Fast Plasma Shutdowns Obtained With Massive Hydrogenic, Noble and Mixed-Gas Injection in DIII-D

by
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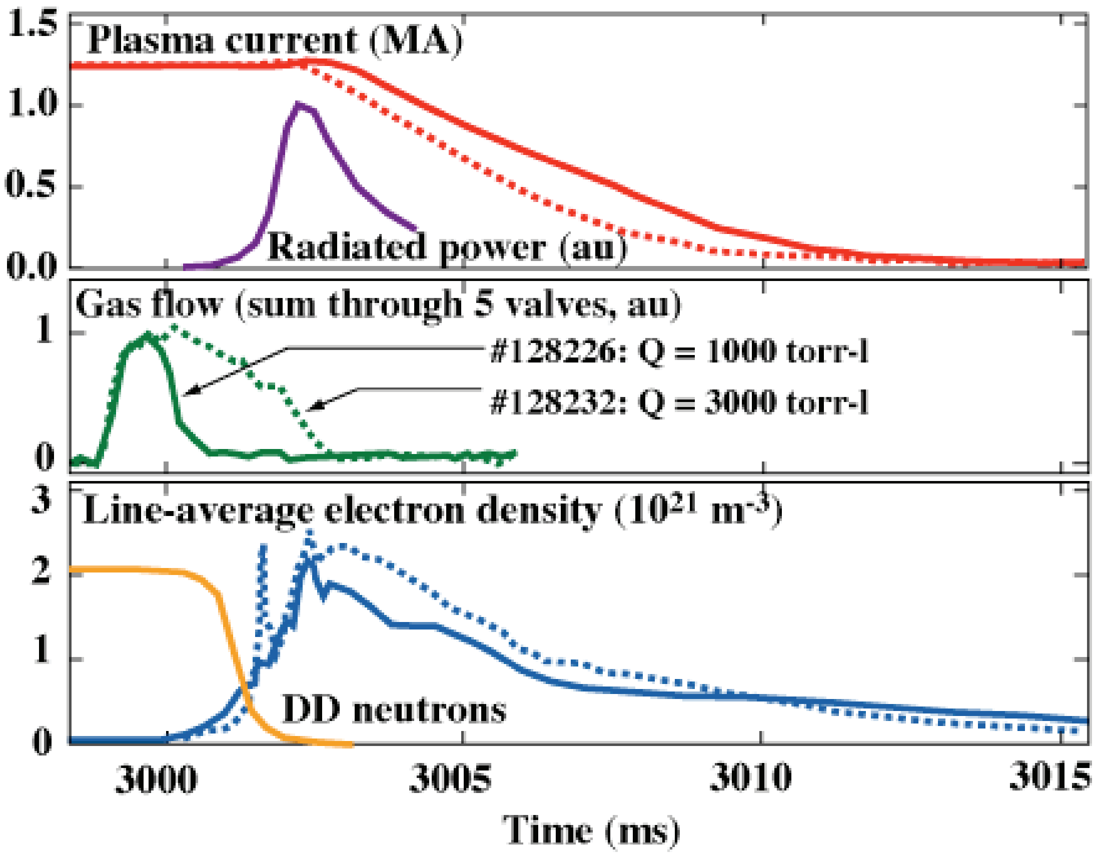
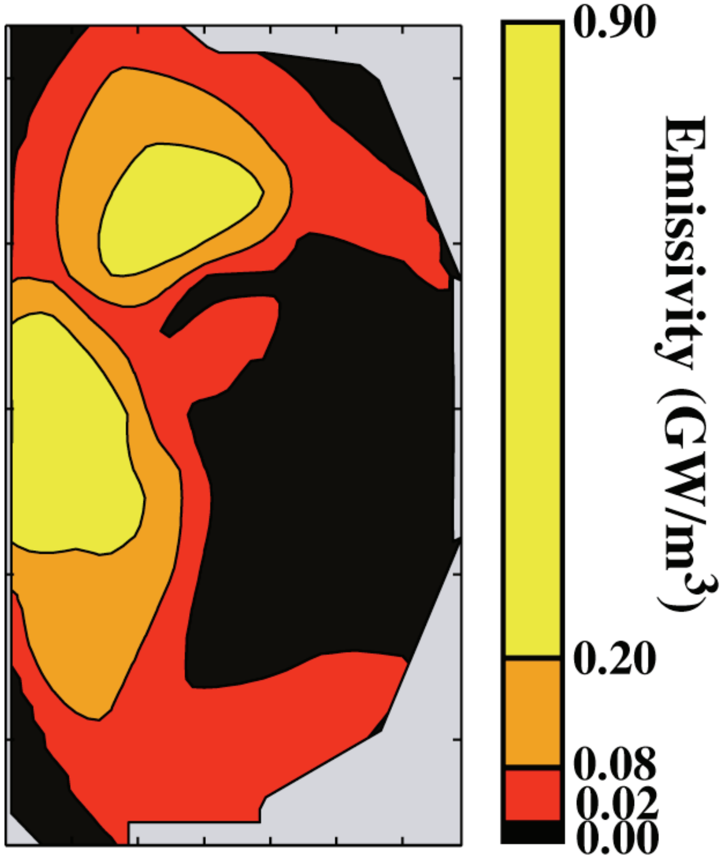
Summary

Massive gas injection (MGI) experiments with H_2, D_2, He, Ne and Ar and mixed H_2+Ar and D_2+Ne gases injected into ITER-similar 1.3-MA H–mode plasmas are described. Gas species, injected quantity *Q*, delivery time t_{inject}, and added impurities are all found to affect the attributes and disruption mitigation efficacy of the resulting fast plasma shutdowns. With sufficient *Q* and $t_{injject} \leq 2$ ms ('short-pulse' injection), all species provide fast (within 3 ms), more-or-less uniform radiative dissipation of the 0.7-MJ plasma thermal energy, and fast but benign current decays with reduced vacuum vessel vertical force impulse. With pure and mixed low-*Z* gases, free-electron densities up to $2 \times 10^{21} m^{-3}$ are obtained. While these densities are high relative to normal tokamak practice, they are still an order of magnitude less than densities required for unconditional collisional mitigation of the runaway electron avalanche. Key information applicable to MGI model validation and design of MGI systems for larger tokamaks and ITER has been obtained.

High-Q helium MGI capabilities yield record free-electron densities; SXR data show benign thermal energy radiation characteristics





High-Q helium injection produces a prompt, high-n_e FPS with 1-ms radiative dissipation ($\leq$ 0.3 $MJm^{-2}s^{-0.5}$) and a fast but benign (low vessel force) current decay

2-D emissivity data show W_{th} radiation characteristics are benign (details in Hollmann *et al*, Nuclear Fusion 2008)

Background, motivation and application to ITER

- Pre-emptive Massive Gas Injection (MGI) is the leading candidate for the ITER disruption mitigation system (DMS): see Whyte and Wesley *et al*, IT/P1-23
- Three types of disruption mitigation are needed for ITER:

  1) Quasi-uniform radiative dissipation of plasma thermal energy (TE):

     $W_{th}/A_{FW}\, t_{rad}^{0.5} \leq \sim 10$ MJ m^{-2}s$^{-0.5}$; avoid strong spatial and temporal peaking

  2a) Reduction of in-vessel halo current (HC) magnitude and toroidal peaking:

     $I_{h,max/Ip0}$ = 40%→ ≤ 20%; TPF → 1 (increased structural margins)

  2b) Reduction of maximum vacuum vessel vertical force (VF):

     120 MN → ≤ 60 MN (increased structural margins)

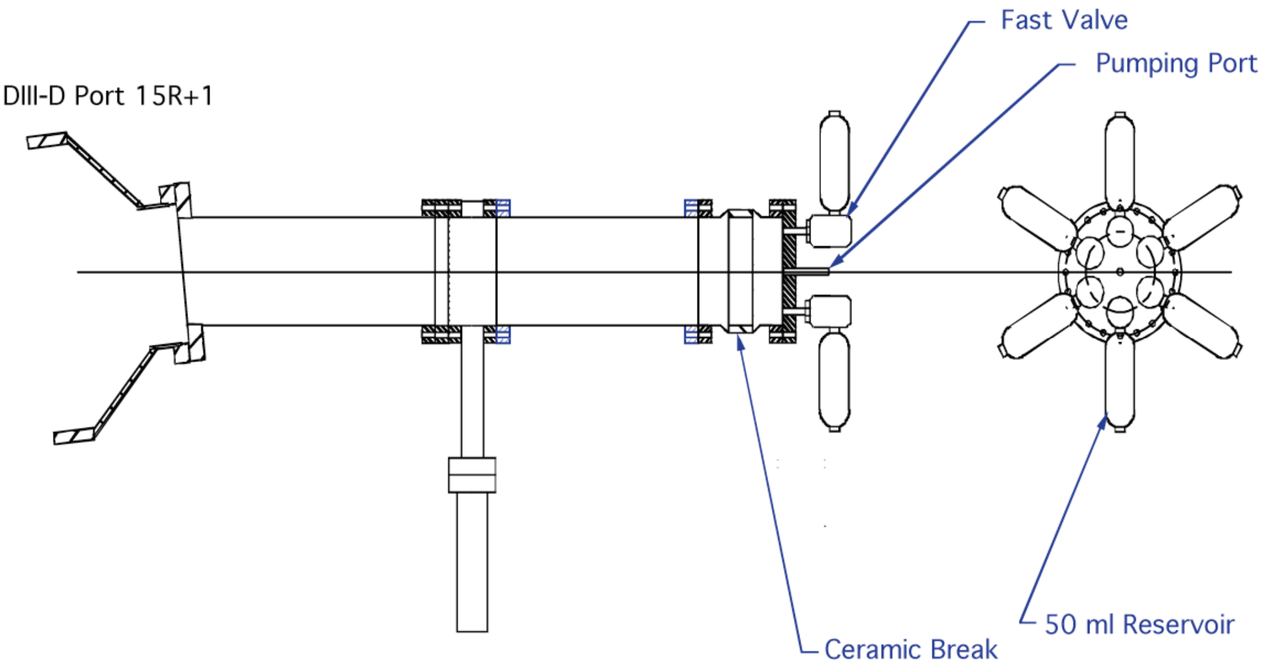
  3) Avoid or limit runaway electron (RE) avalanche

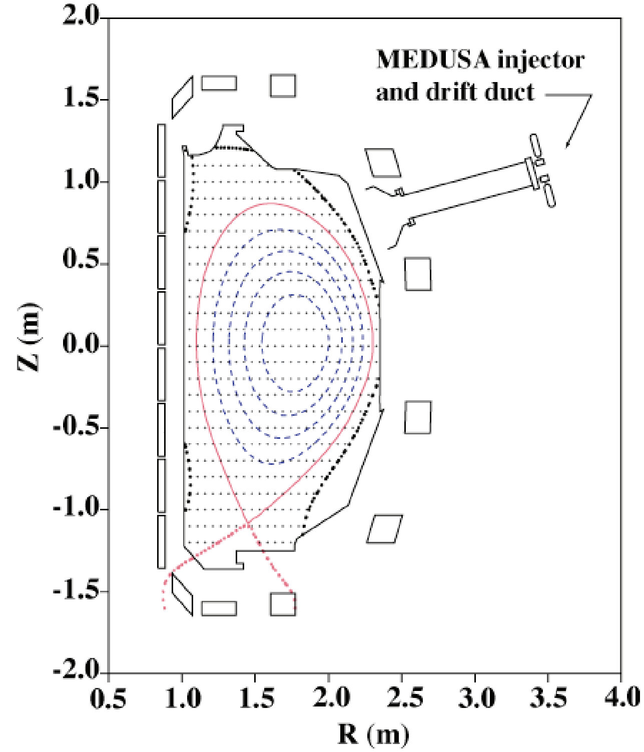
     $n_e \geq 10^{22}$ m^{-3} or $\gamma_{loss} > 100$ s^{-1} → $I_{RE} \leq \sim 1$ MA (cf ~10 MA w/o mitigation)

- Feasibility of TE and HC/VF mitigation by MGI is well documented in many tokamaks and is reasonably well understood re ITER (see, eg., *Progress in the ITER Physics Basis*)
- Feasibility of high-n_e (collisional) RE mitigation by MGI is not yet confirmed

⇒ Results presented here address all three aspects of ITER DM and DMS design. Several findings have direct import for ITER DMS concepts and 'requirements'

MEDUSA experiments test the effect of gas quantity, species and mixtures on DM attributes of MGI fast plasma shutdowns





6-valve MEDUSA injector, $t_{open/close}$ = 0.2 ms, $\Phi(He/D_2) \approx$ 1-6*200 torr-*l*/ms (0.7-4 x 10^{22} atoms/molecules per ms); t_{inject} typically ≤ 2 ms (0.5 → 6 ms)

H-mode target plasma
1.3 MA, $W_{th} \approx$ 0.7 MJ
$W_{mag} \approx$ 0.9 + 0.6 MJ

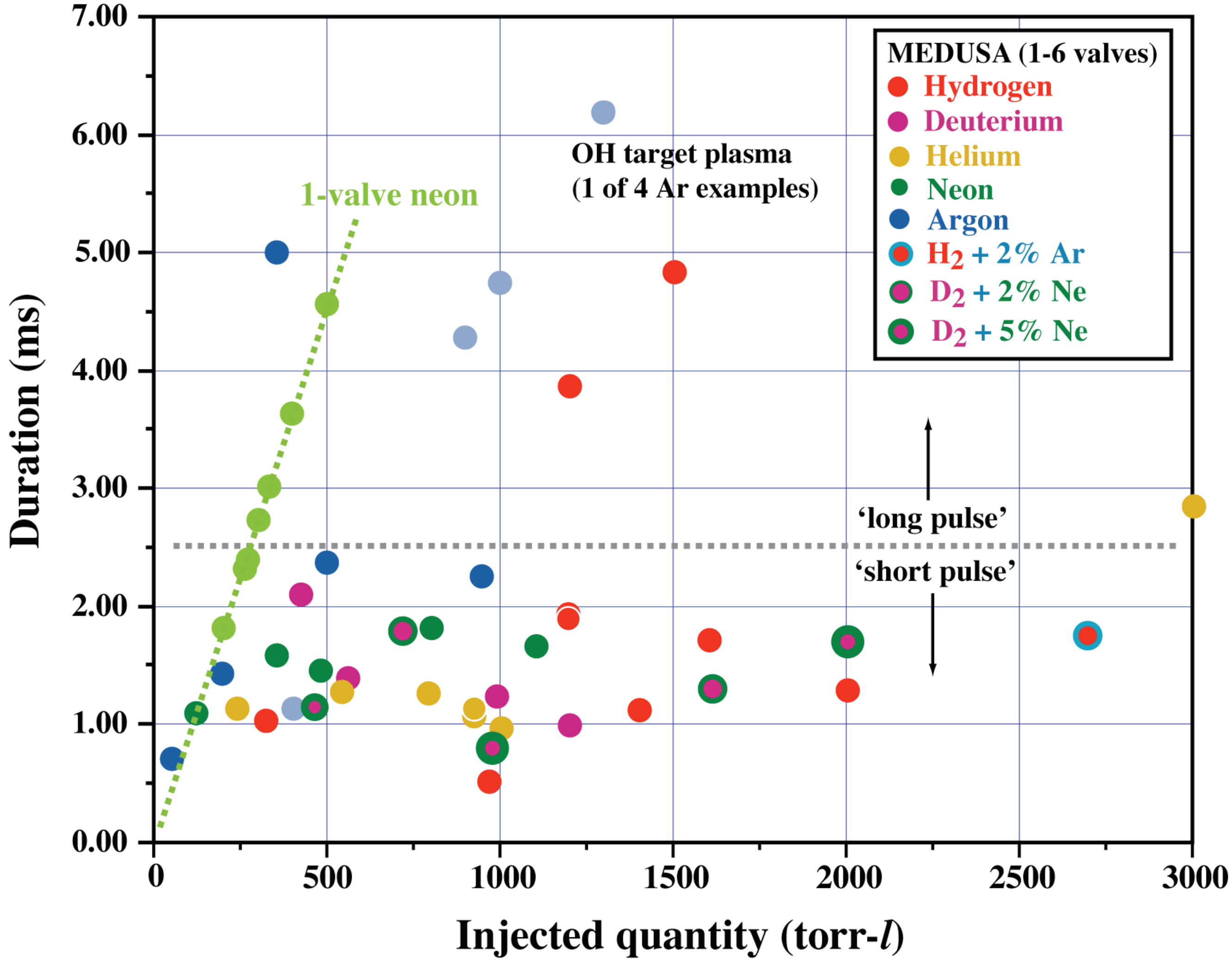
- Pure and mixed species: H_2, D_2, He, Ne, Ar, plus H_2 + 2% Ar, D_2 + 2% Ne and D_2 + 5%Ne
- 50 ≤ *Q* ≤ 3000 torr-*l*; controlled 'short-pulse' Q-scans (see following VGs)

MEDUSA pulse duration and flow control capabilities facilitate making 'same-Q' comparisons among gas species and mixtures

Gas	M (AMU)	γ	v_s (300K) (m/s)	Flow (Φ) (He = 1)	Z or $\langle Z \rangle$	Q_e/Q	$\Phi Q_e/Q$ (He = 1)
H_2	2.00	1.40	1320	1.295	2.00	2.00	1.295
H_2 + 2% Ar	2.76	~1.40	~1124	~1.103	2.32	2.32	~1.279
D_2	4.00	1.40	933	0.916	2.00	2.00	0.916
D_2 + 2% Ne	4.32	~1.40	~898	~0.881	2.16	2.16	~0.951
D_2 + 5% Ne	4.80	~1.40	~852	~0.836	2.40	2.40	~1.003
He	4.00	1.67	1019	1.000	2.00	2.00	1.00 0
Ne	20.1	1.67	456	0.447	10	10	2.235
Ar	39.9	1.67	322	0.316	18	18	2.844

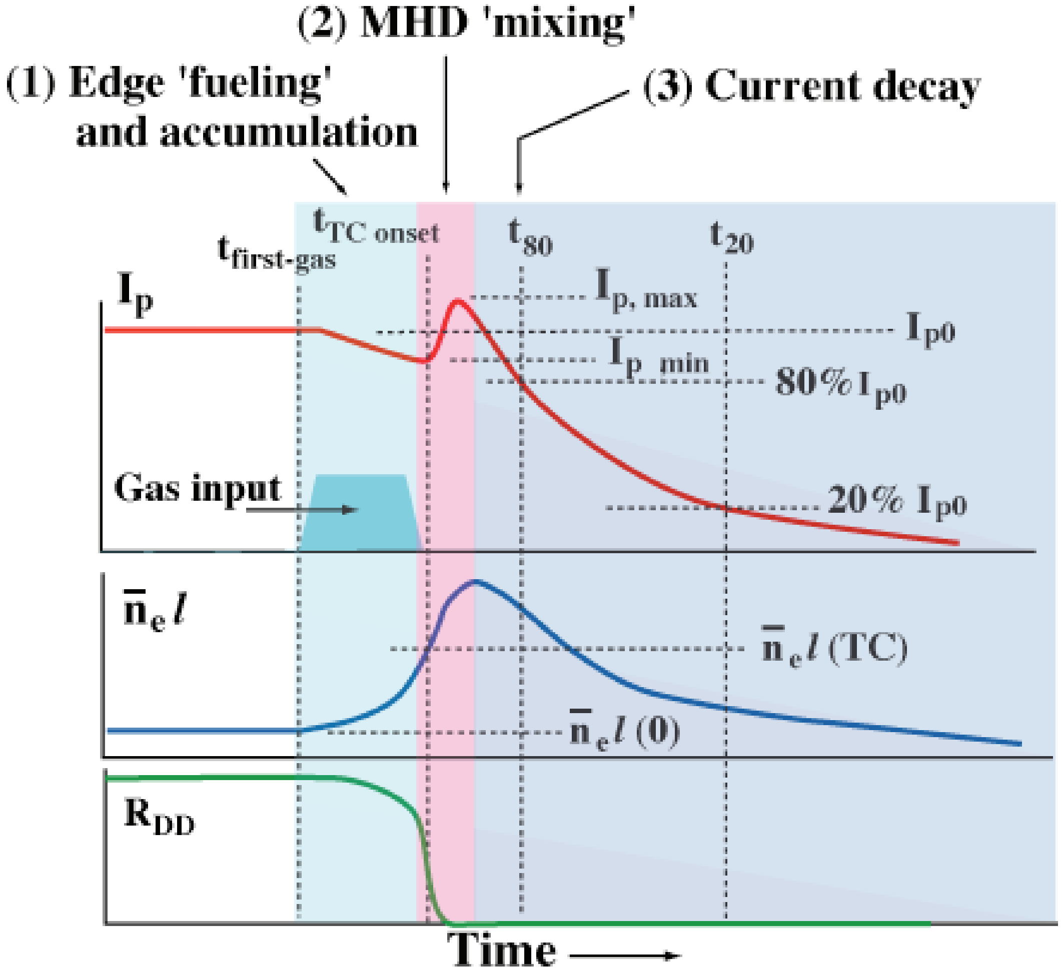
- Per-valve gas flow, Φ, and total electron delivery, $\Phi Q_e/Q$, for low-Z species (including H_2 or D_2 mixtures) are similar and dominated by e- content of the H_2 or D_2 'carrier gas'. Helium (He) delivery is the same as H_2 or D_2. Differences in e- delivery owed to sound speed (v_s) variations among low-Z gases are small
- Per-atom e- deliveries for high-Z gases (Ne and Ar) are higher, but offset by lower v_s and flow. $\Phi Q_e/Q$ data (right column) compare helium-normalized total e-deliveries among the various low-Z and high-Z species
- Data identification in subsequent VGs follows the color coding introduced here

Multiple valves ('flow control') allow quantity variation ('Q-scan') experiments with 'constant' pulse duration (typically 1–2 ms)



- The significance of 'short-pulse' versus 'long-pulse' follows in subsequent VGs

All MEDUSA examples follow standard 3-phase FPS phenomenology; I_p and n_e waveforms provide metrics to quantify DM attributes



FPS phases, waveforms and fiducial data used to develop fast shutdown metrics (schematic)

Fast shutdown metrics:

M1 TC onset time: $t(R_{DD}\downarrow) \approx t(I_p\text{-spike}\uparrow)$

$Dt_{TC\ onset} \approx t(I_p\uparrow) - t_{first\text{-}gas}$

M2a I_p 'contraction': $I_p^*(-) = I_{p,min}/I_{p0}$

M2b I_p 'expansion': $I_p^*(+) = I_{p,max}/I_{p,min}$

M2c 'Expansion/contraction' ratio:

$R = [I_p^*(+) - 1] / [1 - I_p^*(-)]$

M3 I_p decay time (IDDB metric):

$t_{CQ}/S = 5/3^*[t_{20} - t_{80}]/S$

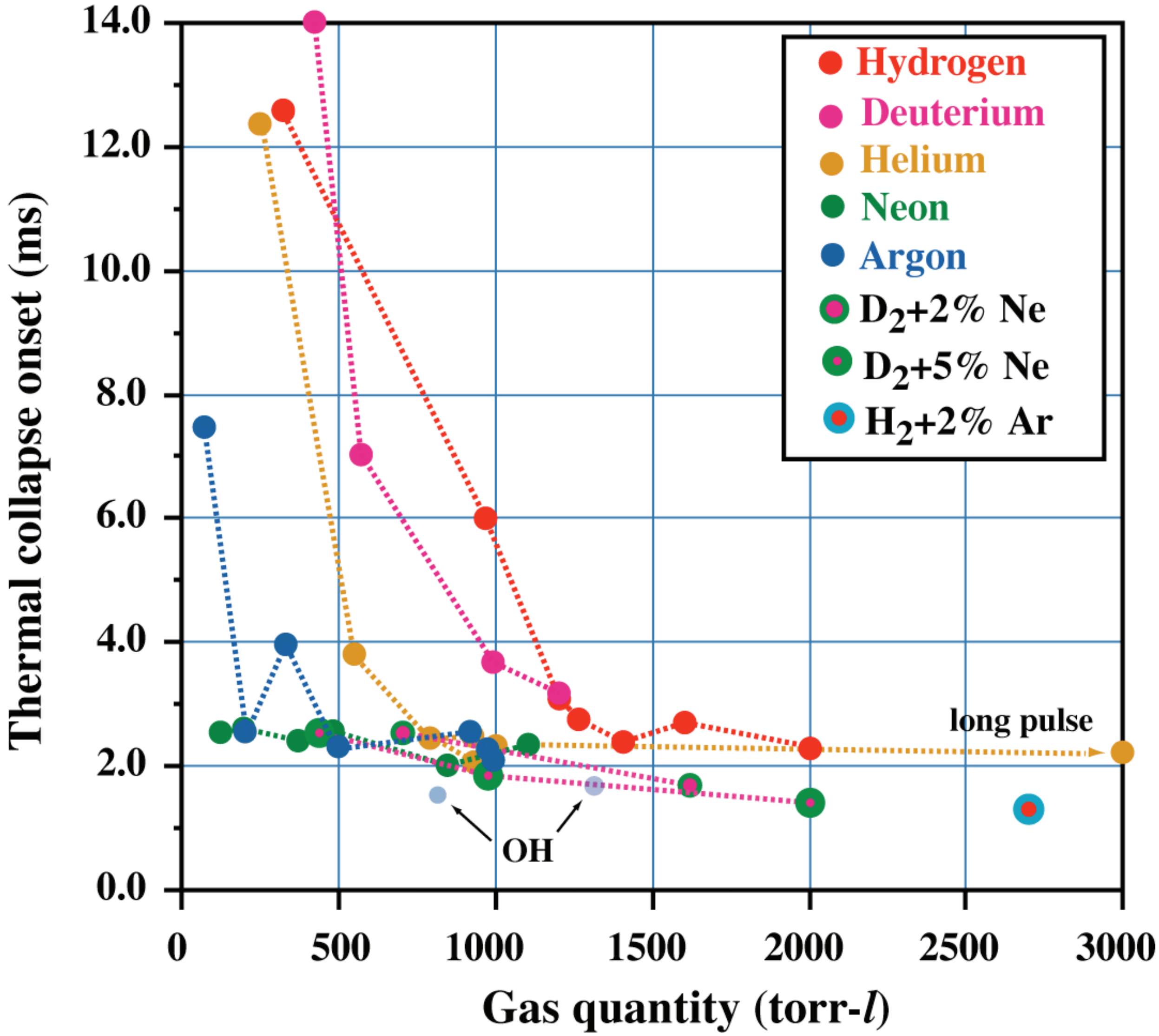
S = poloidal cross-section area

M4 Added electron line-density:

$Dn_{e,bar}l = n_{e,bar}l\ (TC) - n_{e,bar}l\ (0)$

$\approx n_{e,bar}l\ (TC)$

M1 thermal collapse onset: *with sufficient Q*, TC onset delays for pure and mixed gases approach species-independent minima



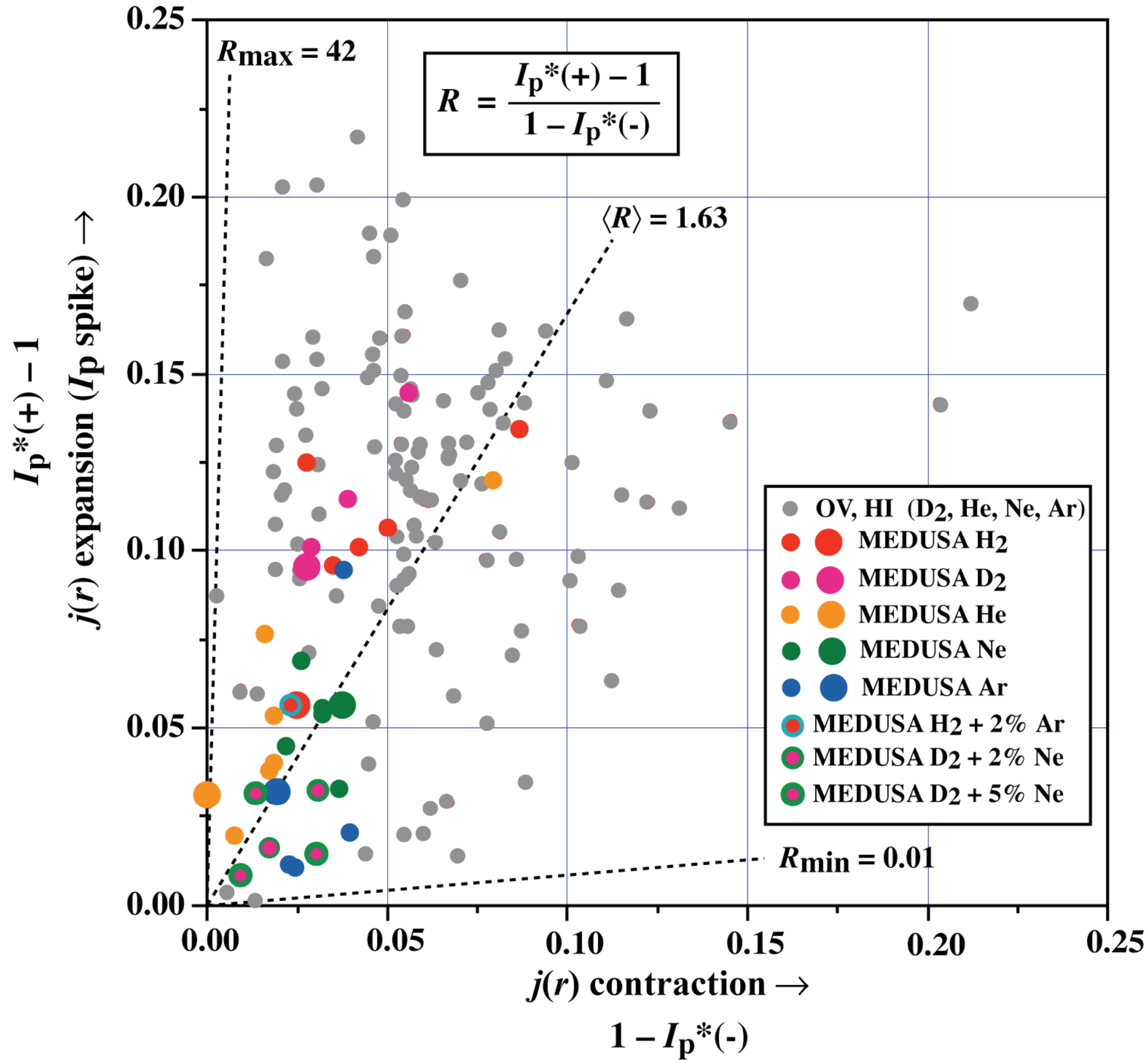
- For pure gases, delay from first gas to TC onset → 2.2 ms
- 'Sufficient Q' =
  ~ 200 torr-*l* for Ne and Ar
  ~ 800 torr-*l* for He
  ~1500 torr-*l* for H_2/D_2
- For mixed gas, TC onset delay → 1.4 ms; whether this is the high-Q limit is not yet clear
- Lack of strong species and Q dependencies suggests [*j*(*r*)] diffusion and/or gradient in the edge sets the 'MHD-mixing' onset time
- M1 and M2 data (next VG) are inconsistent with 'fraction of sound speed' hypothesis re cold -front propagation velocity

M2 Current profile dynamics: *with sufficient Q, j(r) contraction and expansion indicators become small (≲ ~0.05), nearly independent of Q*

- For past 'open-valve' and 'high-intensity' single-valve MGI, wide range of expansion and contraction indicators and their ratio, *R*
- MEDUSA indicators are systematically smaller and decrease with increasing *Q* (small → large symbols)
- Highest-*Q* examples:
  $1 - I_p{*}(-) \lesssim 0.04$
  $I_p{*}(+) - 1 \lesssim 0.06$

⇒ With sufficient short-pulse *Q*, fueling and mixing proceed with minimal changes in *j*(*r*)

- Little indication of strong species and/or mixture dependence ⇒ model validation challenge(s)



M3 current decay: *with sufficient Q*, all gases produce fast plasma current decays

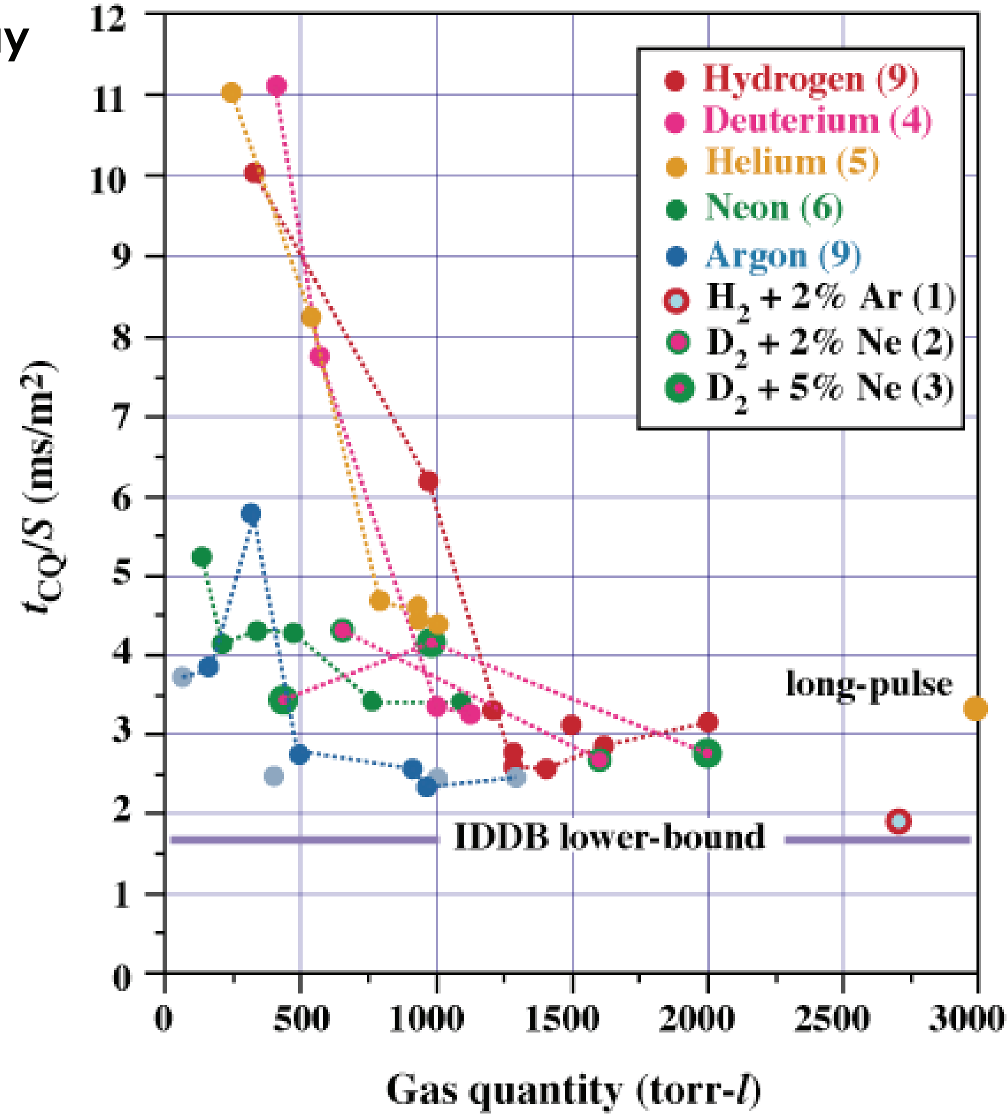
- With sufficient *Q*, area-normalized decay times for most species and mixtures approach 2.5 ms/m², ~1.5-x the IDDB lower bound
- Three significant exceptions:

  He → 4 ms/m² (short pulse);
  → 3 ms/m² (long pulse)
  H_2 + 2%Ar → 1.7 ms/m²
- 'Sufficient *Q*' to obtain minimum CQ time is comparable to the same-species *Q* for minimum TC delay

⇒ Hence species and *Q*'s that provide good TE mitigation also produce a fast I_p decay

- Vacuum vessel vertical force impulse data (next) show that 'sufficient *Q*' MGI and the resulting fast I_p decays als

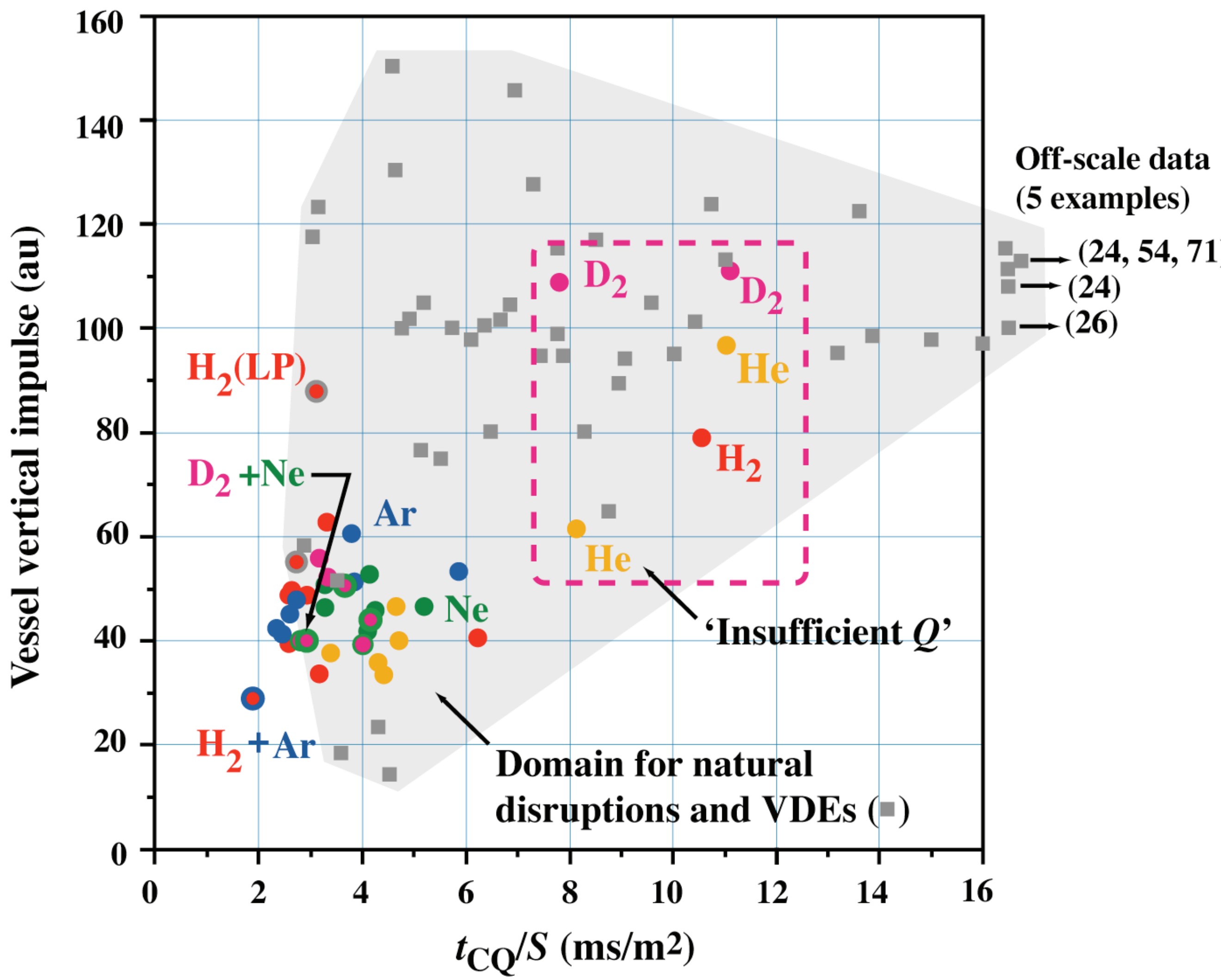
o provide vessel force/impulse reduction



Vessel vertical force: *with sufficient Q,* all gases yield reduction in $\int F_z dt$, typically 3-x smaller than that from natural disruptions or VDEs

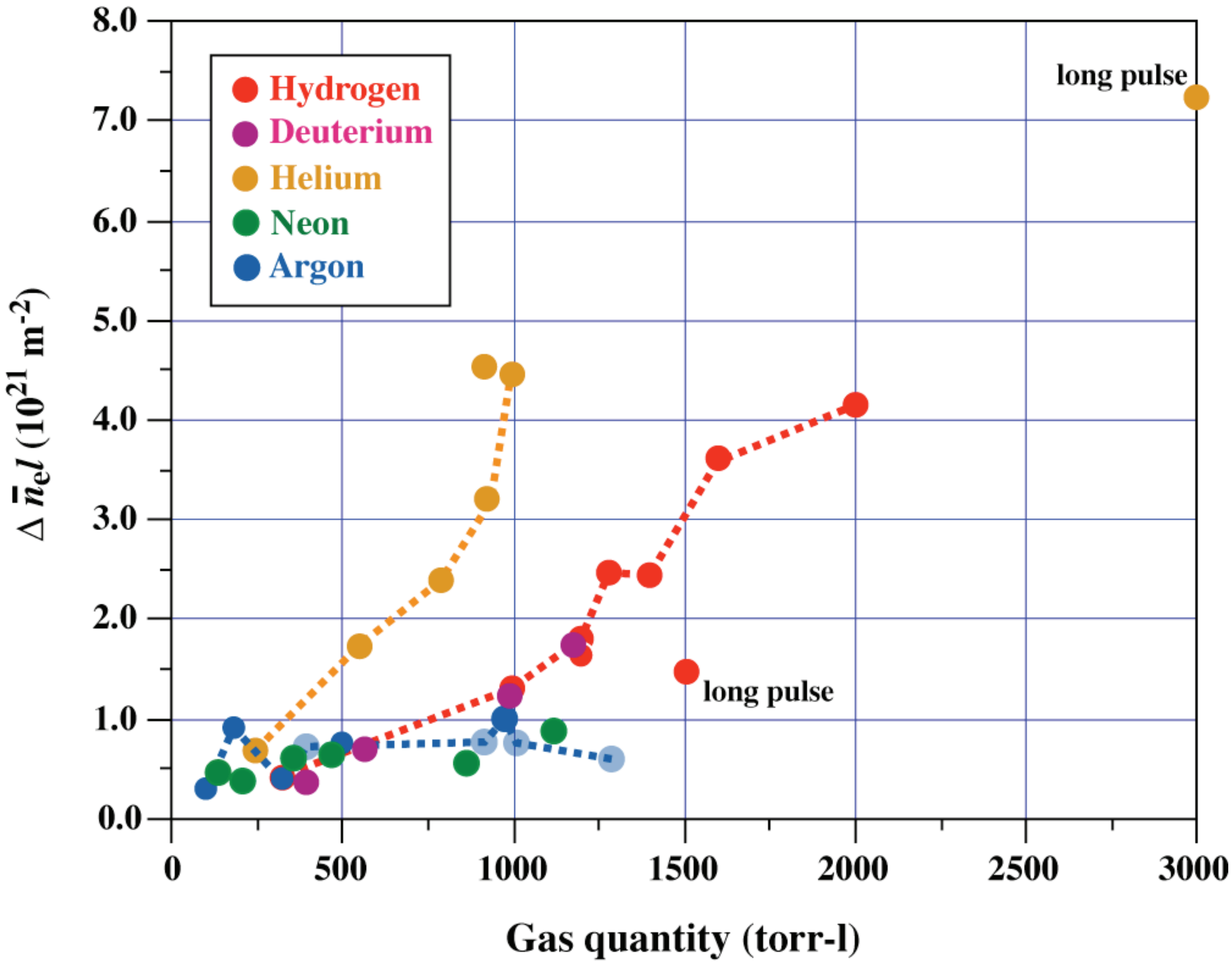
- Natural disruptions and VDEs →20-160 *au* vertical impulse. High impulse data, ≥ 100 *au*, are almost all from VDEs (drift → quench)
- 'Sufficient-*Q*' MGI produces 30-60 au. threshold for 'full' mitigation is $t_{CQ}/S \leq 5$ ms /m²
- 'Insufficient *Q*' MGI → 60-110 *au* impulse
- Hence 'strong MGI' and a fast CQ are needed for effective vessel vertical force mitigation

⇒ MEDUSA M1-M3 and VF data show the need for and inevitability of having a fast (≤ ~5 ms/m²) current decay



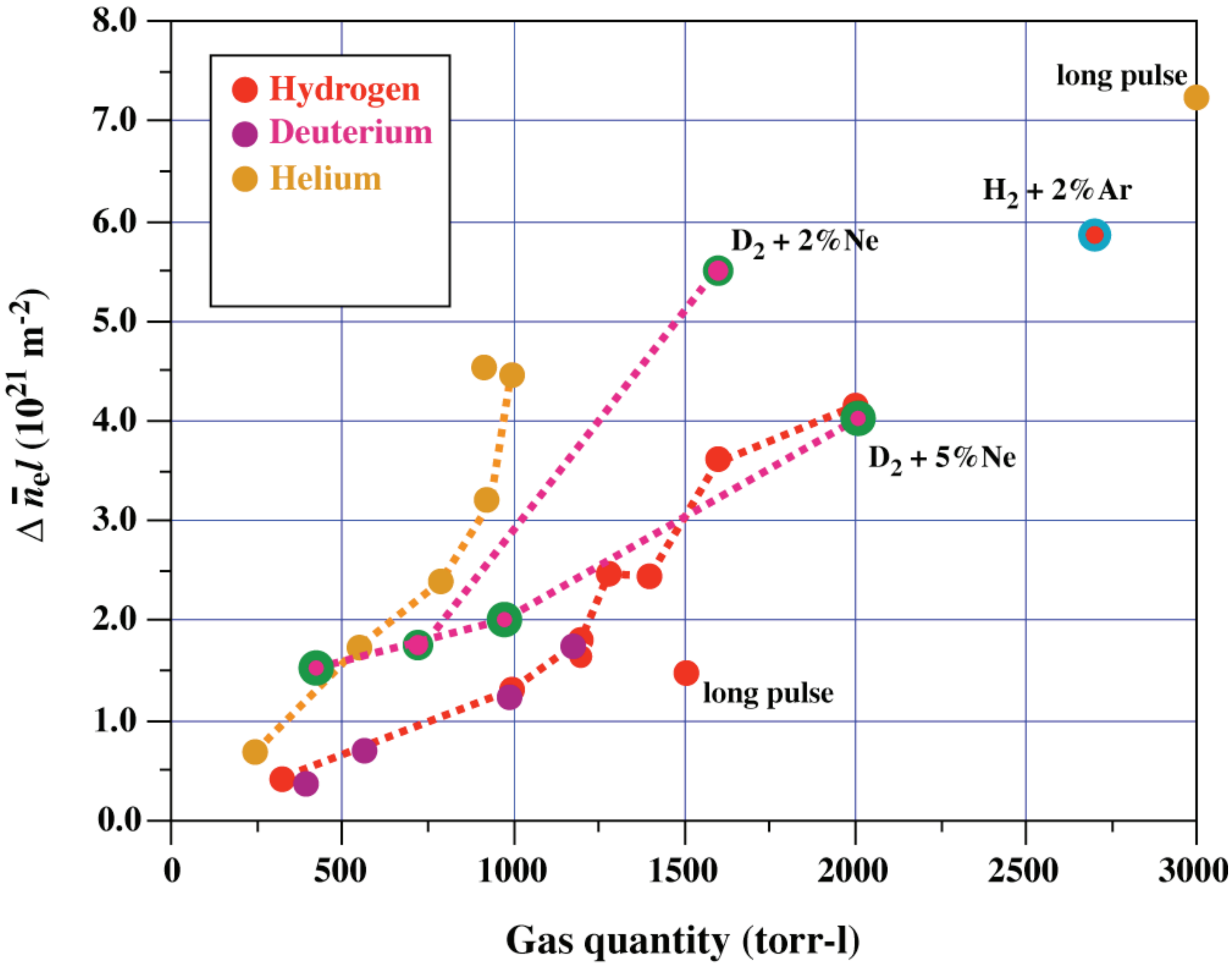
M4 Added n_e at CQ onset: magnitude and Q-scaling of $n_e l$ at TC onset (at max I_p spike) differs dramatically for low-Z and high-Z injection

- Line-densities at or just after TC onset for short-pulse low-Z injection show a strongly-positive Q dependence
- Maximum $n_e l$ for He reaches $4.5 \times 10^{21} m^{-2}$; maximum for H_2 with 2-x Q is similar
- Line densities for high-Z are lower, $\leq 1 \times 10^{21}$ m^2
- The Q-scalings are different:
  - $\propto Q^{1+\varepsilon}$ for low-Z
  - $\propto Q^0$ for high-Z
- Long-pulse H_2 and He data well below short-pulse data or the extrapolated short-pulse scaling (He) ⇒ gas delivered during/after the 'MHD mixing phase' is not assimilated as well as gas delivered before



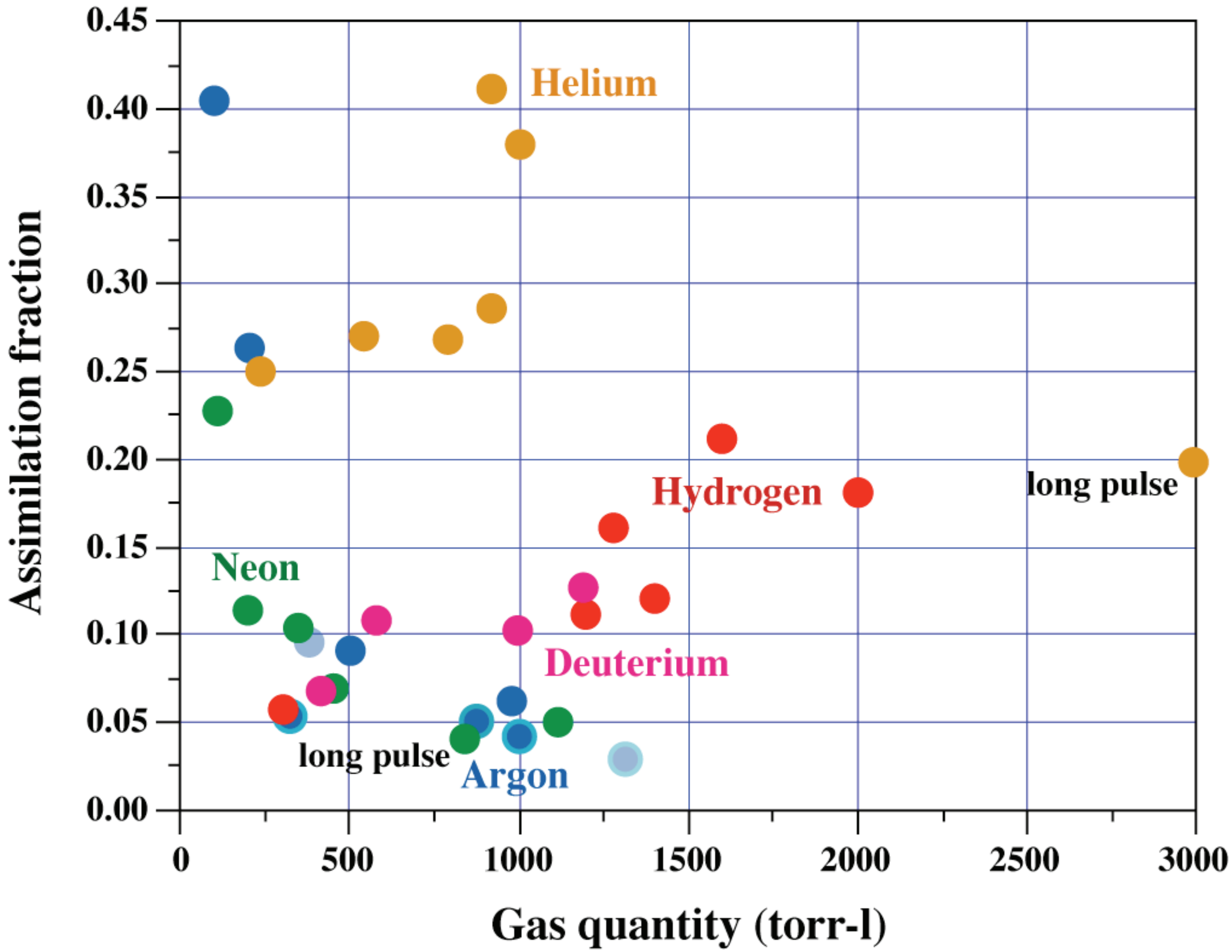
M4 Added n_e for mixed gas: D_2 + Ne and H_2 + Ar yield higher, near-record $n_e l$'s. But the data show that improvements are 'non-linear'

- Line-density increases for D_2 + 2% Ne are appreciable relative to same-Q D_2 or H_2
- Increment from 'weak' 2% neon mixture is remarkably 'non-linear': 8% increase in electron delivery yields ~80% higher line density
- Similar gain at higher *Q*: $n_e l$ = 5.5 x 10^{21} m^{-3} (*cf* 3.5 x 10^{21} for H_2)
- Effect of 'strong' 5% mixture more complex: at low Q, ~300% 'gain' relative to H_2/D_2, but gain disappears at higher Q
- H_2 + 2% Ar consistent with empirical extrapolation of H_2/D_2 data

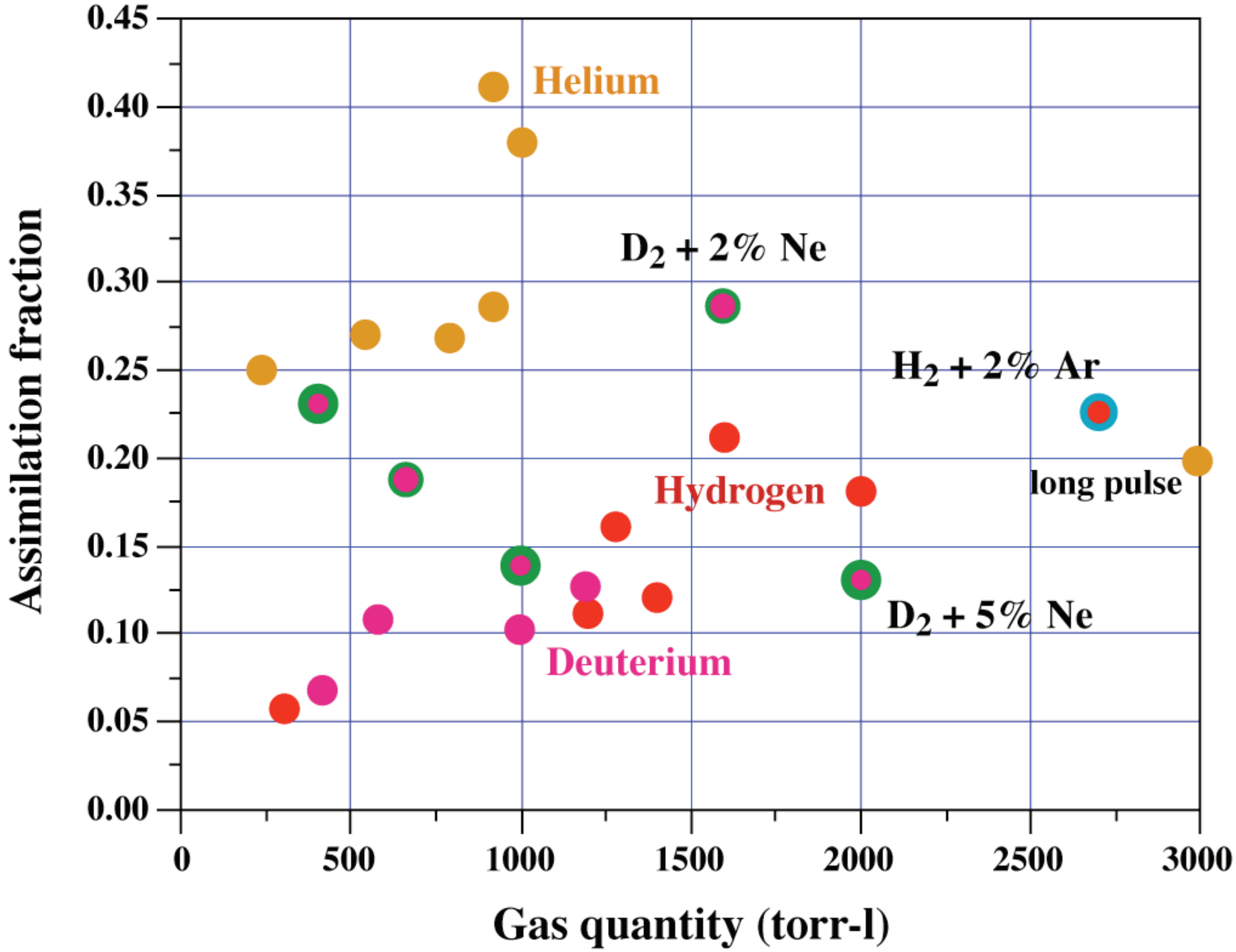


M4 Assimilation fractions: the $n_e l$ data can, with certain caveats, be converted to an assimilation fraction, f_{assim}, defined here as N_{ion}/N_{gas}

- f_{assim} data for pure low-Z and high-Z gases highlight the Q-scaling trends in $n_e l$ data
- In all instances, f_{assim} is substantially less than unity
- Q-scalings and f_{assim} at higher Q's are different for low-Z vs. high-Z
- While there are caveats – related to ⟨Z⟩ – about the high-Z data, a conclusion that f_{assim} is low for all 'sufficient Q' examples is inescapable
- Assimilation for long-pulse He drops by a factor-of-two



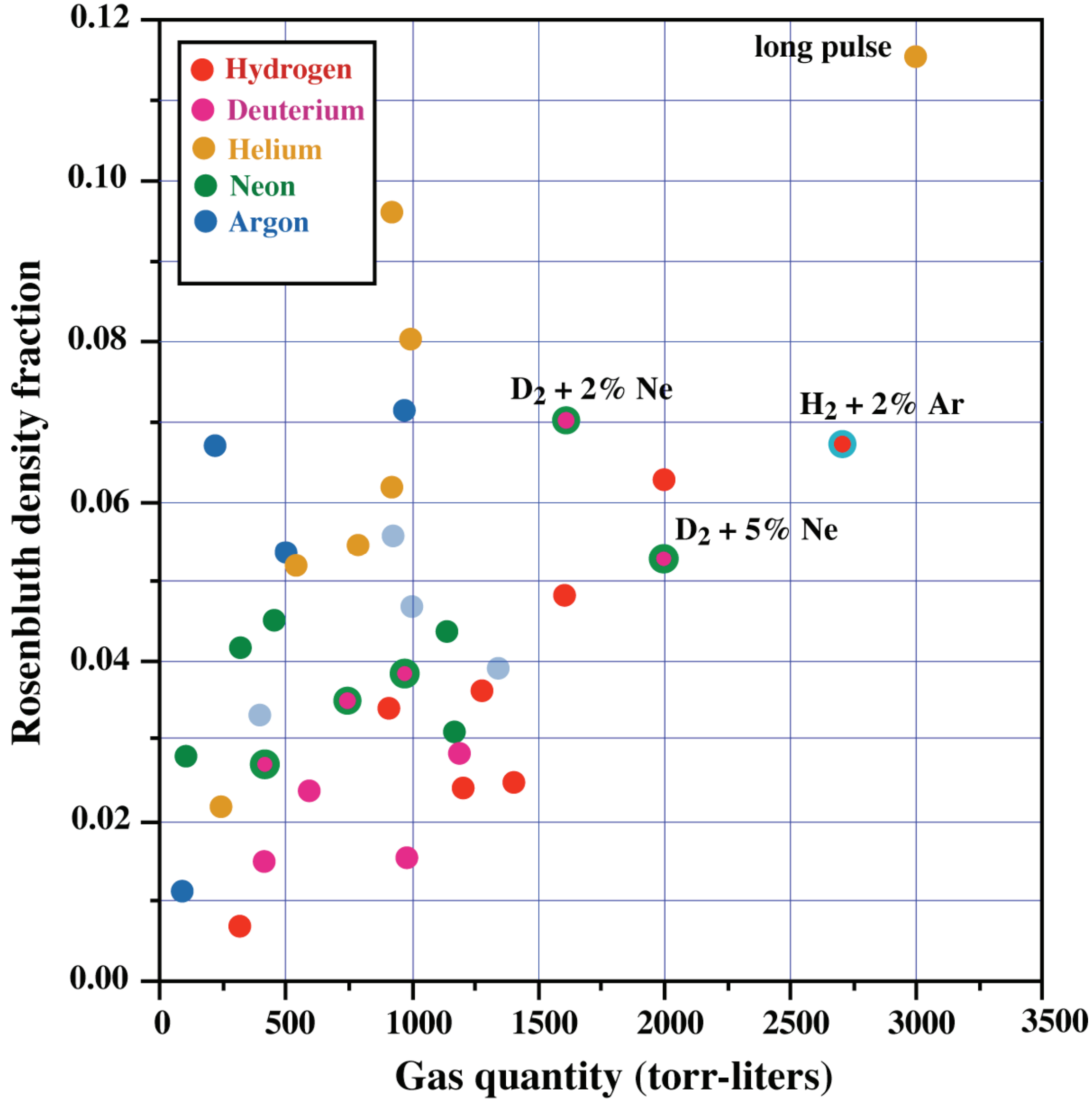
M4 Assimilation fractions for mixed gases: assimilation data highlights the non-linear effects of admixture and Q on overall assimilation



M5: Runaway avalanche mitigation: Helium yields highest f_{RB}; short-pulse H_2/D_2, He and mixed gases all show favorable Q scaling

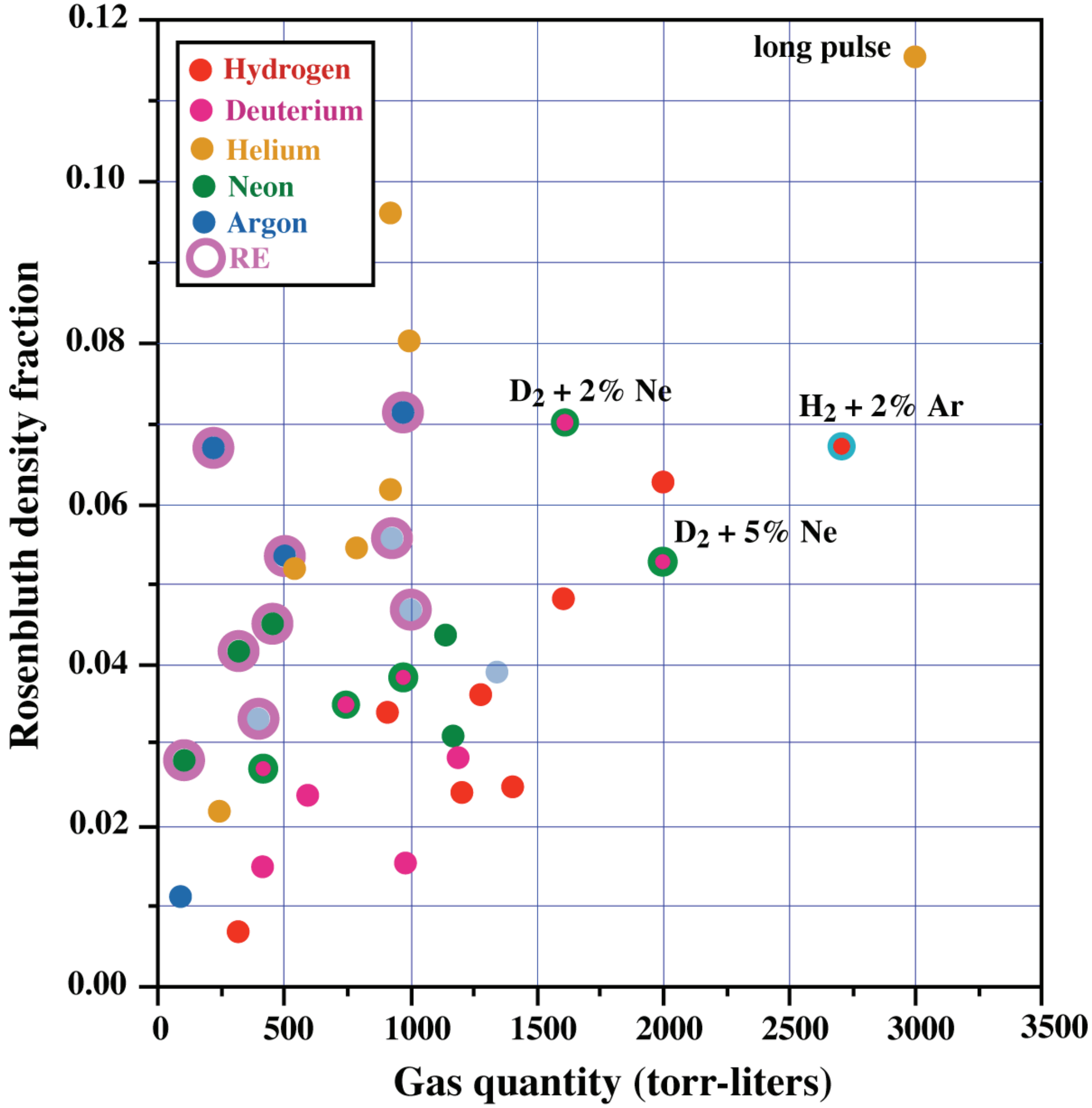
- Avalanche mitigation metrics (M5)
  $n_{RB}(10^{20}\ m^{-3}) \approx 8\ E(V/m)$;
  $f_{RB} \equiv n_e(\text{total})/n_{RB}$
- Short-pulse He ⇒ 8-10% f_{RB}; Q scaling is strongly positive
- Long-pulse He ⇒ ~12% f_{RB}; long-pulse ⇒ modest f_{RB} increment, albeit with reduced assimilation
- Short-pulse H_2/D_2 and mixed gases ⇒ 1-7%, with ~Q^1 scaling; modest benefit from 'weak' mix (D_2 + 2% Ne)
- High-Z ⇒ 1-7%, albeit with 'saturated' Q^0 scaling at high Q
- Basis for high-Z is total e- content, albeit with some uncertainty re ⟨Z⟩

⇒ Key observation: High-Q He ⇒ high n_e+ slow CQ (~4 ms/m²); "I ♥ helium!"



M5: Runaway avalanche mitigation: High-Z MGI *makes* low levels of runaway electrons (9 of 14 examples with argon and neon injection)

- Low levels RE sometimes detected by HXR emission near end of I_p decay
- HXR emission coincides with loss of closed flux surfaces; detectable current loss (~10 kA) in one example
- Recent experiments indicate RE generation with neon occurs during thermal collapse and that the resulting at-I_p-end HXR levels are erratic
- No detectable HXR for any low-Z or mixed gas example
- Maximum expected avalanche gain is $\exp[2.5\ I_p(\text{MA})] \approx 25$, so lack of major RE current suggests either low 'seed' level or competing RE losses
- Avalanche gain in ITER is 10^{16}, so even very low levels of MGI-generated 'seed' REs are a serious concern



Summary I: With sufficient Q, all gases tested provide effective thermal energy and halo current + vessel force mitigation

- With sufficient Q, all pure and mixed gases provide similar and adequate TE and HC/VF mitigation:
  - ~ 2-ms onset of thermal collapse, then benign radiation of $\underline{W}_{th}$
  - Principal W_{th} radiation over ~1-ms interval, quasi-uniform distribution to FW; $\langle W_{th}/(At^{0.5})\rangle < 0.3$ MJ m^{-2} $s^{-0.5}$ (⇒ 3 MJ m^{-2} $s^{-0.5}$ for ITER)
  - Fast CQ, t_{CQ}/S = 2-4 ms/m^2, with 3-x reduction of vessel vertical impulse
- Inadequate Q ⇒ slow initial CQ → high, VDE-like vertical impulse (not good!)
- $\Delta t_{TC\ onset}$ decreases with increasing short-pulse Q: to ~2 ms for pure species (H_2, D_2, He, Ne and Ar), to ~1.4 ms for low-fraction mixed species
- Species independence suggests $j(r)$ diffusion at edge controls MHD mixing onset
- Asymptotic behavior of $\Delta t_{TC\ onset}$ at highest Q still somewhat uncertain (short-pulse injection capability to test higher Q's lacking)

⇒ Adequate TE and HC/VF mitigation with injected gas quantities Q and at-CQ onset n_e well short of ~10^{22} m^{-3} levels needed for avalanche mitigation

Summary II: Fast shutdown attributes related to RE mitigation exhibit strong species, quantity and duration sensitivities; low-Z most promising

- Free and/or total n_e at and after CQ onset *depends* on species, mixture, Q and injection duration (short versus long pulse): there is no simple empirical scaling or model basis for the behaviors observed during MEDUSA 'Q-scan' and species-scan experiments
- Q-scaling tendencies for added n_e and f_{RB} are opposite for low-Z versus high-Z:
  - – H_2, D_2, He and 'weak' mixed gas: $f_{RB} \propto Q^{(1 \pm \varepsilon)}$; $0.20 \leq f_{RB} \leq 0.40$
  - – Ne, Ar and 'strong' mixed gases: $f_{RB} \propto Q^{(0 \pm \varepsilon)}$; $0.05 \leq f_{RB} \leq 0.20$
  - ⇒ Maximum f_{RB} , ≈ 0.12, achieved with long-pulse He injection
- Short-pulse H_2, D_2, He and 'weak' D_2 + 2%Ne show *promise for RE mitigation*, but higher Q capabilities are needed. Injection duration ≤ 2 ms preferred
- Short- and/or long-pulse Ar and Ne *not promising for RE mitigation*: low f_{assim}, unfavorable Q scaling and production of detectable levels of seed RE
- Minimum Q for $f_{RB} \approx 1$ in DIII-D is ~3 g (compare to ≤ 0.3 g for MEDUSA);
- Minimum Q for $f_{RB} \approx 1$ in JET is ~15 g; minimum Q for $f_{RB} \approx 1$ in ITER is ~150 g

⇒ Major improvements in 'short-pulse' gas/mass injection capabilities in DIII-D and other tokamaks needed to test high-n_e RE mitigation. We should expect new and not necessarily 'linear' behaviors at the very high injection rates required. ITER mass injection needs are 'very challenging' (!)