USBPO Disruption Task — Critical Issues and Research Needs for the ITER DMS

by
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"Research in Support of ITER"

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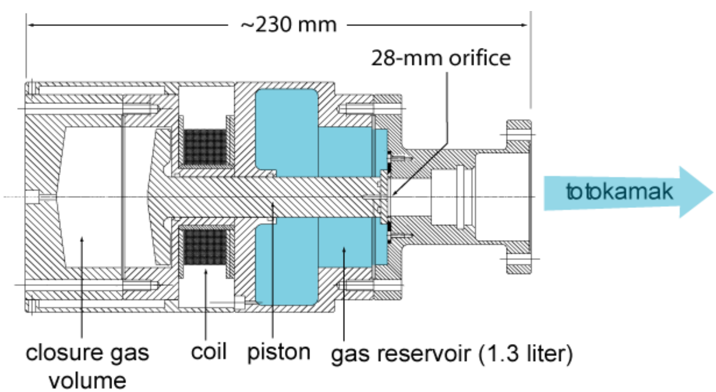
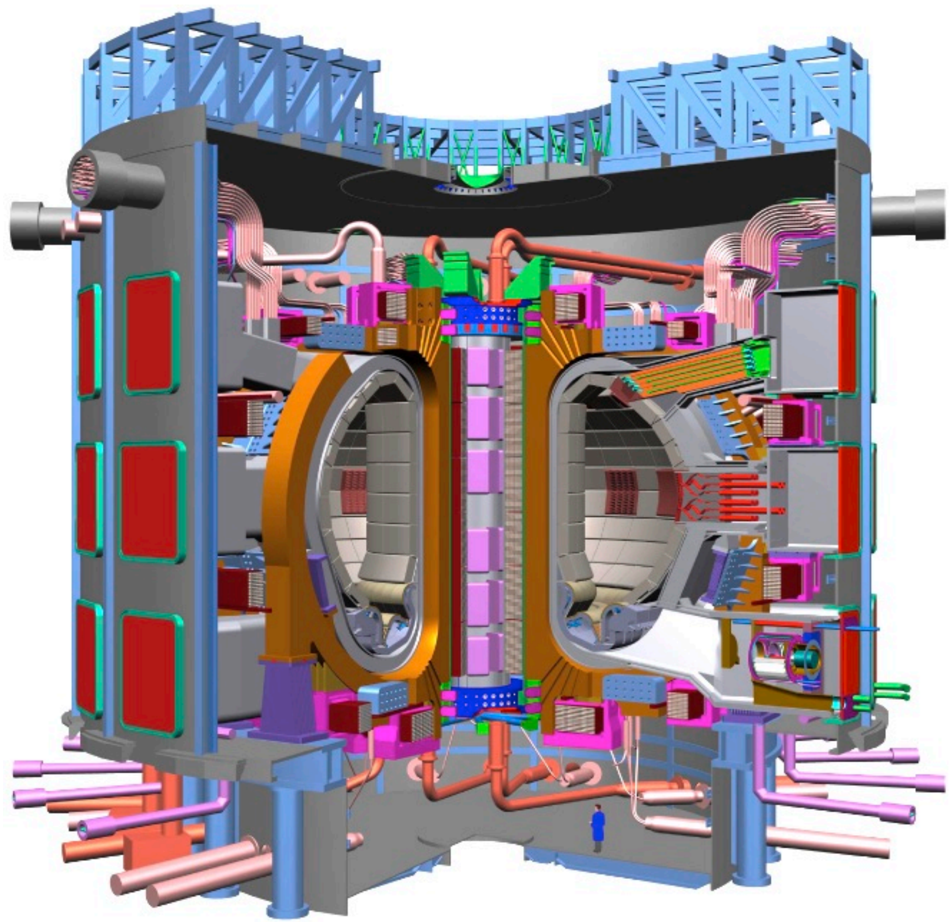


JET DMV30 MGI valve
Finken *et al*, NF51 (2011)



ITER (not to same scale)

Disclaimer: Personal opinions, not representative of positions of IO, USDOE, USIPO, USBPO, GA or DIII-D

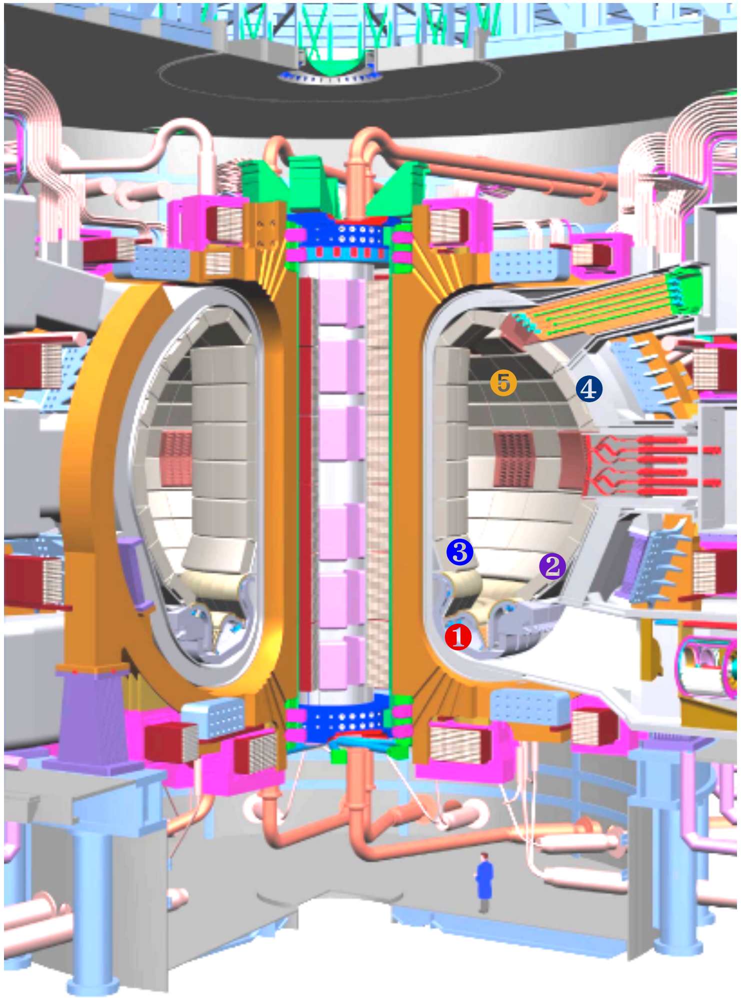
Effective Disruption + RE Mitigation are *Essential* for ITER

- **DMS has 5 critical functions:**
  ❶ limit W_{th} deposit on divertor and first wall surfaces
  ❷ prevent 'hot plasma VDEs' and FW energy deposit
  ❸ limit halo current forces in blanket/shield modules
  ❹ control eddy current forces in B/S modules
  ❺ control and dissipate runaway electron currents

- **MGI (massive gas injection) identified as primary approach; MPI (massive pellet injection) as alternate**

- **ITER current and energy introduce R&D needs**
  - **Control** thermal and magnetic energy radiation
  - **Avoid** and **mitigate** runaway electrons
  - **Provide adaptive control**, with high reliability and nuclear compatibility

- **USIPO to provide DMS: physics + technology R&D, experiments and modeling critical for meeting 2016 FDR milestone**



Three Critical Issues Constrain the Disruption Mitigation Strategy Proposed for ITER

1) **Structural capabilities** of the blanket-shield module attachments + VDE avoidance mandate control of the current decay rate

⇒ 50-150 ms I_p decay; ≤ 35 ms decay "not allowable"

2) **Rapid radiation** of 350 MJ of plasma thermal energy can melt the surface of the beryllium first wall

⇒ t_{rad} > 0.8 ms*(PF)^2

3) **MGI or MPI strategies** that satisfy requirements 1) and 2) likely to produce high levels of after-mitigation *runaway electron current*

⇒ Must have *independent* RE mitigation capability

Multiple challenges, constraints and interactions for DMS concept selection and deployment

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168-12/JCW/rs

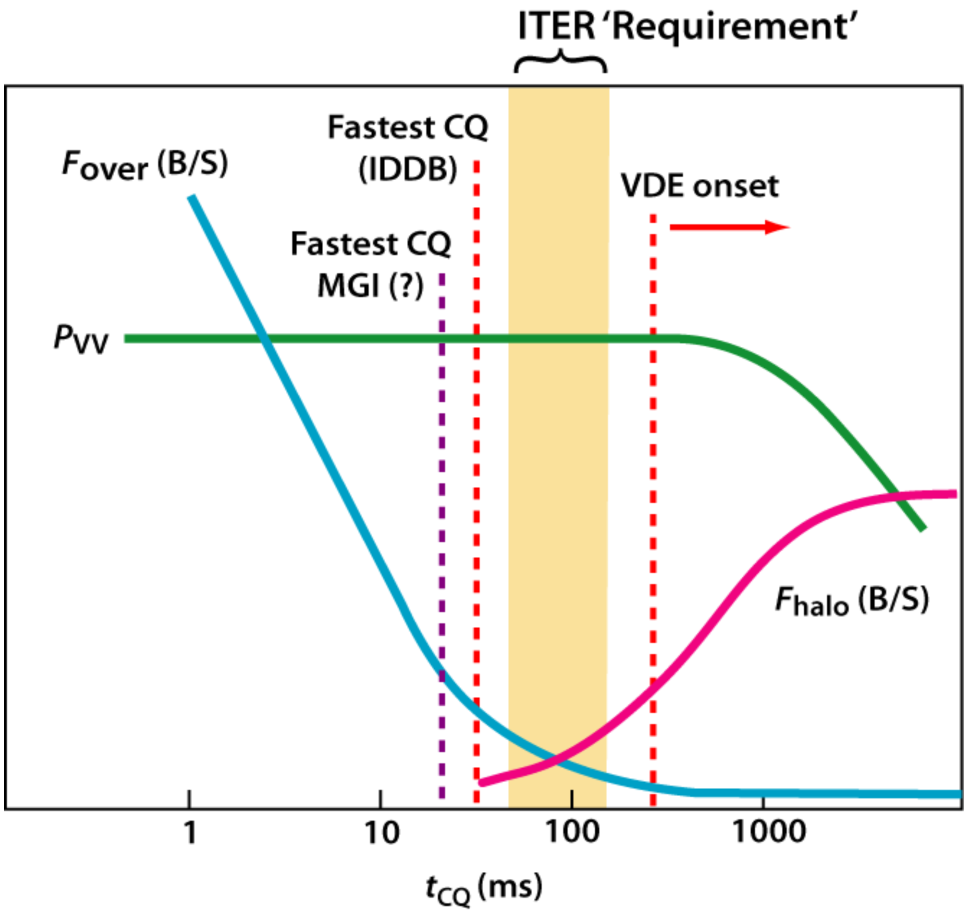
Narrow Range of Current Quench Time (t_{CQ}) is Allowed

- F_{over}(B/S) ∝ dI_p/dt (actually dB_p/dt)
- F_{halo}(B/S) ∝ ~(dI_p/dt)$^{-1}$ (from VDE)
- P_{VV} independent of dI_p/dt

  ⇒ $50 \leq t_{CQ} \leq 150$ ms

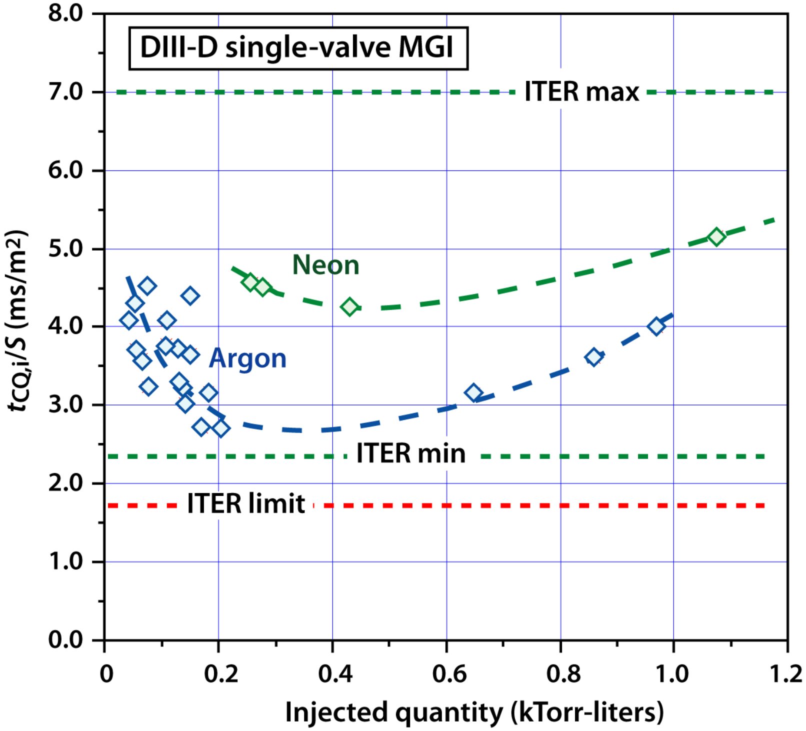
- "Natural" disruptions (with Be) → $t_{CQ} \geq 150$ ms, with major vertical instability + halo currents
- Number of ≤ 35-ms CQs = "a few" (lifetime)

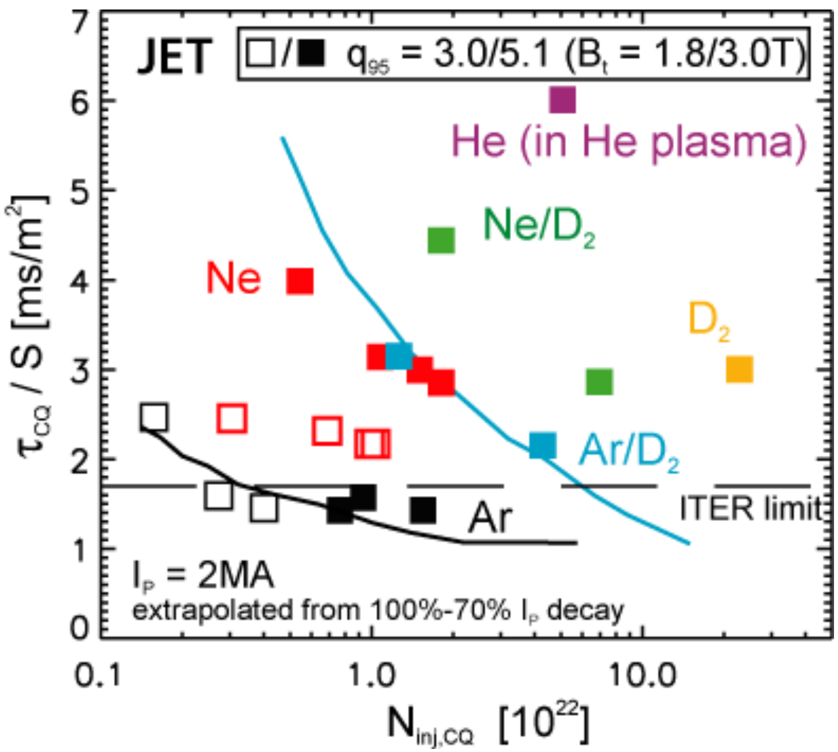
  B/S attachment fatigue risk!



- Too-fast or too-slow disruptions + excessive MGI/MPI *"shall not occur"*

High-Z MGI Results Demonstrate CQ "Control" Success, Albeit with Residual Variance + Target Sensitivity





S = poloidal cross-section area; $j_p = I_p/S$

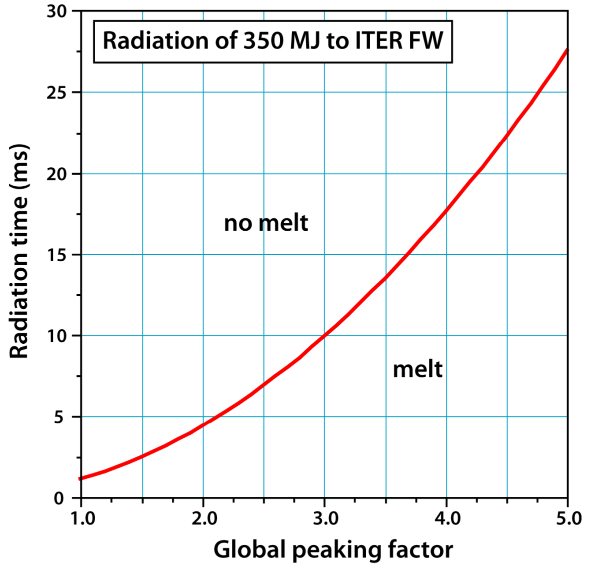
- **ITER: Will MGI/MPI that satisfies TE mitigation requirements also meet CQ control requirement?**

First Wall Must Accommodate 350 MJ Thermal Energy + 700 MJ Magnetic Energy without Melting

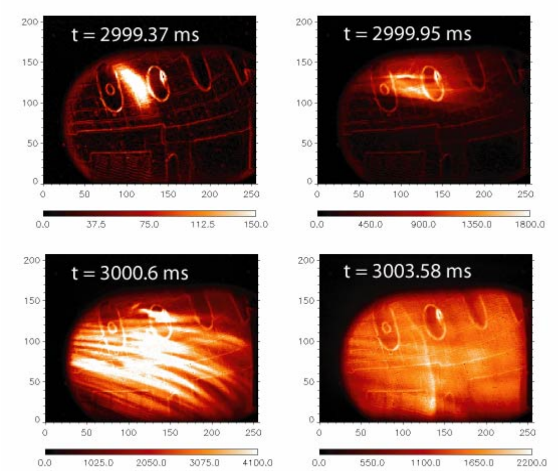
- $W_{th}/A_{FW} \cong 0.5\ MJ/m^2$ (uniform)
- For 'square' $P_{rad}(t)$, Be melt at ~20 MJ $m^{-2}\ s^{-0.5}$

  $\Rightarrow\ t_{rad} > \cong 0.8\ ms * (PF)^2$
- Experiment: W_{th} radiation peaking factors for MGI

  $1.1 \le PF \le 5$ (poloidal + toroidal)
- Impurity plume and radiation source dynamics ⇒ need for 3D+*t* diagnosis
- NIMROD modeling (Izzo, PI2.00003) suggests MHD may set irreducible peaking factor
- C-Mod 2-valve expts (Granetz, UO7.00002) beginning to provide validating data



DIII-D MGI imaging



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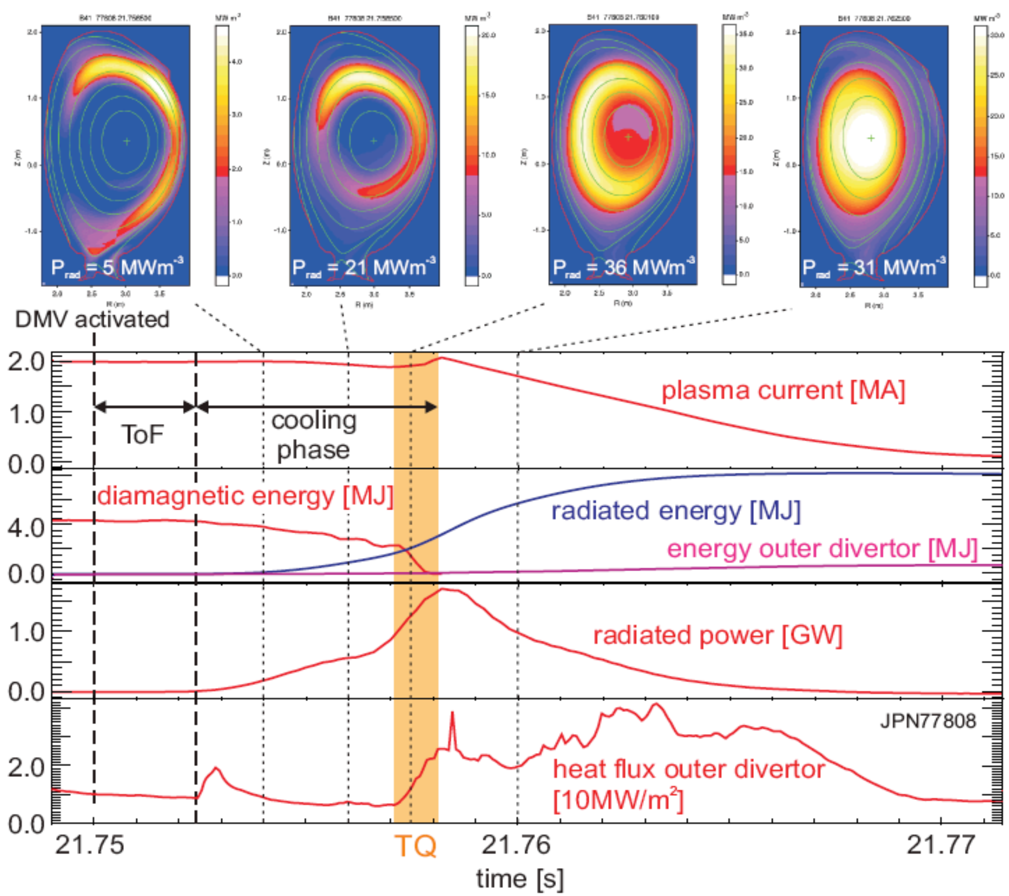
MGI Experiments Show Multiple Time Scales and Control Challenges for Thermal and Magnetic Energy Radiation

- 1-ms TE radiation pulse from "MHD mixing" of edge-deposited impurities into core
- Preceded by 5-ms "cooling phase" radiation; followed by 10-ms CQ radiation
- Mixing onset delay decreases with increasing injection, but duration doesn't change much
- **ITER: Can we "control" TQ onset, radiation duration + uniformity?**
- For FDR, we need a validated model for MHD mixing, t_{rad} and PF(t), for both W_{th} and W_{mag}

JET: data from M. Lehnen *et al*, 2010 IAEA



ITER RE Avoidance and Mitigation Strategies are Based on the Same Connor-Hastie Critical Field/Density Theory

- Runaway growth rate, γ_I, is given by

$$\frac{1}{I_{RE}}\frac{\partial I_{RE}}{\partial t} = \frac{e}{mc\ln\Lambda}\sqrt{\frac{\pi\gamma_{NC}}{3(Z+5)}}\,(E-E_c)$$

where

$$E_c = \frac{4\pi e^3 n_e}{mc^2}\ln\Lambda \cong 0.12 n_{e,20}\ [\mathrm{V/m}]$$

is the Connor-Hastie critical field (drag = eE_c at ~1 MeV)

- For DIII-D, ITER, etc., $\gamma_{NC} \cong 0.45$, hence

$$\gamma_I(\mathrm{s}^{-1}) = 164/\ln\Lambda\,(E-E_c) \cong 8\,\Delta E\ [\mathrm{V/m}]$$

- Strictly valid only for $\Delta E \geq 0$ (growth)
- C-H/E_{crit} *theory* not yet precisely tested; on-going experimental investigations

ITER RE Strategies Compared

	Avoidance	Mitigation
When:	CQ start	RE start
E(V/m)	~20	~0.5
$n_{e,20}$ (RB)	~200	~5
Species	D_2	Ne or Ar
Q (kPa-m^3)	~30	~5
m (g)	~50	~5-9
Delivery:	SPI, RDI	MGI
Initiation:	before TQ	at/after CQ

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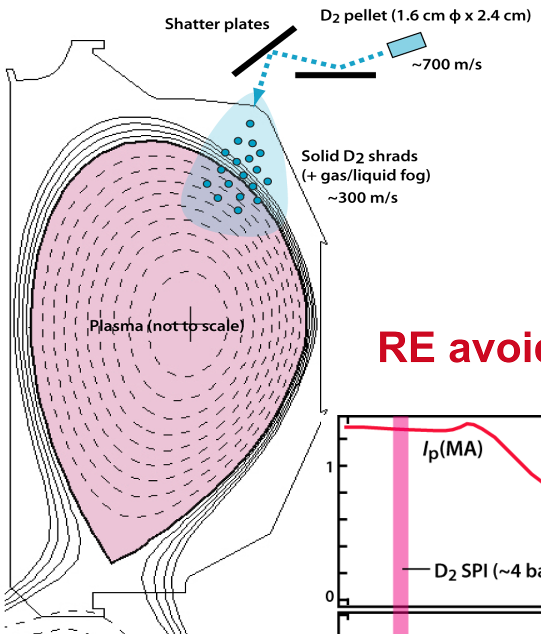
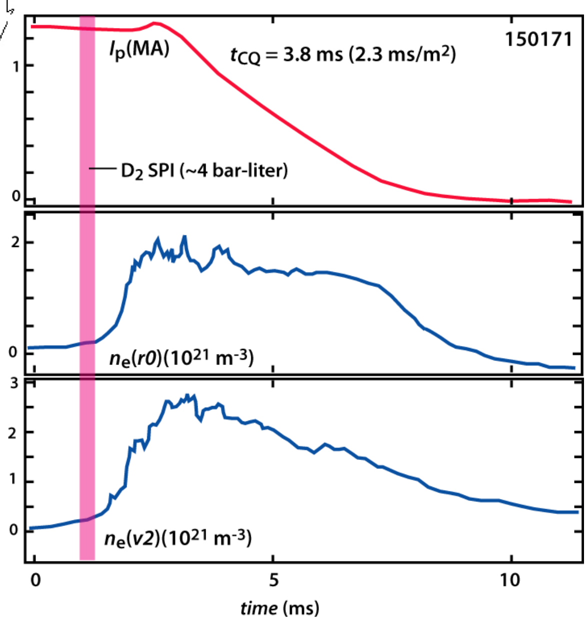
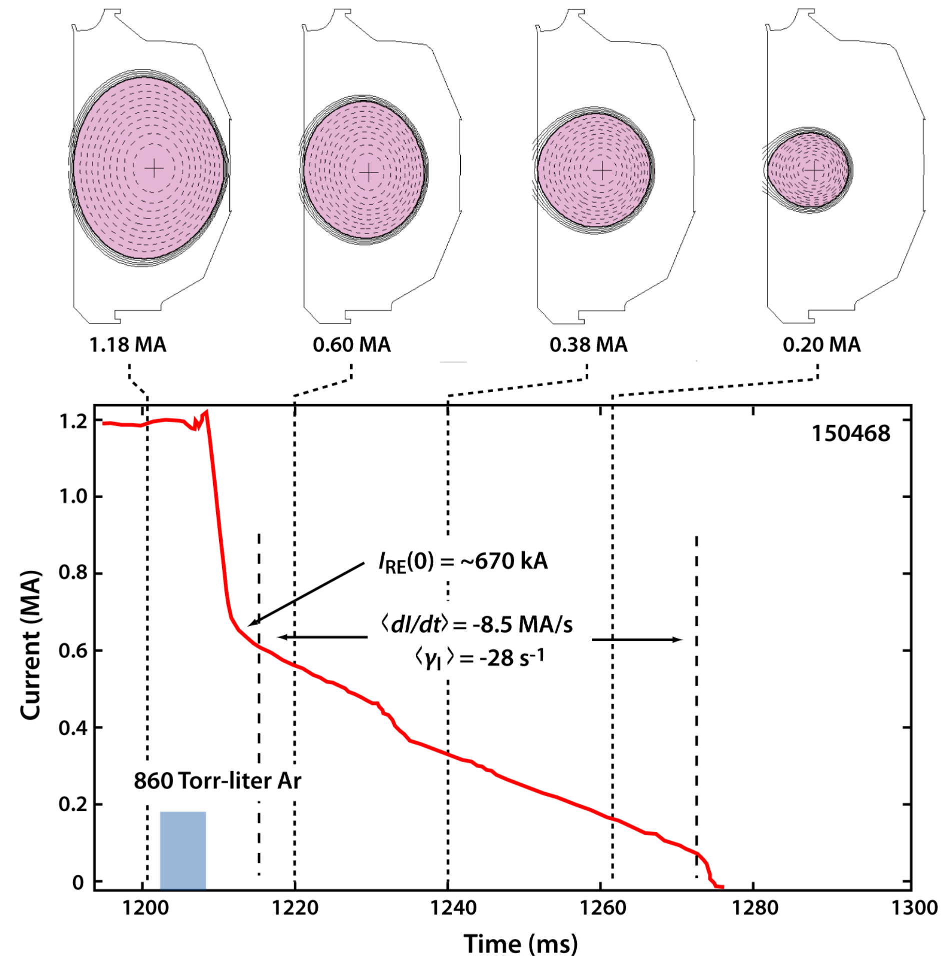
Tests of Candidate ITER RE Avoidance and Mitigation Strategies and Technologies are in Progress



RE avoidance: D_2 SPI

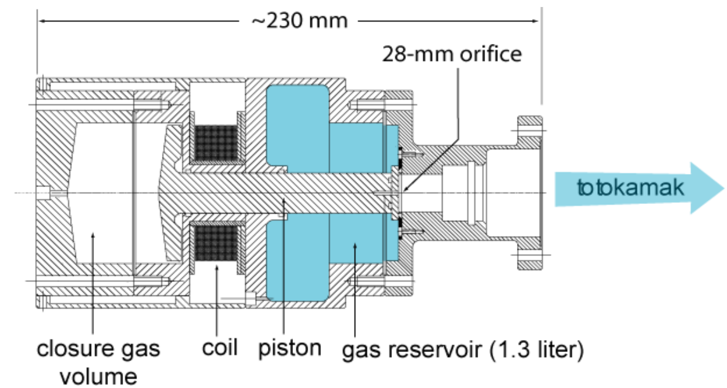


RE mitigation: Ar MGI



ITER-Scale Injection Technologies in Development; Needed *Now* to Advance Present-day n_{RB} and RDI Tests

- **"ITER-size" fast-valve developed for JET [Finken NF51 (2011)]; awaiting test**
- **Similar "hardened" valve(s) suitable for ITER TE+CQ mitigation or plateau RE MGI**
- **Active quantity and flow rate control required**
- **14-mm D_2 SPI (shatter pellet injection) system tested in D-III (~1/3 m_{RB})**
- **20-mm SPI proposed for ITER:**
  - ~1 neon pellet for TE+CQ mitigation
  - ~30 D_2 pellets for RB-density mitigation
  - ~ 3 neon pellets for plateau RE mitigation
- **20-mm RDI cartridges tested on Tore Supra**
- **Common issues: reliability + how to implement flexibility and "control" in ITER**



JET DMV30 fast valve

20-mm SPI pellet (same scale)

Tore Supra RDI cartridge (~ same scale)

An Issue-driven Framework Identifies R&D Needs for the DMS Final Design Review (2016)

	2012	2013	2014	2015	2016
1. TE mitigation and disposition Limit TE to DIV and FW Disposition of TE (control + diagnostics) Modelling + validation					1.1 TE mitigation? 1.2 TE disposition 1.3 Hand off to CQ
2. Current quench control Limit VDEs and associated EM loads CQ control and optimization					2.1 VDE control? 2.2 CQ control? 2.3 RE avoidance or generation?
3. RE avoidance Density for collisiona… Methods to realize/s… Integrated modeling… (eg., radiation opacity, pellets + superthermal)					…le? …bles? 3.3 Within exhaust allowables?
4. RE physics and dissipation Avalanche, plateau and end-phase physics (E_{crit}, other losses, limiter interaction) Diagnostics and Modeling (F-P, RE EQ, MHD,...) Rapid dissipation by MGI/MPI					4.1 EQ control possible? 4.2 Benign dissipation possible? 4.3 Sensitivity to I_{RE} level 4.4 Normal + off-normal sequences
5. Technology, reliability + control issues Access, environment and materials Present reliability and controllability RT control, system integration and 'flexibility'					5.1 Technologies available? 5.2 Needs for further R&D 5.3 Emerging concept(s)?

Coming soon on the BPO website!

DM solution

RE solution(s)

ITER DMS FDR
1. Concept selection(s)
2. Access and facility req'mnts
3. Open R&D and test req'mnts
   3.1 Physics
   3.2 Technology
4. Fab and deployment plan
5. Commission + operations plan
6. Adequacy + risk assessment

- **Assimilation + radiation duration/symmetry/control with multi-valve MGI**
- **Achieving super-high densities via D_2 SPI and/or D_2 RDI**
- **RE + E_{crit} physics + rapid dissipation + "ITER-like" control**
- **Integrated model development, validation and application**

Time is Passing…

We are here (2012)

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DM solution (items 1–2)

RE solution(s) (items 3–4)

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- **US/BPO cannot cover all bases; need AUG, C-Mod, JET, TEXTOR, Tore Supra, ….**
- **Test articles and testing with ITER-like magnetic, PFC and impurity environments (non-carbon) with high avalanche gain are critical**
- **Opportunities (need!) for domestic + international collaboration and coordination**

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Please contribute!

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