Disruptions and Related Off-Normal Events: Consequences, Avoidance and Mitigation and What to Do

A personal opinion
prepared and presented by

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Explanation and Acknowledgements

- **Originally motivated by/for ReNeW**
- **Based on preparation and content for the *ITER Physics Basis* (1998) and *Progress in the ITER Physics Basis* (2007)**
- **Not a review or presentation of data; see the *IPB* + *PIPB***
- **Intended to be a call to action**
- **Your support, participation and contributions are needed**
- **Acknowledgements to US DOE, General Atomics and DIII-D, ITER, the ITPA and many individuals, past and present**

Some preliminaries

- **Tokamak (and ST) only, focus on ITER**
- **ITER (the program) must succeed; must not fail owing to disruptions (too slow progress ⇒ failure ⇒ no DEMO)**
- **Disruptions present a serious problem**
- **How can we confront the problem?**
- **A "PAM" strategy is needed (Predict/Avoid/Mitigate)**
  - — PAM 'elements' must be developed, validated and deployed well before first ITER plasma
  - — PAM will provide a 'broad spectrum', multi-layer solution and will be amenable to 'distributed' R&D
- **Major enhancements in present and emerging program commitments will be needed; ITER must be prepared to be the test bed for PAM, and to contribute in-kind for DEMO**

‘Threats’ from disruptions, VDEs and REs are well-known

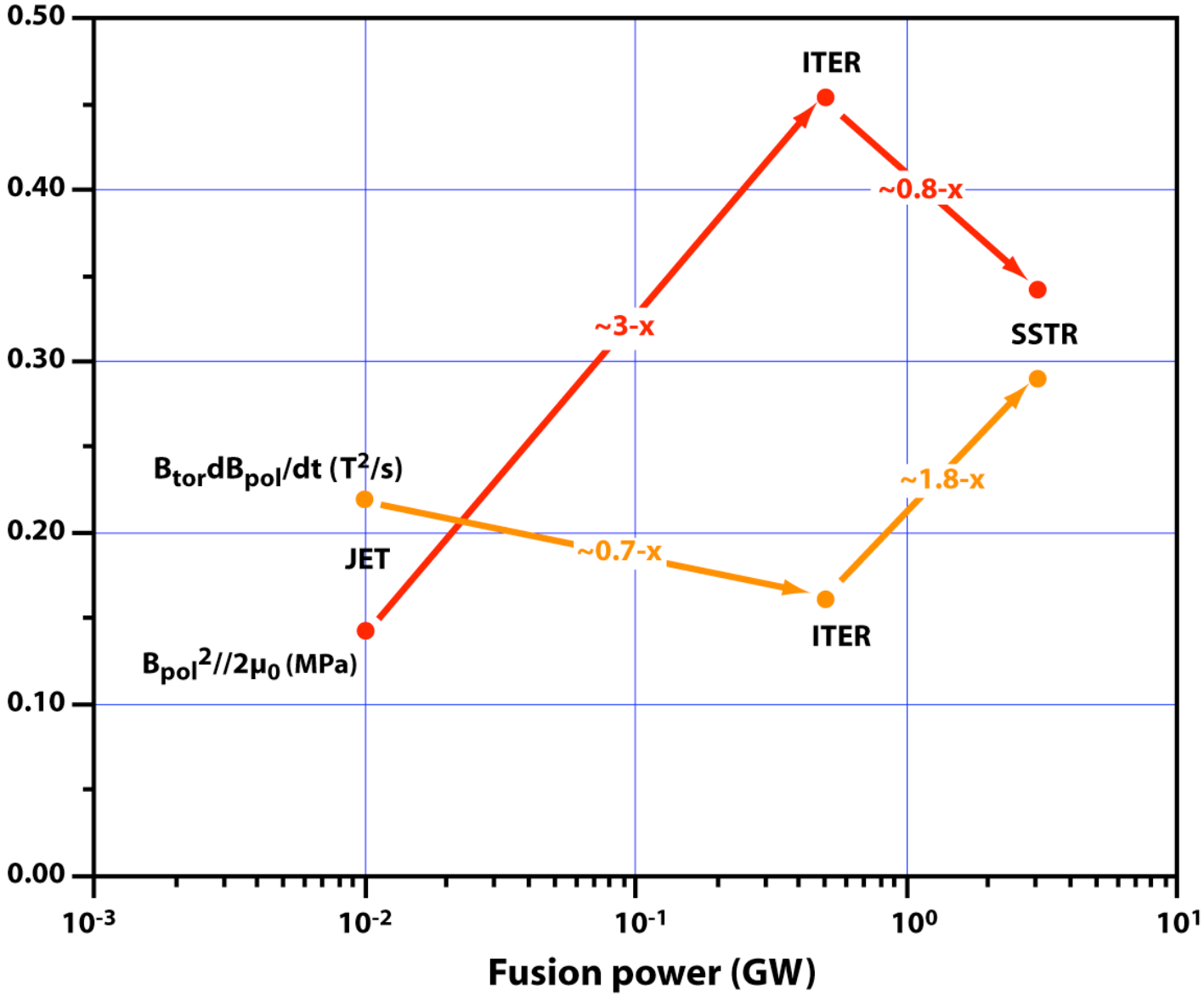
- **Impulsive plasma thermal energy deposit** on PFC surfaces ⇒ melt/ablate (μm)/crack/mobilize and redeposit ⇒ plasma operation delays, need to replace PFCs **($ 10^9)**
- **Transient local and global EM loadings** on in-vessel and VV structures ⇒ transient structural loads, fatigue and design constraints (*eg* reduced TBR), ⇒ **‘safety event’**
- **Avalanche multiplication** of multi-MeV runaway electrons ⇒ PFC surface and volume melt/ablate/crack (mm ⇒ leak!)/ mobilize and redeposit; ⇒ **‘safety event’**

The magnitude of these threats increases for ITER and beyond

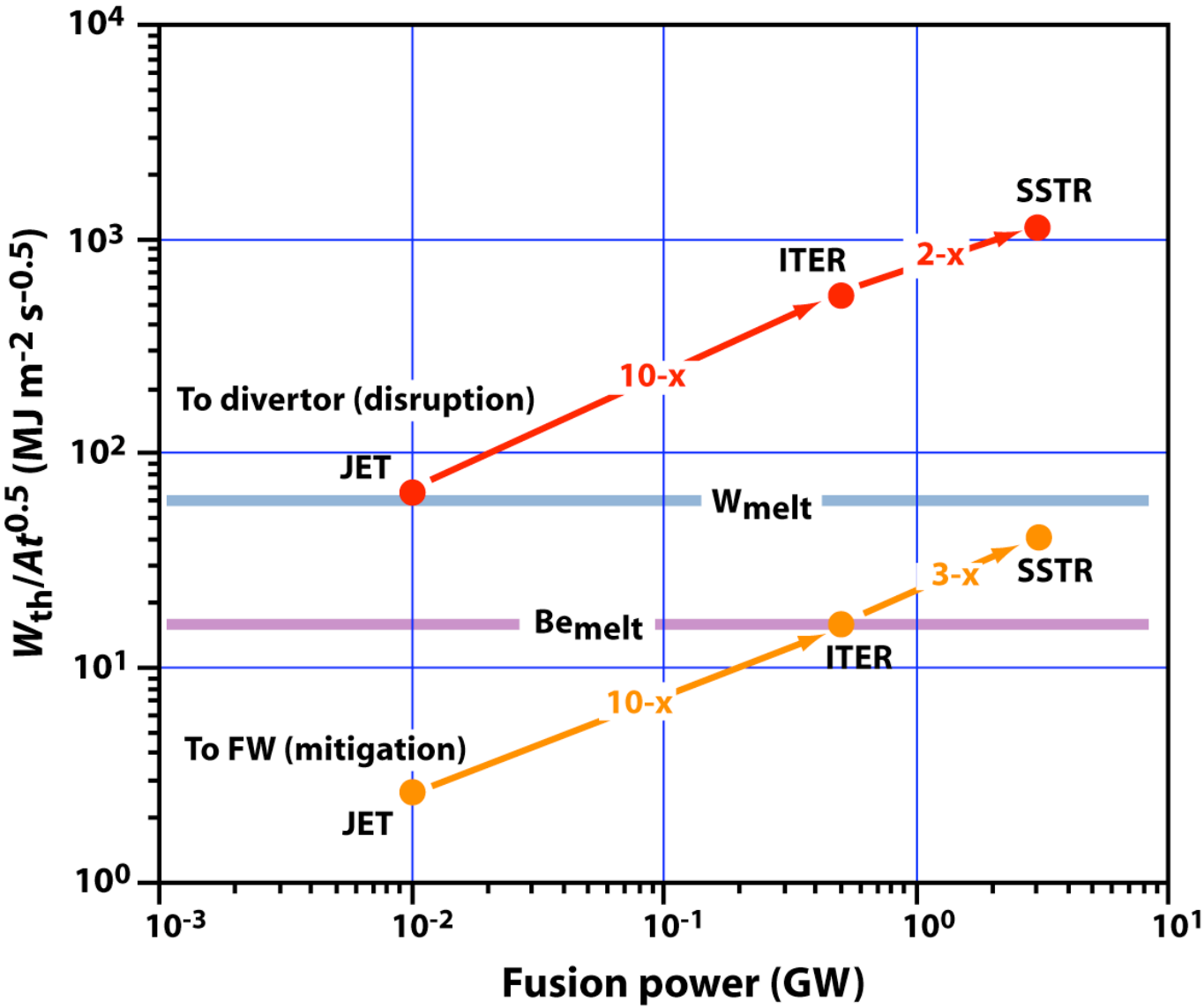
Concern about the consequences and costs also increases

ITER will be very challenging; DEMO will be even more so….

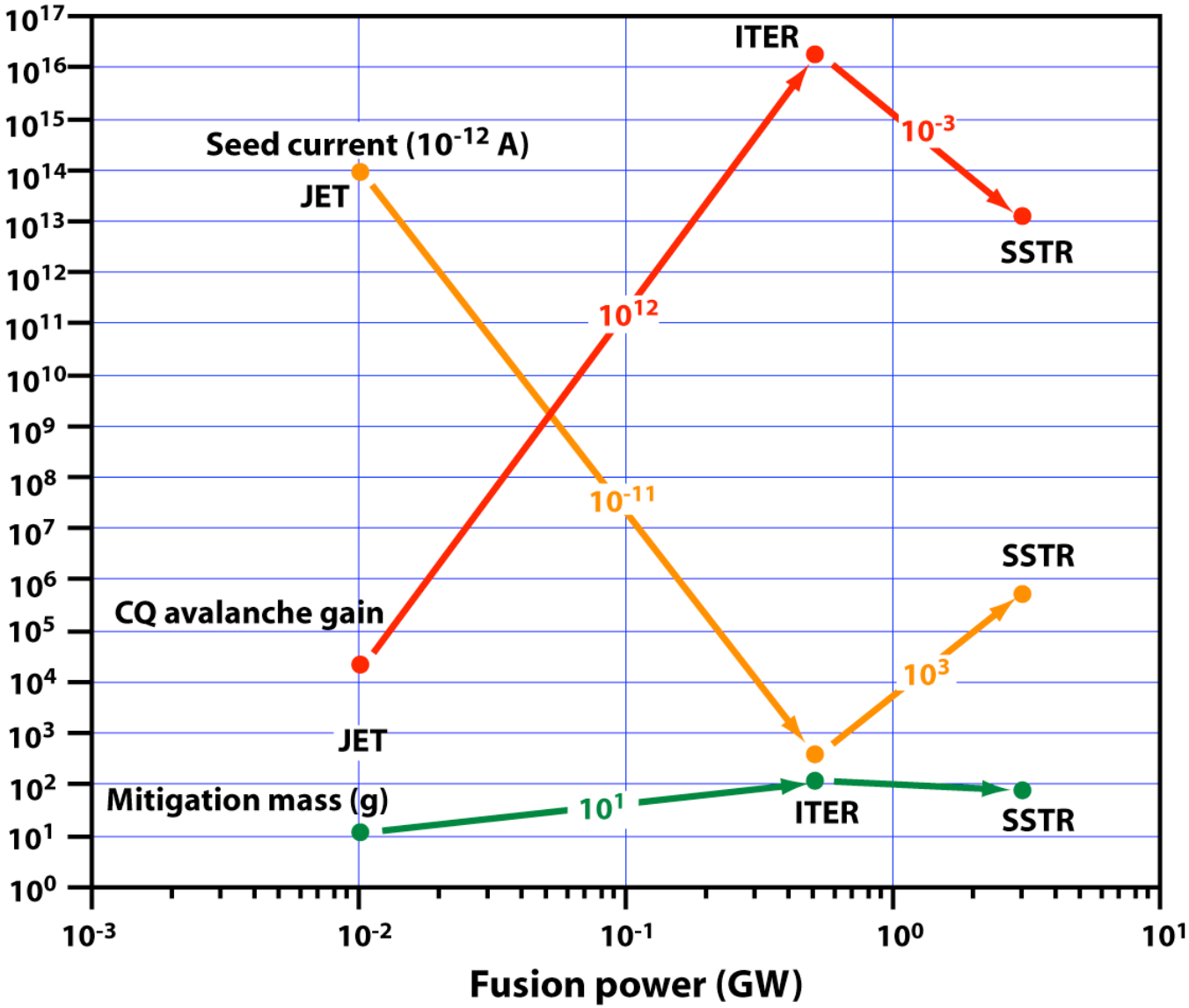
EM loads increase [only] modestly in ITER and DEMO



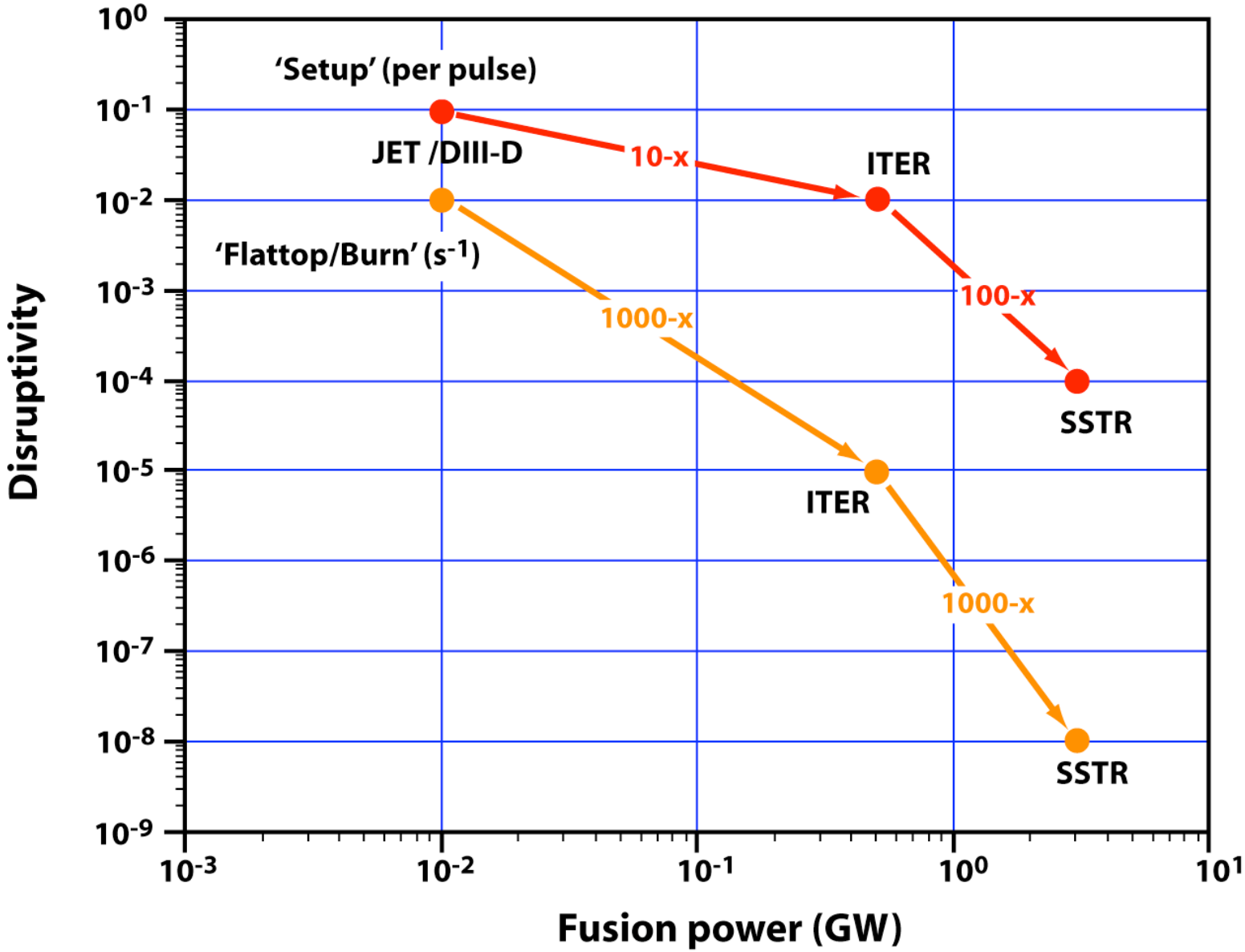
Thermal loadings increase ~10-x, exceed melt thresholds



RE gain increases exponentially; mitigation mass by 10-x



Allowable 'disruptivities' decrease, especially for DEMO



Requirements for ITER

- ITER can allow very few disruptions (bad ones, or any?)
- Recovery times from actual disruptions will be [very] long
- There may be administrative consequences and/or long operation resumption delays (*eg.,* for full in-vessel inspection); $200M/year
- At-risk ITER systems *must* be designed not to fail in a catastrophic manner owing to a limited number of 'worst-case' disruptions, VDEs or RE strikes (will damage overlap?)
- Significant RE risk may develop very early (eg., 7.5 MA H_2)
- Some number of modest-current disruptions will be required to validate EM load design assumptions, predicted 'load scalings' and RE conversion attributes owed to D, VDE and DM

PAM will be needed from Day-1

What is PAM?

- **Homework**: wall prep, operations pre-flight simulation, facility readiness check; provide precision control, redundant systems, approved mini-proposal
- **Monitor**: systems and plasma status (comprehensive diagnostics, full kinetic profiles [? early availability ?], reliable calibration, real-time data (ms delay)
- **Predict** onset of disruption (all causes, multiple predictors, finite look-ahead)
- **Avoid** disruption onset
  - In-situ repair and recovery (continue pulse), or
  - Retreat and 'normal' shutdown, or
  - 'Soft-landing' via fast[er] shutdown
  - Intelligent plasma-state and cause-dependent action(s); consider facility status, 'threat level' and recovery consequences
- **Mitigate** if necessary/warranted:
  - If avoidance fails, or
  - If evolving prediction indicates avoidance failure, or
  - If original prediction indicates immediate need for hard mitigation
  - Intelligent plasma-state and disruption-state actions (I_p level, VDE started, TQ started, CQ started, RE developed, threat level low/med/high, ….)

Comments about prediction

- MHD stability, ideal and otherwise, will not always be the best early predictor for disruption onset
- Can predictions of ideal and/or resistive instability thresholds be made accurate enough [via real-time diagnostic data] to provide warning for limit approach? Limits complex, interactive; what is Δ'?
- Need precision kinetics monitoring, with ms data and evaluation
- Look-ahead time + reliability ⇔ Avoidance options
- Look-ahead time + reliability ⇔ Mitigation options
- After-TQ mitigation presently looks very problematical
- Cause/type ⇔ predictor; need broad 'P-portfolio' + redundancy
- Vetting the adequacy/reliability of predictors will require 'close approach' to onset, or occurrence of disruptions (tune thresholds)
- **We cannot be [too] afraid to proceed…**

Comments about avoidance

- **Hierarchy:**
  - repair and continue
  - retreat and shutdown (~normal)
  - faster ‘soft-landing’ (rapid stop)
  - differences among recovery/restart times
- For ITER Physics: maximize science progress (higher disruptivity OK)
- For ITER TBM test or DEMO: maximize on-line/at-power time
- **Avoidance strategies for ITER may be limited** or constrained relative to present and emerging experiments
- Normal ITER shutdown is already slow, challenging, highly constrained; are there credible faster shutdowns?
- **Look-ahead time ⇔ A and M method(s) ⇔ threat level**
- **Present facility R&D + modeling needed; broad A-portfolio suggested**

Comments about mitigation + RE avoidance

- **DM objectives**
  - Reduce conducted W_{th} to FW (for VDE)
  - Reduce conducted W_{th} to divertor (avoid erosion, mobilization)
  - Reduce halo currents
  - **Avoid RE generation and/or avalanche multiplication**
  - Prevent/minimize PFC de-conditioning from disruption
- **DM consequences**
  - Fast CQ, radiate W_{th} to FW (VDE, disruption); **peaking = ?**
  - Reduced I_{halo} ⇔ fast CQ; **potential for RE avalanche**
  - High mass/gas input; FW deposition for condensable injectants
  - Possible localized FW melting; hydrogenic or noble gas loading; major deposition and dust generation for condensable injectants
- **Candidate methods**: mass injection (gas, liquid, solid; Z = 1– 92), moderate to large quantities (moderate for TQ + HC, large for RE avoidance); static RMP; dynamic RMP (feasible?) (do RMPs work?)
- **TQ and HC mitigation** (+ fast CQ) in present experiments, **RE generation and avalanche in some instances**

Comments about mitigation + RE avoidance

- Few options for mitigation after mature RE discharge develops
  - Must maintain equilibrium control (feasible in ITER?)
  - Gas injection (problematic with thermal plasma present)
  - Mechanical limiter (dynamic)
  - Pulsed (strong) RMP
  - High reverse voltage (several seconds) + controlled rampdown
- **High priority for RE avoidance ⇔ TQ + HC mitigation selection**

My opinion: none of the disruption mitigation methods proposed for ITER ($G_{RE} = 10^{16}$) have yet been shown capable of avoiding a possible RE 'problem'. MGI and equivalent MPI at sub-ITER quantities show appreciable side- and after-effects; ITER-level gas, pellet and/or liquid injection remains to be tested in, eg,, JET. In-vessel deposition and dust generation by condensable injection pose serious issues. Some recent progress in mature RE mitigation, but issues remain. **We are still very much in the concept-definition phase of D and RE mitigation R&D**

What to Do for ITER?

- **Don't panic, but….**
- **Don't ignore or minimize the "problem"**
- **Implement** a world-wide program to develop PAM for ITER, with emphasis on developing prediction and avoidance means
- **A broad portfolio and parallel/redundant approaches** to all three elements — **P, A and M** — are needed
- **Mitigation is essential** for asset protection and P+A backup. We must develop, test and ITER-qualify effective and benign mitigation technologies. A parallel/redundant approach **(more than one option)** will be essential
- **ITER must provide whatever is required to implement and 'reactor-test' a portfolio of DM and REM options**
- **Commitment from present and emerging facilities** to validate and test ITER-applicable elements of PAM is essential. **M-tests at the highest possible plasma current and energy are needed**

What to Do beyond ITER?

- **ITER must develop 'PAM v.2' for DEMO**
- DM methods/strategies successful in ITER should translate well to an 'ITER-based' prototype reactor
  - — assumes ITER test of DEMO plasma operation mode(s)
  - — higher performance DEMOs ⇒ new M requirements
- **Prediction and Avoidance can be more focused for DEMO**
  - — Proven operation mode and scenario, likely steady-state
  - — No physics explorations
- **But… prediction reliability and avoidance success must be vastly better than for ITER**
- It's likely that DEMO-1 will have to 'bootstrap' its own PA improvements (to PAM v.3)
- **DEMO concept(s) must be robust enough to support improvements of PAM to 'commercial' levels**