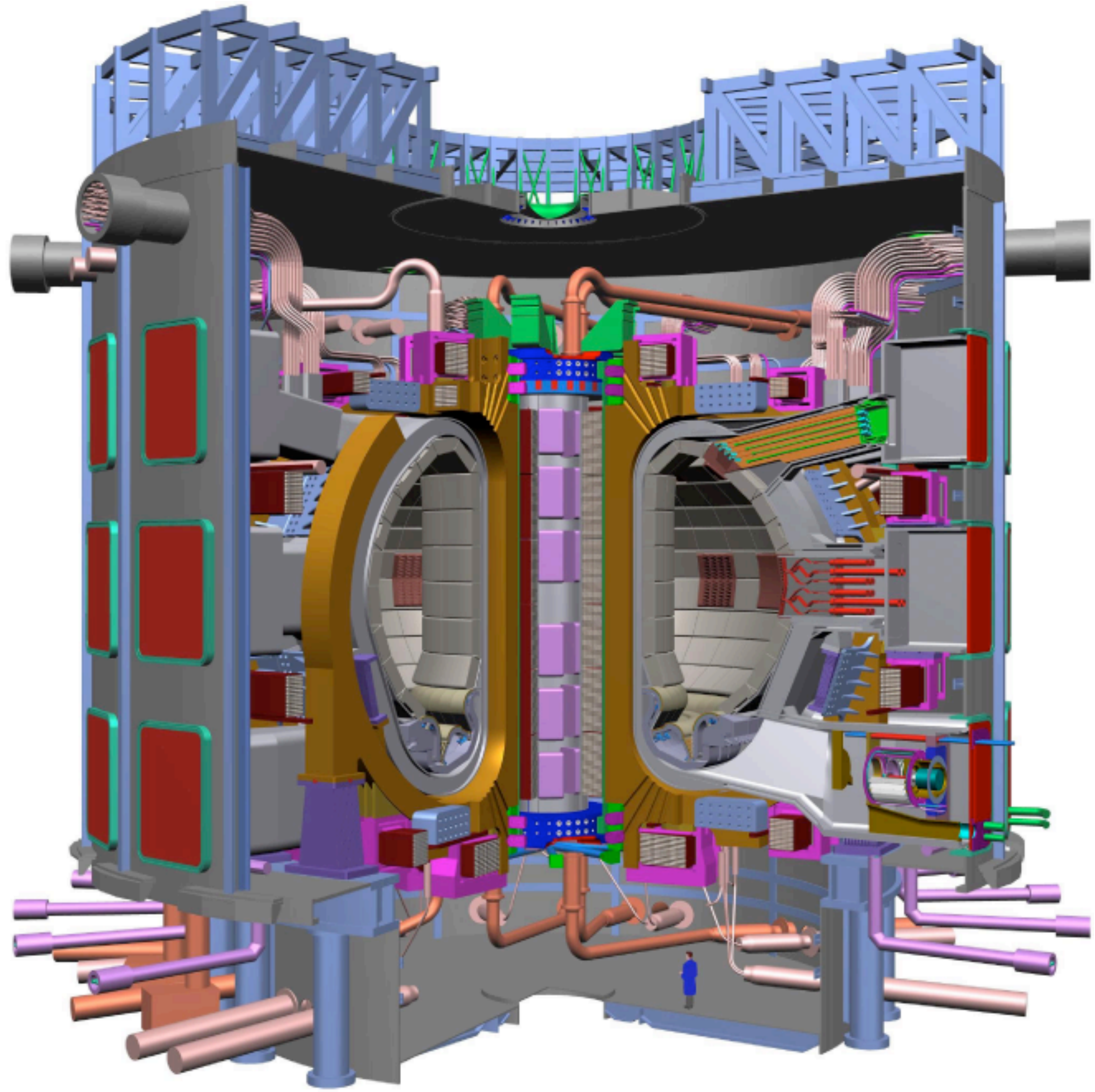
Disruption Avoidance and Mitigation Challenges for ITER and Beyond



A personal narrative
prepared and presented
by John Wesley

for the

15th Workshop on MHD Stability Control and Joint US-Japan Workshop

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Explanation and Acknowledgements

- **My opinions; 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 latest data; see the *IPB* + *PIPB*; also 2008 and 2010 IAEAs**
- **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**
- **Special thanks to Ted Strait, Richard Buttery and Rob La Haye for encouragement and this invitation**

Disruptions present critical challenges for ITER

- ITER (the program) must not fail owing to disruptions (too many disruptions or too slow progress ⇒ failure ⇒ no DEMO)
- VV/in-vessel failures or premature PFC replacement ⇒ major costs + painful program delays (or worse)
- Disruption consequences ⇒ ‘safety’ + regulatory issues
- A “PAM” strategy is needed (Predict/Avoid/Mitigate)
  - — Develop, validate and deploy before first plasma
  - — MHD stability and stability control critical to P and A
  - — Program efforts so far mostly focused on M

⇒ Major enhancements in present and emerging program commitments will be needed

⇒ ITER must be prepared to be the test bed for ‘reactor’ PAM, and to contribute in-kind for DEMO

Organization and Topics

- **Definitions**
- **Disruption ‘threats’; scaling to ITER and DEMO**
- **Why PAM?**
- **Prediction requirements and options**
- **Avoidance issues and options**
- **Disruption mitigation challenges and interactions**
- **Conclusions and recommendations**

Basic definitions (ITER and DEMO context)

- **Disruption: sudden loss of thermal energy and particle confinement owed to global MHD instability**
  - — often preceded by 'trigger' MHD instability, slowly-growing resistive MHD, cascade of MHD and profile deterioration
  - — followed by some degree of vertical instability and development of in-vessel 'halo currents' (aka 'vertical disruption' or VUD)
  - — rapid I_p decay; time → 1.7 ms/m^2 (36 ms in ITER)
- **Vertical Displacement Event (VDE): slowly-growing vertical instability; DIV → LIM, then rapid thermal collapse**
  - — major vertical displacement, accompanied by 'slow' thermal loss
  - — then fast 'disruption-like' thermal and current collapse
  - — toroidally-asymmetric **poloidal halo currents** + $\boldsymbol{F_Z}$**(VV)**
  - — toroidal I_p asymmetries in JET AVDEs; $\boldsymbol{F_{side}}$**(VV) force**
- **Rapid shutdown: pre-emptive fast W_{th} and I_p 'shutdown', by massive H/D or impurity injection (gas or pellet)**

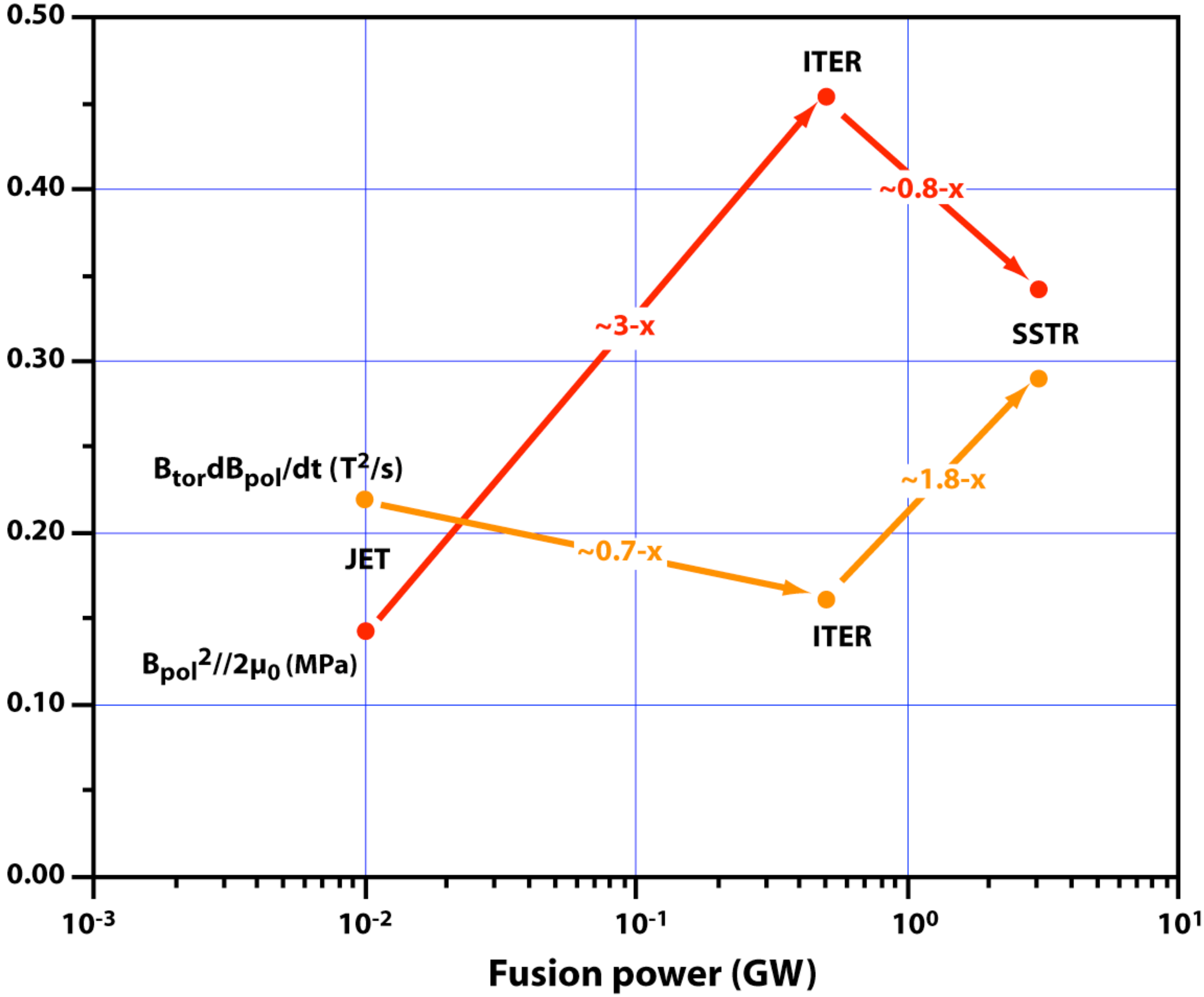
‘Threats’ from disruptions and VDEs are well-known

- **Impulsive plasma thermal energy deposit** on PFC surfaces
  ⇒ melt/ablate (μm)/crack/mobilize and redeposit
  ⇒ plasma operation delays, replace PFCs **($ 10^9 + 1-3 years)**
- **Transient local and global EM loadings** on in-vessel and VV structures ⇒ transient structural loads, fatigue and design constraints (*eg* reduced TBR), effects ⇒ **‘safety event’**
- **Avalanche conversion to multi-MeV runaway current**
  ⇒ PFC surface and volume melt/ablate/crack **(mm ⇒ leak!)** mobilization and redeposit; effects ⇒ **‘safety event’**

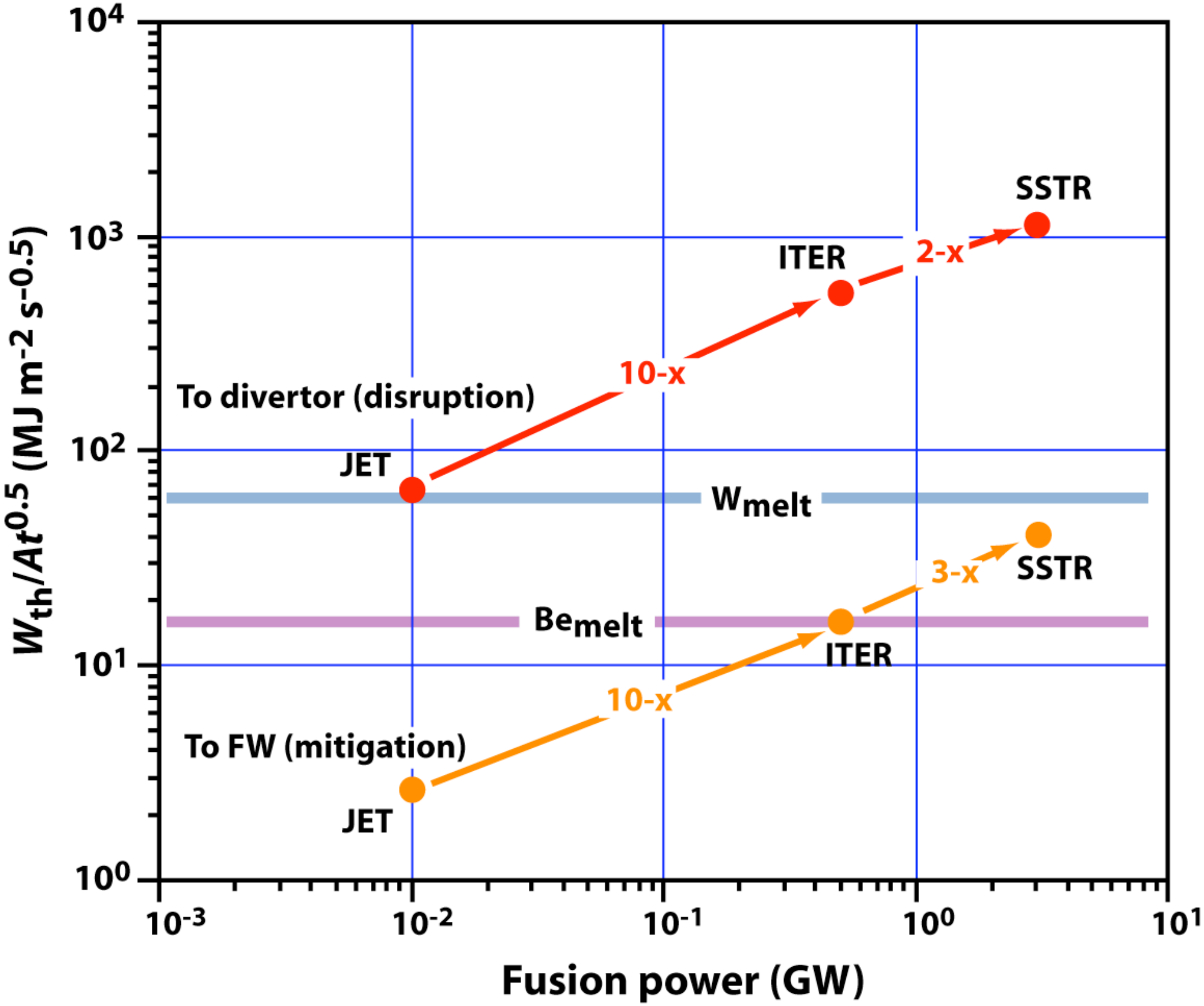
- **Threat magnitudes increase for ITER and beyond**
- **Concern about consequences and costs also increases**

⇒ ITER needs an ‘integrated’ strategy to counter these threats

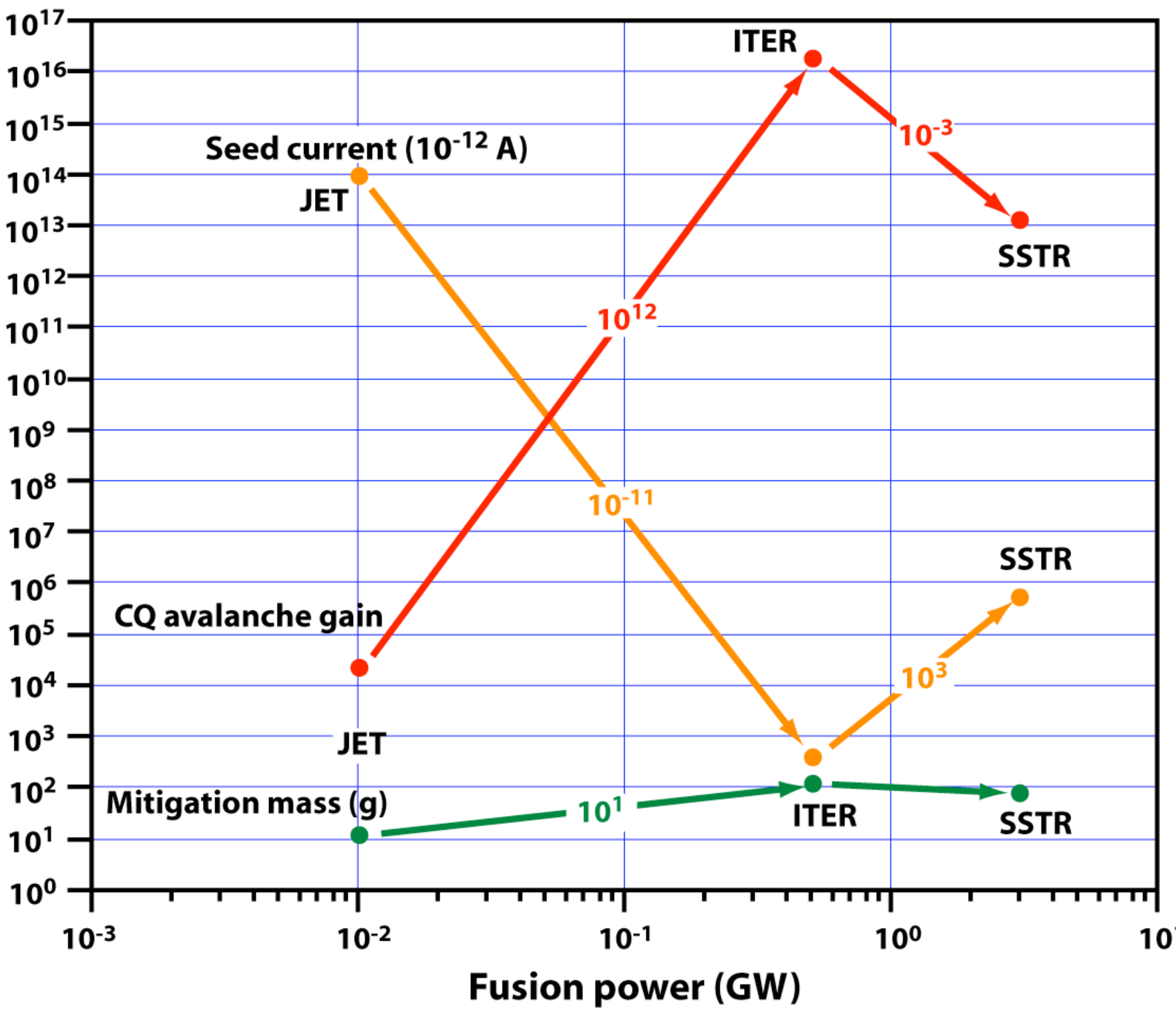
EM loads increase [only] modestly in ITER and DEMO



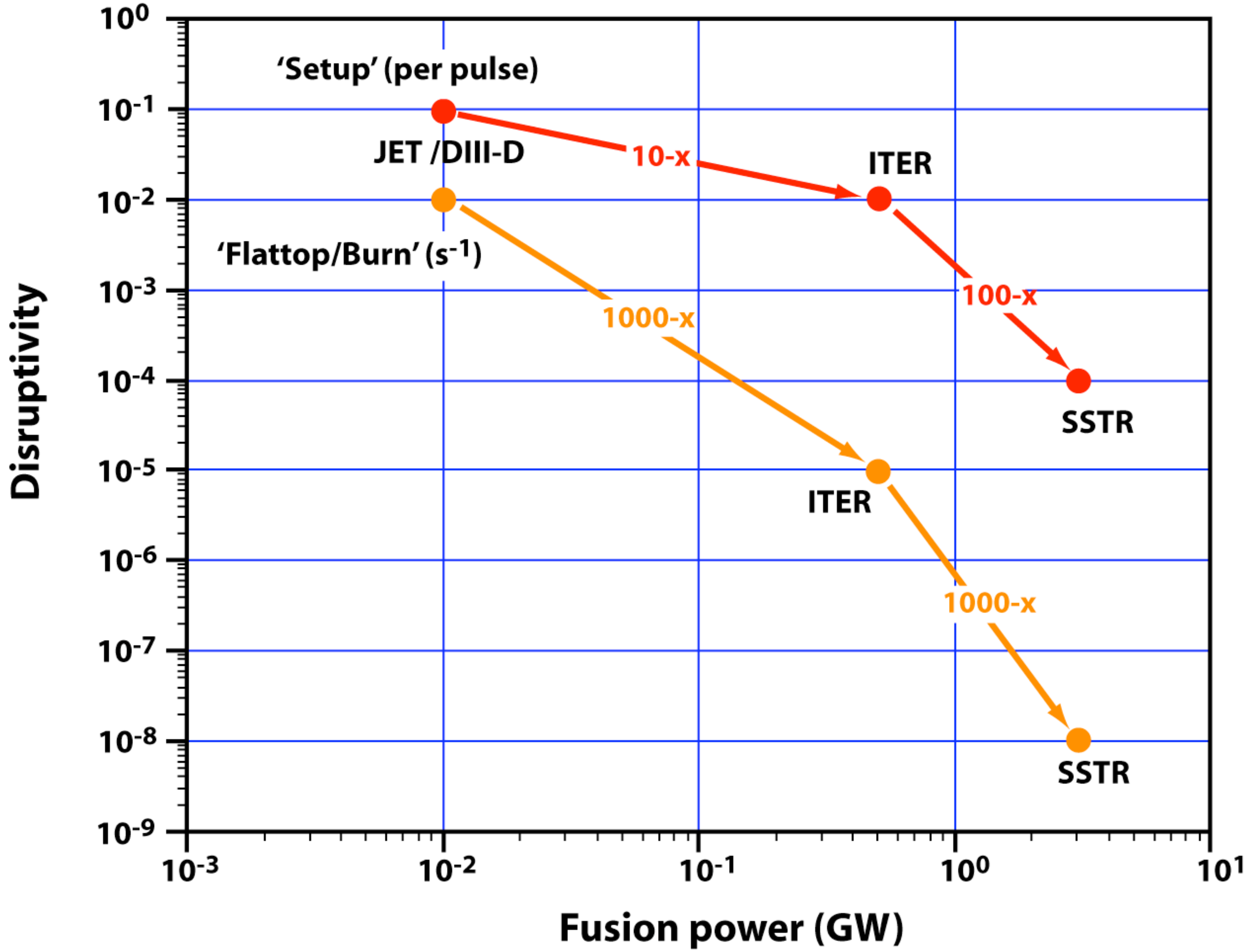
Thermal loadings increase ~10-x, exceed melt thresholds



RE conversion gain increases exponentially ⇒ $I_{RE} \cong I_p$



Allowable ‘disruptivities’ decrease, especially for DEMO



Requirements for ITER are very challenging

- **30-year lifetime, up to 50,000 pulses, 2600 disruptions (mixture of severities) allowed (≤ ~0.5% 'disruptivity')**
- **Recovery time and methods must support timely experimentation**
  - **Wall and PFC reconditioning method = ?; time = hours (?)**
  - **Gas mitigation pump-out time ≤ 3 hours (desired)**
  - **'Severe disruption' ⇒ administrative consequences and/or operation resumption delay (*eg*., full in-vessel inspection)**
  - **Premature divertor PFC replacement costly (~$\$10^9$ + 1-3 years); FW PFC replacement = ???**
  - **Vessel, in-vessel B/S and B/S attachments are 'permanent'**

⇒ At-risk components *must* not fail catastrophically owing to a credible cumulative number of 'worst-case' disruptions, VDEs and RE strikes; minimize PFC replacement

Mitigation alone will be insufficient; need PAM

- **Homework**: wall prep, operations pre-flight simulation, facility readiness check; provide precision control, redundant systems, vetted ops/expt plan
- **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
  - Requires intelligent plasma-state and cause-dependent action(s); consider facility status, 'threat level' and recovery consequences
- **Mitigate** when/if necessary:
  - If avoidance fails, or
  - If prediction indicates avoidance failure, or
  - If original prediction indicates 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, ….)

Prediction essential for both Avoidance and Mitigation

- **Many candidate P methods proposed and/or tested:**
  — Single or combination of parameters: $P_{rad} > P_{in}$; $\beta_N > C_\beta l_i$, …

  — Neural net (scalar or rate-of-change); $L_{dis}(\Delta t_{dis}) = \Sigma\, w_i X_i$

  — Pre-disruptive events: H-L, MARFE, $-\partial\Omega/\partial t$, (2,1) TM onset+growth, TM lock, VDE $Z(t)$ drift, …

  — Proximity to real-time-estimated ideal, resistive or empirical limit

  — MHD spectroscopy (instability proximity probe)
- **MHD stability, ideal and otherwise**, may not always be the best early predictor for disruption onset
- **Will real-time predictions** of ideal and/or resistive instability be accurate enough to provide reliable warning for A or M?
- **Need precision kinetics monitoring (physics quality data!)**, with ms data availability and evaluation, plus intelligent 'reactive' control

Strategies for Avoidance require further study

- **Hierarchy:**
  - repair and continue
  - retreat and shutdown (~normal)
  - faster 'soft-landing' (rapid stop)
  - differences among recovery/restart times
- **Candidate methods:**
  - MHD instability control (aka ST, NTM, ELM, … control)
  - MHD instability intervention (ECH, ECCD, ICRF, RMP drive, …)
  - Slow gas or pellet injection
  - All with coordinated magnetic and kinetic (fueling/H/CD) control
- **For ITER Physics:** maximize progress (higher disruptivity maybe OK)
- **For ITER TBM Test or DEMO:** maximize on-line/at-power time
- **Avoidance strategies for ITER may be limited** or constrained relative to those used in present and emerging experiments; time scale slow

Disruption mitigation has complex consequences

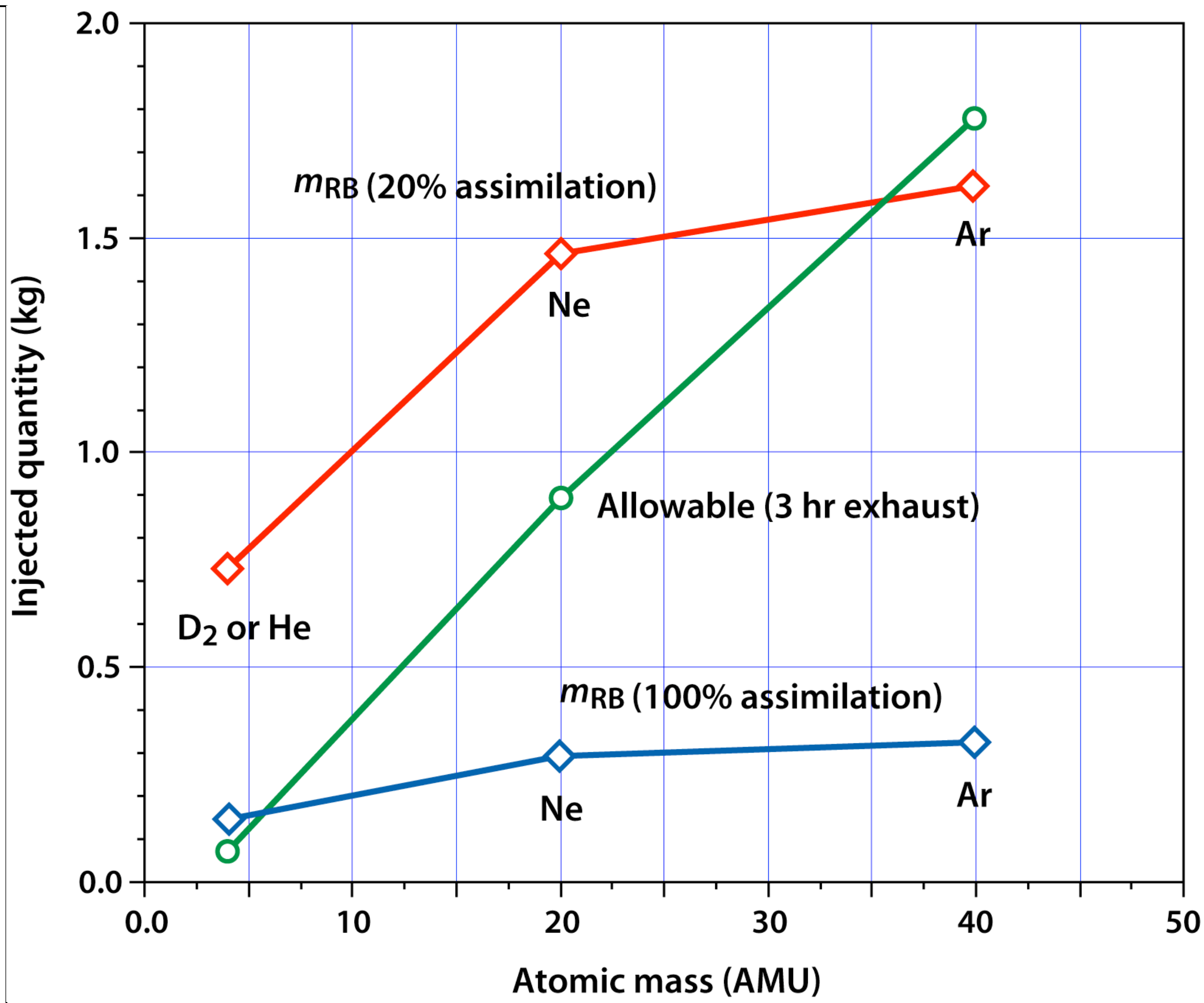
- **DM and VDE-M objectives**
  - — Reduce conducted W_{th} to FW (VDE)
  - — Reduce conducted W_{th} to divertor (avoid erosion, mobilization)
  - — Reduce halo currents
  - — Prevent/minimize PFC de-conditioning from disruption
- **Candidate methods:**
  - — mass injection (gas, liquid, solid; $Z = 1$–92), moderate to large quantities: **moderate for TQ + HC, large for RE avoidance**
  - — static RMP; dynamic RMP (feasible?) (are RMPs effective?)
- **High-quantity RS has consequences:**
  - — Fast CQ **(EM loads),** radiate W_{th} to FW **(local peaking)**
  - — Reduce I_{halo} $\Leftrightarrow$ fast CQ $\Rightarrow$ **high EM loads + RE avalanche**
  - — **RS $\Rightarrow$ 'hot tail' and/or 'reconnection' RE seeds**
  - — High mass/gas input $\Rightarrow$ **gas exhaust system impact, ops delay**
  - — **Possible localized FW melting**; hydrogenic or noble gas loading; major deposition and dust generation for condensable injectants

Runaway electron avoidance is critical

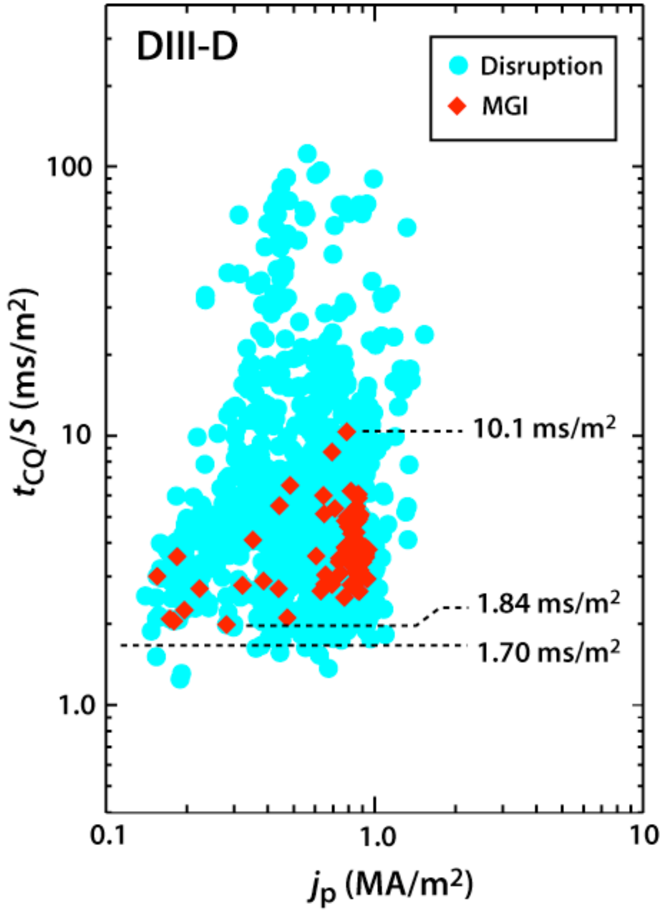
- **Few options for mitigation once mature RE discharge develops**
  - — High-Z gas injection may be effective (DIII-D, Tore Supra)
  - — Mechanical limiter (dynamic)
  - — Pulsed (strong) RMP
  - — High reverse OH voltage (several seconds) + controlled rampdown
  - — But… is long-term RE equilibrium control feasible in ITER?
- **Importance of RE avoidance ⇒ TQ + HC mitigation selection**
- **Opinion: none of the DM methods proposed for ITER ($G_{RE} \approx 10^{16}$) are yet shown capable of avoiding a possible RE 'problem'**
  - — MGI and MPI at sub-ITER quantities show side- and aftereffects;
  - — ITER-level gas, pellet or liquid injection remains to be tested in **JET or JT-60SA (need combined high I_p + high W_{th})**
  - — In-vessel deposition and dust generation by local FW heating and/or condensable injection pose serious issues
  - — Recent progress in mature RE mitigation, but issues remain….

DM Challenge #1: Gas exhaust and processing constraints

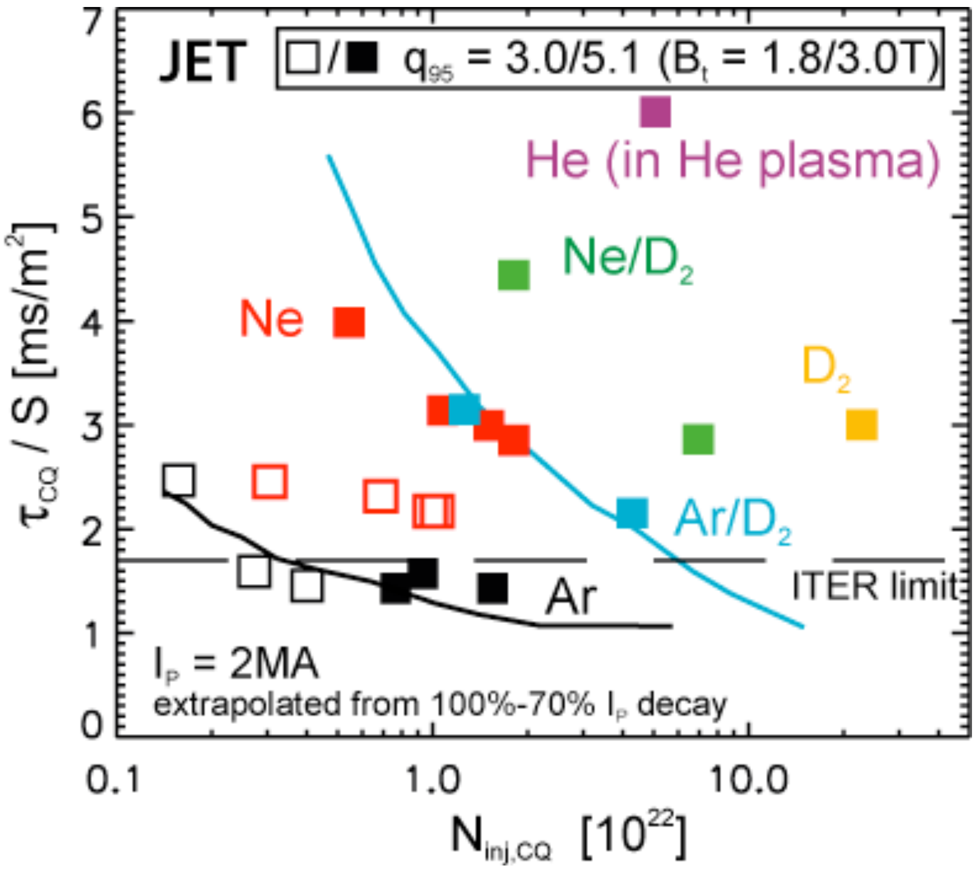
- **Exhaust and processing of mitigation gas limits allowable quantity**
- **D_2 quantity also limited by deflagration avoidance**
- **Rosenbluth 'no-avalanche' injection quantities (m_{RB}) for 20% assimilation ≥ allowables**
- **For 100% assimilation, neon and argon, m_{RB} < allowables**
- **Obtaining highest assimilation critical**
- **With finite assimilation, Ne or Ar feasible, but…**
- **Ne and Ar already tend to create REs in present 'low-gain' experiments**



DM Challenge #2: High-quantity injection ⇒ 'very fast' CQ



Wesley *et al* (2006 IAEA)



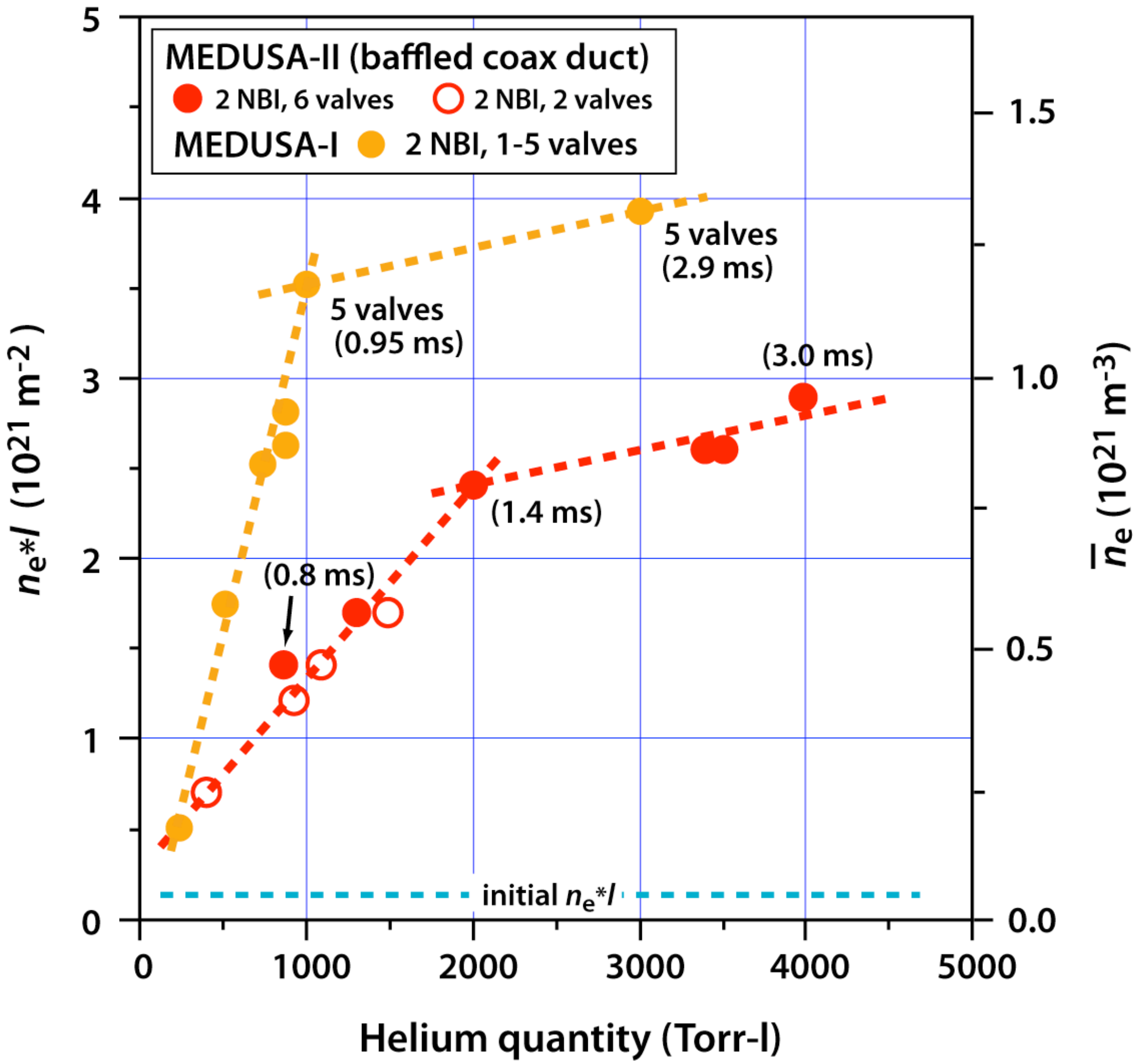
Lehnen *et al* (2010 IAEA)

- **In all examples, $n/n_{RB} << 1$**
- **Does t_{CQ}/S continue to decrease with increasing quantity?**
- **Can ITER allow repeated very-fast CQs?**

DM Challenge #3: High-quantity short-pulse injection required

- **DIII-D MGI: n_e increment decreases for $t_{open} \geq \Delta t_{TCO}$**
- **Same 'rollover' behavior for direct (MEDUSA-I) and baffled (MEDUSA-II) configurations**

⇒ Assimilation of gas added after TCO (W_{th}) lower



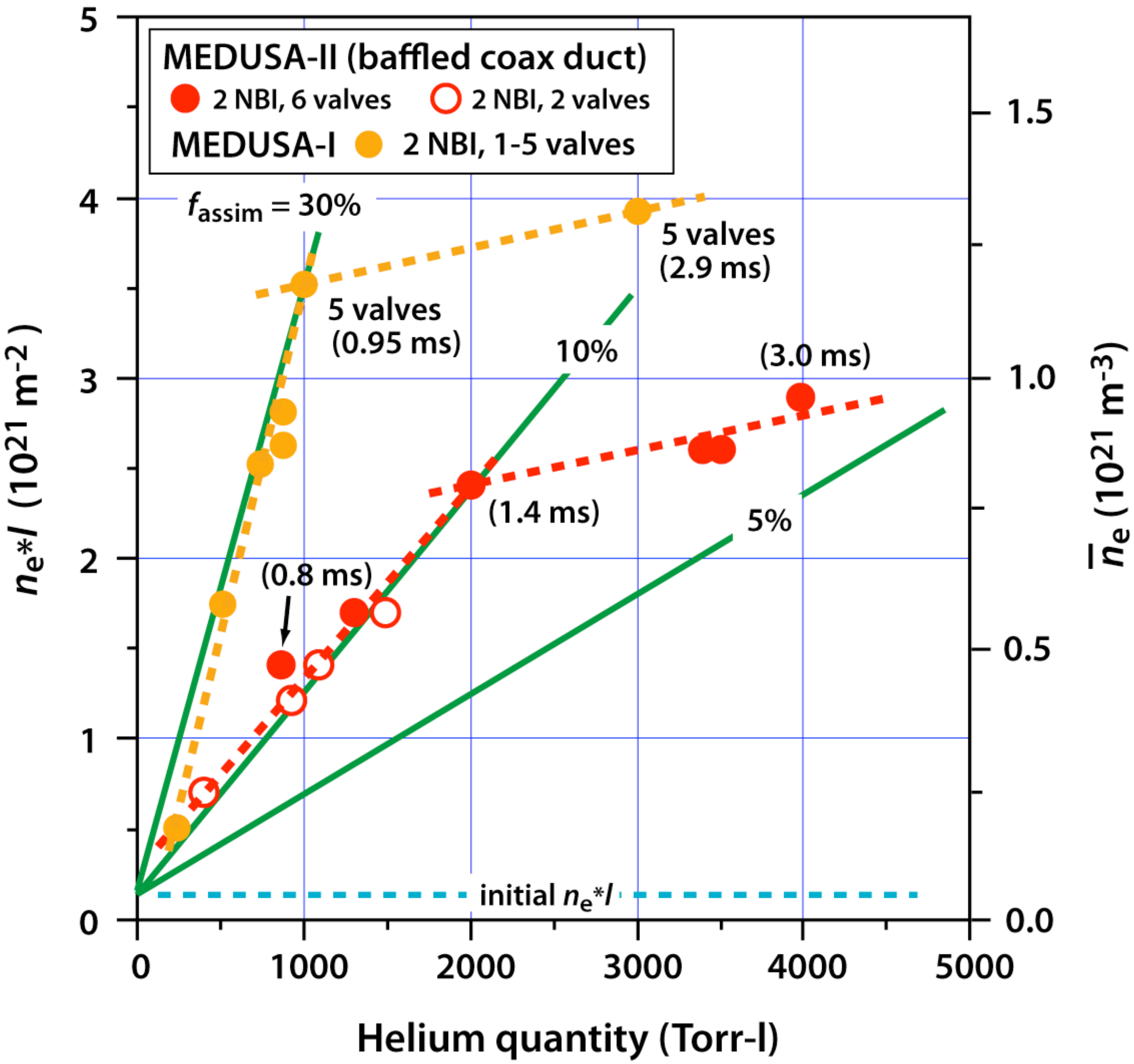
See Commaux *et al* (2010 IAEA, submitted to NF)

DM Challenge #3: High-quantity, short-pulse injection required

- DIII-D MGI: n_e increment decreases for $t_{open} \geq \Delta t_{TCO}$
- Same 'rollover' behavior for direct (MEDUSA-I) and baffled (MEDUSA-II) configurations

⇒ **Assimilation of gas added after TCO ($\dot{W}_{th}$) lower**

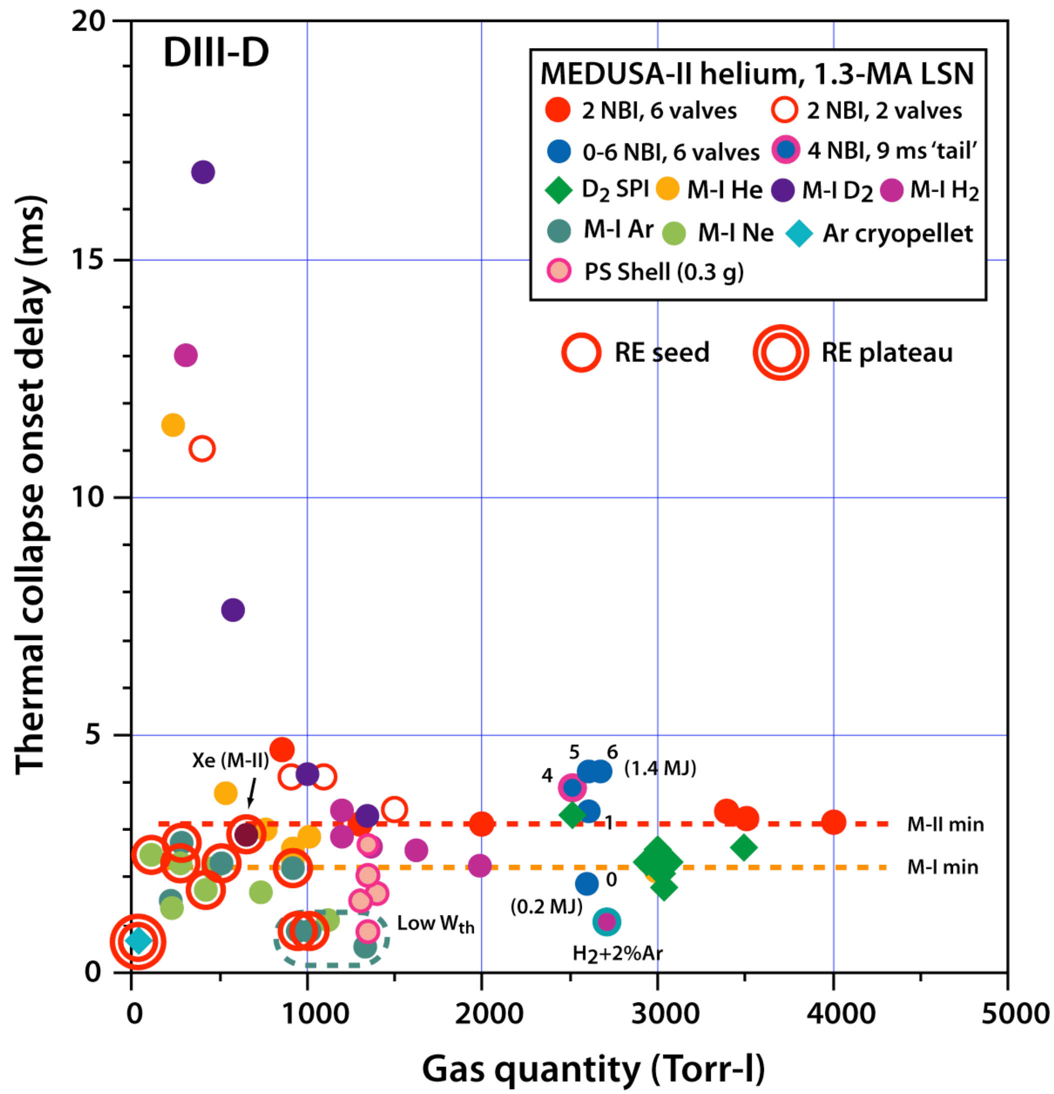
- **3-x assimilation for M-I (remember Challenge #1)**
- **2-x higher neon assim and record n_e/n_{RB} with close-coupled AUG in-vessel valve (Pautasso *et al* 2008 and 2010 IAEA)**



See Commaux *et al* (2010 IAEA, submitted to NF)

DM Challenge #4: Avoid RE seed generation and/or avalanche

- **DIII-D high-Z MGI yields ‘trace’ RE seeds**
- **Small Ne or Ar cryopellets yield seed + sustained plateau (from avalanche)**
- **TEXTOR and JET also observe major REs with high-Z MGI**
- **NIMROD MHD modeling (Izzo, 2010 IAEA) suggests initial seed losses decrease with increasing plasma size; surfaces reheal after TC**
- **Minute residual seed in ITER → 12 MA RE…**
- **unless $n_e \geq n_{RB}$ throughout I_p decay ($\leq$ ~50% n_{RB} NG)**



Wesley *et al* (2009 IEA Workshop)

Summary re ITER disruption mitigation challenges

- Gas exhaust and processing limits impose major DM constraints; appear to preclude low-Z options
- Massive short-pulse gas (mass) injection needed (~ 1 kg)
- Close coupling of gas 'jet' to plasma essential to achieve good assimilation; pellet stream or liquid jet may be alternatives
- Important to minimize activation and flight-time delays
- High-Z or mixed RS options likely to generate significant REs
- All options generate 'very fast' current decays
- Few/difficult options for 'ex-post-facto' RE mitigation

⇒ None of the DM methods proposed for ITER ($G_{RE} \approx 10^{16}$) have yet been shown to be capable of avoiding REs

⇒ Disruption avoidance looks to be increasingly critical …

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 more emphasis on developing prediction and avoidance
- **A broad portfolio** and parallel/redundant approaches to all three elements — **P, A and M** — are needed
- **Mitigation 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 P, A and 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**
- **M 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**
- DEMO-1 will likely have to 'bootstrap' its own P+A improvements (to PAM v.3)

⇒ DEMO concept(s) must be robust enough to support tests and improvements of PAM to 'commercial' levels