requirement #2: Faster-than-realtime modeling of plasma evolution to assess where heading in plasma operating space[3]

[1] KEJ Olofsson PPCF 2018
[2] A. Glasser PoP 2018
[3] F. Felici NF 2018
[4] A. Pajares FED 2019

Practical example of proximity control: Vertical growth rate

- **Feedback on vertical growth rate (γ) estimate generated by neural network**
- **Takes into account uncertainty in γ**
- **Steer away from $\gamma_{critical}$, which leads to vertical displacement event (VDE)**
- **Proximity alarm initiates shape modification to reduce elongation (κ) & thus γ**
- **Disruption avoided by never leaving controllable operating region**

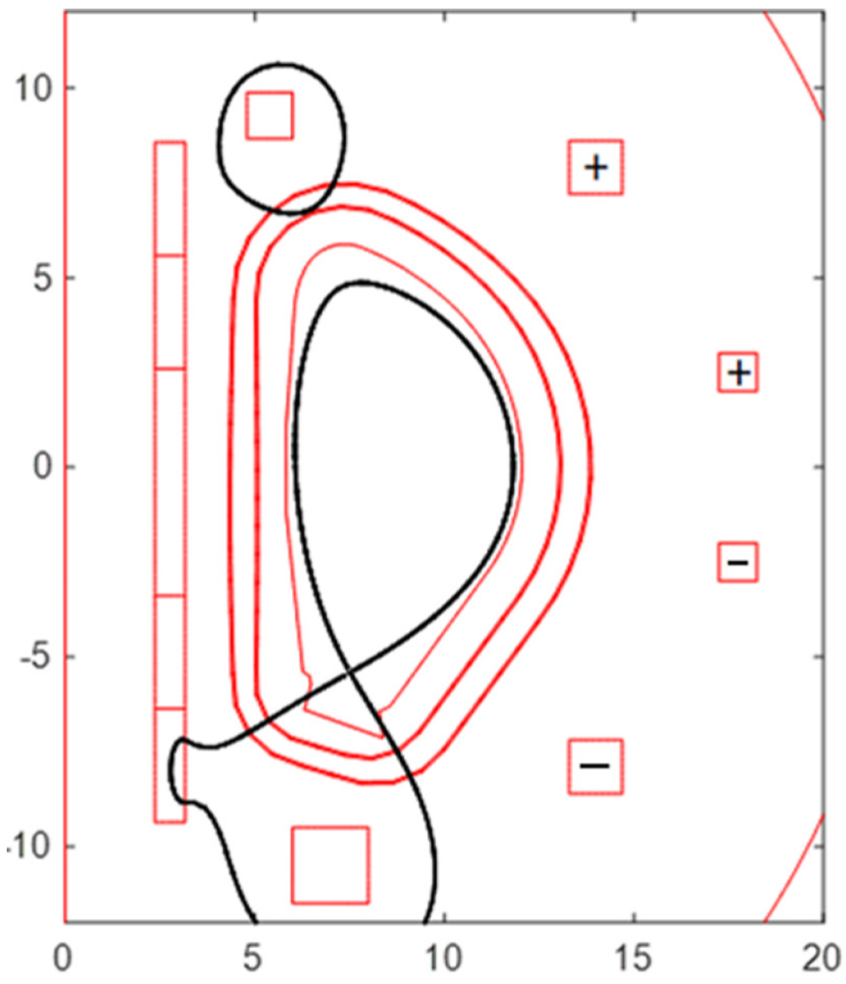




B. Sammuli FED 2021

** Important Caveat **
No likely tokamak reactor will be completely passively stable

- **Almost all designs require diverted, elongated plasma for performance & heat exhaust**



EU-DEMO[1]

[1] Albanese FED DEMO 2019

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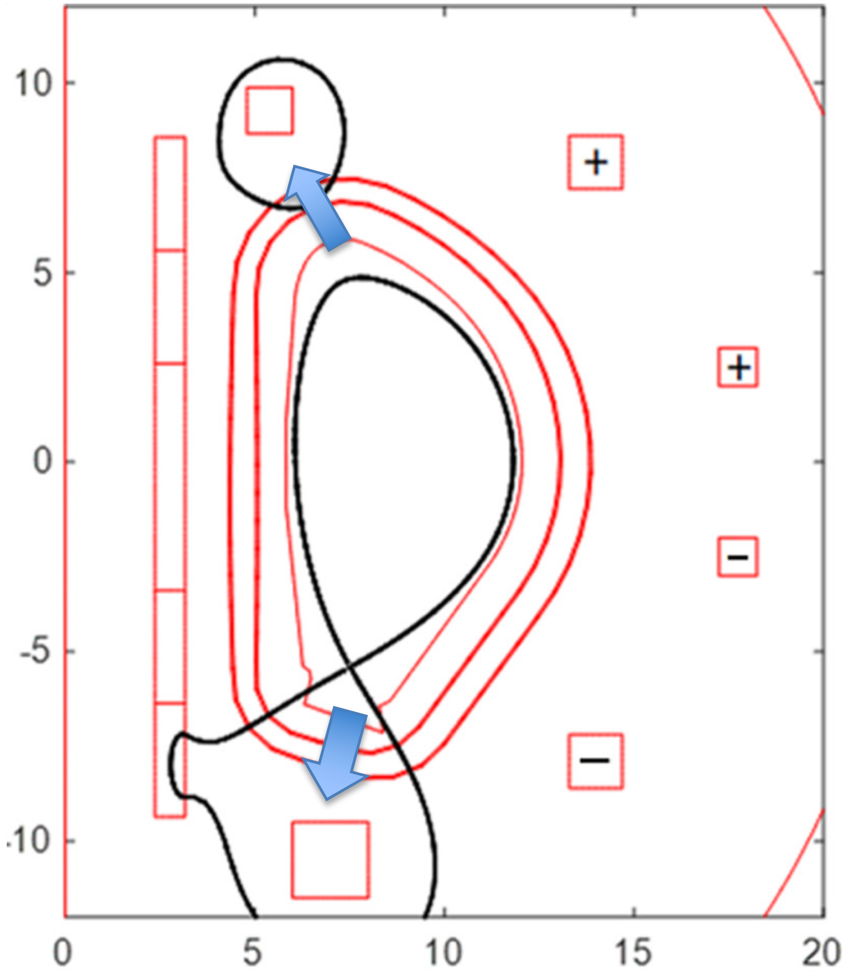

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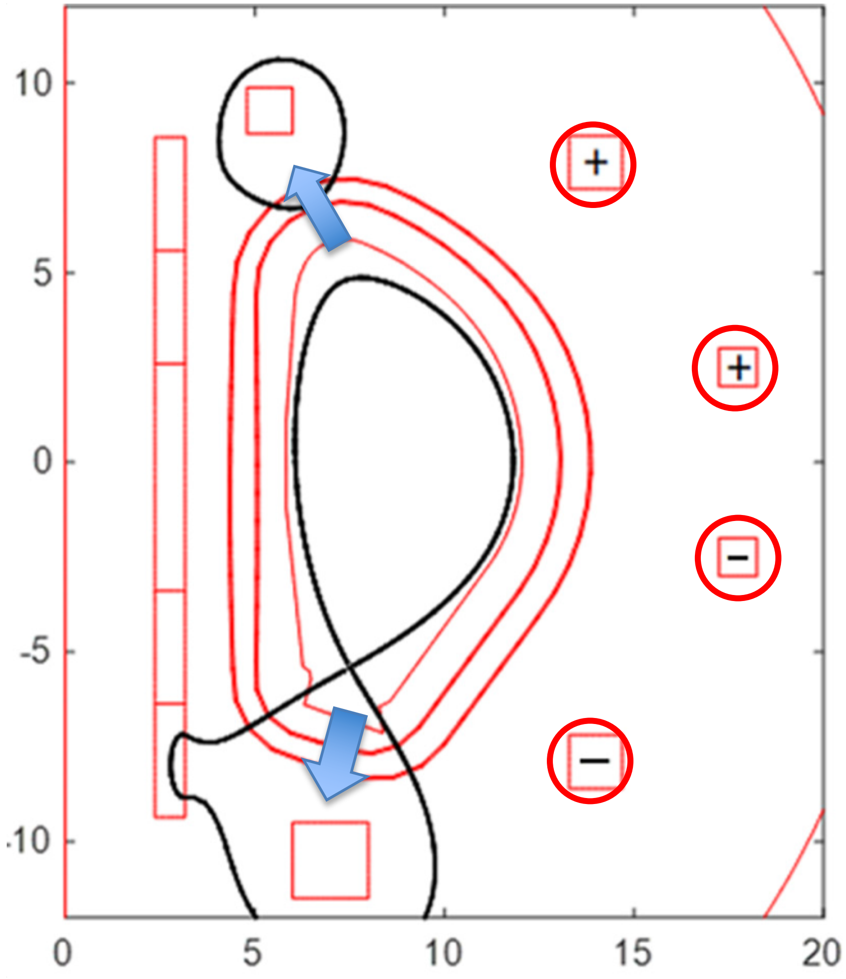
- **Continuous active vertical stabilization essential!**

Loss of vertical control **prior to** disruption = Vertical Displacement Event (**VDE**)
after disruption = Vertically Unstable Disruption (**VUD**)



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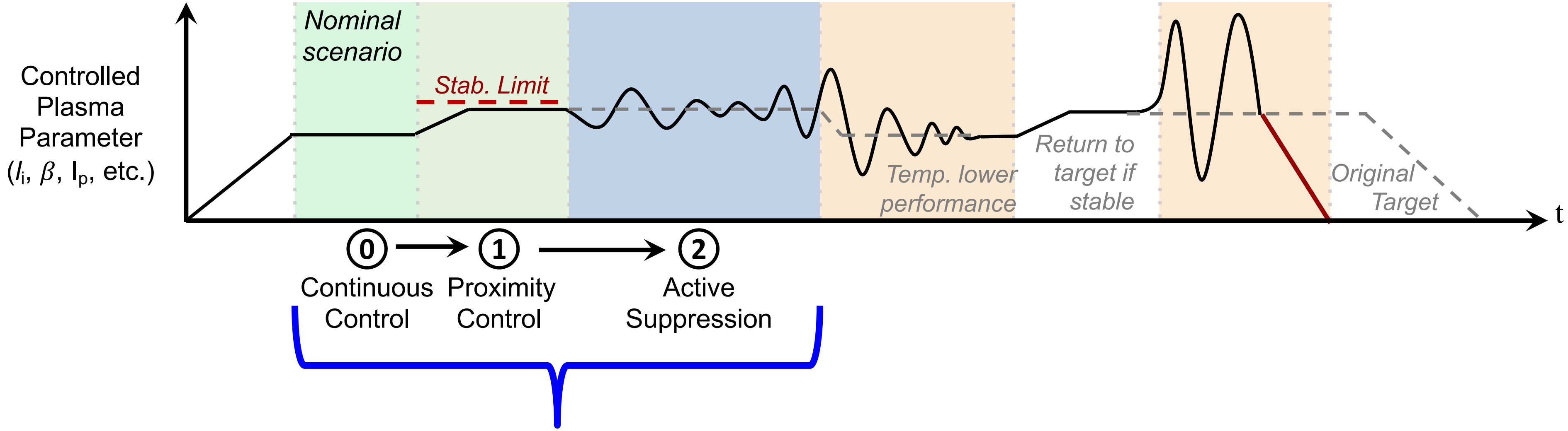
Disruption handling is a multi-stage process: Functional view



Stage 0 & 1: Avoid unstable regimes

Stage 2: Stabilize existing instabilities

Stage 2. Active stabilization of growing instability

(this is what is usually called "Disruption Avoidance")

- **Control system senses & suppresses mode**
- **Requires accurate real-time sensing & identification of instability**

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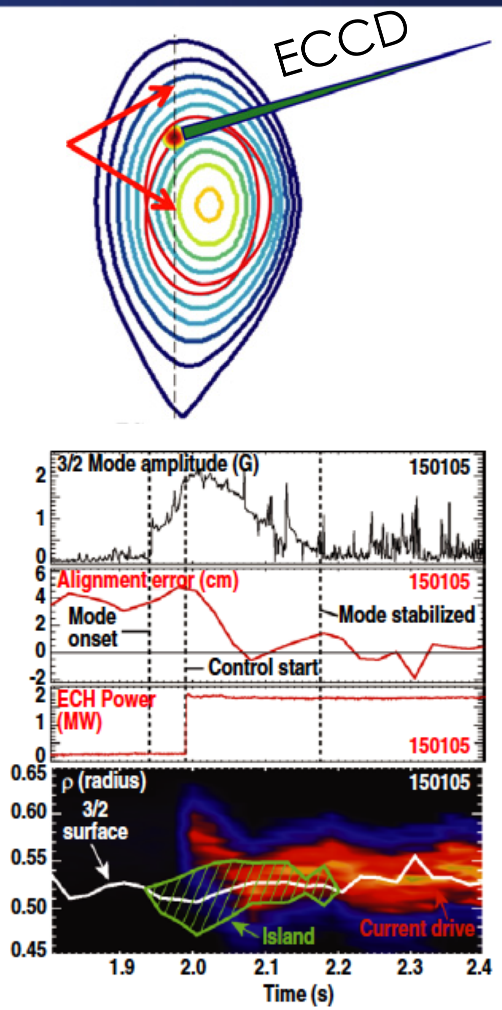

DIII-D NTM Stabilization[1]

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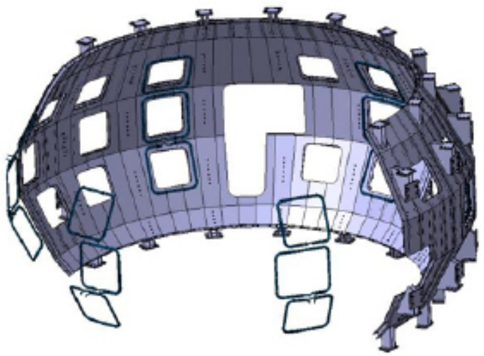
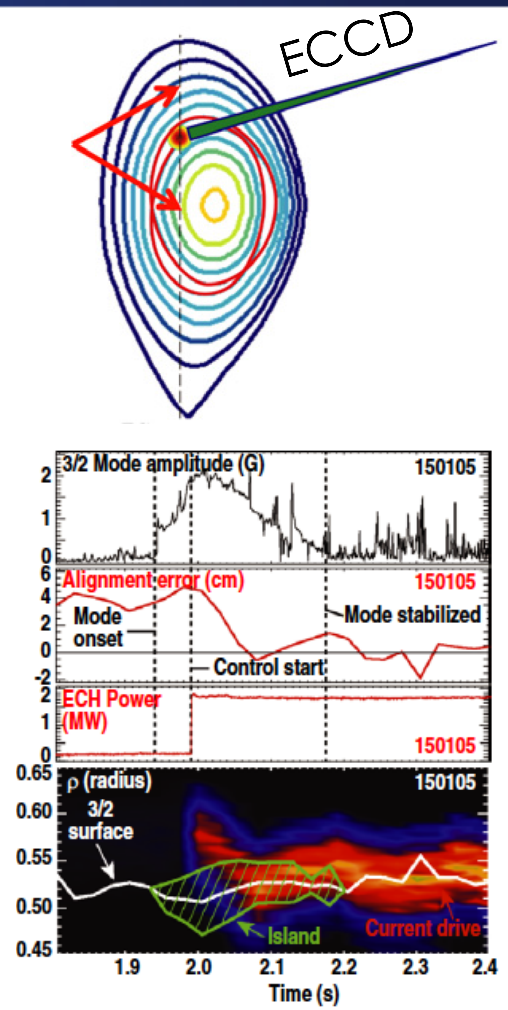


JT-60SA RWM Control Coils[2]



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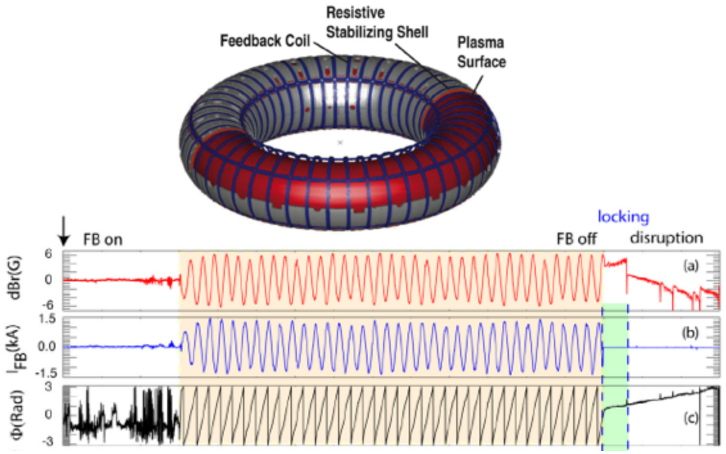
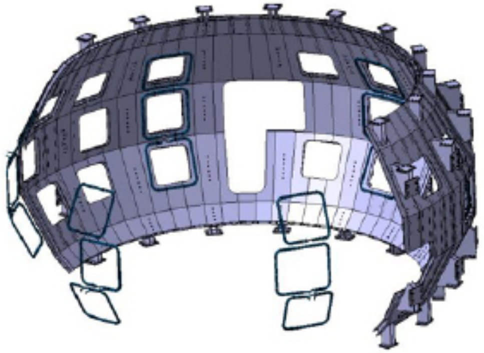
  - Rotating field entrainment of locked modes



RFX-mod Locked Mode Entrainment[3]



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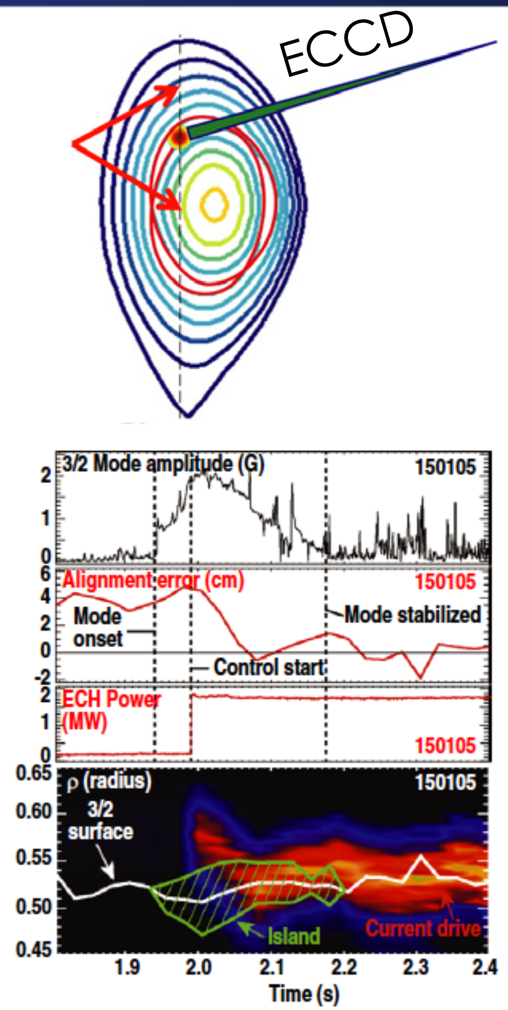

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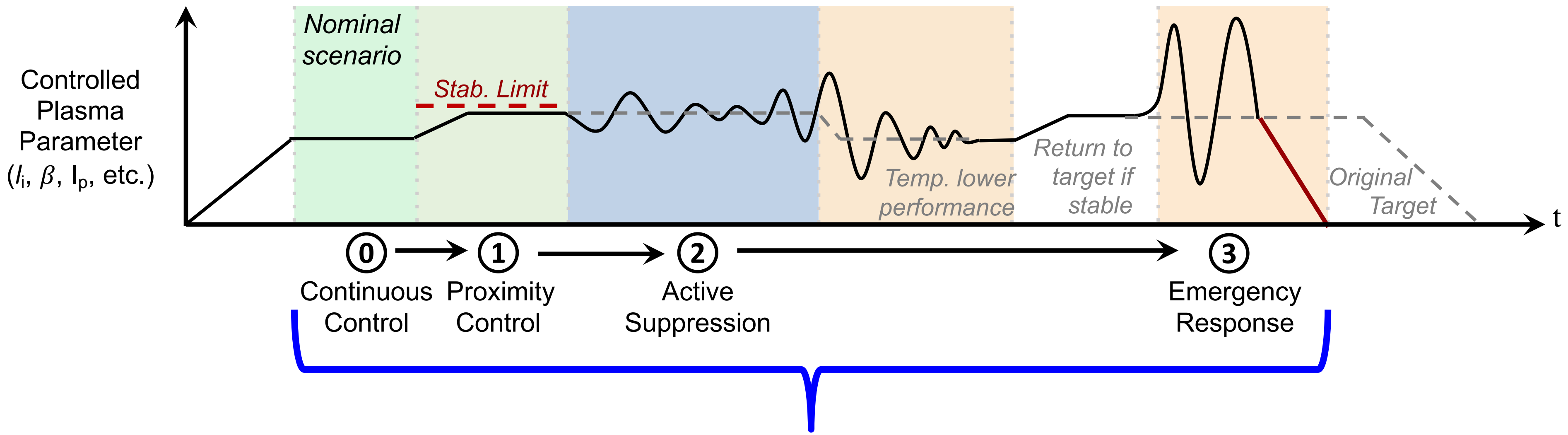


Stage 0 & 1: Avoid unstable regimes

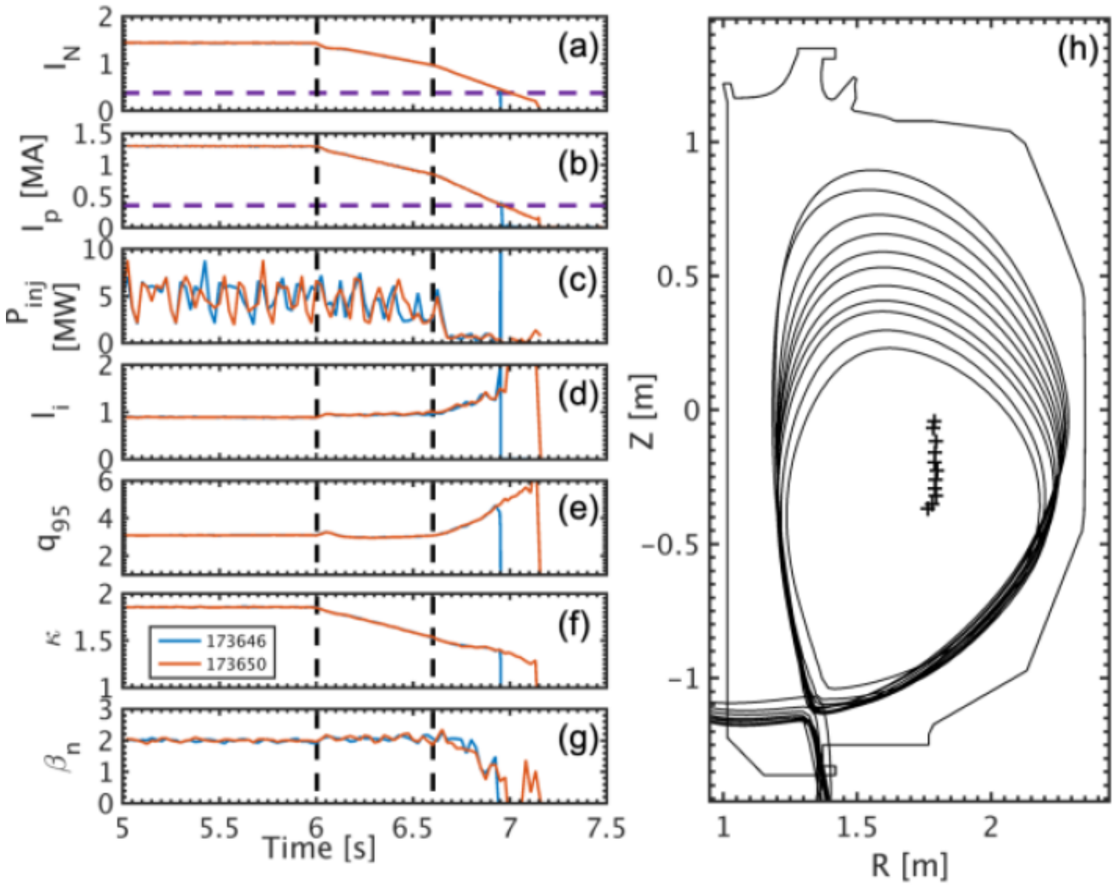
Stage 2: Stabilize existing instabilities

Stage 3: Prevent unstable plasma from disrupting

Stage 3. "Soft" shutdown to avoid disruption

- **When all else fails, rapidly ramp down current to reduce instability drive & available thermal/magnetic energy**
  - "Rapid" in ITER ~ 60s

- **Rapid variations in plasma parameters near coil control saturation make scenario very difficult**



ITER Fast Ramp-down Studies on DIII-D

J. Barr IAEA FEC 2020, submitte to NF

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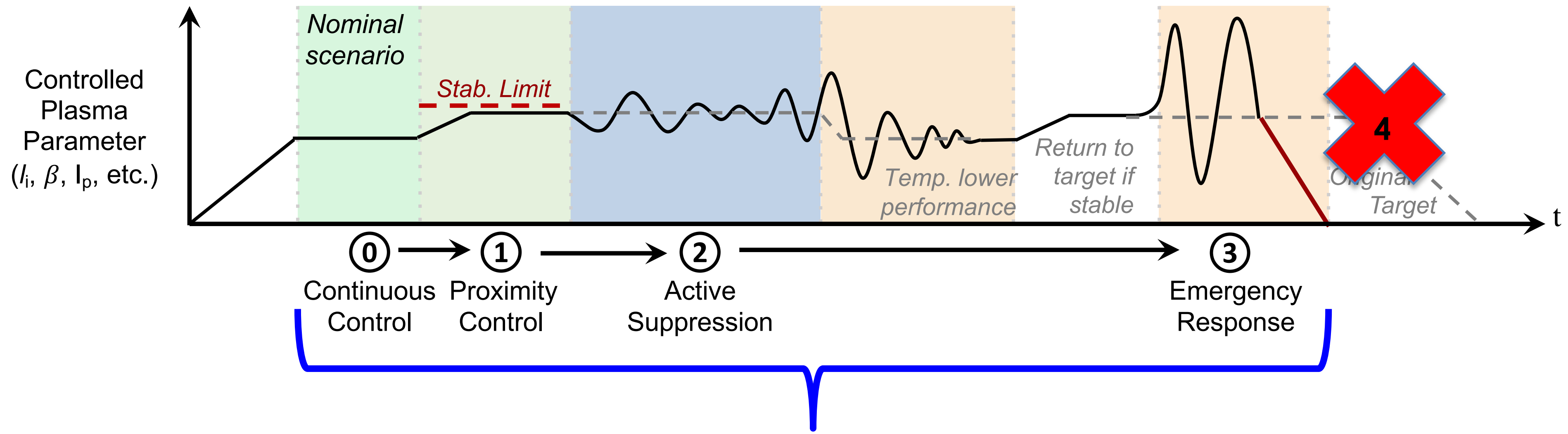

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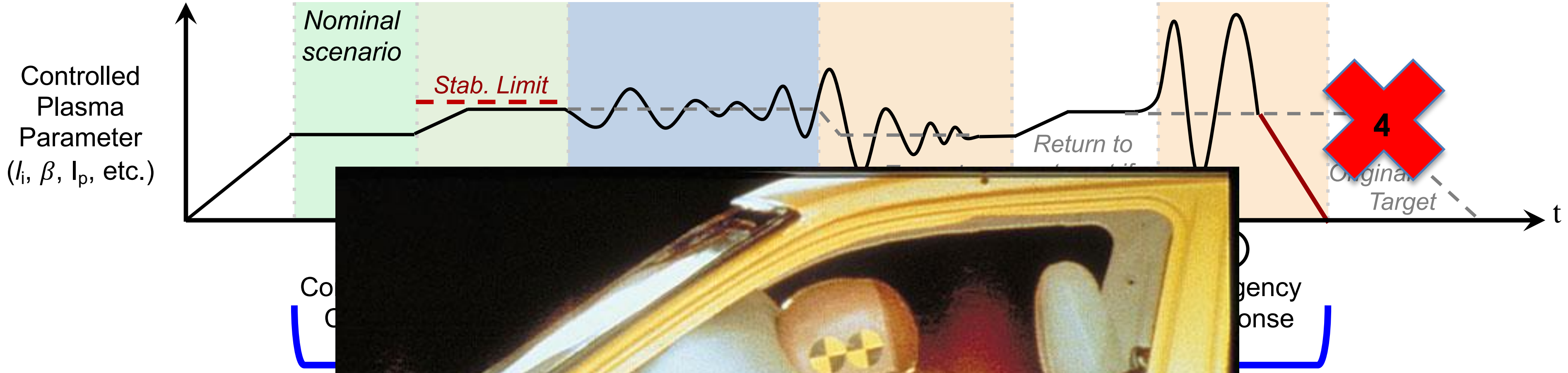
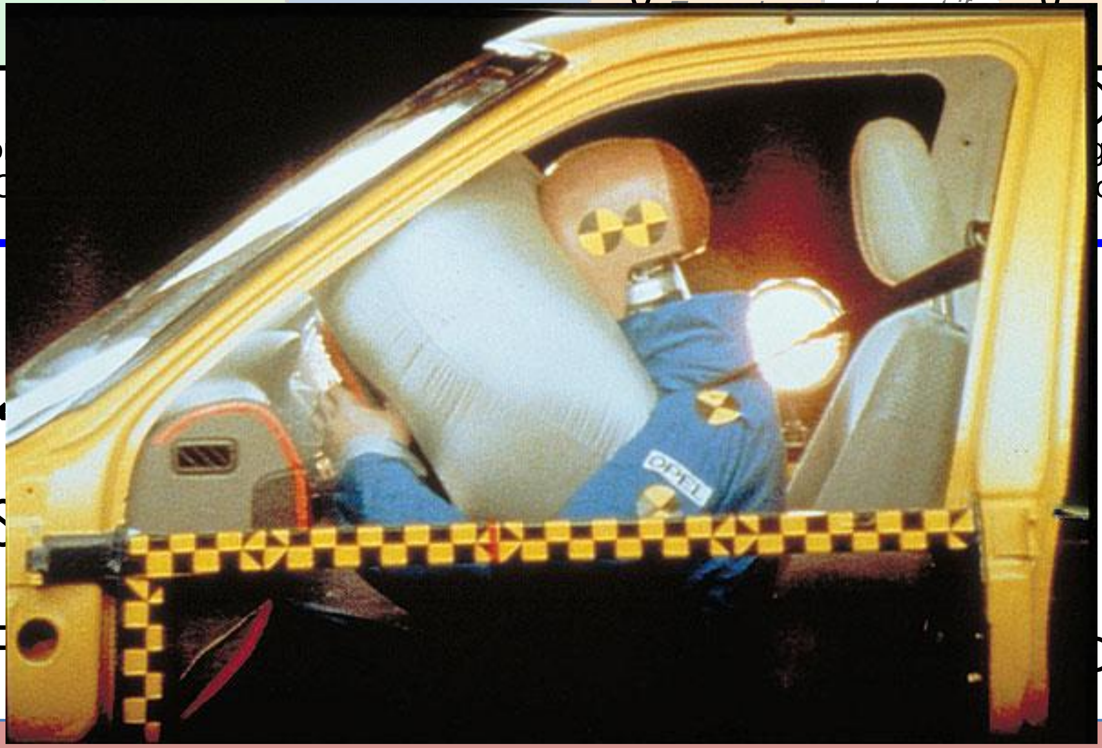




Stage 0 &

Stage 2: S

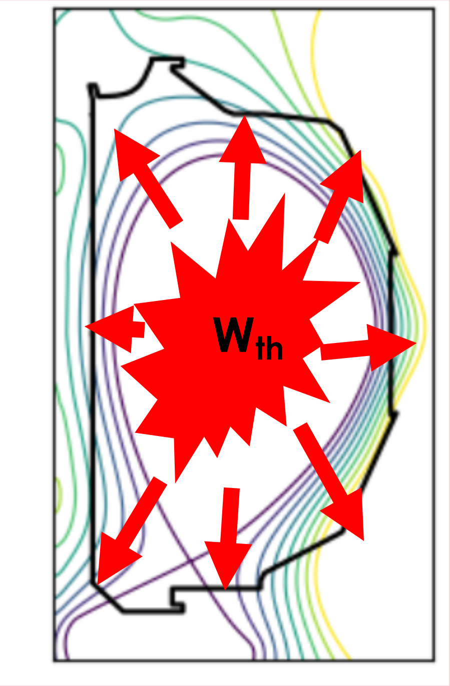
Stage 3: F … oting

Stage 4: Rapid termination: Mitigate unavoidable disruption

Disruption mitigation has three goals that are very difficult to meet simultaneously

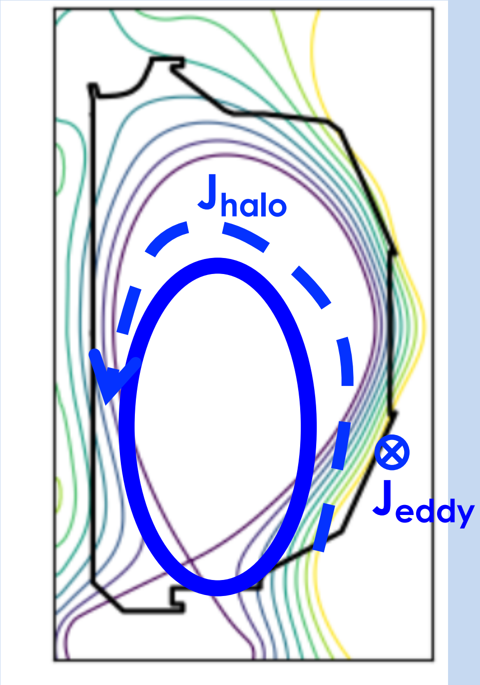
TQ

Radiate thermal energy to wall before conducted to divertor



CQ

“Goldilocks”: Keep CQ short enough to avoid halo forces & heating, long enough to avoid damaging eddy forces



RE

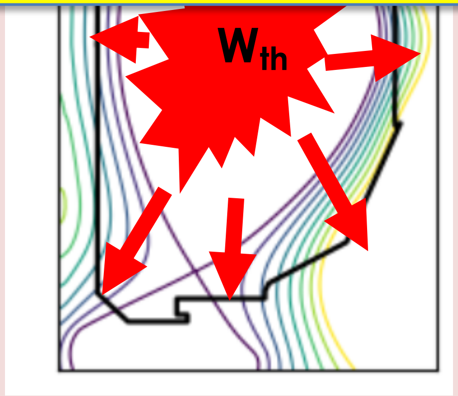
Suppress formation of RE or rapidly dissipate existing RE plateau

Disruption mitigation has three goals that are very difficult to meet simultaneously

TQ

Radiate thermal energy to wall before conducted to divertor

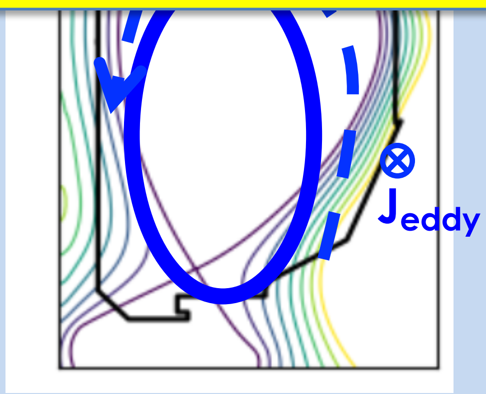
Desirable:
Large quantities of very high-Z impurities



CQ

"Goldilocks": Keep CQ short enough to avoid halo forces & heating, long enough to avoid damaging eddy forces

Desirable:
Moderate quantities of moderate → low-Z radiator



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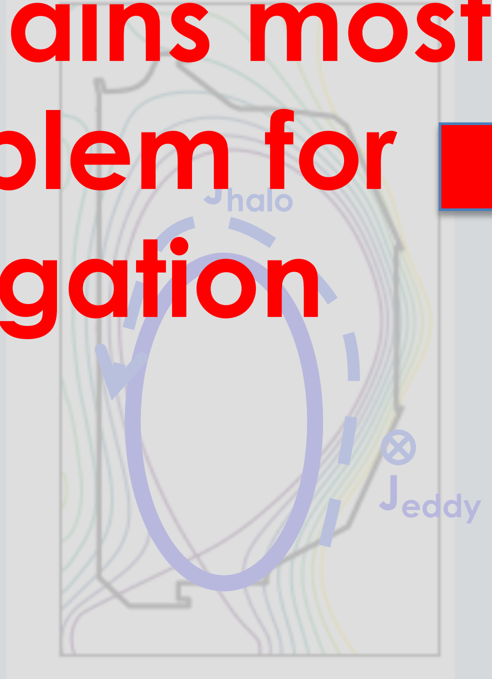

RE mitigation remains most intractable problem for disruption mitigation

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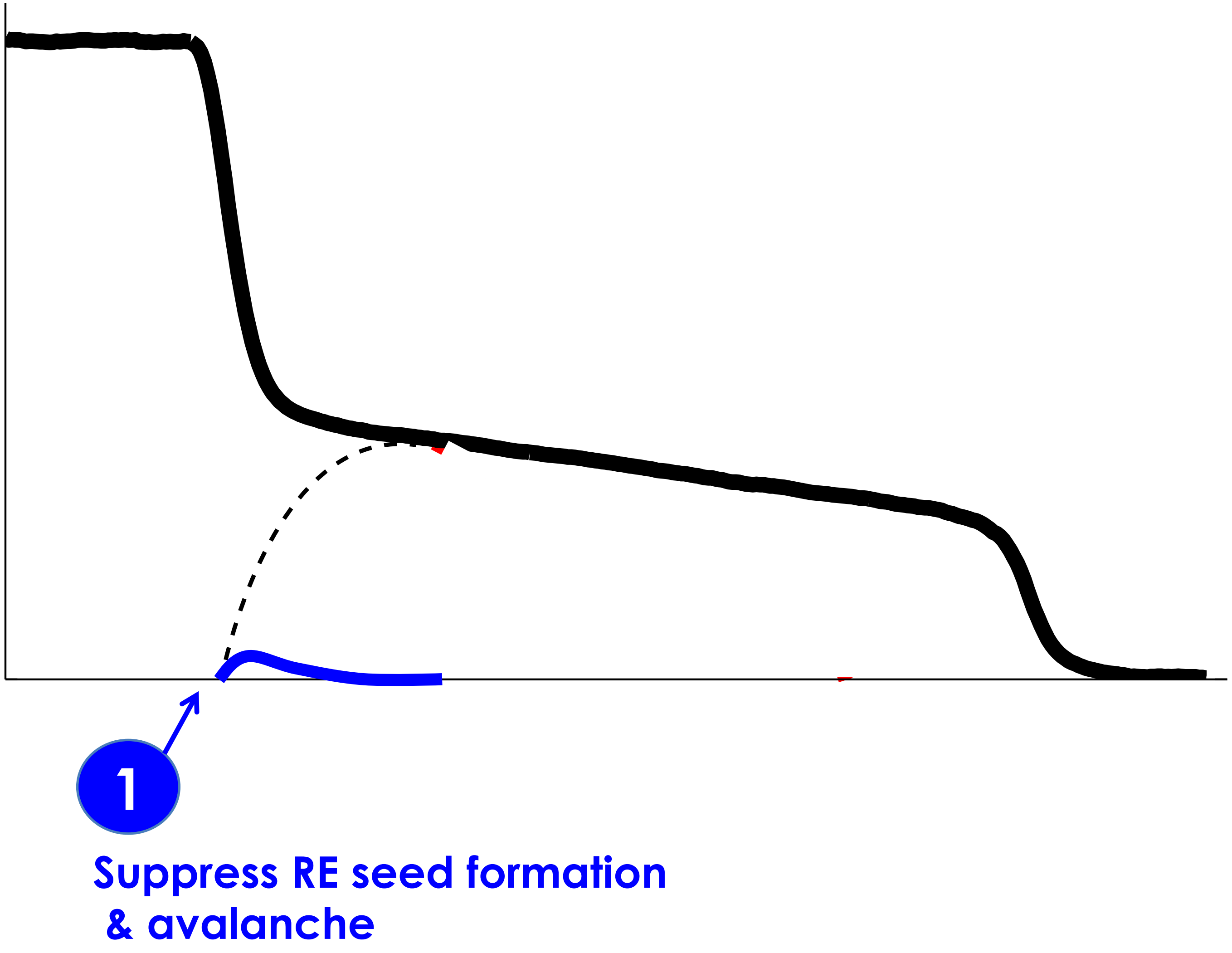
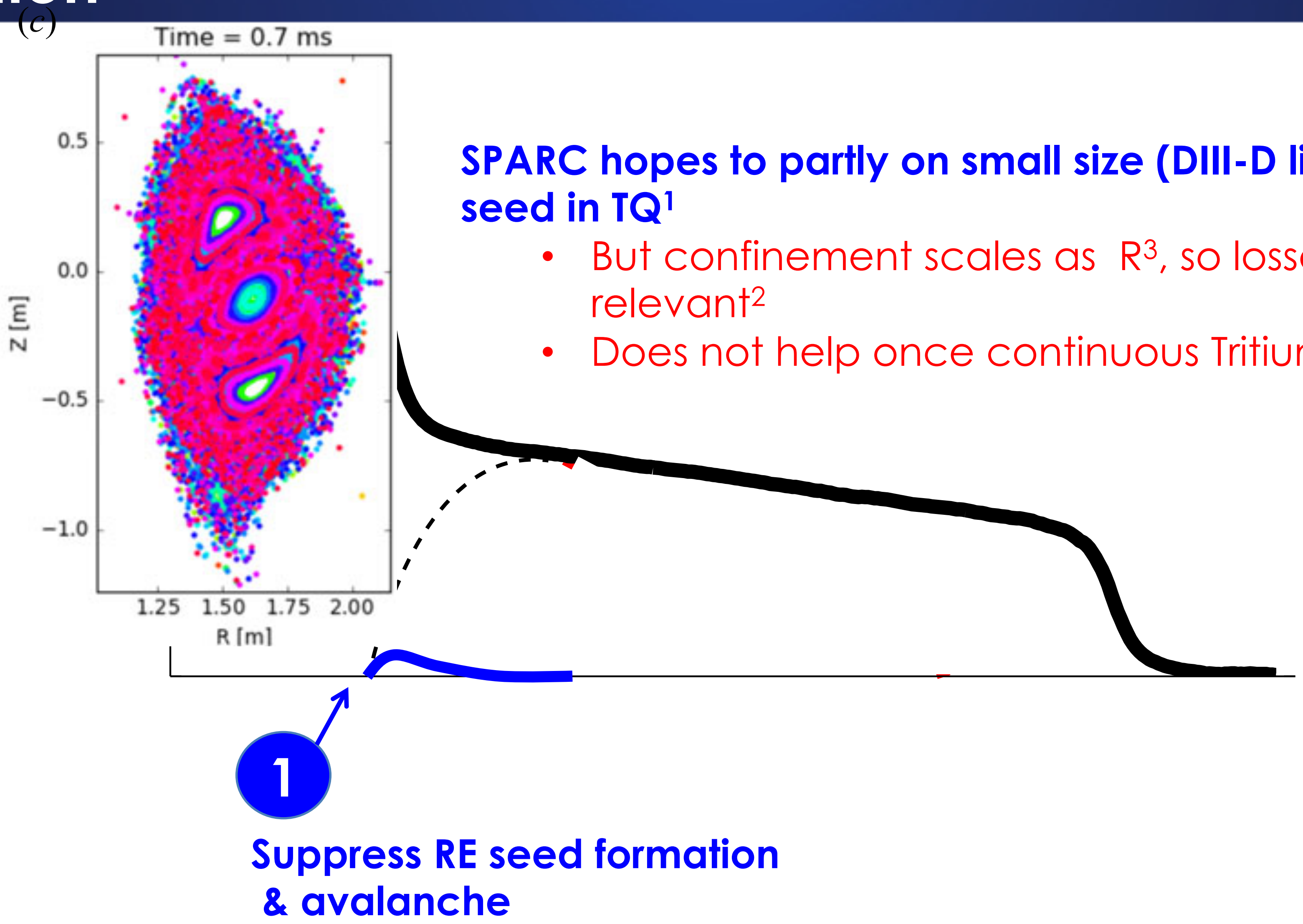


RE mitigation remains most intractable problem for disruption mitigation

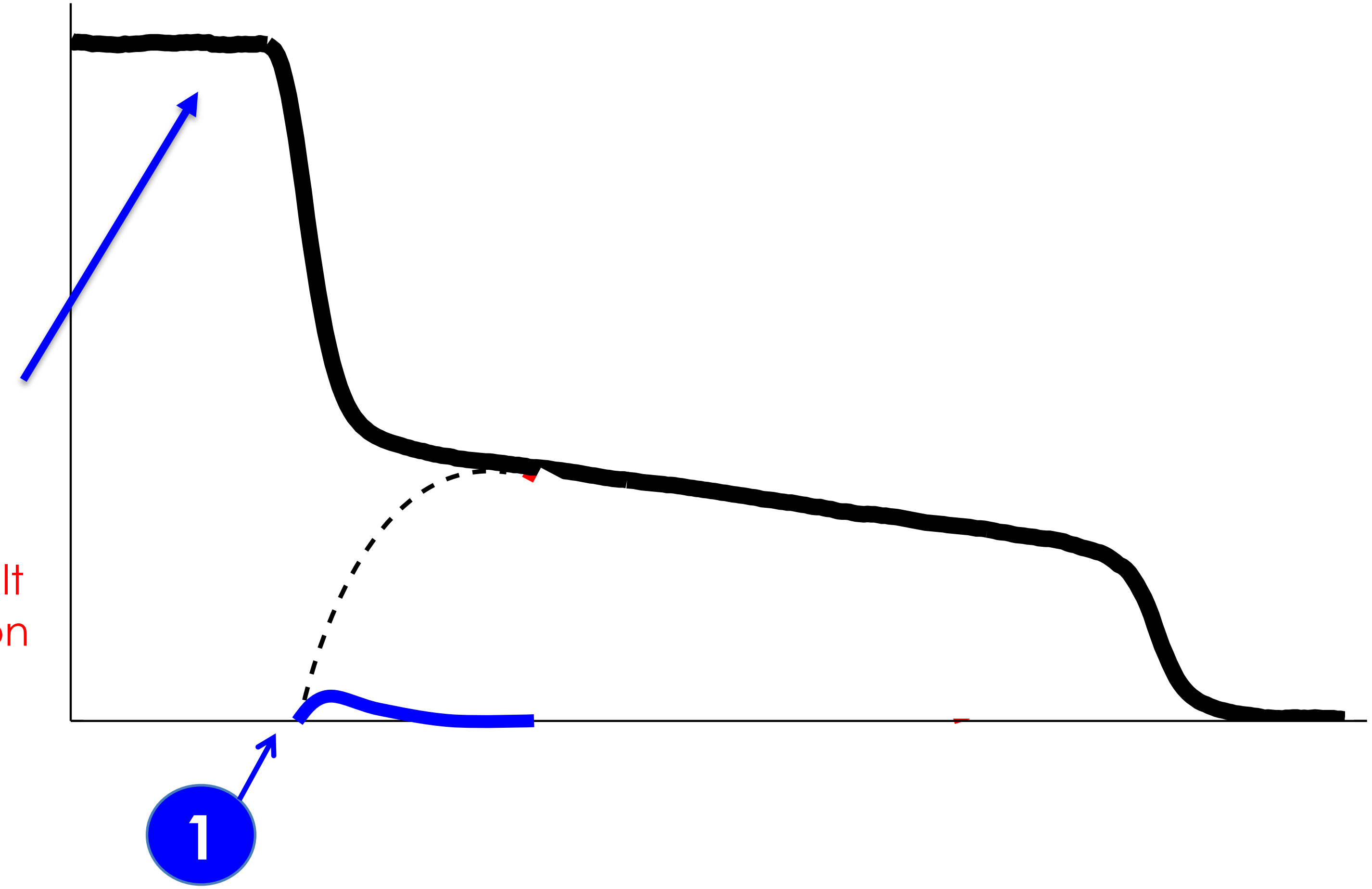


SPARC hopes to partly on small size (DIII-D like) to deconfine RE seed in TQ[1]

- But confinement scales as R^3, so losses not reactor relevant[2]
- Does not help once continuous Tritium seed present

1. R. Sweeney JPP 2020
2. V.A. Izzo NF 2011

RE mitigation remains most intractable problem for disruption mitigation



ITER Plan: Massive pre-TQ D_2/H_2 injection[3]
- Technically difficult
- Requires prediction
- Physics in doubt[4]

Suppress RE seed formation & avalanche

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3. JR Martín-Solís NF 2017
4. O. Vallhagen JPP 2020

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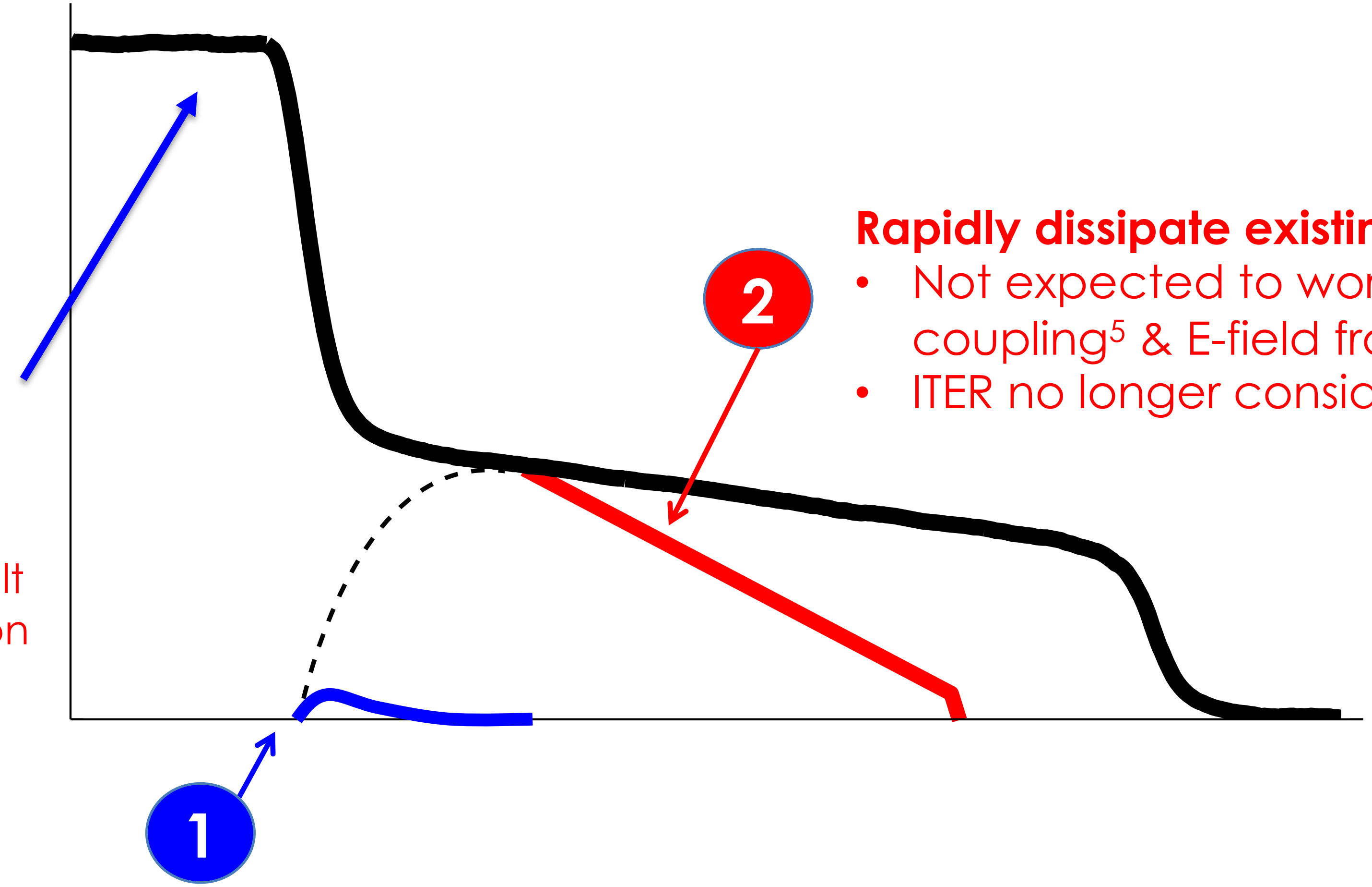

Rapidly dissipate existing RE beam

- Not expected to work due to Z/Ip coupling[5] & E-field from scrape-off[6]
- ITER no longer considering

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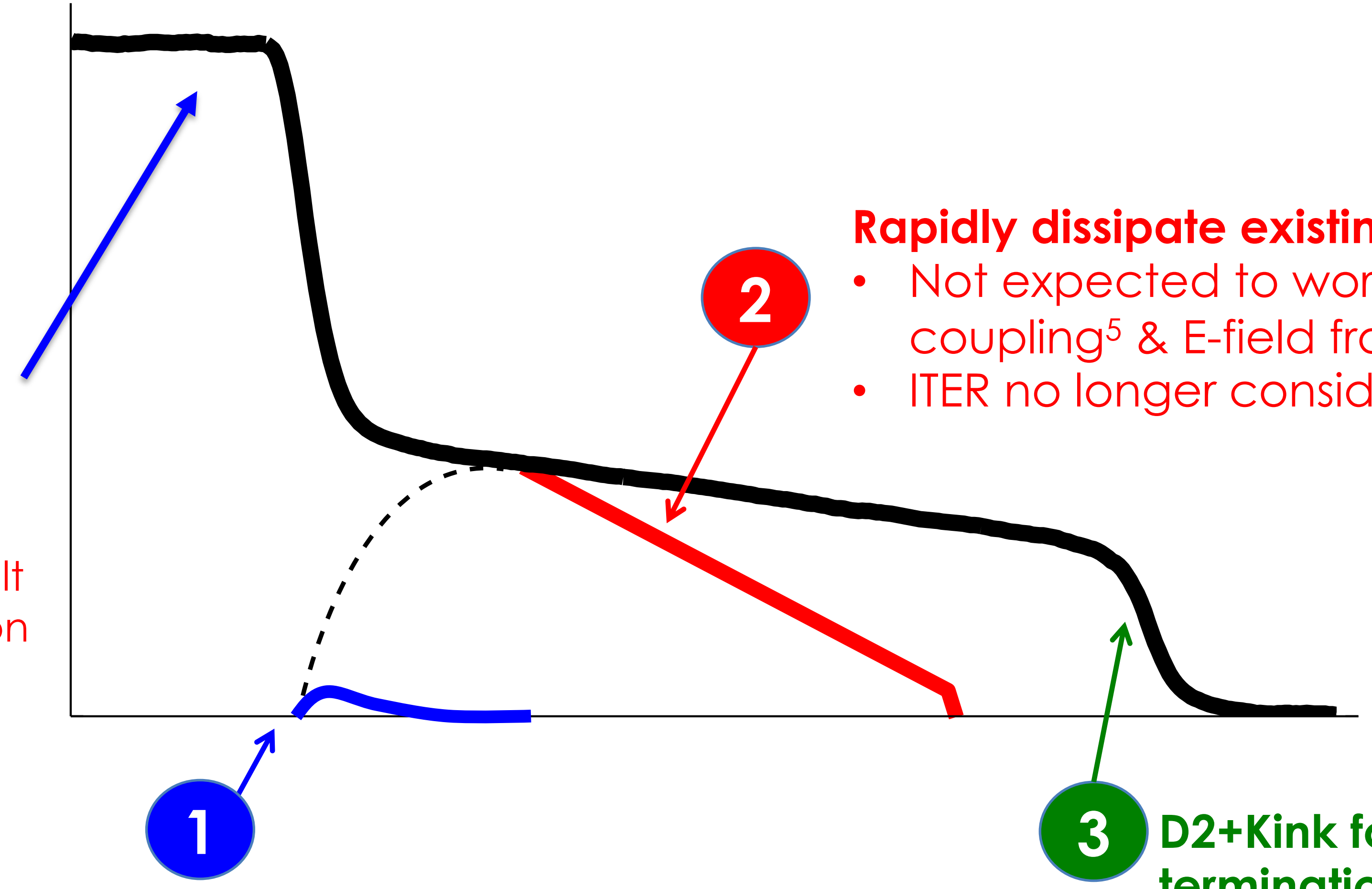

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1 **Suppress RE seed formation & avalanche**

3 **D2+Kink for benign termination**

1. R. Sweeney JPP 2020
2. V.A. Izzo NF 2011
3. JR Martín-Solís NF 2017
4. O. Vallhagen JPP 2020
5. Kiramov PoP 2018
6. Konvovalov IAEA 2016

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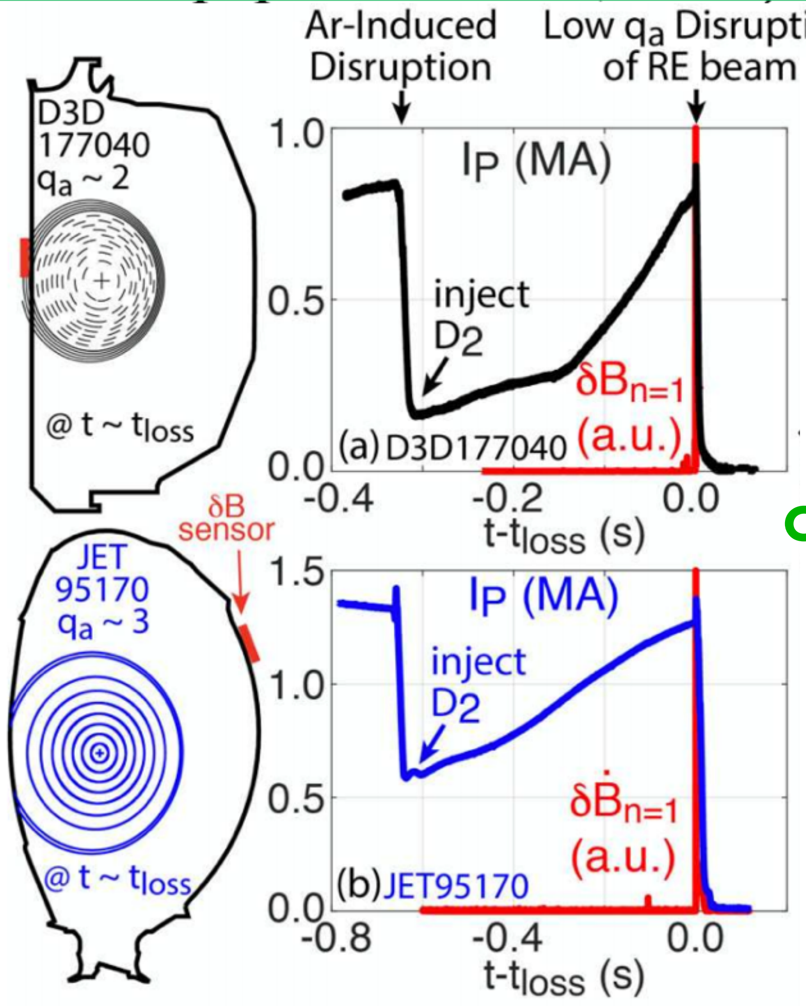
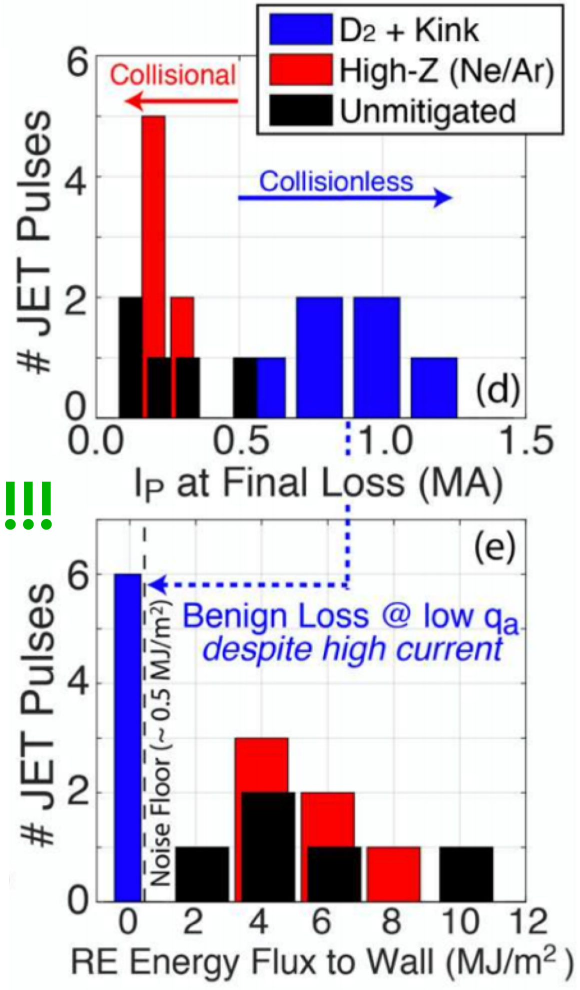


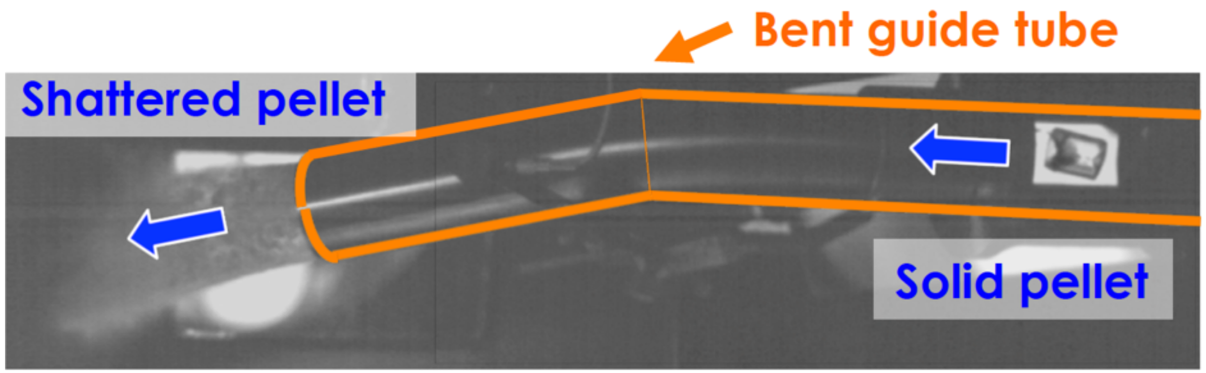
Highest current RE beams cause least heating[7,8]!!!!



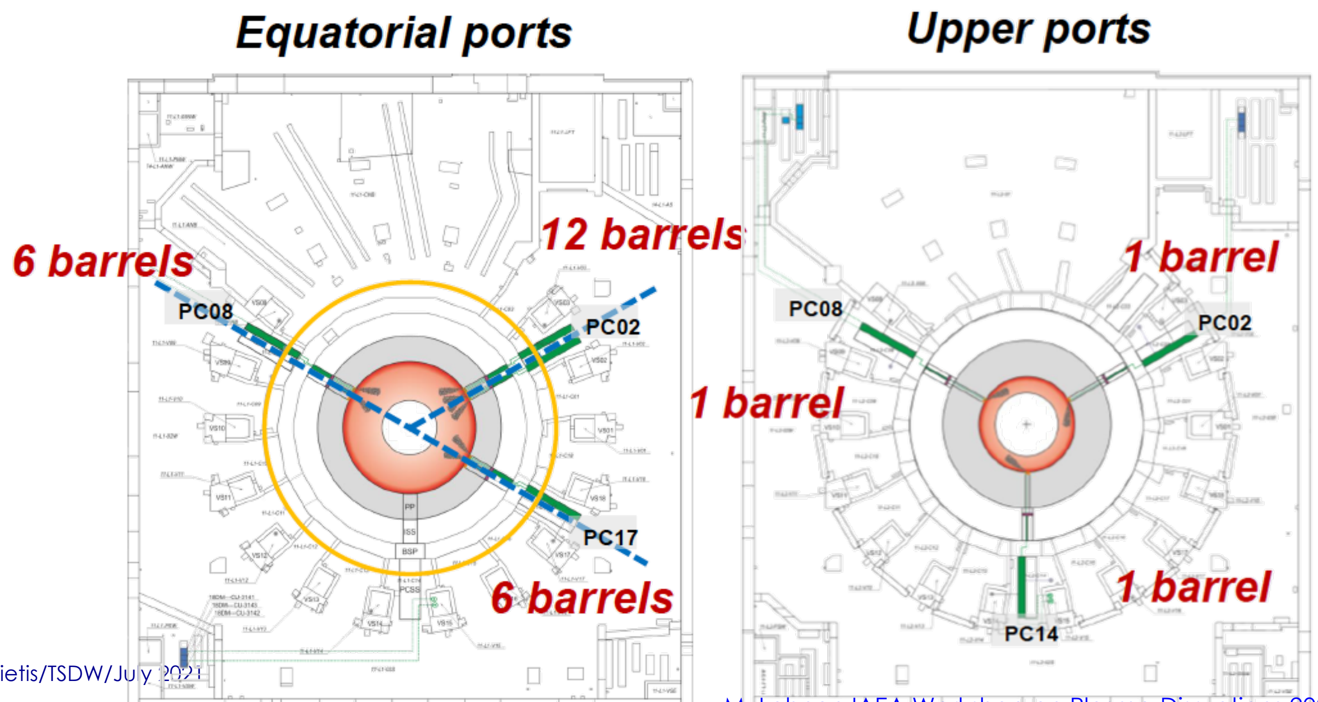
6. Konvovalov IAEA 2016
7. C Reux IPRL 2021
8. C. Paz-Soldan IAEA FEC 2021

Shattered pellet injection (SPI) is baseline ITER disruption mitigation system (DMS) technology

- **Solid cryogenic impurity pellet shattered prior to entering plasma**
  1. Protects in-vessel components from a large solid pellet
  2. Improves assimilation due to increased surface area
  3. Provides faster response over long distances than massive gas injection (MGI)
- **Test systems installed on DIII-D, JET, J-TEXT, KSTAR, and soon AUG, HL-2A**



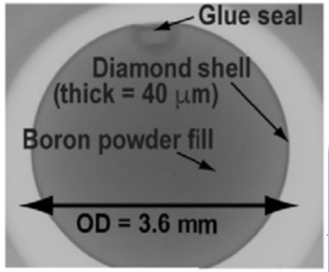
Composite image from ORNL laboratory tests



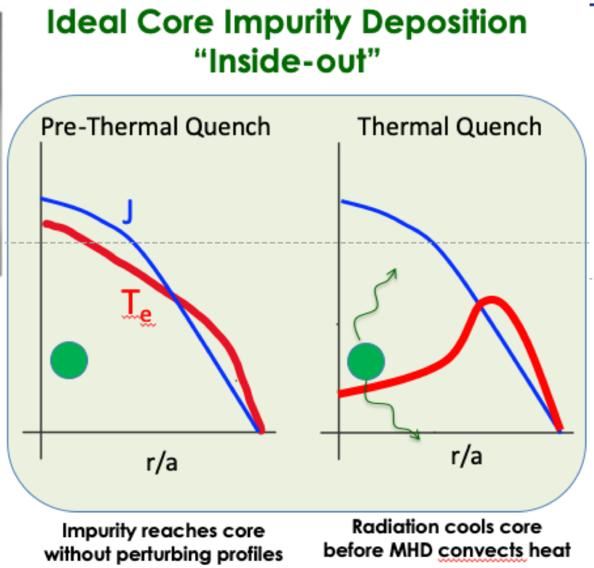
M. Lehnen IAEA Workshop on Plasma Disruptions 2020

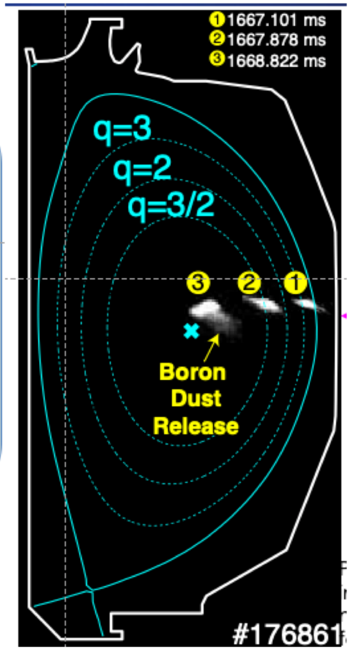
Other mitigation technologies addressing shortcomings in SPI are in various stages of development

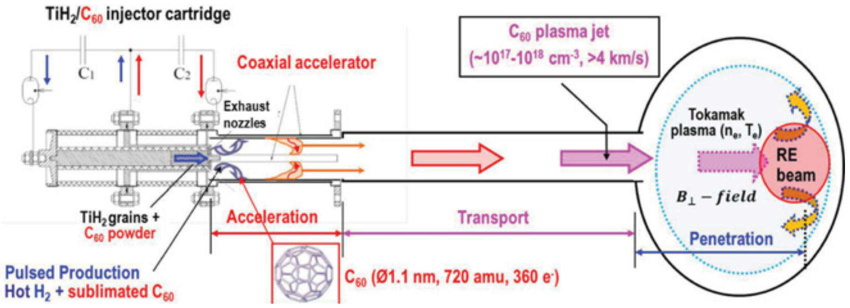
- **Dispersive shell pellet for for core impurity deposition**
- **High-speed injection for fast response time and deep core penetration**
  - Railgun
  - 2 stage light gas gun
  - Linear induction motor
  - Nano-particle plasma jet



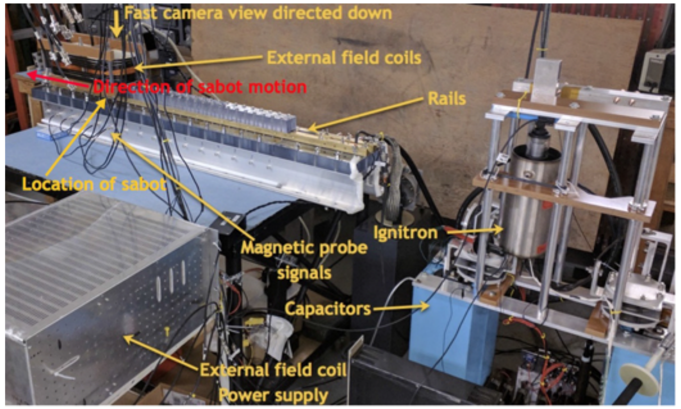
Shell Pellet
E. Hollmann PRL 2020



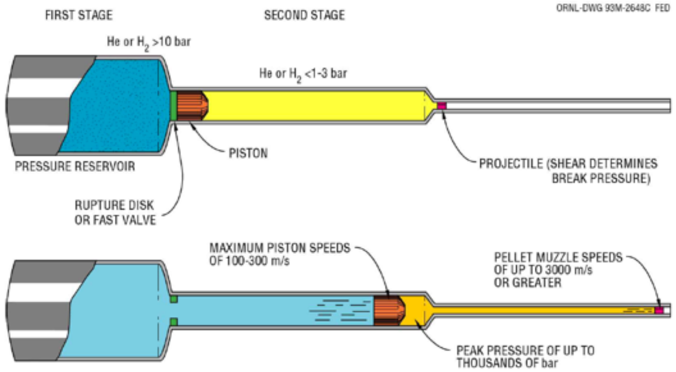




NPPJ
N. Bogatu FST 2013



Railgun
R. Raman NF 2019



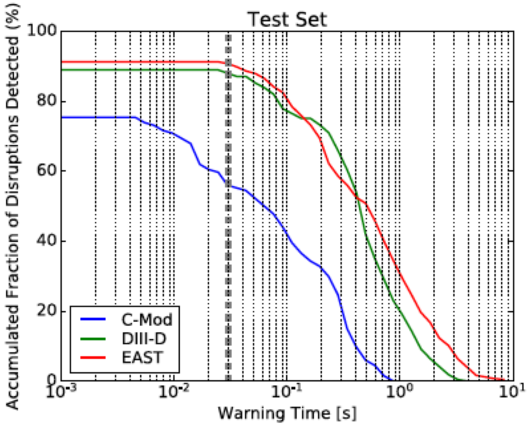
2 stage light gas gun
R. Raman IAEA Workshop on Plasma Disruptions 2020 (ORNL contribution)

Mitigation requires a disruption predictor to trigger DMS

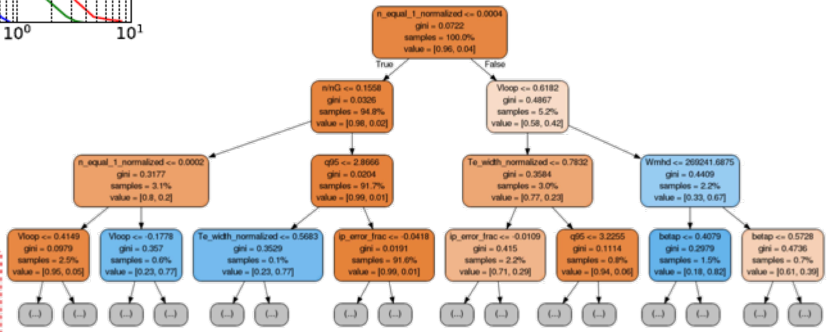
- **Requires extremely high performance**: Both missed disruptions and false shutdowns are damaging to commercial reactor mission

- Context: At full operation, ITER requires ~100% of disruptions to be detected at least 30ms ahead of time (flight time)

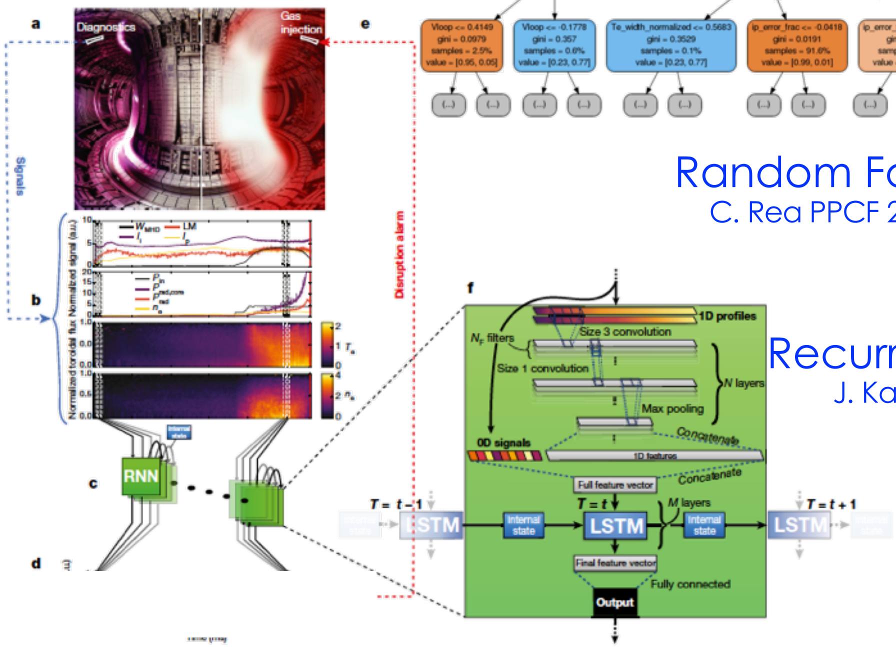
- Methods range from simple thresholds to very complex machine learning methods



K. Montes NF 2019

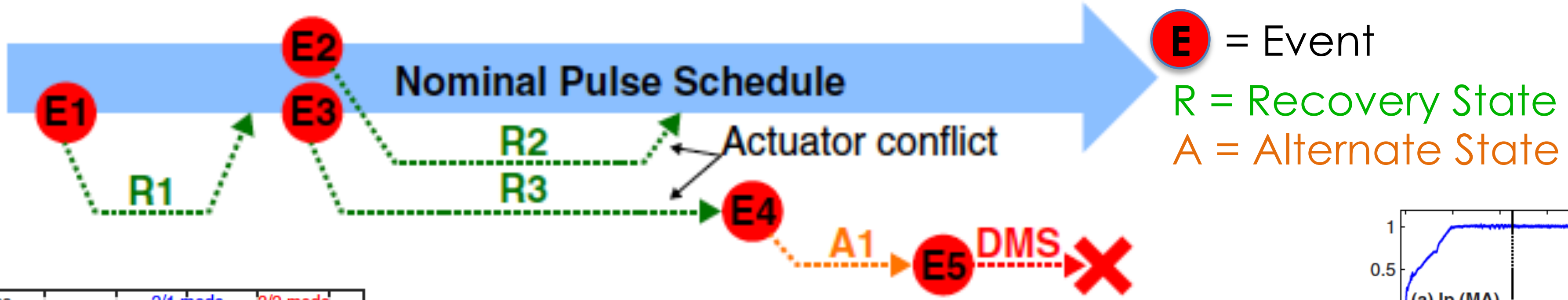


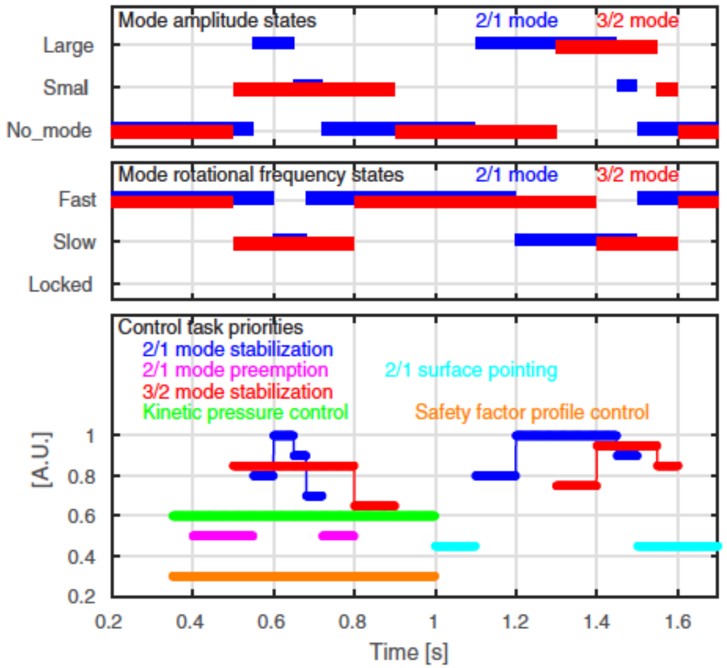
Random Forest
C. Rea PPCF 2018



Recurrent Neural Network
J. Kates-Harbeck Nature 2019

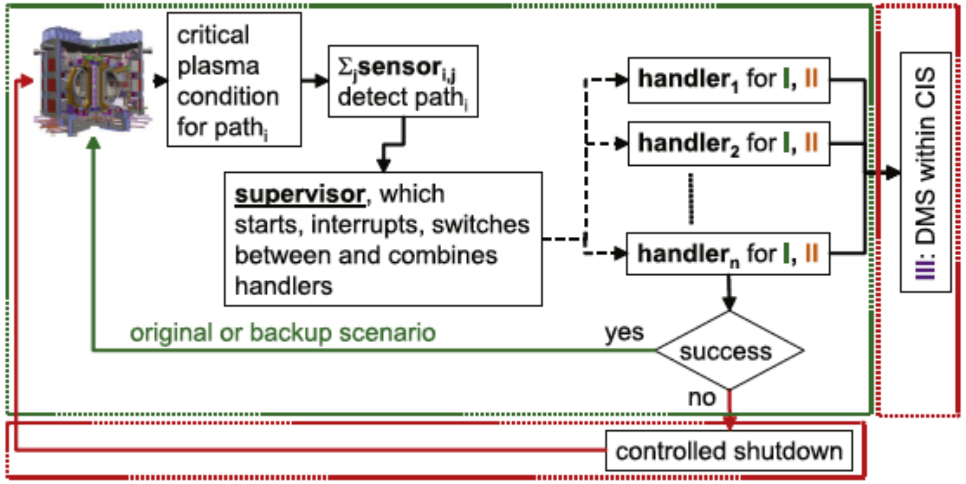
Advanced supervisory control is required to negotiate various stages of disruption prevention





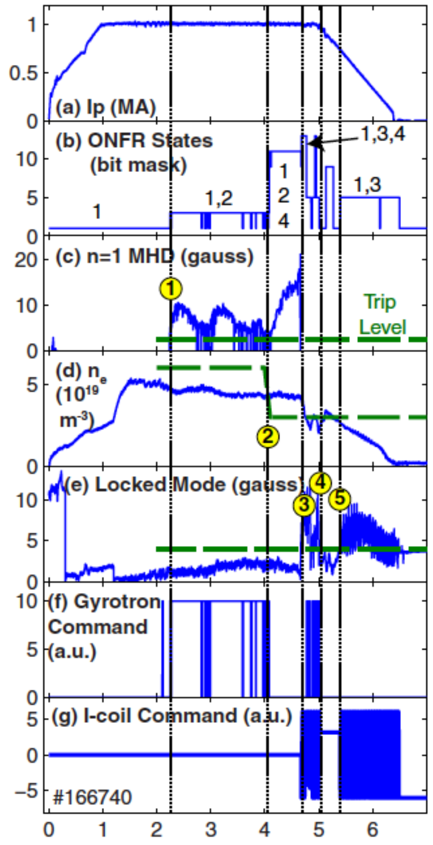
TCV

T.C. Blanken NF 2019



AUG & TCV

M. MARASHEK NF 2018



DIII-D

EIDIETIS NF 2018

Outline

1. **What are disruptions & why/how do we handle them?**
2. **Evolution of disruption handling requirements: Research → Commercial Reactor**
3. **Contemporary state of disruption handling**
4. **Challenges to disruption prevention posed by a commercial reactor**
5. **Resilient design**

Extreme environment posed by commercial reactor vs ITER poses many challenges for disruption handling

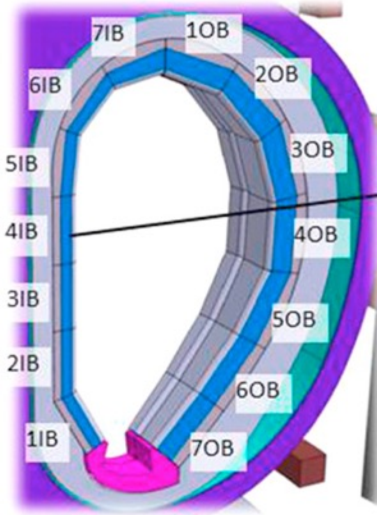
- **Neutron fluence: Order of magnitude(s) greater**

Table 1. Maximum expected total dose for alumina near the FW.

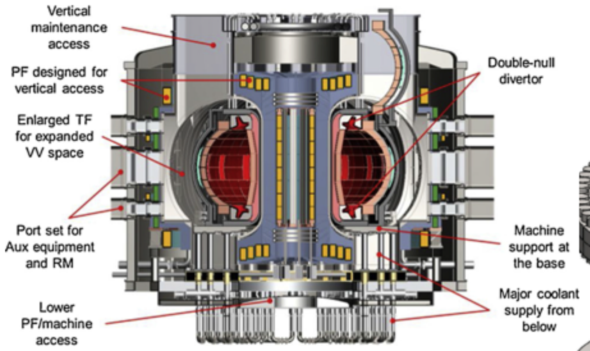
For insulators	Dose (dpa)	Dose (GGy)
ITER	<0.3	<10
DEMO	≈8	≈250
PP	>15	>470

Gonzales de Vicente NF 2017

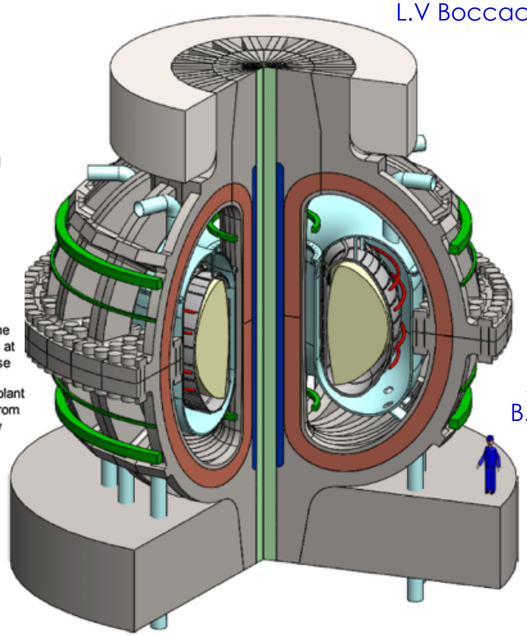
- **Lack of access (blankets)**
- **Much longer acceptable mean time between failure (MTBF)**
- **High field (ARC, K-DEMO)**



EU DEMO blanket Study
L.V Boccaccini FED 2016



K-DEMO
H.W. Kim FED 2019



ARC Concept
B.N. Sorborn FED 2015

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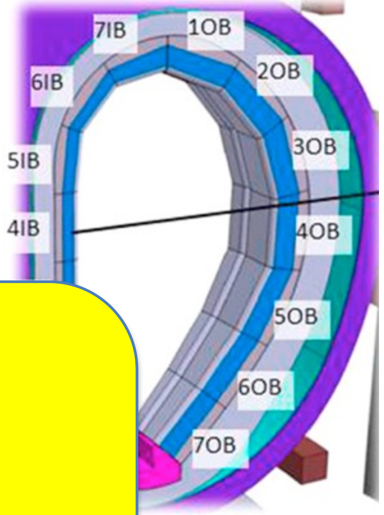


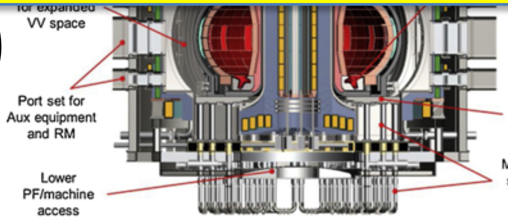
O blanket Study
ccaccini FED 2016

- **Lack**
- **Much failur**

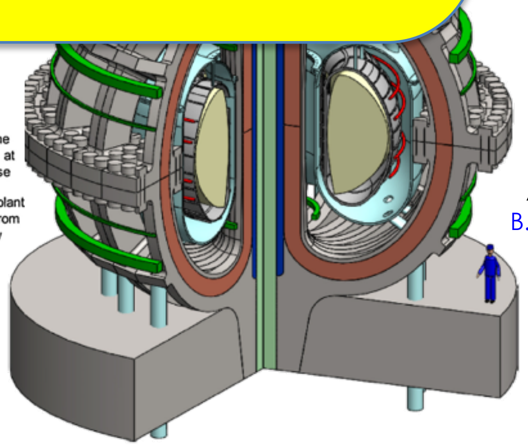
DEMO Mission Goals ≠ Commercial Reactor…

but presents many of the same technical problems

- **High field (ARC, K-DEMO)**



K-DEMO
H.W. Kim FED 2019



ARC Concept
B.N. Sorborn FED 2015

Reactor Disruption Prevention Challenge #1: Diagnostic restrictions

- **Reliable diagnostics critical to guide disruption prevention**
- **Reactor environment poses several unique challenges:**
  - Magnetics prone to failure at unknown rate (neutrons)
  - No localized arrays (limited lines of sight through blanket)
  - Visible diagnostics unlikely

See [Biel FED 2019] overview

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See [Biel FED 2019] overview

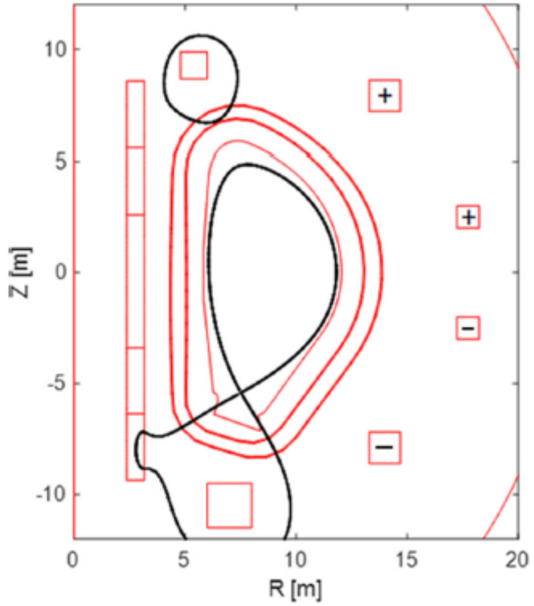
Reactor Development Opportunities

1. **Technology:** Develop magnetics replaceable with blankets
2. **Redundancy:** Develop/demonstrate "multi-messenger" measurements of key plasma parameters
3. **Control:** Incorporate real-time observer models to integrate multiple messengers[1] & make control robust to diagnostic failure[2,3]

[1] L. Stagner PhD Thesis 2018
[2] J.H Donné Plasma & Fus Research 2013
[3] F. Feilici NF 2018

Reactor Disruption Prevention Challenge #2: Actuator restrictions

- **Reliable, effective actuators key to all stages of disruption prevention**
- **Reactor actuator restrictions:**
  - In-vessel coils unlikely/impossible
    - **Vertical control**: Ex-vessel coils shielded by vessel, reducing maximum controllable displacement[1]
  - Gyrotrons: 9T compatible not presently available



EU DEMO Z control Simulation
R. Albanese FED 2019

[1]D. Humphreys NF 2009

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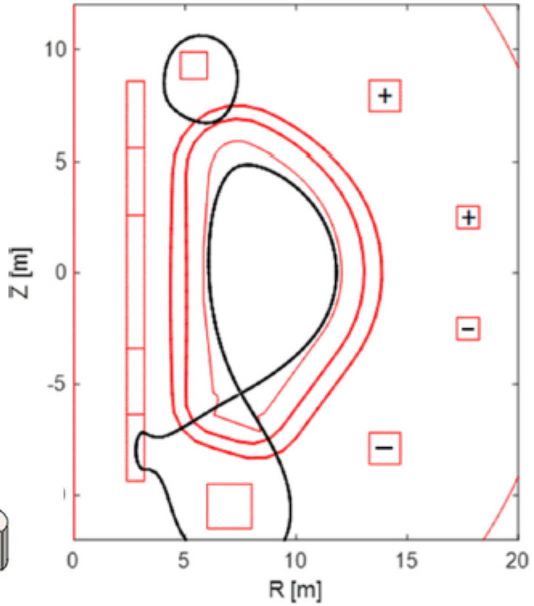

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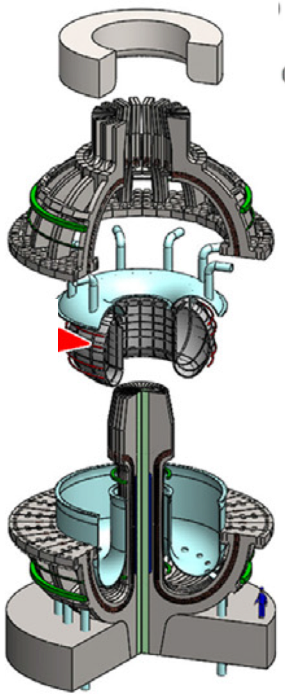


Reactor Development Opportunities

1. **Coils:** Make replaceable. Remote in-vessel replacement or replace with vessel (e.g. ARC[2])
2. **Microwave source (High Field):** Sub-mm localized current drive (e.g. MASER[3])

(also run low-beta to remove need for localized CD)

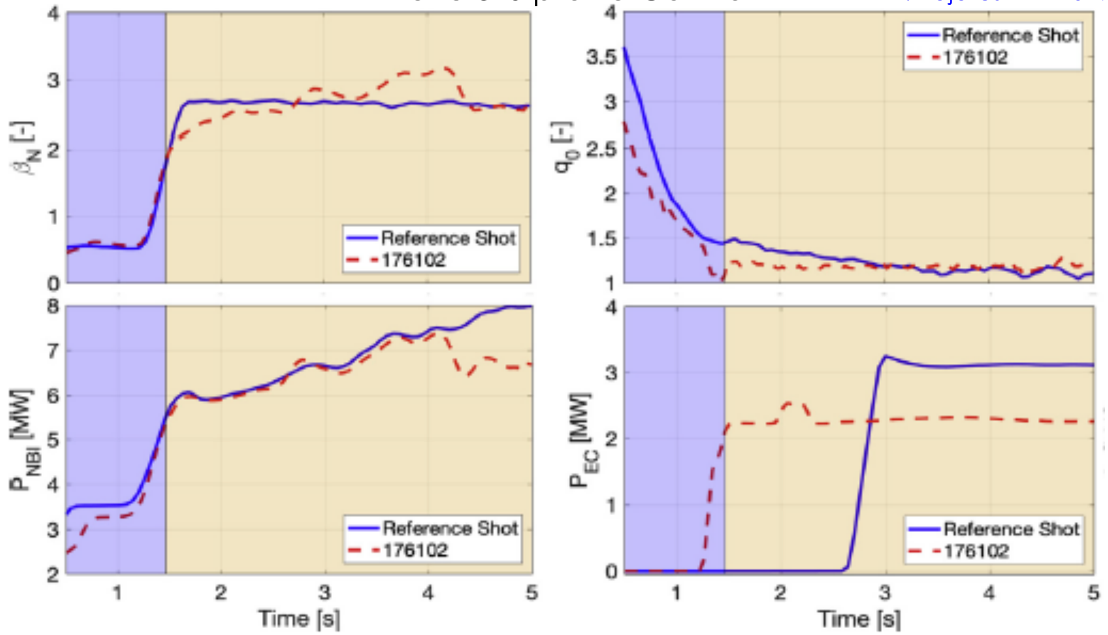
[1]D. Humphreys NF 2009
[2]B.N. Sorborn FED 2015
[3]Thumm Nucl. Instr. Meth. 2002

Reactor Disruption Prevention Challenge #3: Plasma self-organization

- **Kinetic & profile control key to remaining in regulated passively stable regimes**
- **Reactor challenge:** High Q (beyond ITER Q=10) diminishes authority of external heating/CD

Kinetic & J profile Control

A. Pajares FED 2019



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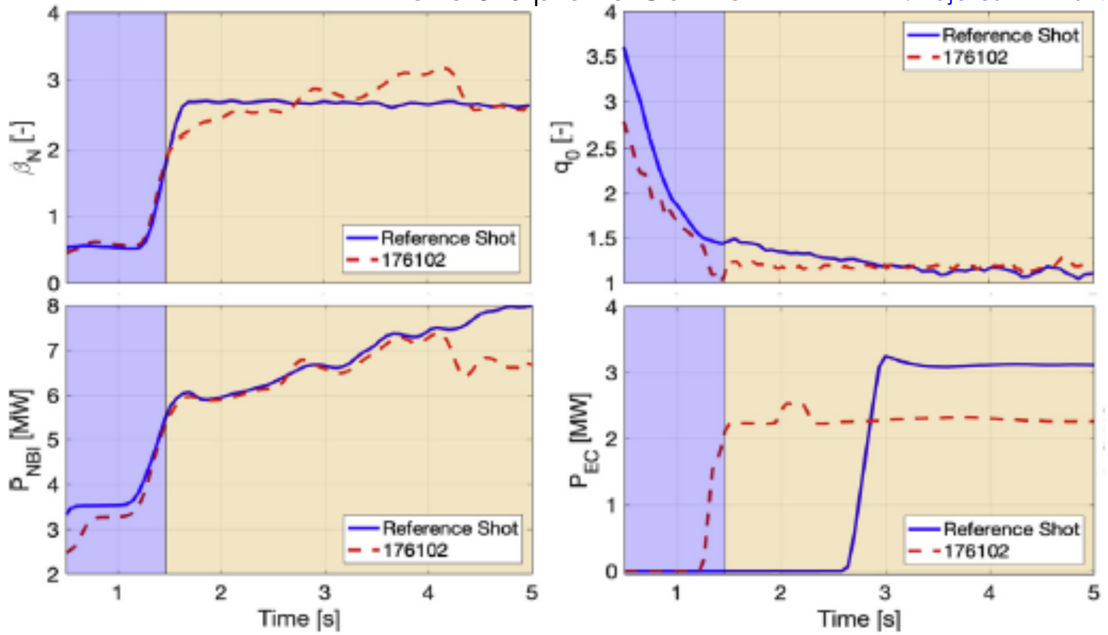


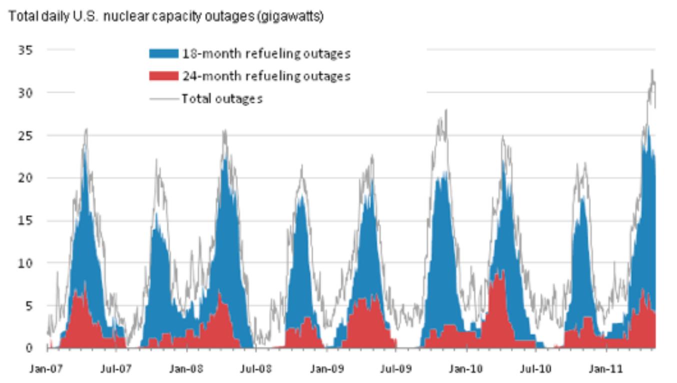
Reactor Development Opportunities

1. **Burn control:** Develop methods to guide self-organized state to desired operating point[1]
2. **Alternative actuators:** Non-heating actuators (i.e. fueling profile control with compact toroid injection[2] or low-voltage NBI for edge rotation modification) to modify profiles without large degradation in Q

[1] A. Pajares NF 2019
[2] R. Raman FED 2008

Reactor Disruption Prevention Challenge #4: Hardware reliability

- **Commercial reactor requires continuous disruption prevention ~ 18+ months to reach parity with fission reactors**
  - *Integrated plasma time on DIII-D since 1987: < 3.5 days*



- **Reactor reliability challenge:**
  1. VS system (coils + power supplies + diagnostics + control system) operate without failure between maintenance cycle
  2. Wall fragments dropping must be sustained without disruption
     1. CMOD very disruptive[1], JET not at all[2], may be negative size scaling?
  3. Coil systems failures cannot cause disruption (gross loss of control)

1. R. Granetz IAEA TM 2020
2. M Sertoli Phys Script 2014

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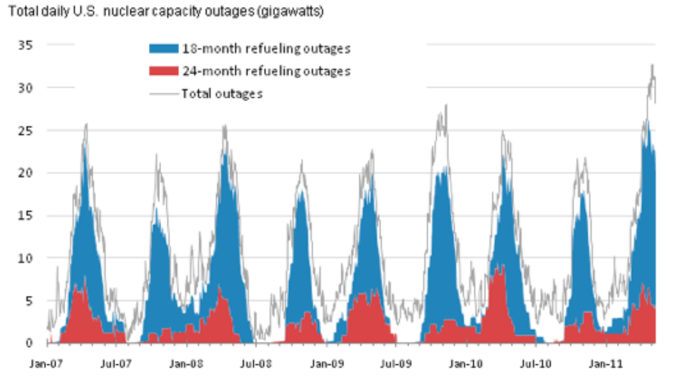

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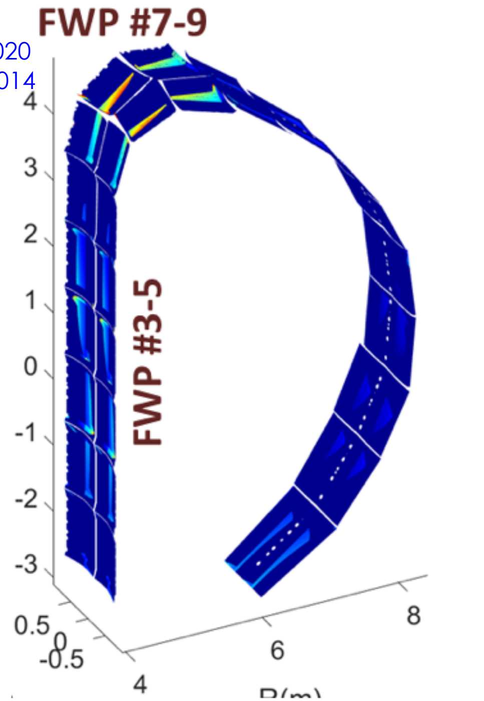


Realtime ITER power flux monitoring
H. Anand NF 2020

Reactor Development Opportunities

1. **VS Redundancy/Reliability:** Test redundant VS systems for seamless switchover in case of VS failure
2. **Wall integrity monitoring:** Develop wall monitoring for predicting "unpredictable" debris dropping into plasma
3. **Predictive coil failure monitoring**: Constantly assess likelihood of coil failing in order to execute controlled shutdown before fault occurs

Outline

1. What are disruptions & why/how do we handle them?
2. Evolution of disruption handling requirements: Research → Commercial Reactor
3. Contemporary state of disruption handling
4. Challenges to disruption prevention posed by a commercial reactor
5. **Resilient design**

Singularly destructive disruptions motivate investment in passively resilient design for commercial reactor

- **Reactor disruption consumption budget will likely resemble ITER's (or be more conservative due to increased thermal & mag energy density)**
  - Assume roughly similar wall & vessel technology.

- **Key Feature: Singular events exceeding engineering limits**

- **Even ideal mitigation must be actively triggered by predictor – failure at any point (detection, trigger, hardware) = no mitigation**

- **Risk-benefit: Low-probability high impact failure must be protected against in commercial reactor needing decades to break even**

ITER Disruption Budget Consumption in %

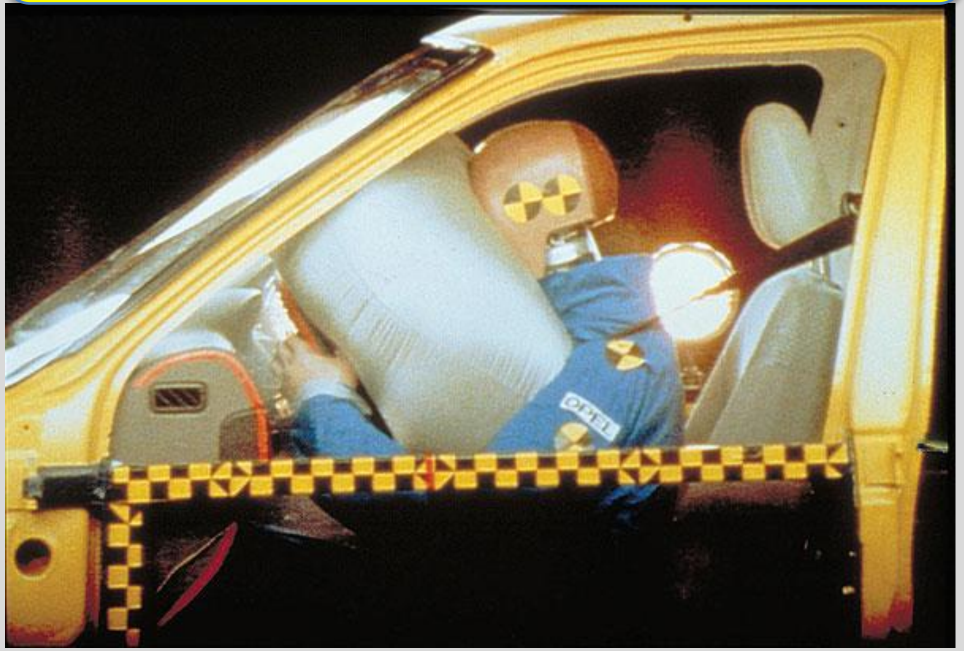
		fatigue		VV plasticity		halo heat flux		heat fluxes TQ			runaways	
		unmitig.	mitig.	unmitig.	mitig.	unmitig.	mitig.	unmitig. VDE	unmitig. MD	mitig.	unmitig.	mitig.
3.5 MA	H/He limiter 1500	0	0	0	0	0	0	0	0	0	33	5
	H/He L-Mode 6500	0.01	0.01	0	0	0.33	0	0.5	0.1	0	100	20
7.5 MA	He H-Mode 2000	0.2	0.05	0	0	0.33	0	1.5	0.3	0	100	20
	D H-Mode 2500	0.2	0.05	0	0	0.33	0	7.5	1.5	0.12	∞	50
	H L-Mode 500	1.0	0.2	100	0	6.67	0	2.5	0.5	0	100	50
	D L-Mode 3000	1.0	0.33	100	0	6.67	0	7.5	1.5	0.12	∞	100
15 MA	D H-Mode 2800	1.0	0.33	100	0	6.67	0	17.5	3.5	0.64	∞	100
	DT H-Mode 2700	1.0	0.33	100	0	6.67	0	20	4.0	1.12	∞	100

0 200 400
thermal energy [MJ]

M.Lehnen IAEA FEC 2016

Singularly destructive disruptions motivate investment in passively resilient design for commercial reactor

This is NOT what makes modern cars so safe…



…this is

A tokamak-based commercial fusion reactor must be viewed through lens of Probabilistic Risk Assessment

RISK =

(Probability of Event) X (Impact of Event)

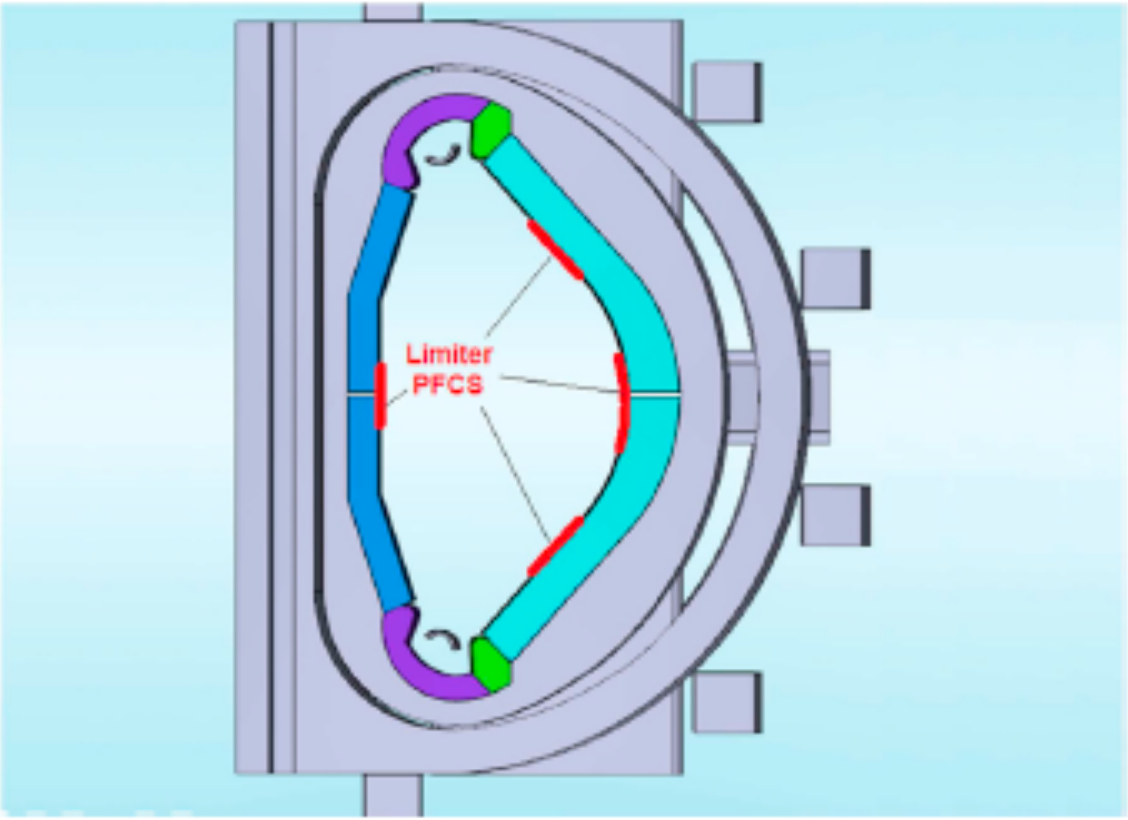
Disruption Prevention
Mitigation
(*we discussed this*)

Resilient Design
(*here we go*)

(Saying "it will not disrupt" is not defensible…
But lost time is part of doing business if risk is contained)

Passively resilient design: Sacrificial limiters to prevent or protect from VDE/VUD

- **Rapidly limiting plasma on at "neutral point[1]" near inner wall midplane enables robust vertical stabilization during disruption, no VUD**
  - Drastically reduced forces, benign, controlled RE
  - Robustly safe soft shutdown
- **Failing stabilization, upper/lower limiters can protect blankets from VUD/RE**
- **Do not prevent maintenance, but properly designed for rapid replacement these limiters these limiters can vastly reduce downtime[2]**

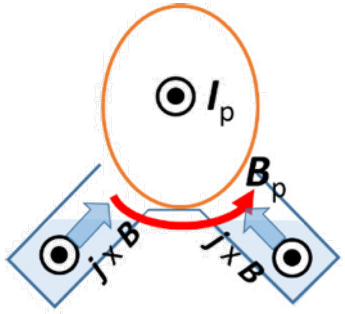


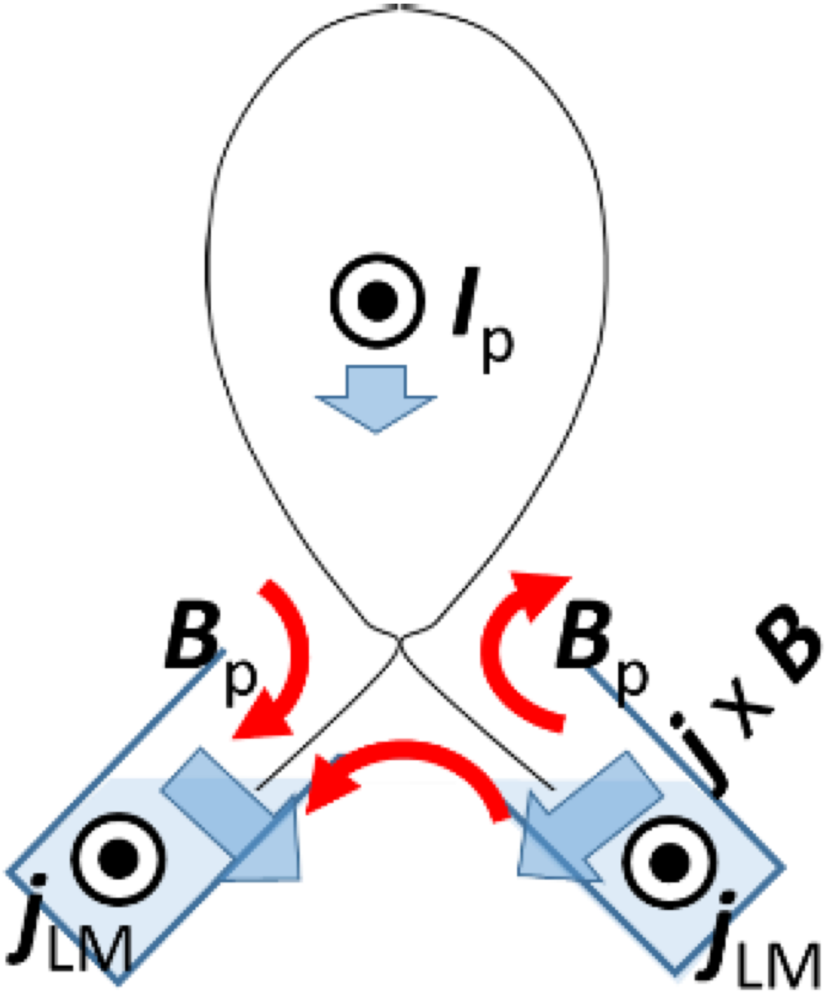
Conceptual Limiters
EU DEMO[2]

[1] V. Luksash PPCF 2005
[2] C.Bachmann FED 2019

Passively resilient design: Liquid metal divertor (LMD) to recover quickly from disruption

- **Thick LMD (Li or Sn) can sustain TQ & VDE heat flux without damage**
  - Mitigation: Negates need for high-Z radiator & fast pre-TQ time response
- **Possible passive mitigation of VDE when limits on LMD**
- **Sn LMD provides significant stopping power to absorb RE before reaching critical joints or water lines**





Magnetically Guided Liquid Metal Divertor Concept

M. Shimada Plasma & Fus. Research 2020

Passively resilient design:
Liquid metal divertor (LMD) to recover quickly from disruption

- **Thick LMD (Li or Sn) can sustain TQ & VDE heat flux without damage**
  - Mitigation: Negates radiator & fast pre-T

Removes need for TQ prediction & relaxes "Goldilocks" constraint on active mitigation

- **Possible passive mit VDE when limits on**
- **Sn LMD provides significant stopping power to absorb RE before reaching critical joints or water lines**

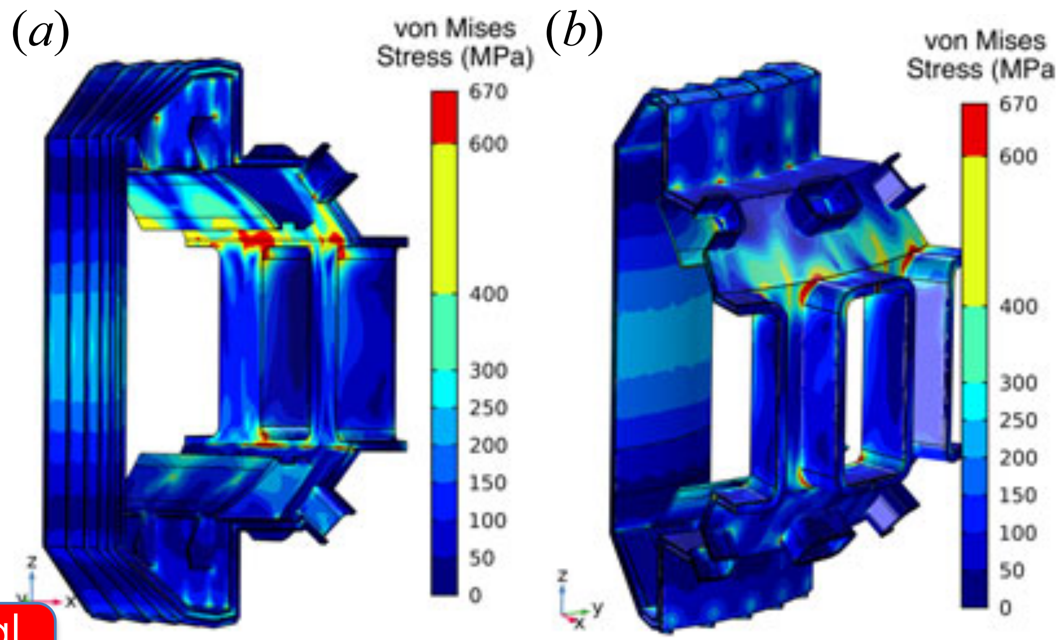
Magnetically Guided Liquid Metal Divertor Concept

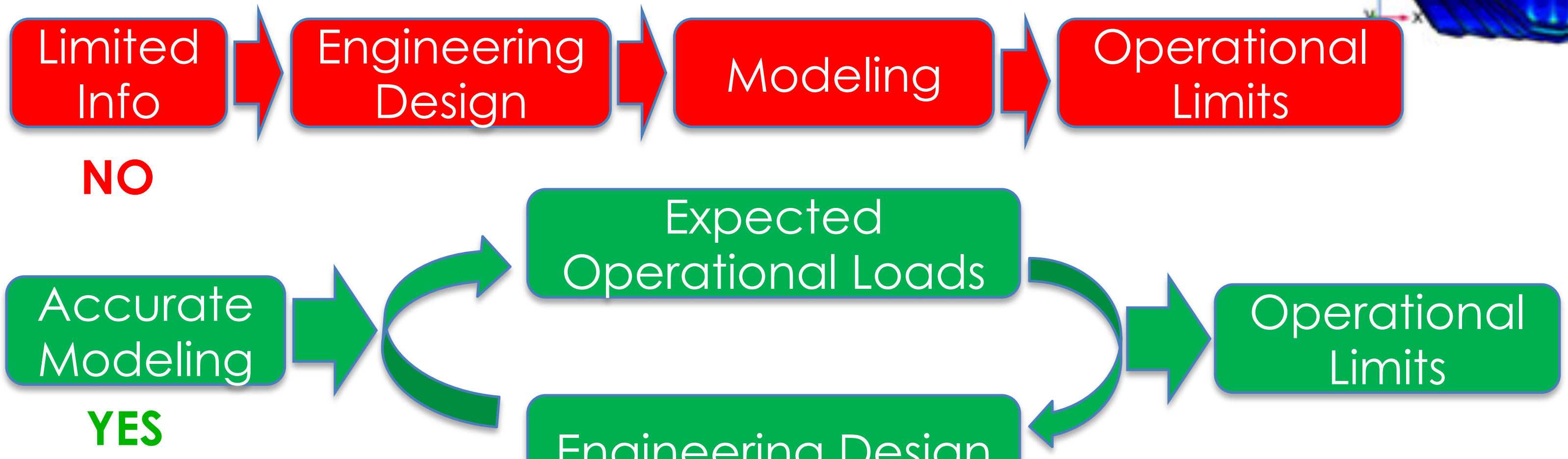
M. Shimada Plasma & Fus. Research 2020

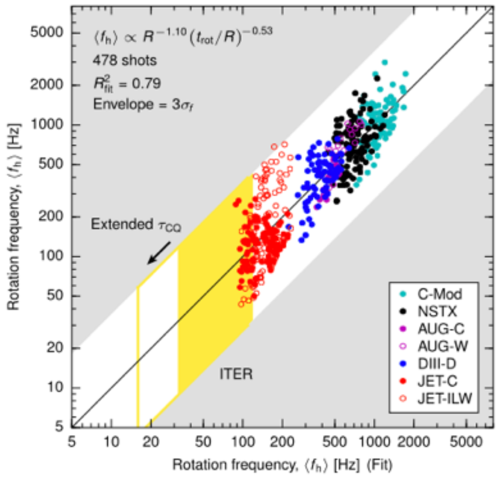
Passively resilient design: Engineer device to the operating loads (not vice versa)

- **Fast CQ decay (eddy) and slow CQ decay (halo) limits in ITER set after-the-fact because modeling showed problems[1]**
- **Creates major constraints in mitigation "Goldilocks" condition**
- **THIS IS NOT INTRINSIC: WE CAN ENGINEER MORE ROBUSTLY BECAUSE WE KNOW MORE**

SPARC Vessel Forces[2]







Halo rotation[3]

1. M. Sugihara NF 2007
2. R. Sweeney JPP 2020
3. C. Meyers NF 2018

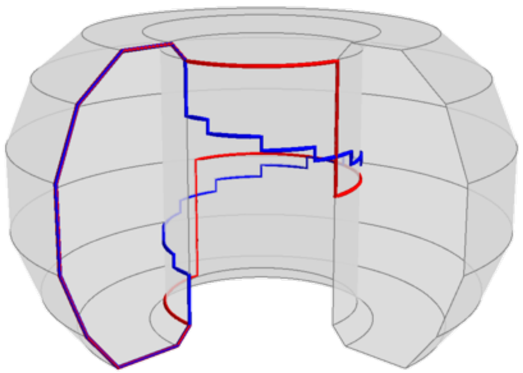
Passively resilient design:
Passive 3D coils to suppress RE formation

- **Passive 3D coils can use TQ & CQ loop voltages to create stochastic 3D fields that rapidly transport RE seeds to wall, suppressing RE formation[1]**
  - Can continue through CQ, deconfining Tritium seeds

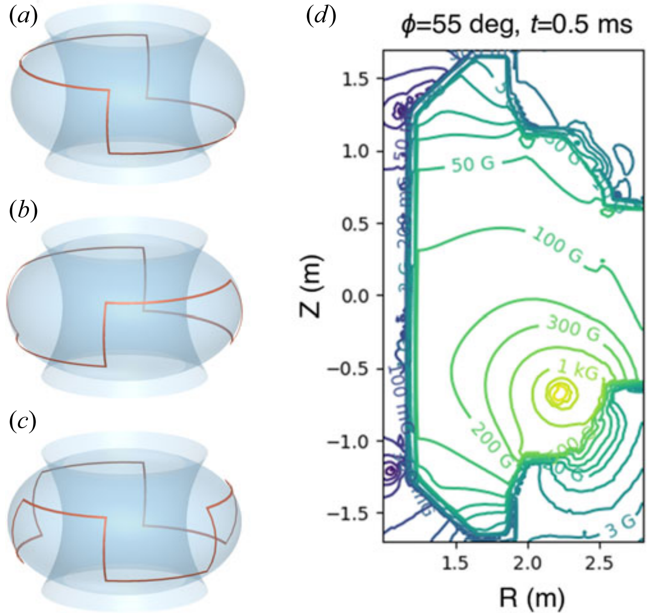
- **Feasible discrete passive coil designs modeled for D3D**
  - Addition of spark gap to coil circuit can make it entirely passive, but transparent to startup

- **For maximum current (& RE losses), 3D current structures could be engineered into vessel/blanket**

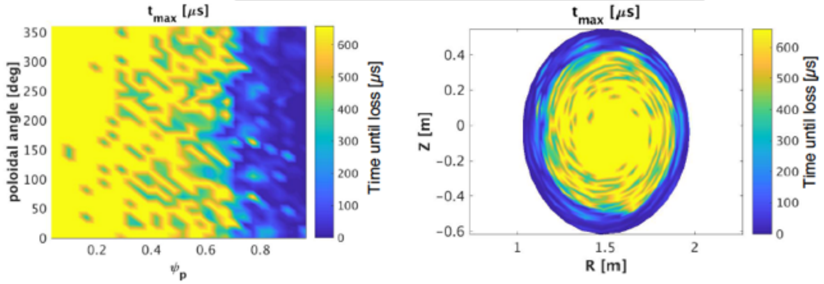
DIII-D Mark-I & Mark-II designs
(Courtesy D. Weisberg, GA)

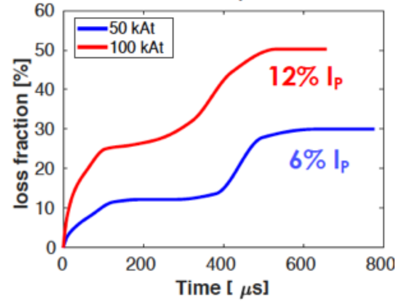


SPARC Concept
(R. Sweeney JPP 2020)



CP coil mk2, I_P=0.52MA, I_C=100 kAt





1. H. Smith PoP 2020

See R. Sweeney's presentation…

Robust disruption handling is essential to the prospects of a viable tokamak-based commercial fusion reactor

- **Disruption handling is a multi-layered process**
- **Commercial reactor environment presents unique challenges to disruption prevention well beyond ITER requirements**
- **Numerous development opportunities exist to enhance the prospects for effective disruption handling in a reactor**

DISRUPTION PREVENTION MUST BE CONSIDERED ON EQUAL FOOTING WITH STEADY STATE PREFORMANCE GOALS IN REACTOR DESIGN PROCESS

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