Challenges and R&D needs for combined thermal and magnetic energy mitigation in ITER

Prepared and presented by

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Theory and Simulation of Disruptions
Princeton Plasma Physics Laboratory
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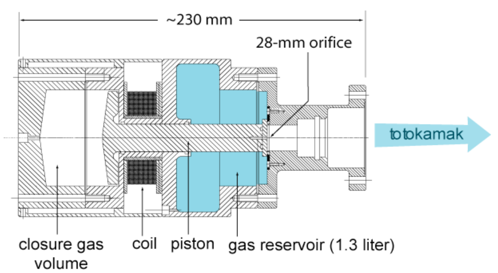
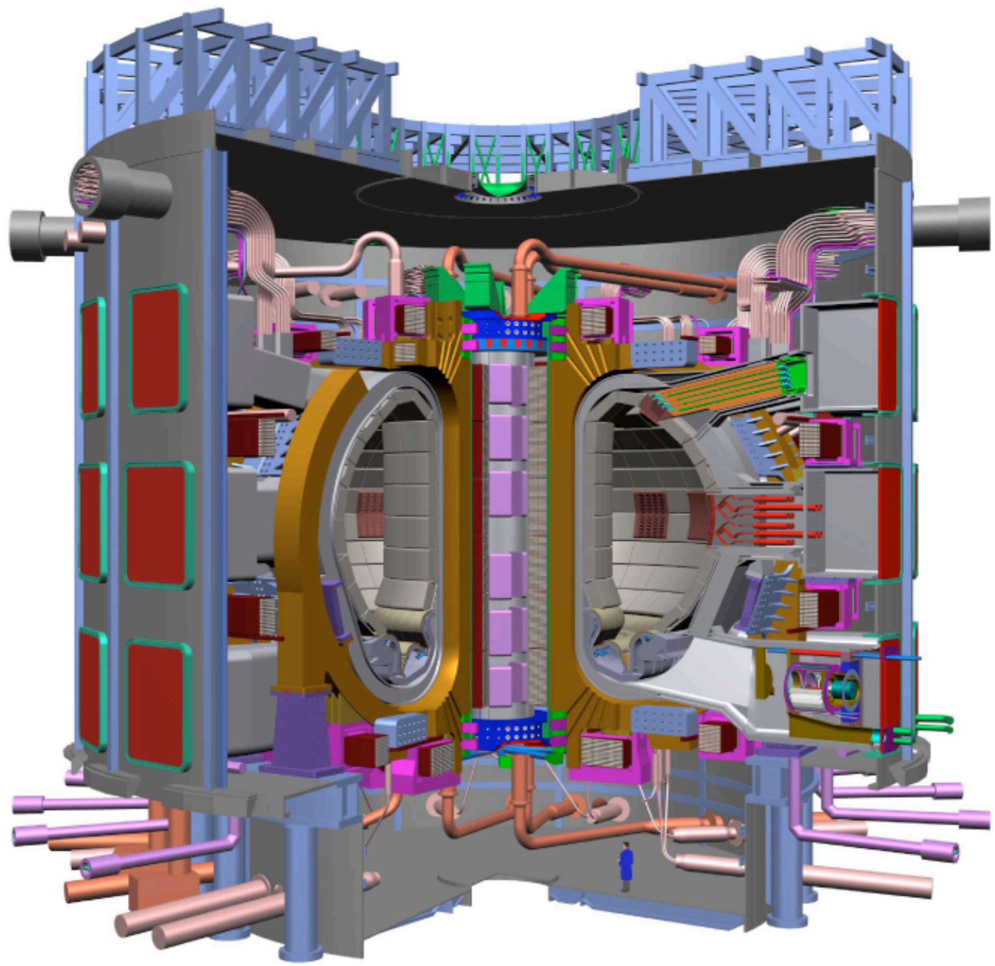


20-mm SPI pellet (same scale)

Tore Supra RDI cartridge (~ same scale)

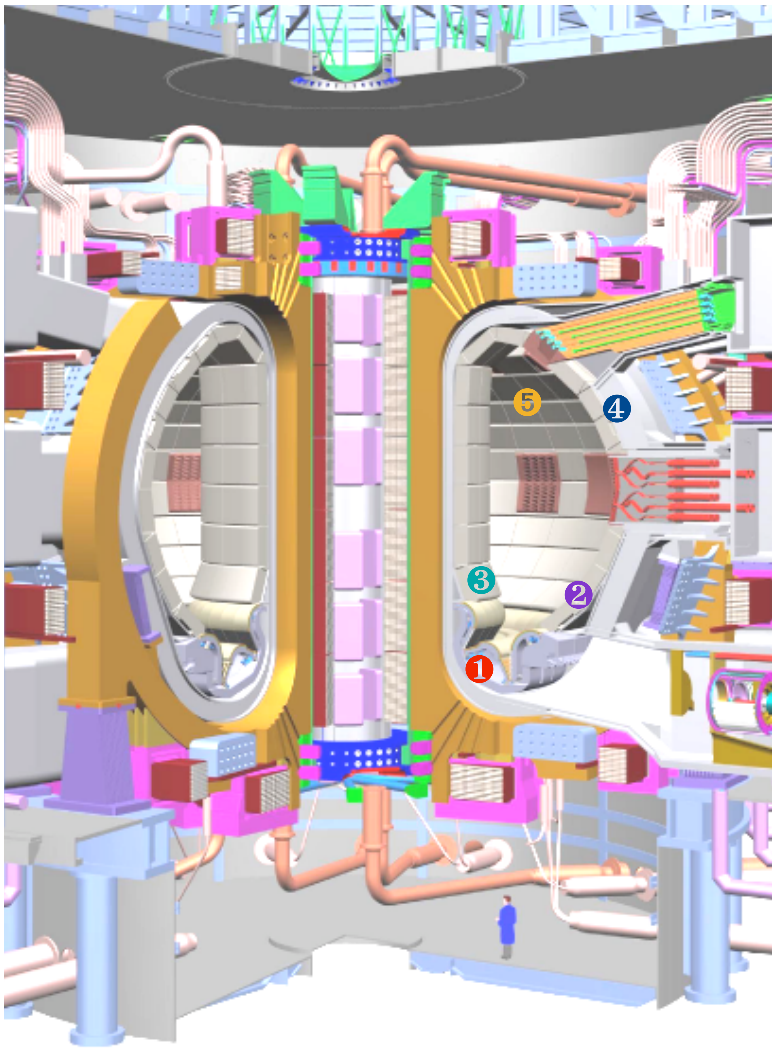


ITER (not to same scale)

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

⇒ $t_{rad} > 0.8\ \mathrm{ms}^*(PF)^2$

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

This talk: focus on combined thermal and magnetic energy mitigation (aka 'basic' disruption mitigation)

- **Energies:**
  - — W_{th} = 350 MJ (DT); = ~50-100 MJ (H_2 or He)
  - — W_{mag} = ~650 MJ (in-vessel, for 15 MA)
- **Three sequential requirements:**
  - — Protect the [tungsten!] divertor: $W_{div} \leq 30$ MJ (ideally <<)
  - — Deposit radiated energy (~1100 MJ) benignly (no Be melt)
  - — Ensure $50 \leq t_{CQ} \leq 150$ ms (limit B/S attachment loads)
- **DMS will comprise the primary 'defense' against disruption damage; must be safe, effective, reliable and controllable**
- **Hardware options: gas or mass injection (VG at end)**
- **What options will be able to meet requirements?**
- **What do we need to know to select and qualify DMS candidates?**

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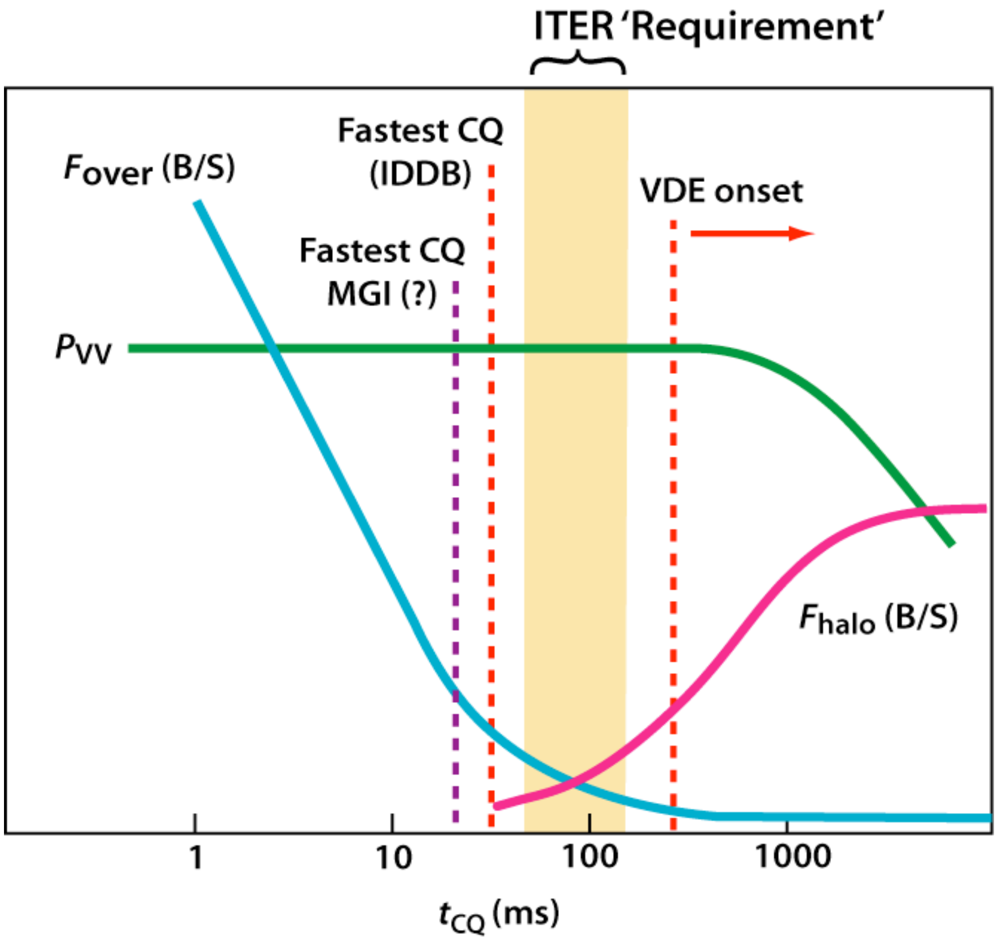
Narrow range of current quench time (t_{CQ}) is allowed

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

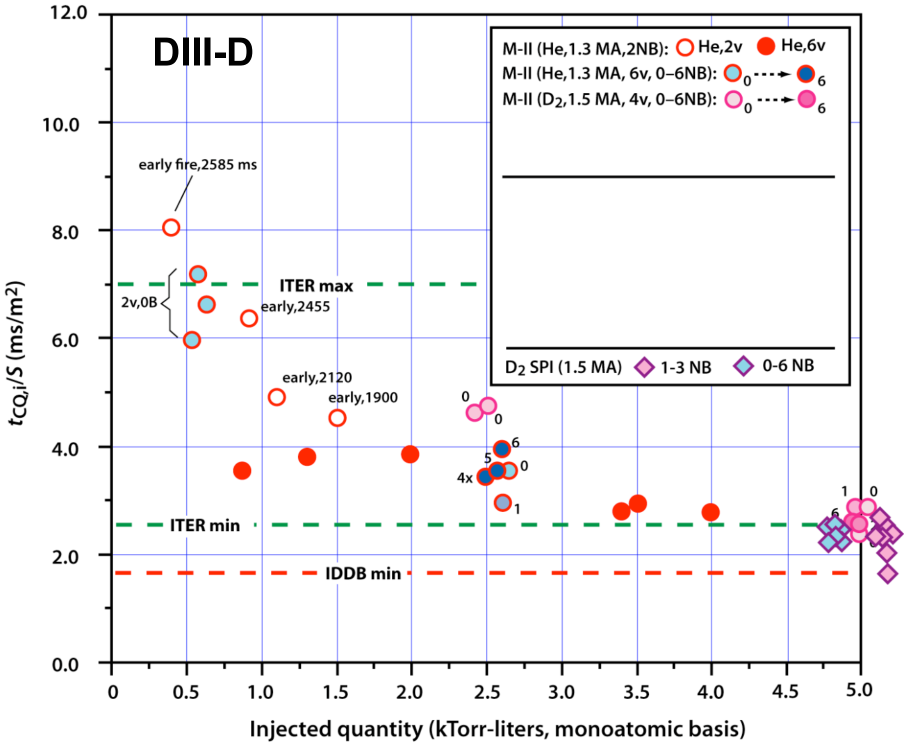
$\Rightarrow$ 50 $\leq t_{CQ} \leq$ 150 ms

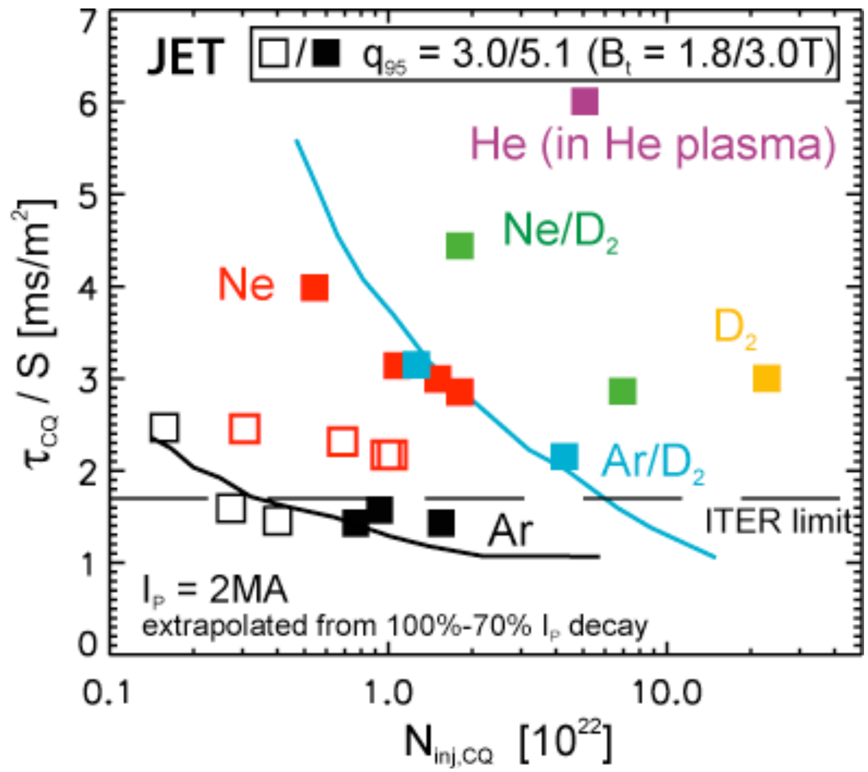
- ‘Natural’ disruptions (with Be) → $t_{CQ} \geq$ 150 ms, with major vertical instability + halo currents
- Number of ≤ 35-ms CQs = ‘a few’ (lifetime)
- CQ physics basis = t_{CQ}/S; set by [radiating] impurity content



$\Rightarrow$ Too-fast or too-slow disruptions and excessive or insufficient MGI/MPI “*shall not occur*”

MGI results demonstrate CQ ‘control’ success, albeit with residual variances + sensitivities to target attributes





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

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

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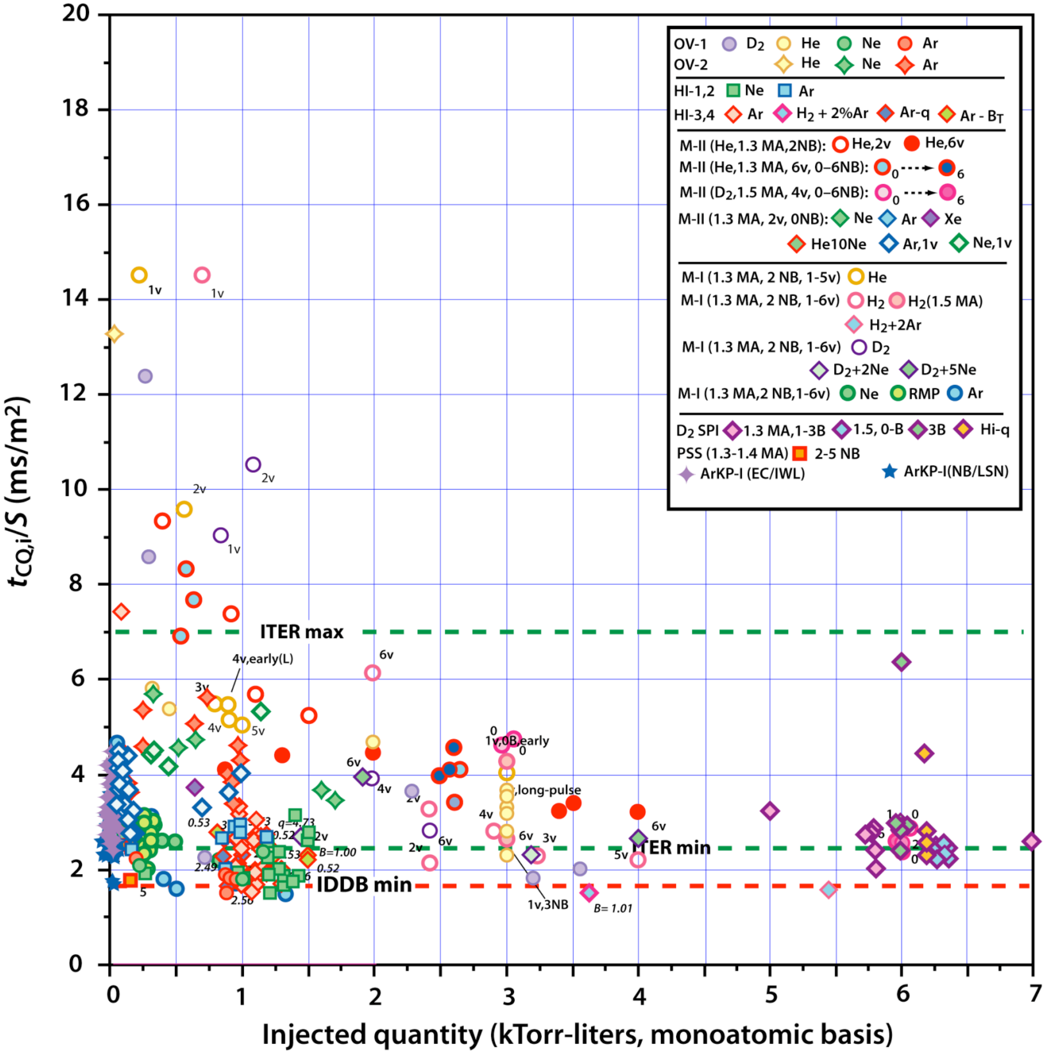
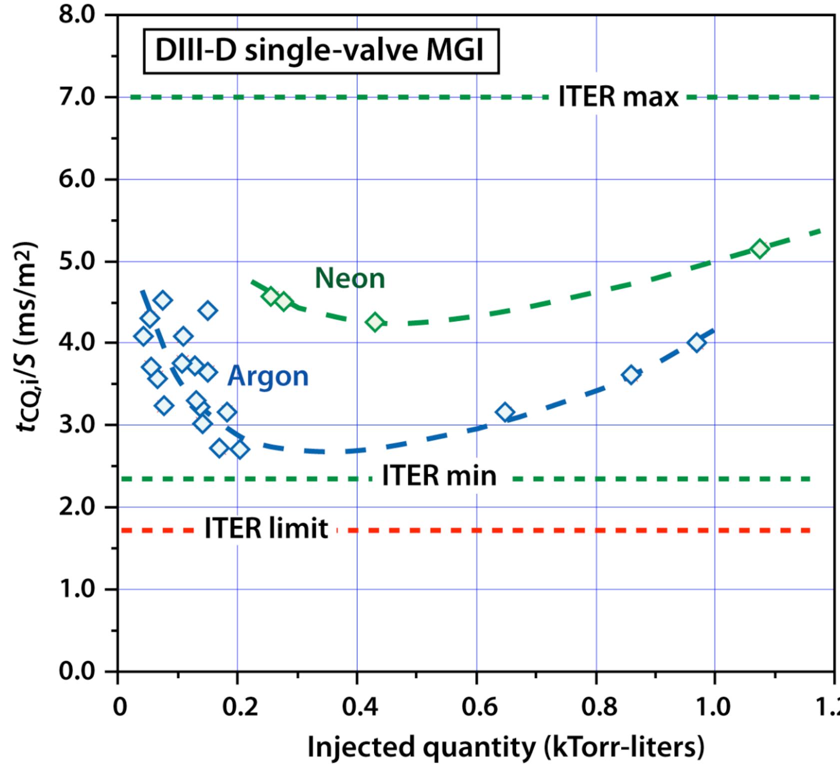
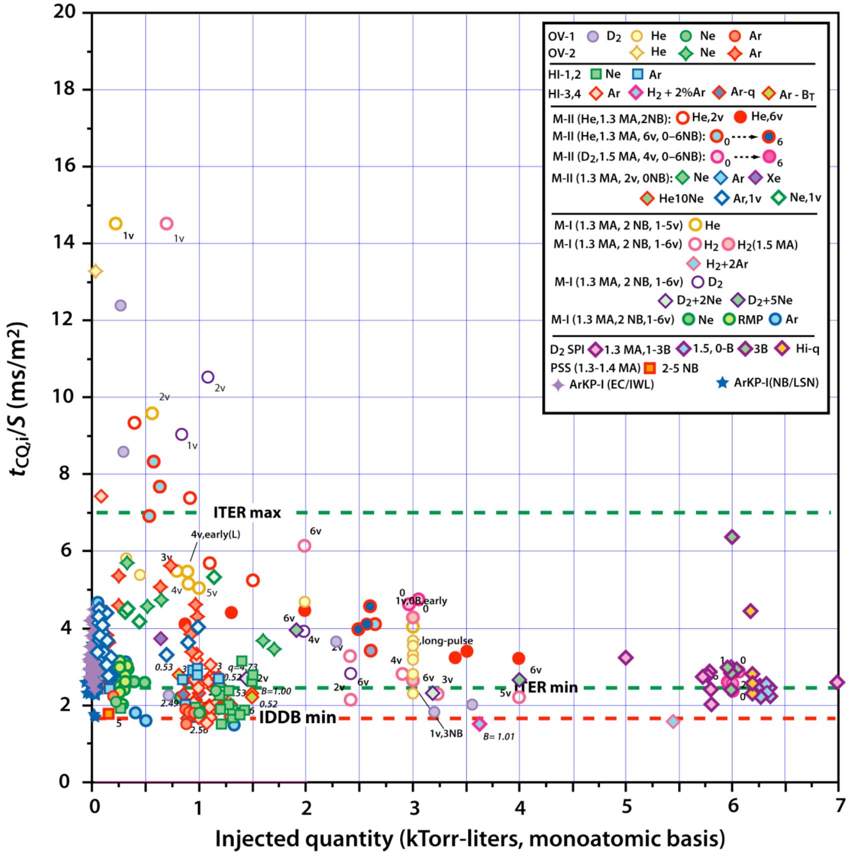
Most DIII-D CQ data near/below ITER minimum; recent 'ITER-like' low-Q examples show unexpected variances and Q scalings

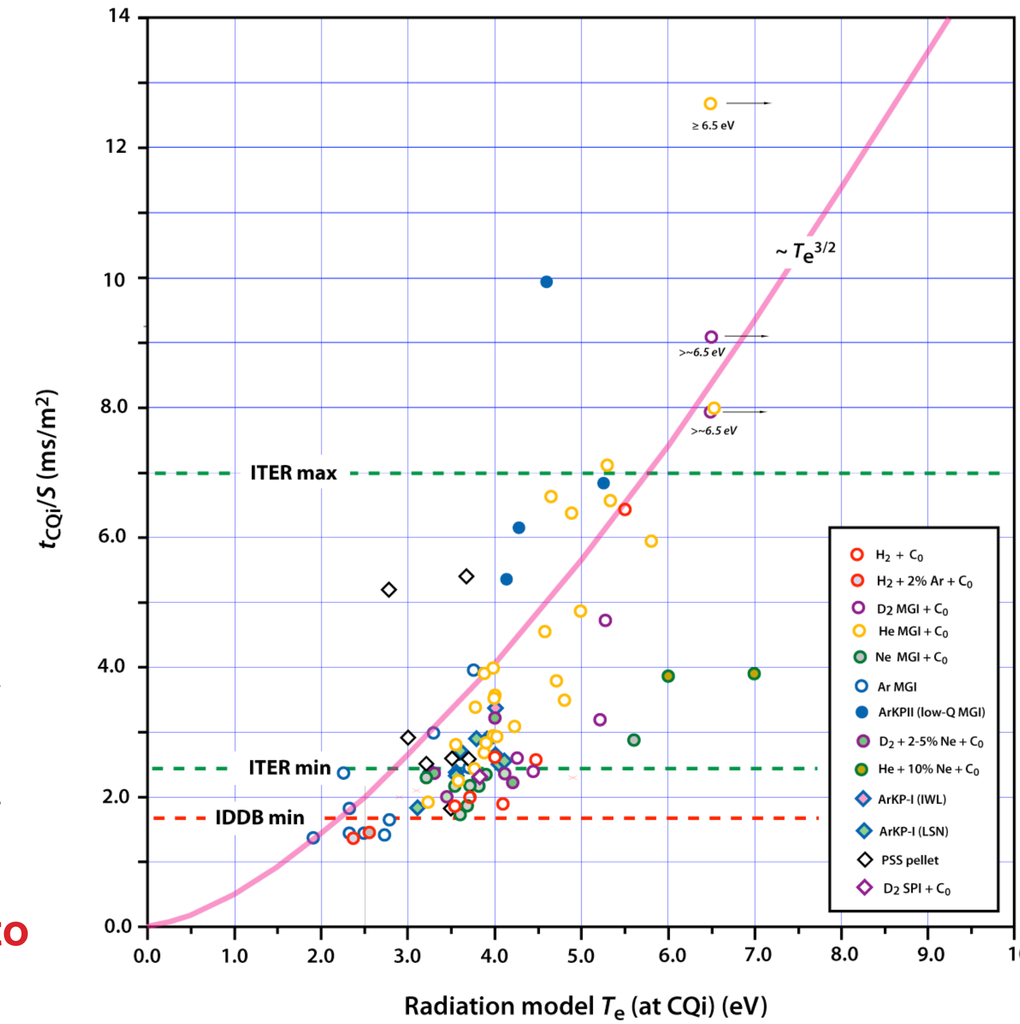




Variance and 'Q-reversal' may be due to MHD mixing (later VG)

DIII-D CQ data consistent with simple 0-D radiation model; native carbon dominates low-Z injection cases





Application of DIII-D low-Z experience to ITER (with Be FW) will require model

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‘ITER-like’ MGI or MPI for t_{CQ}/S ~5 ms/m² requires relatively small quantities of neon or argon

	DIII-D	JET	ITER
V(m³)	18	85	832
N(neon)	1.8e21	8.6e21	8.3e22
Q_{pellet}(Torr-liter) (@ 100% assimilation)	50 (0.06 g)	240 (0.30 g)	2400 (2.9 g)
Gas input @ 15% assimilation			
Q_{inj} (Torr-liter)	340	1620	15700
Q_{inj} (bar-liter)	0.45	2.13	20.6
Q_{inj} (kPa-m³)	0.045	0.21	2.06

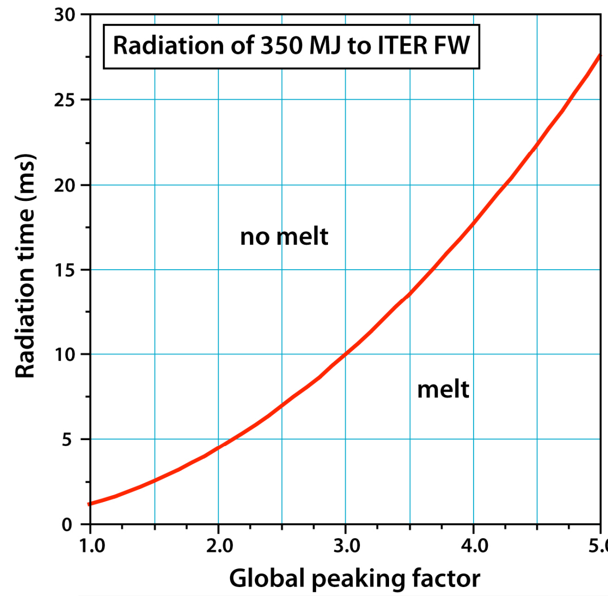
Argon quantity = ~1/3 neon quantity

ITER first wall must accommodate 350 MJ thermal energy + ~700 MJ magnetic energy

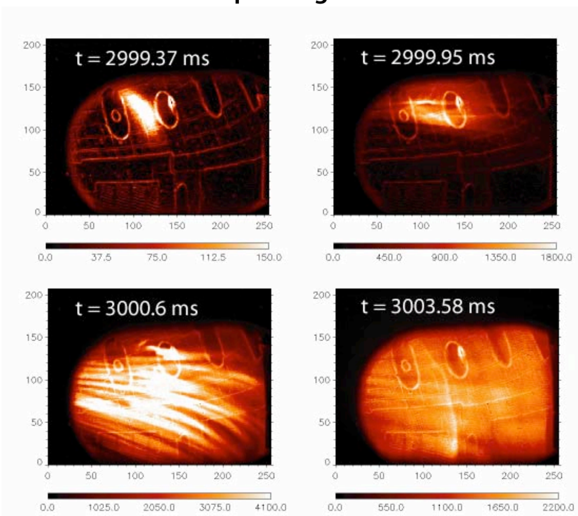
- $W_{th}/A_{FW} \cong 0.5$ MJ/m^2 (uniform)
- For 'square' $P_{rad}(t)$, Be melt at ~20 MJ m^{-2}s$^{-0.5}$

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

  1.1 ≤ PF ≤ 5 (poloidal + toroidal)
- Impurity plume and radiation source dynamics ⇒ need for 3D+*t* diagnosis
- NIMROD modeling [Izzo] suggests MHD may set irreducible toroidal peaking factor
- C-Mod 2-valve expts [Granetz et al] show toroidally-symmetric MGI does not yield toroidally symmetric TE radiation
- DIII-D 2-valve experiments coming; 1-valve MGI and pellet data suggest strong role of 'MHD mixing' in TE radiation attributes



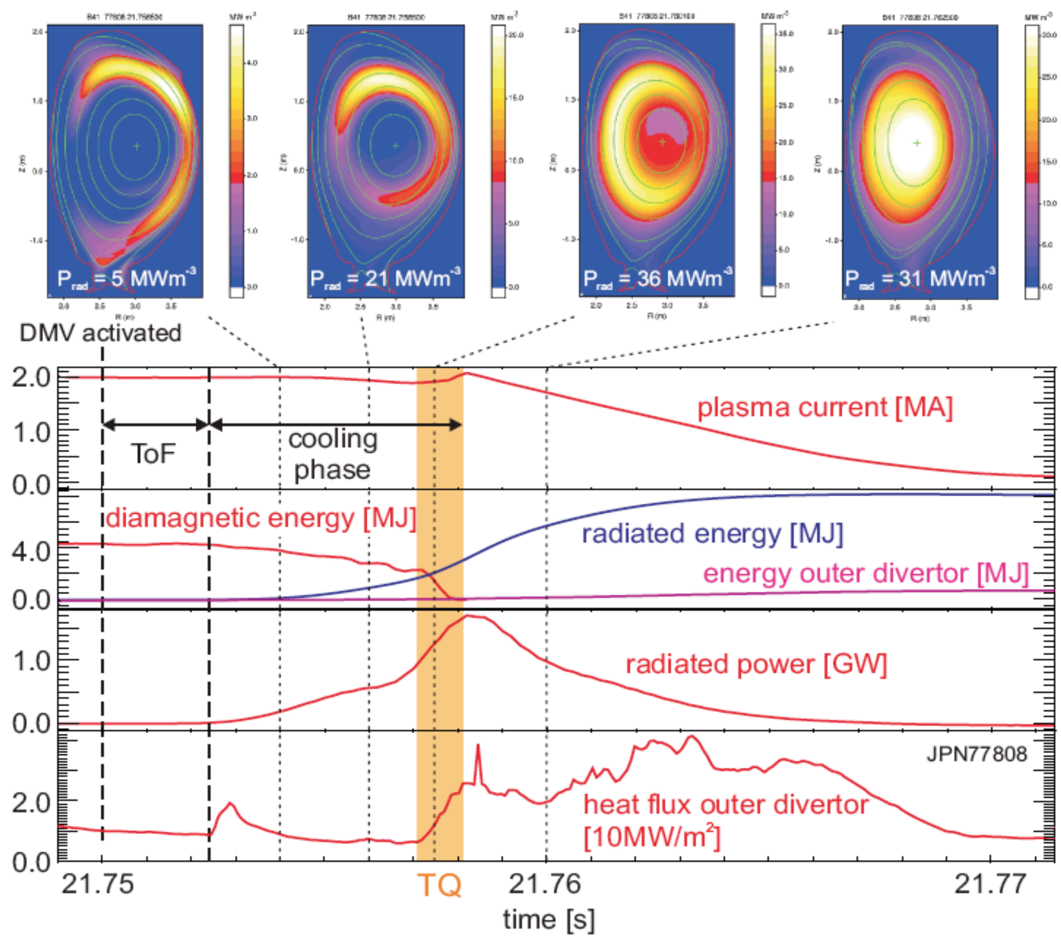
DIII-D MGI imaging



MGI experiments show multiple time scales and control challenges for thermal and magnetic energy radiation

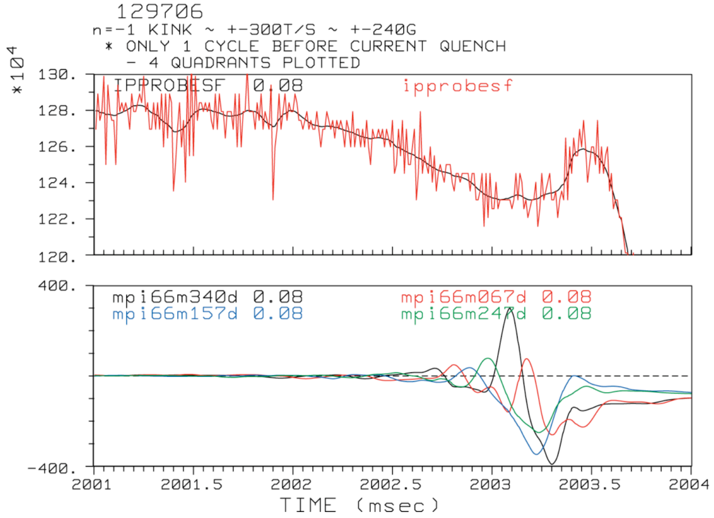
- JET: ~1-ms TE radiation pulse from 'MHD mixing' of edge-deposited impurities into core
- Preceded by 5-ms 'cooling phase' radiation; followed by 10-ms CQ radiation
- Mixing onset delay decreases with increasing injection, but duration doesn't change much
- ITER: Can we 'control' TQ onset, radiation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

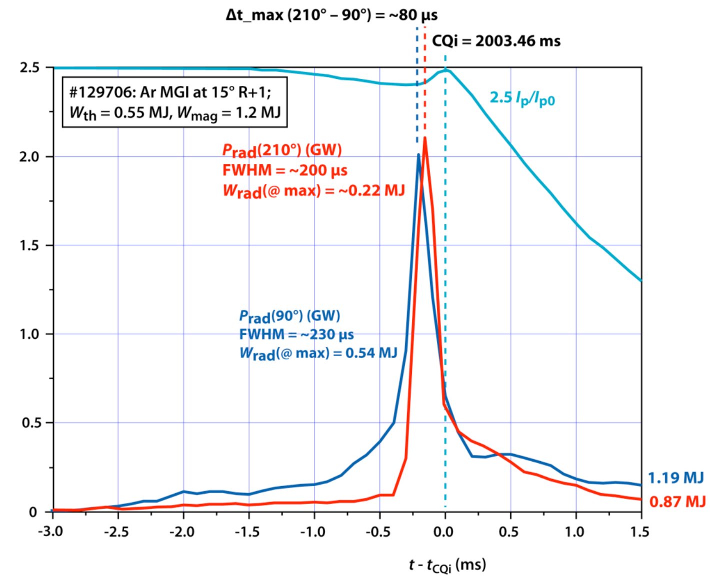
JET: data from M. Lehnen *et al*, 2010 IAEA



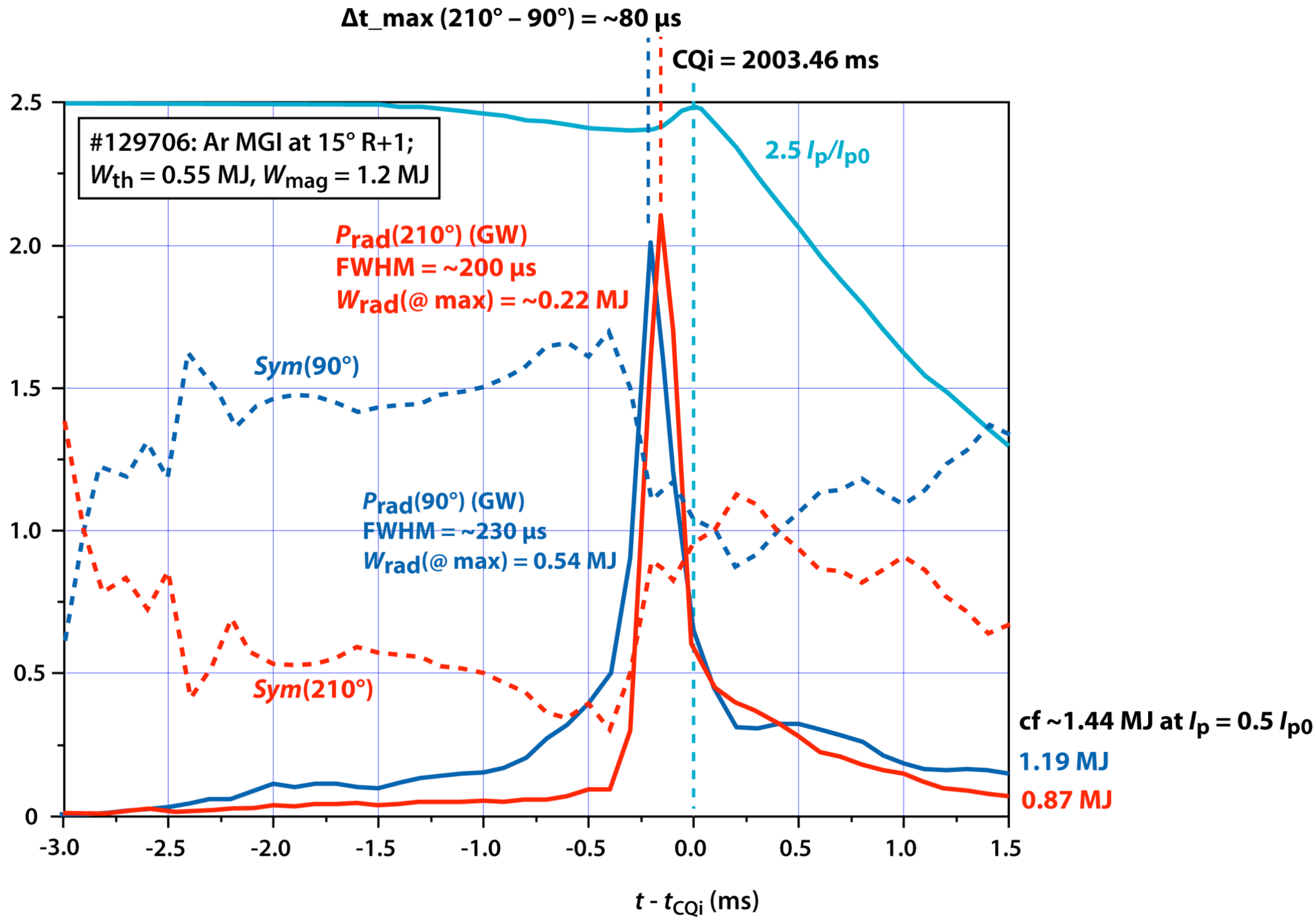
DIII-D MGI and pellet injection examples show ubiquitous presence of MHD mixing + correlation with TE radiation pulse

- **#129706, ArMGI shows peak radiation correlates with onset and decay of a short-lived n=1 kink instability (LaHaye)**
- **Similar 'MHD mixing' signatures seen in a variety of MGI, SPI and ArKP examples. Higher-frequency equivalents seen for both high-*q* and low-*q* disruptions**
- **Relevant to validation of models required to extrapolate radiation duration and symmetry to the ITER**
- **Forthcoming DIII-D MGI, SPI and killer pellet experiments + 3D magnetics can yield more definitive MHD data**
- **Future upgrades to DIII-D fast bolometry (DISRAD) systems needed for better quantification of rad symmetry effects**

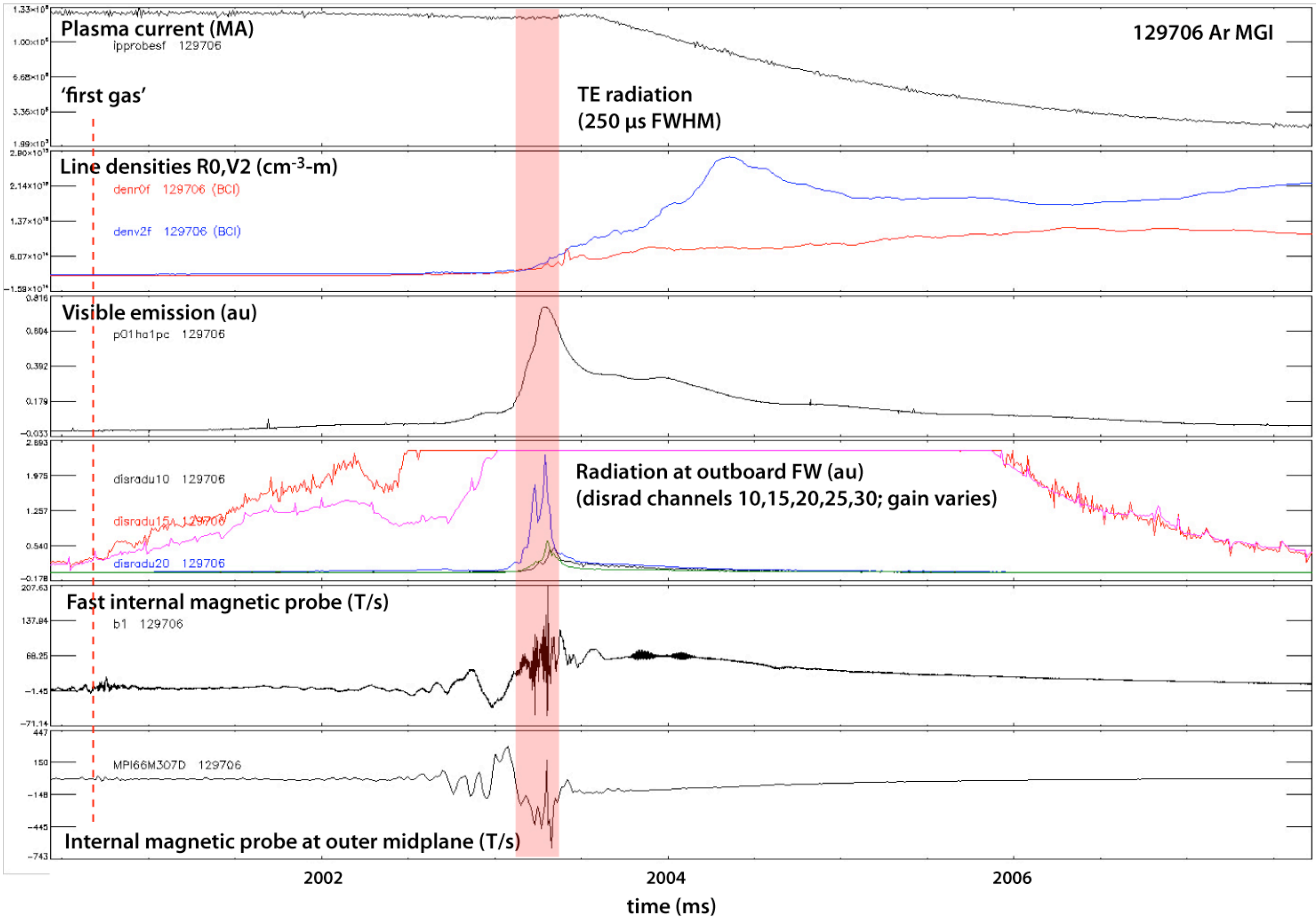




#129706 Ar MGI shows radiation asymmetries, ~250 μs FWHM, ~80 μs time offset of peak radiation (radiation data by Hollmann)



Mixing instability ‘features’ align with radiation peak; higher-frequency precursor + very-high-frequency burst at peak



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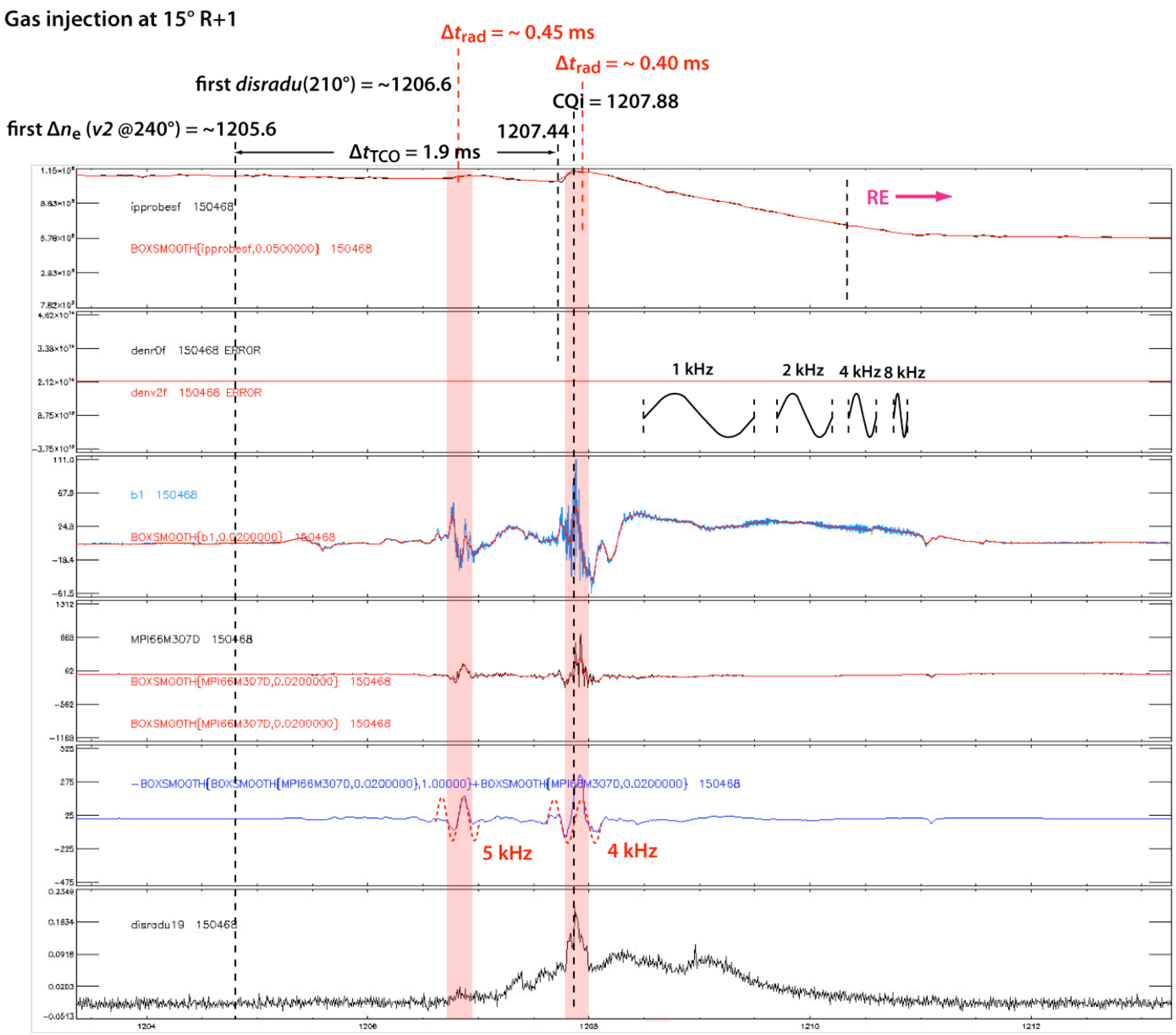
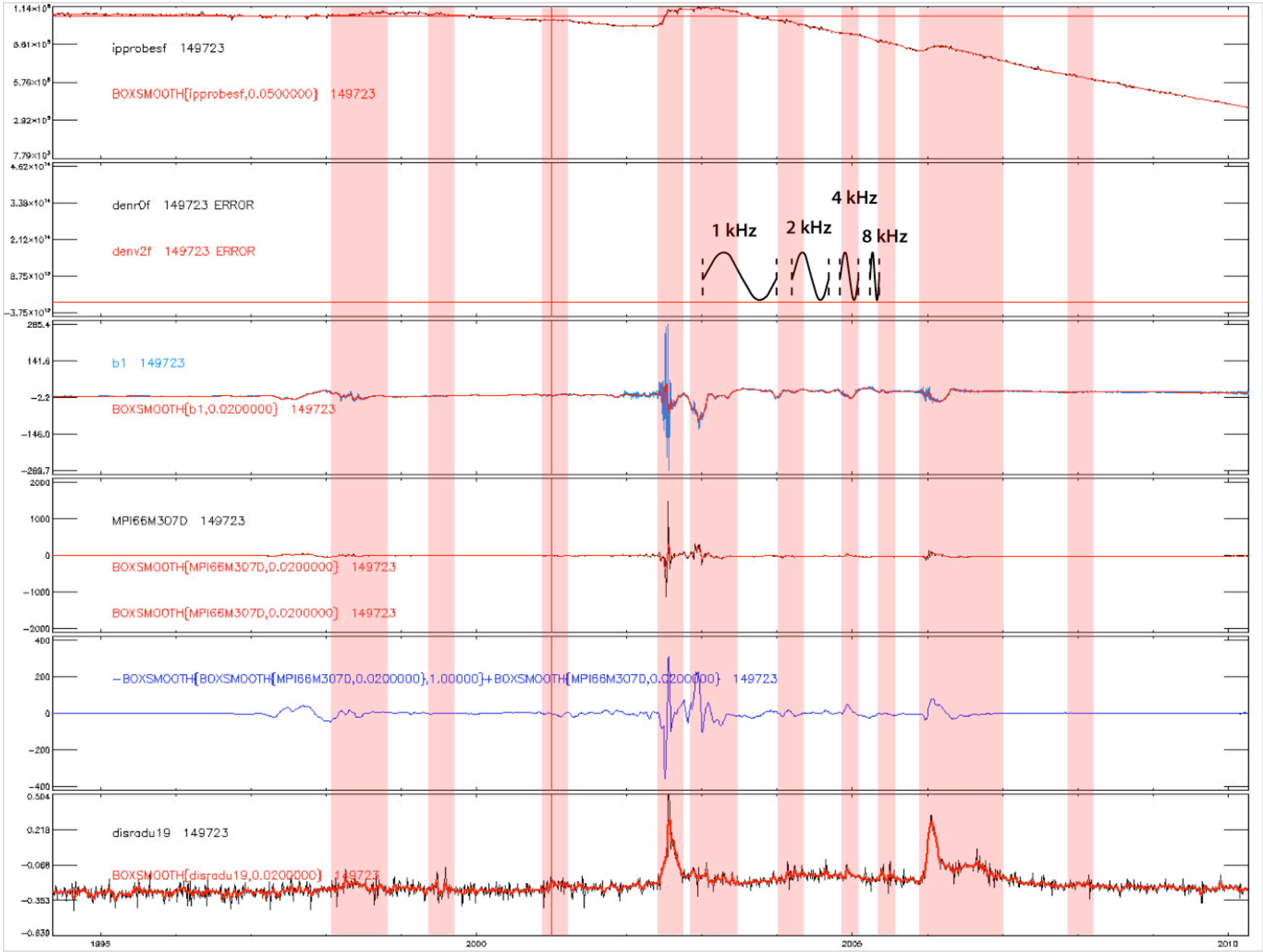
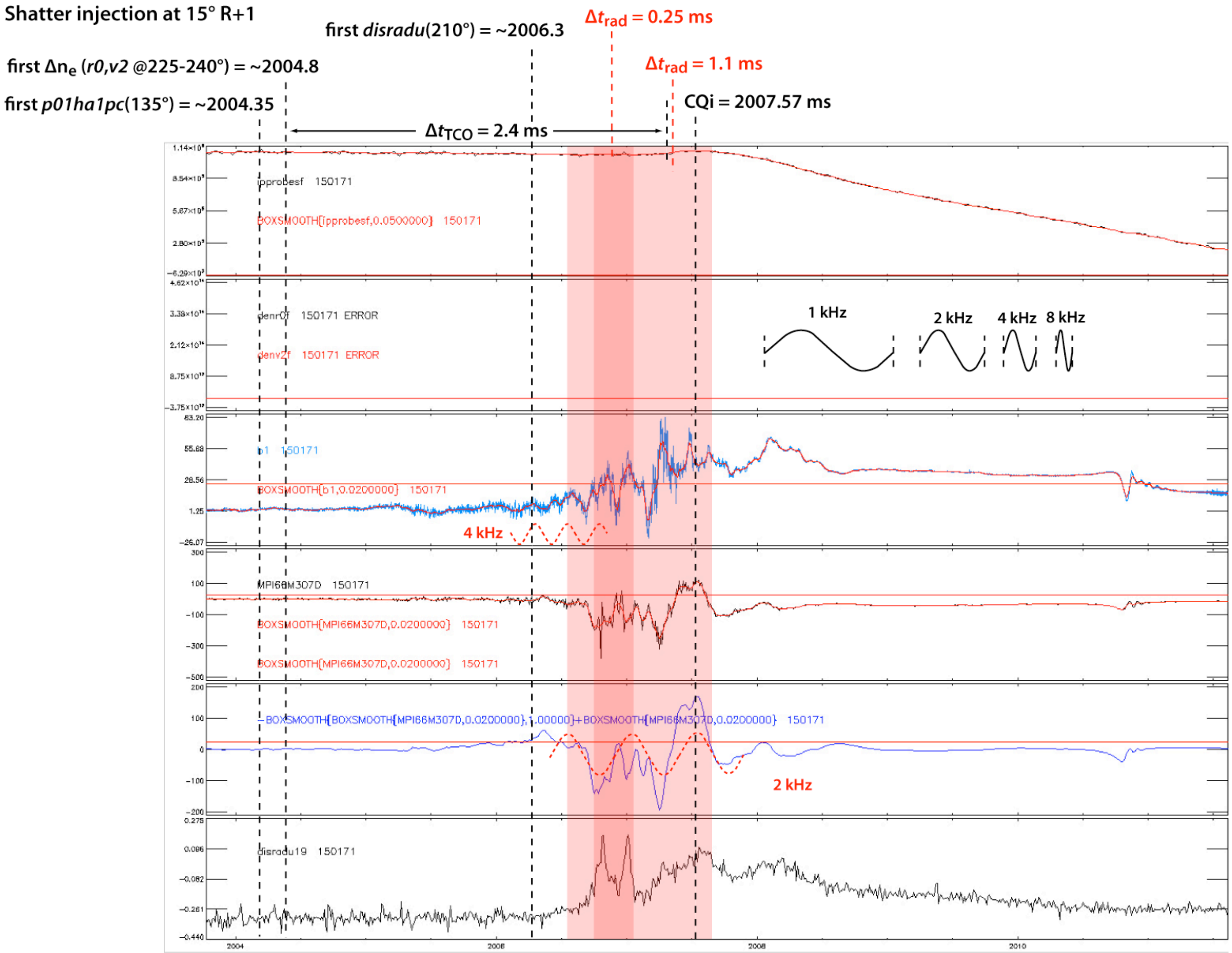
Low-Q Ar (M-II, 1 valve) #150468 with IWL/ECH target yields two reconnections (4-5 kHz), the first *sans* significant radiation



Very-low-Q Ar MGI #149723 shows multiple reconnections, before and after main CQ, many with detectable radiation



D_2 SPI example (#150171) similar, but with gradually-growing precursor + sustained + episodic radiation pulse



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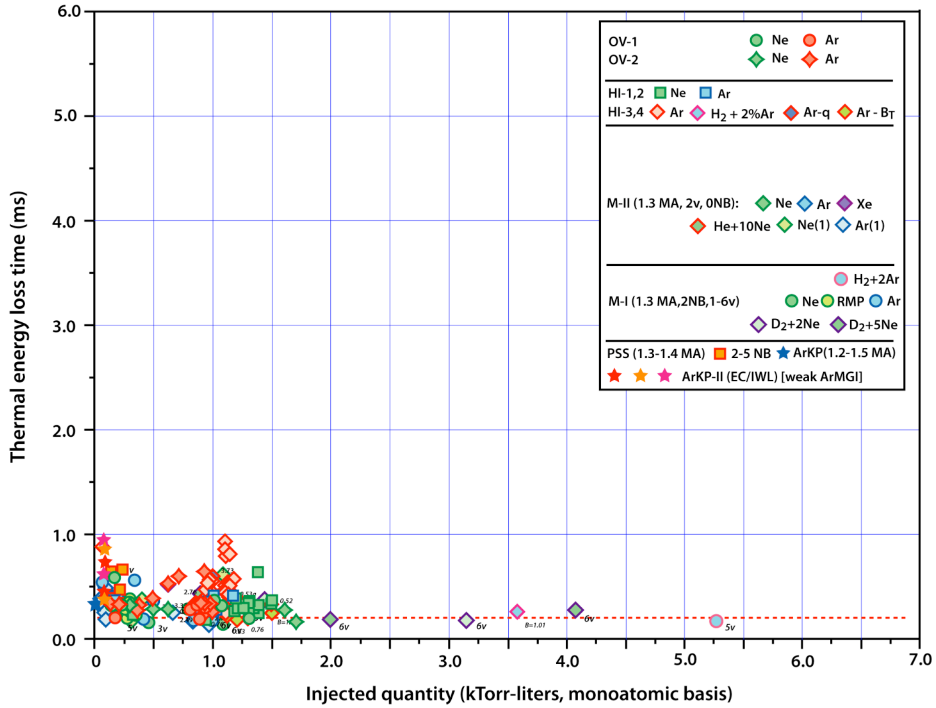
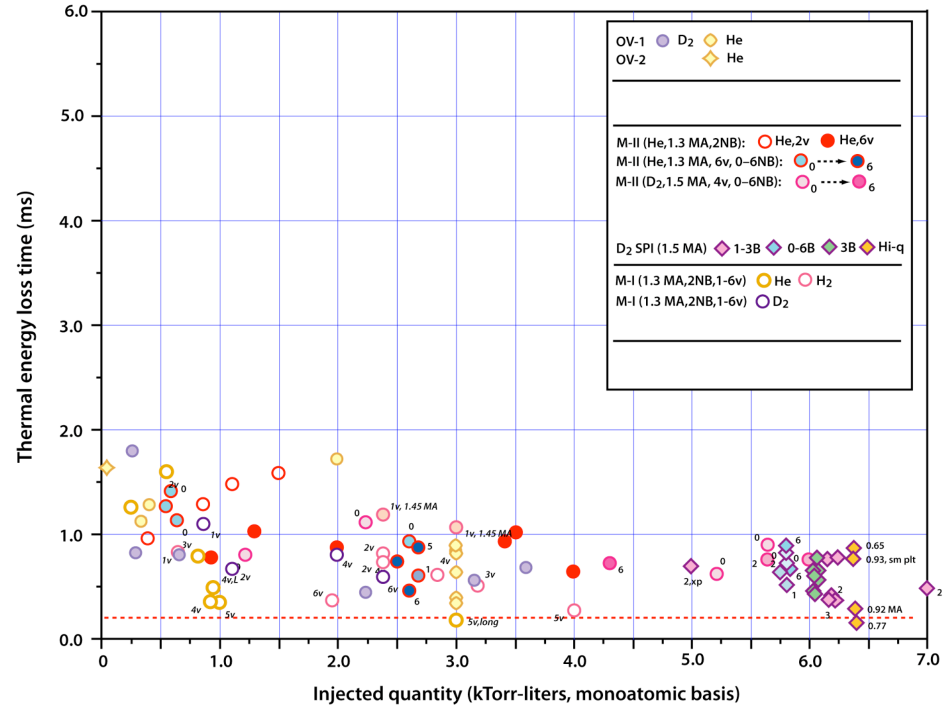
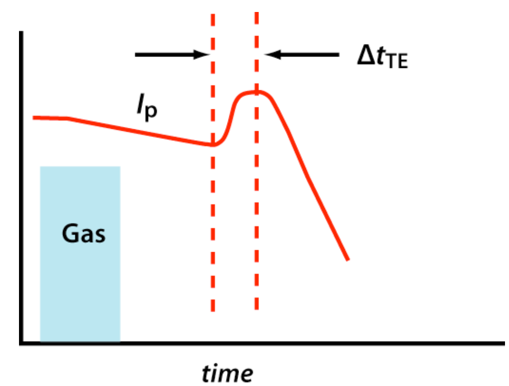
Database for DIII-D TE radiation duration and symmetry lacking; duration estimators suggest low-Z versus high-Z differences





Thermal energy loss time estimator

$= \Delta t(I_p\text{spike}\uparrow \text{ to } I_p\text{spike max})$



JET MGI data may also show presence of multiple reconnections (high time resolution important to showing effects in DIII-D)

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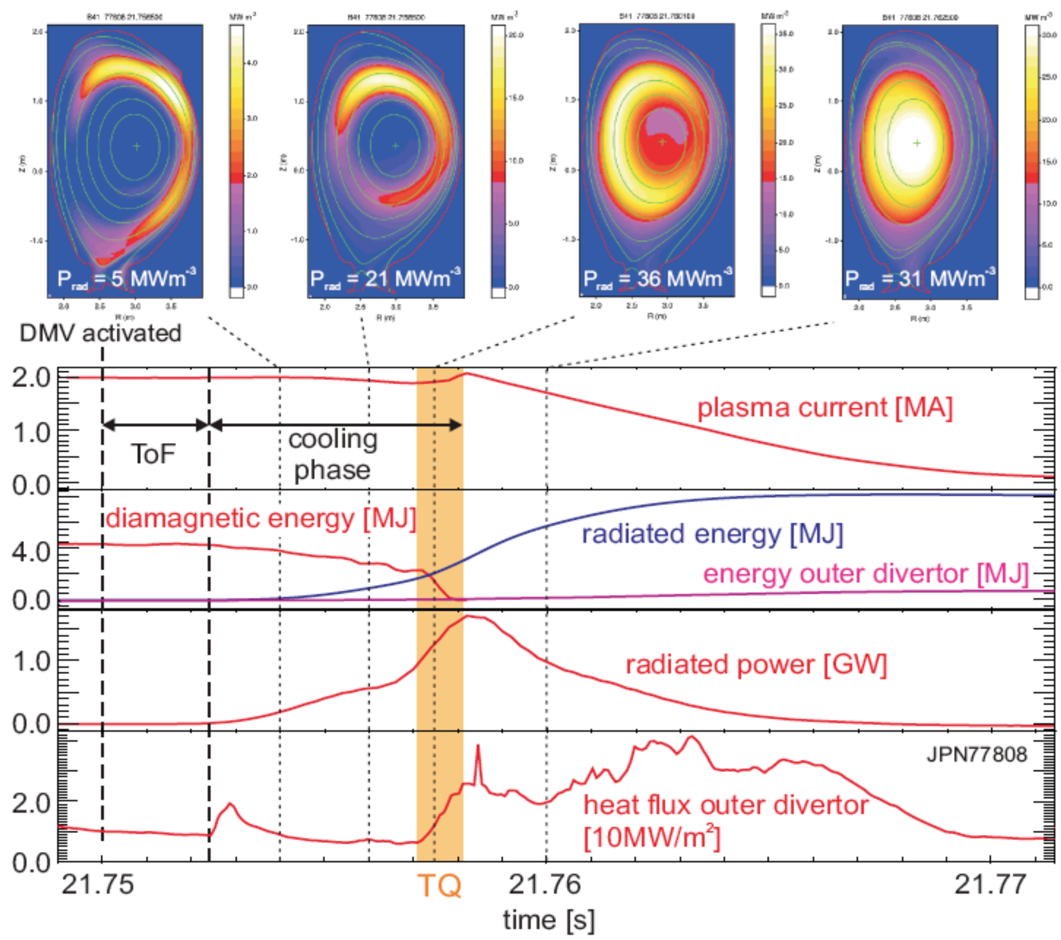
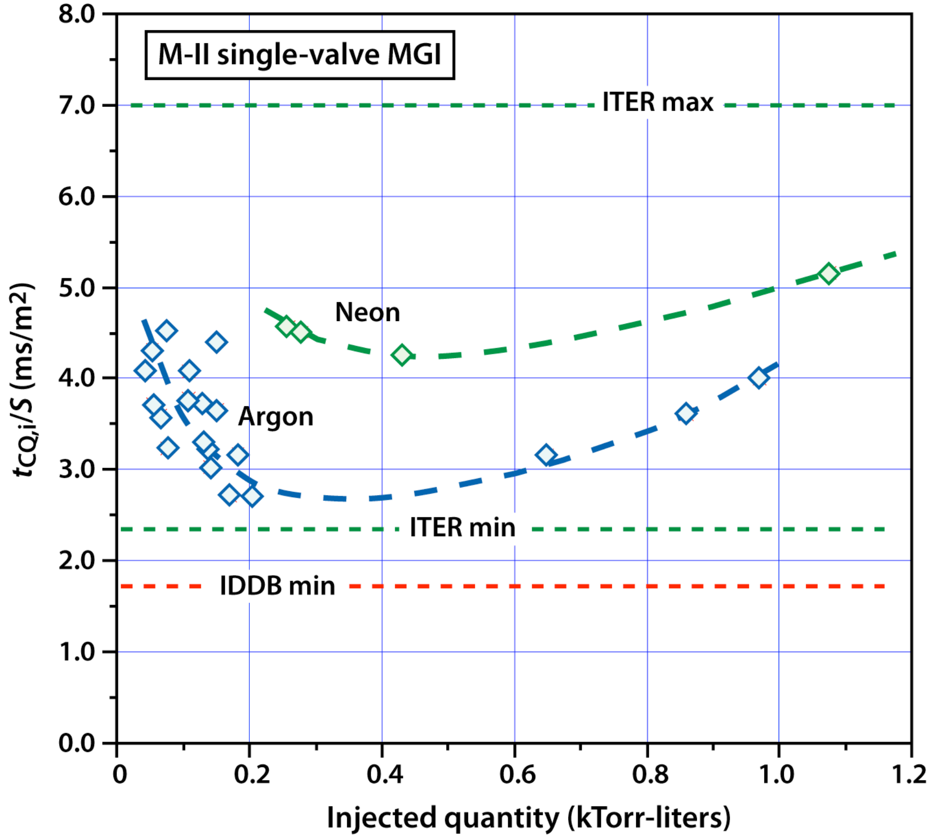
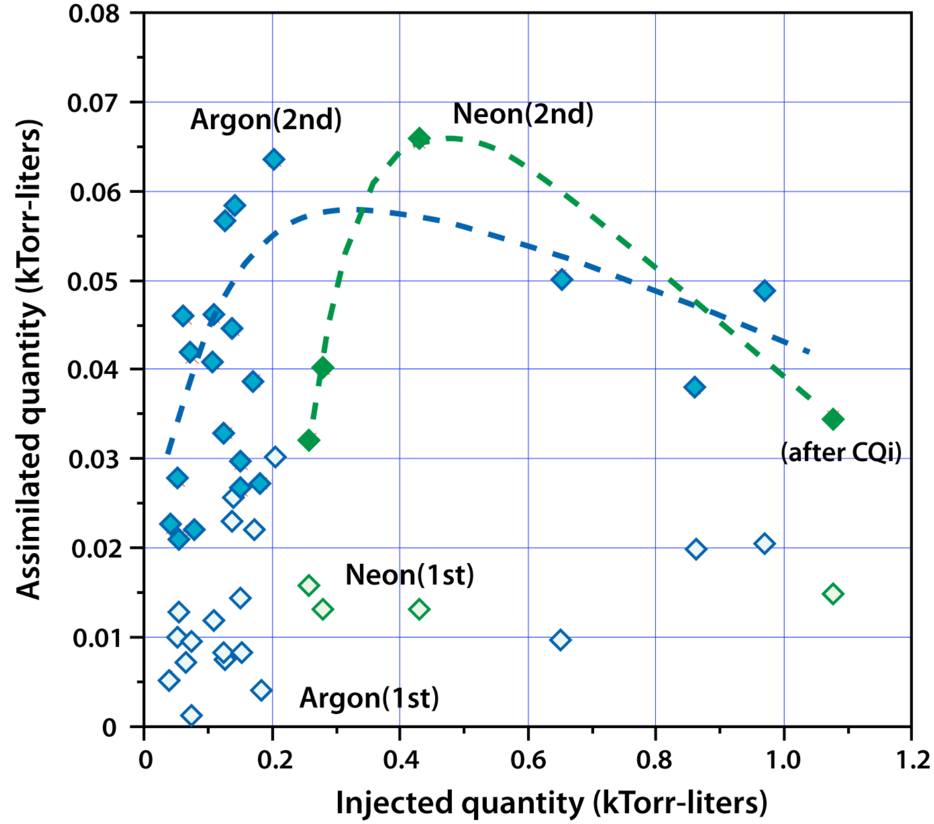


Variance and 'Q-reversal' in low-Q argon MGI 'explained' by variance/decrease in assimilation; due to changes in MHD mixing?





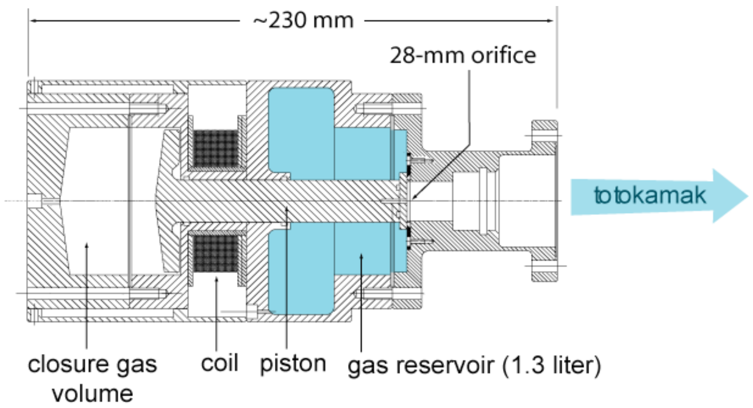
A challenge for integrated modeling!

Disruption mitigation for ITER is predicated on pre-emptive gas and/or mass injection; theory/simulation support urgently needed

- Physics and hardware elements for 'basic' disruption mitigation in ITER have already been identified and have [more-or-less] been demonstrated (hardware in next VG)
- Feasibility of sequential integration and adequacy of 'control' remain as significant DMS concept selection issues
- Integrated '3-D' models that combine impurity delivery and transport, MHD dynamics and subsequent radiative dissipation of thermal and magnetic energies are needed
- Experiments with 'ITER-like' DM are on the 'critical path'; time for experiment ↔ model validation is very short
- Final development and validation will likely have to take place in ITER itself: DMS qualification will be an experiment!

ITER-scale injection technologies in development; needed *now* to advance present-day experiments and model validations

- **'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 in Tore Supra**
- **Common issues: engineering feasibility, reliability + how to implement flexibility + 'control' for 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)

We are here (2013)

	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 collisional mitigation (n_{CH-RB}) Methods to realize/sustain superhigh densities Integrated modeling and other issues (eg., radiation opacity, pellets + superthermal)					3.1 Avoidance possible? 3.2 Within CQ allowables? 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)?

DM solution (items 1–2)

RE solution(s) (items 3–4)

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

Disruption mitigation for ITER must sail between Scylla and Charybdis; are you ready to jump in the water to help?