Characterization and limits of benign termination of runaway electron beams using low-Z massive material injections

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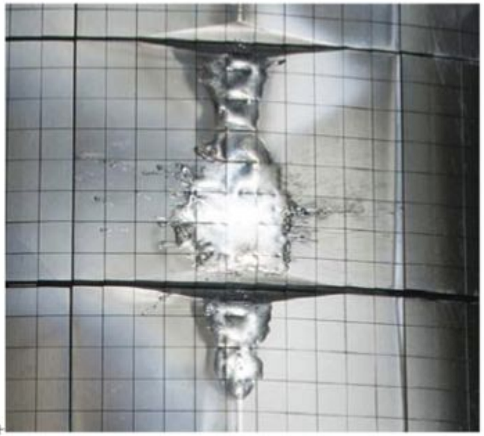
Disruptions and runaway electrons

- ITER disruption mitigation scheme using shattered pellet injection:
  - **First line of defense:**
    - TQ & CQ heat loads mitigation
    - CQ EM load mitigation
    - RE avoidance
    - Which species and quantities should be used?
    - Are all goals attainable simultaneously? (mitigating forces without creating RE?)
  - **Second line of defense:**
    - In-flight RE beam energy dissipation **Main topic of the present talk.**
- Runaways: One of the most difficult disruption consequences for future tokamaks

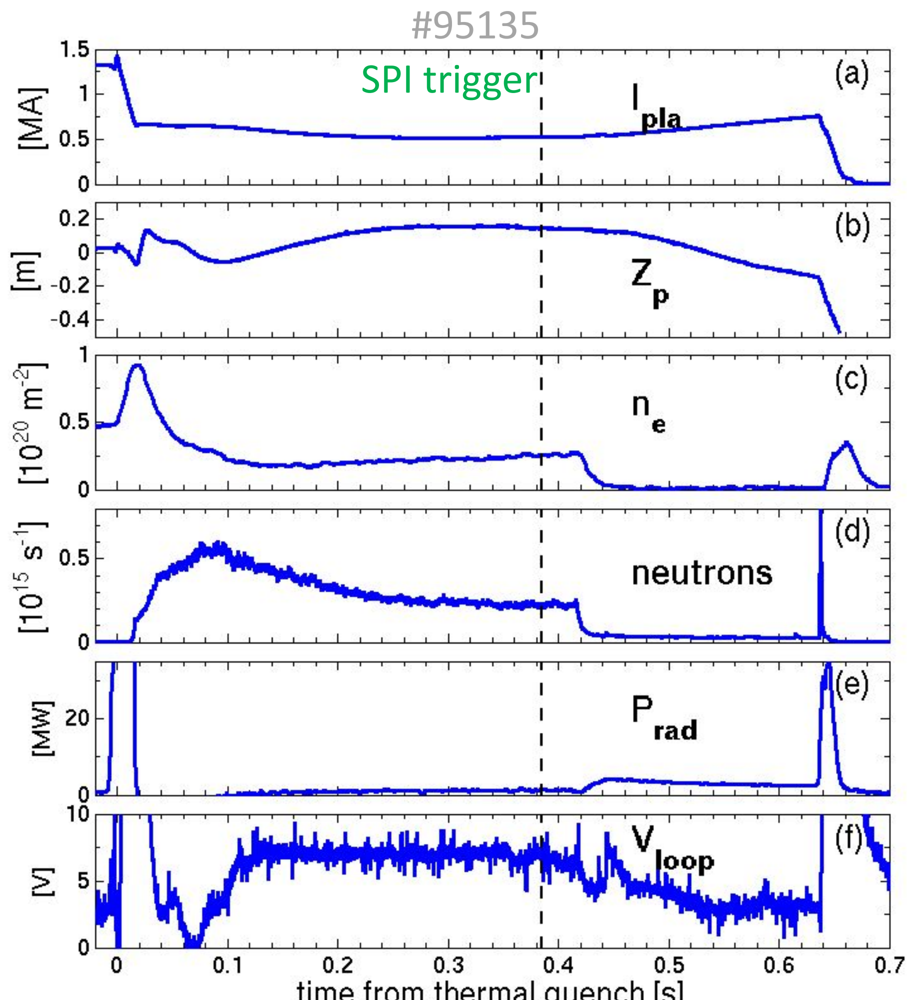
Runaway impact on Tore Supra

JET Beryllium limiters – [G. Matthews, Physica Scripta 2016]



The low-Z benign termination scheme

- **High-Z mitigation: not efficient**
- **Low-Z (D_2 or H_2): current increases** shortly after shattered pellet arrival
  - Similar observations on DIII-D *[Paz-Soldan PPCF 2019],* Compass *[Mlynar PPCF 2019]*, TCV *[Sheikh EPS 2023],* AUG *[Pautasso NF 2020]*, FTU
- Neutrons and HXR drop
- Electron density drops to <10^{18} m^{-2}
  - Plasma **recombination**
- **Argon used to trigger the beam flushed-out**
  - VUV dominated by D lines *[Sridhar PhD]*
- **Runaways disappear in a few ms**
  - Synchrotron emission stops
  - Large neutron/HXR spike
  - Huge **MHD** burst
  - **No visible localized damage**



What are the limits of the benign termination scenario?

Outline

- Introduction
  - Runaways
  - Benign termination scenario
  - Phenomenology: types of runaway beams and their termination

- Operational space for benign termination
  - Influence of the HighZ/LowZ ratio
  - H_2 vs. D_2
  - Current at collapse vs. current at disruption
  - High D_2 amounts
  - Neutral pressure and reionization events

- Final collapse: mechanisms at play
  - MHD growth rate
  - Conversion from magnetic to kinetic energy.

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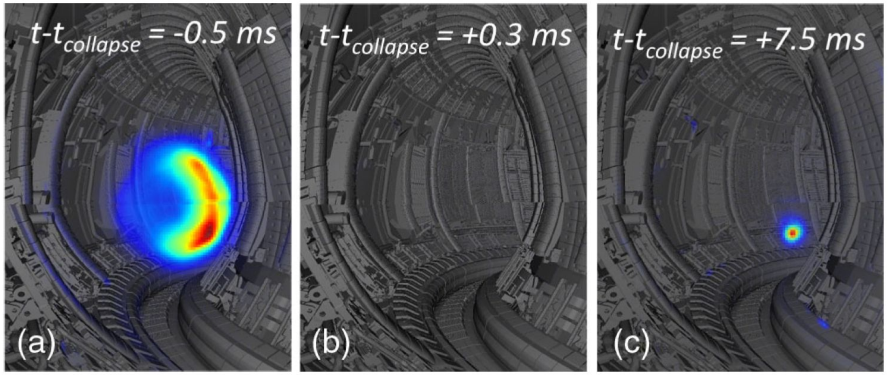
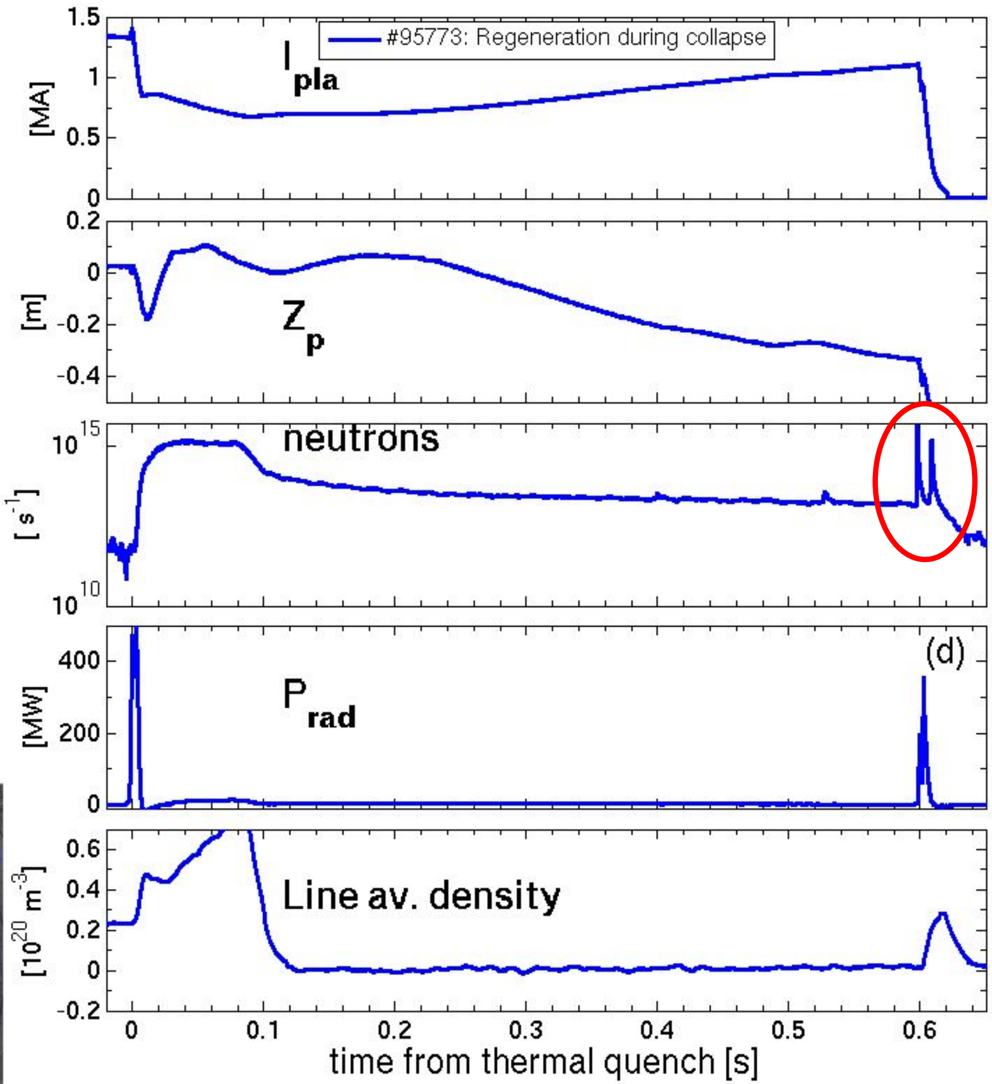
Regeneration during final collapse

- First step when moving across the boundary of the benign termination's operational space.
- Reappearance of a small beam during the final collapse
- Runaways are re-created during the current quench, just like they would in a standard disruption.
- Visible as an additional spike on neutrons
- Increase heat loads

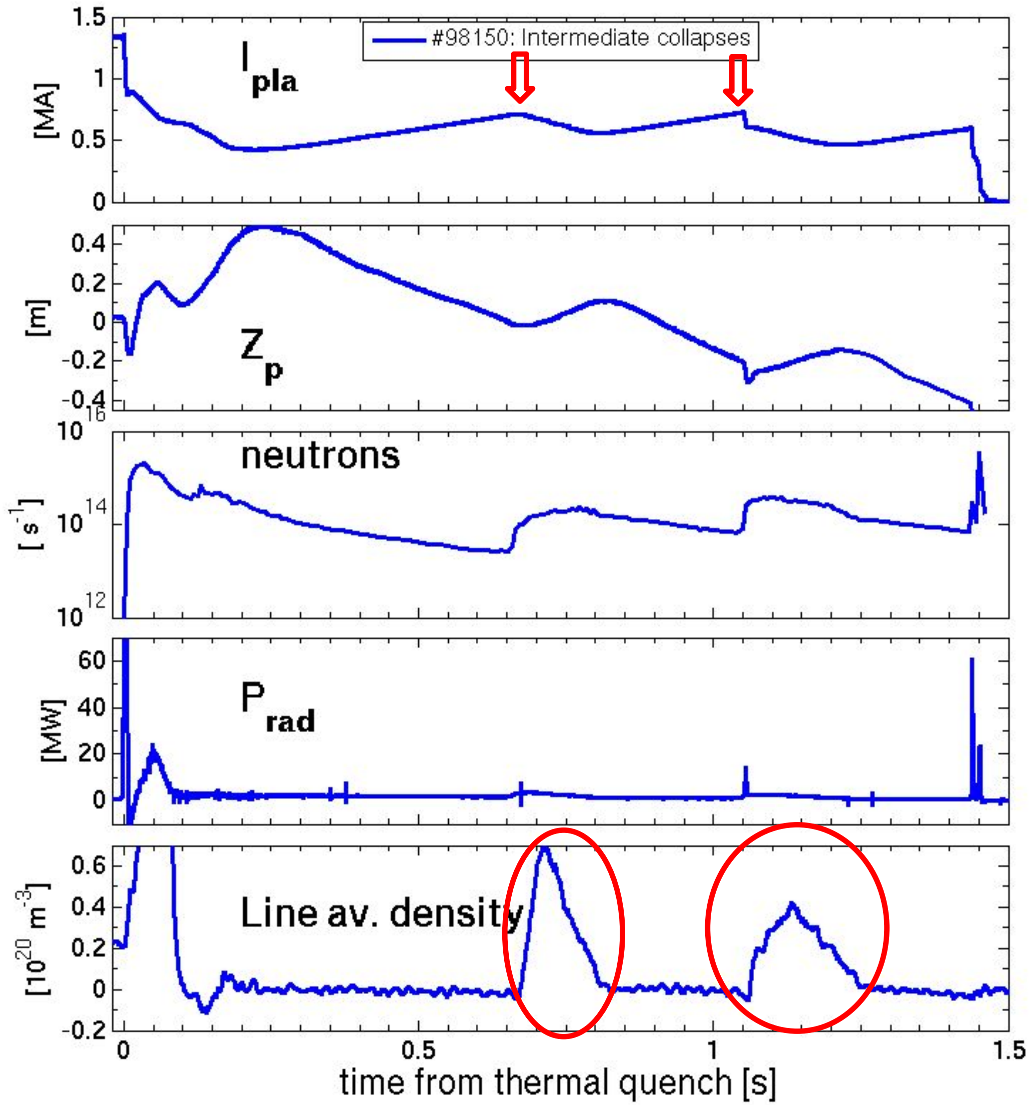




[Reux et al., PRL 2021]

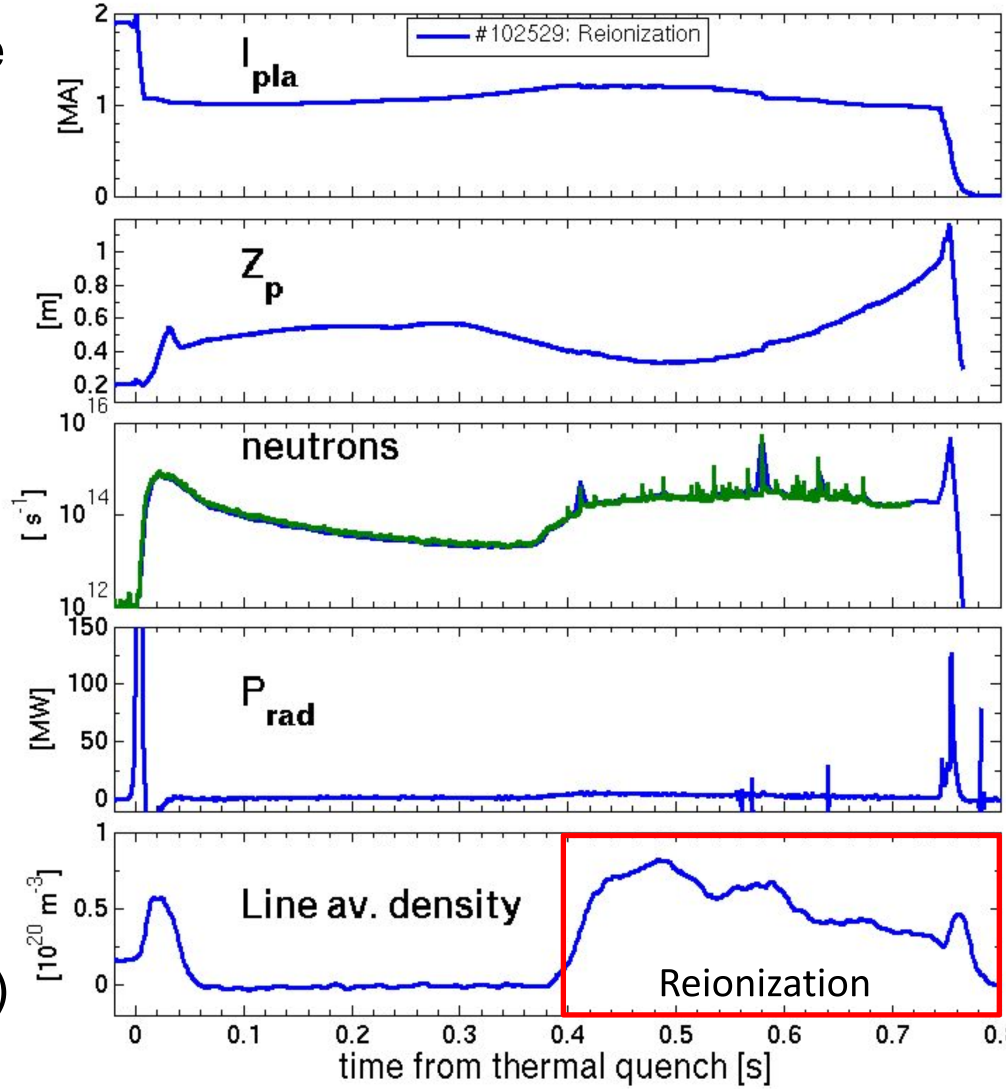
Intermediate collapses

- Intermediate collapses lead to reionization and regeneration of a new runaway beam
- The final collapse is usually less benign, even if the plasma recombined in between.
- Intermediate crashes may be caused by MHD, or may cause instabilities if spontaneous transient reionization occurs
- On average less benign than the small regeneration case



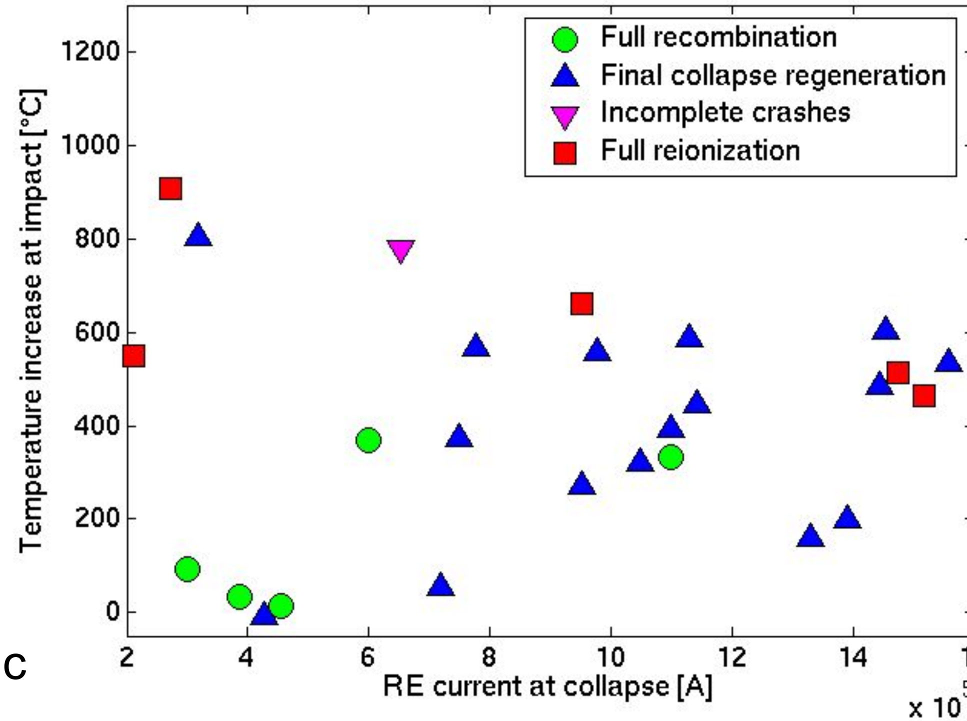
Full reionization

- Full reionization occurs when the conditions are no longer adequate for a benign recombined plasma or if the initial injection is not sufficient
- If the termination occurs during this phase, large heat loads are expected
- Similar to the termination of a high-Z dominated RE beam
- Final collapse has with multiple neutron spikes
- REs are continuously regenerated during collapse (no full stop of synchrotron emission)



How to qualify the benign character?

- Temperature and heat flux should be the main figure of merit, but:
- Runaway do not always hit the same spot. Heat loads depend on the geometry of the impacted PFC
- IR data is a mix of various light-emitting phenomena
  - Toroidal asymmetries in the heat deposition profiles
  - Bremsstrahlung from the companion plasma
  - Synchrotron light from REs
  - Reflections of synchrotron light
  - Pre-disruption ohmic heat flux
  - Ohmic heat flux by the final ohmic collapse.



- Good proxy: the type of companion plasma. In decreasing order of benignness: fully recombined, small regeneration, intermediate collapses, full reionization

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- Final collapse: mechanisms at play
  - MHD growth rate
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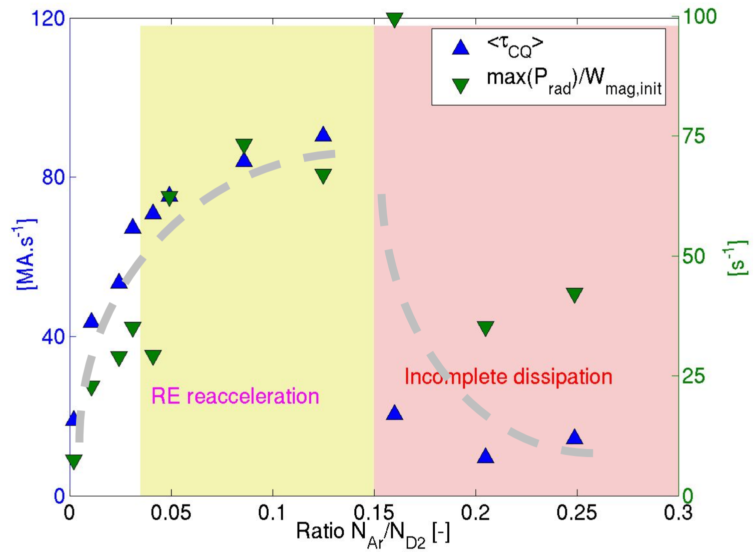
Ratio of high-Z to (low-Z+high-Z) material

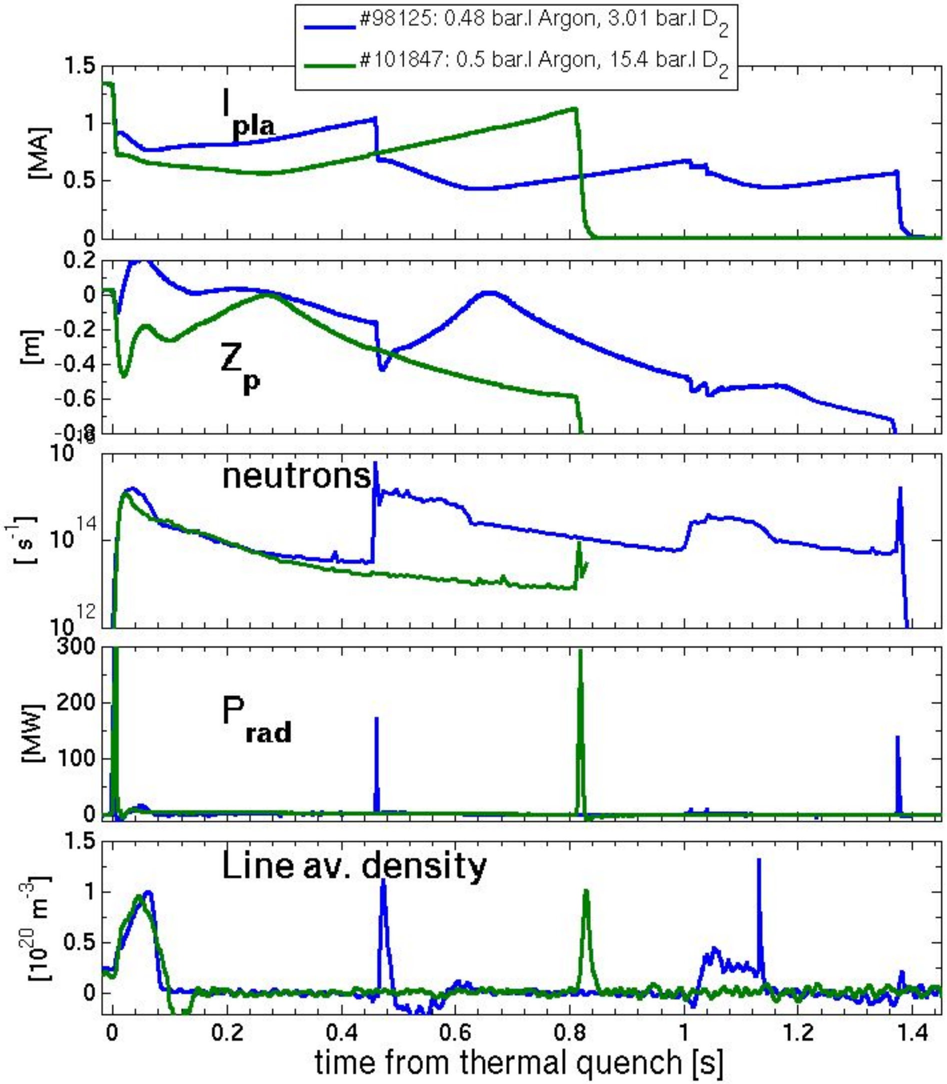
- Earlier datasets showed that for a given D_2 amount, increasing the argon fraction leads to increasingly less benign terminations (regeneration then intermediate collapses)
- Is it only about the ratio, or the total amount of argon?



[Reux et al., PPCF 2022]

Ratio of high-Z to (low-Z+high-Z) material

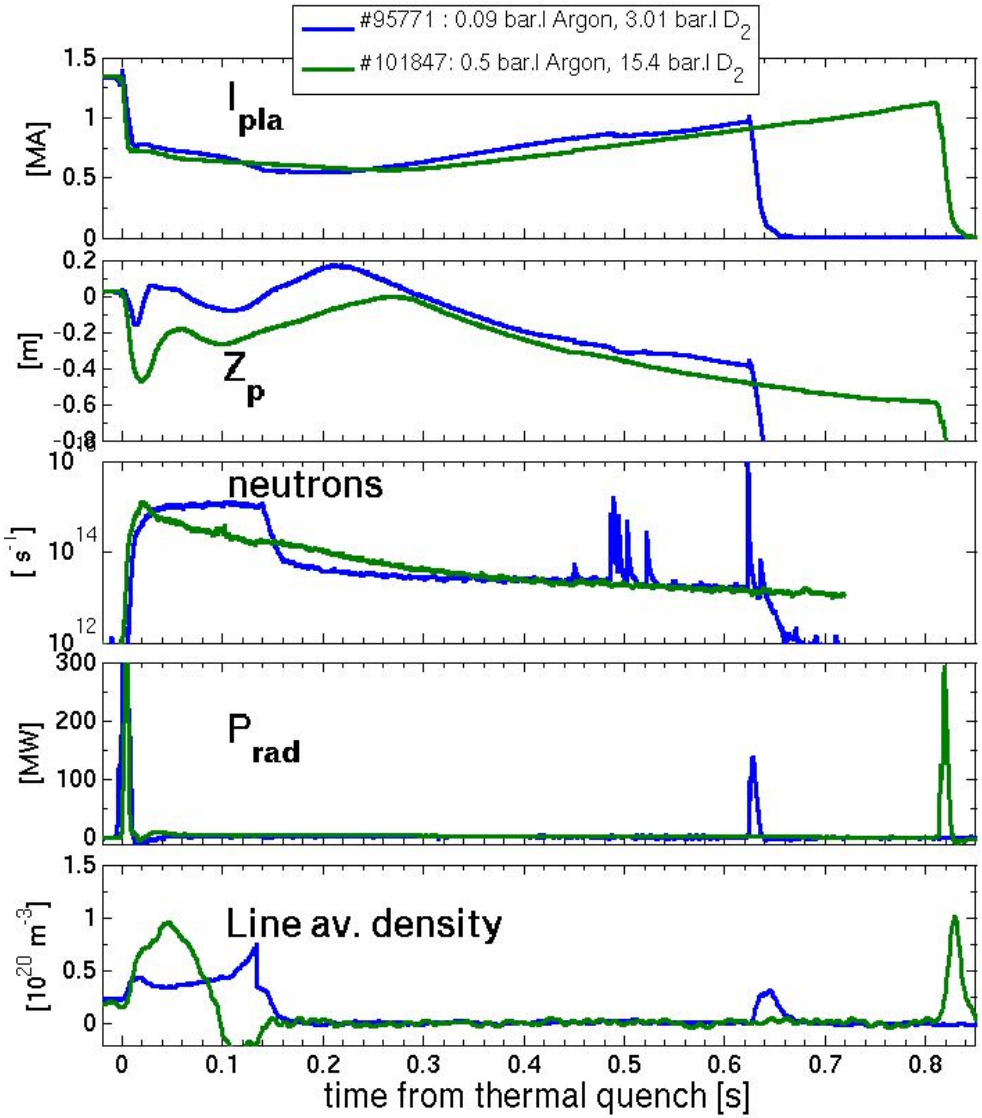
- Earlier datasets showed that for a given D_2 amount, increasing the argon fraction leads to increasingly less benign terminations (regeneration then intermediate collapses)
- Is it only about the ratio, or the total amount of argon?
- Comparison of the same amount of argon injected but two D_2 quantities: 3 bar.l (#98125 – intermediate crashes, non-benign) and 15.4 bar.l (#101847 - benign)



A previously non-benign termination can be made benign provided the high-Z fraction is low enough

Ratio of high-Z to (low-Z+high-Z) material

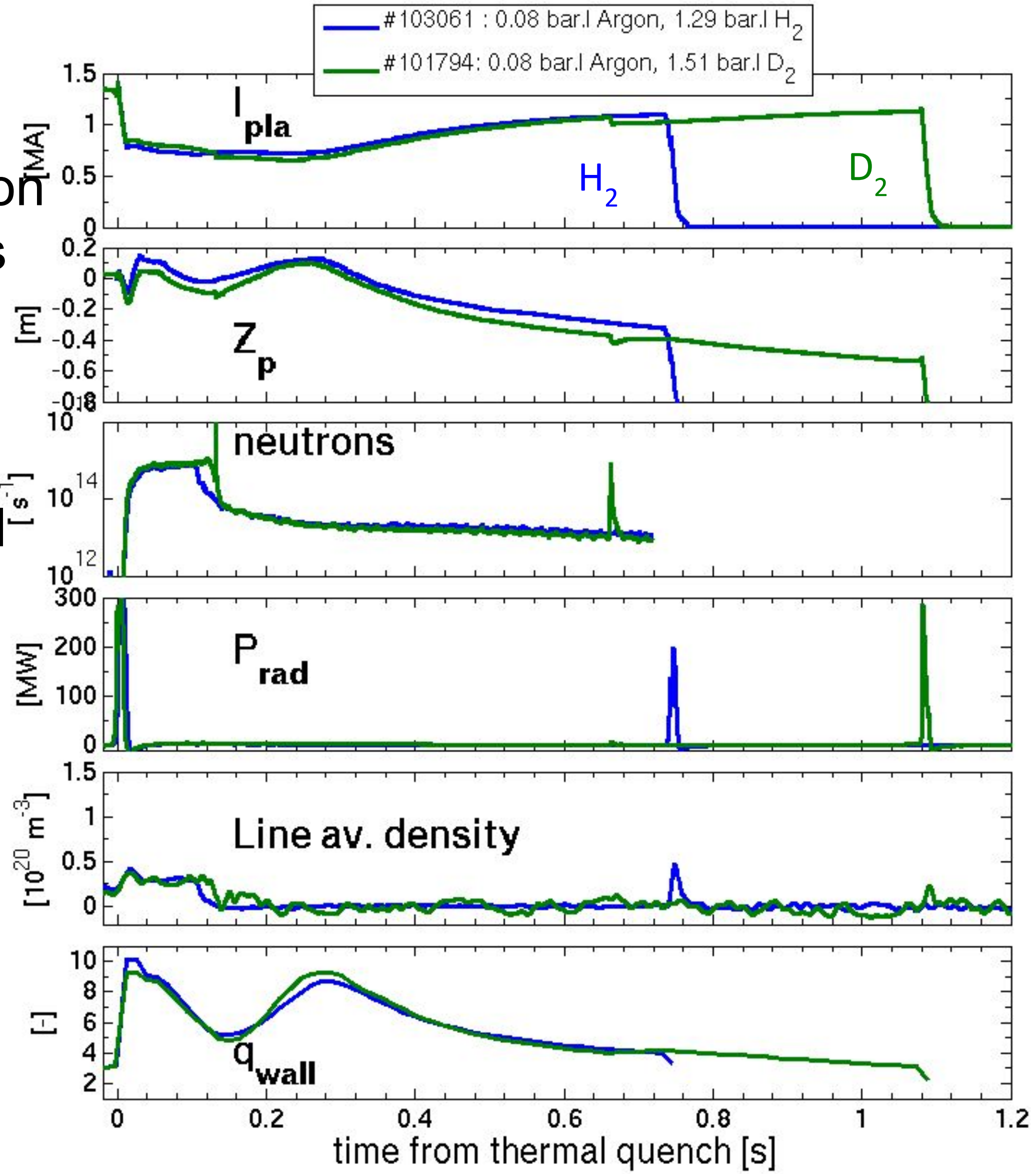
- Using the same high-Z fractions (3%) but different absolute quantities lead to the same kind of RE-beam and companion plasma evolution
- Same current ramp rate, similar neutrons
- Slight difference on the current at collapse, because of the slightly different position time trace
- Both collapse on q_{edge} = 3.



Same high-Z fractions lead to similar RE beams and companion plasmas, and similar collapses

Hydrogen vs. deuterium

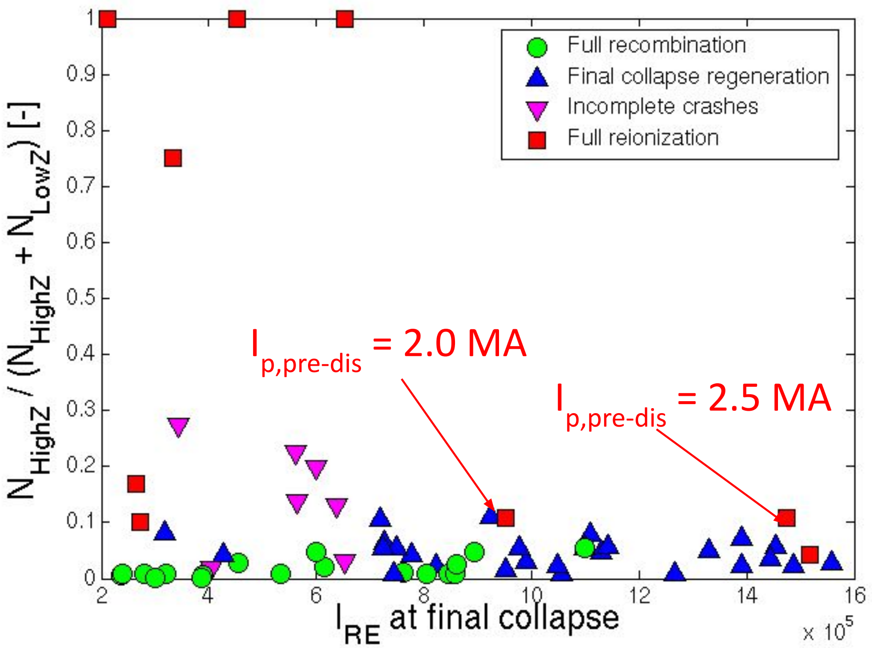
- Hydrogen is ITER-relevant
  - The ITER DMS uses hydrogen
- H_2 being lighter, its heat conduction properties and transport dynamics are different from D_2.
- Exact repeats of pulses in H_2 and D_2
- 3 pairs of pulses in the dataset: all D_2/H_2 pairs are quite similar. Example 103061 vs. 101794.
- On difference: one dies at q_{wall} =4 and the other at q_{wall}=3.
  - Frequent jitter.



H$_2$ and D$_2$ have globally the same behavior.

Influence of the plasma current

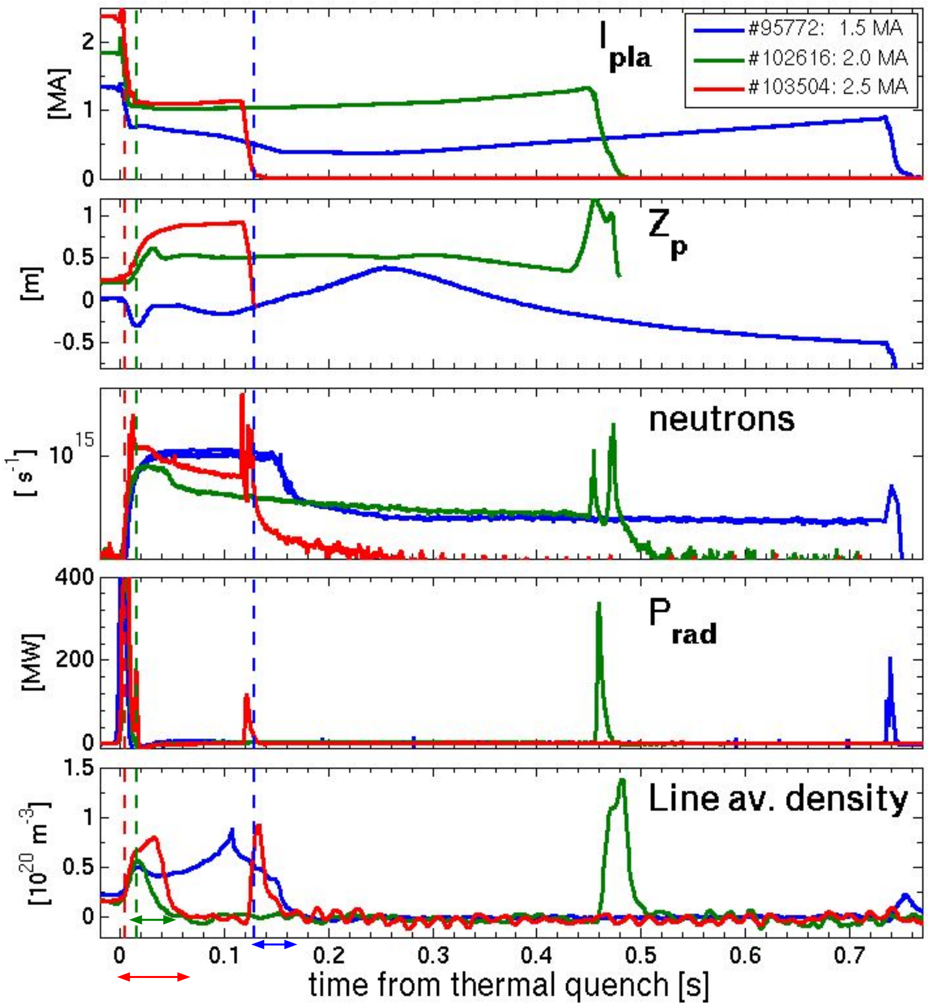
- The high Z fraction threshold above which the termination is no longer benign depends on the current *[Sheikh et al., EPS 2023].*
- The scaling in current is not as clear on JET as it is on AUG/TCV.
- But reionization at low high-Z fractions happen mainly at high current (and high pre-disruption currents – see next slides)
- Confusion factor: Some reionizations happen at low high-Z fraction, some plasmas stay recombined at high high-Z fractions



Collapsing the beam at high current makes non-benign termination more likely.

Effect of the pre-disruption current

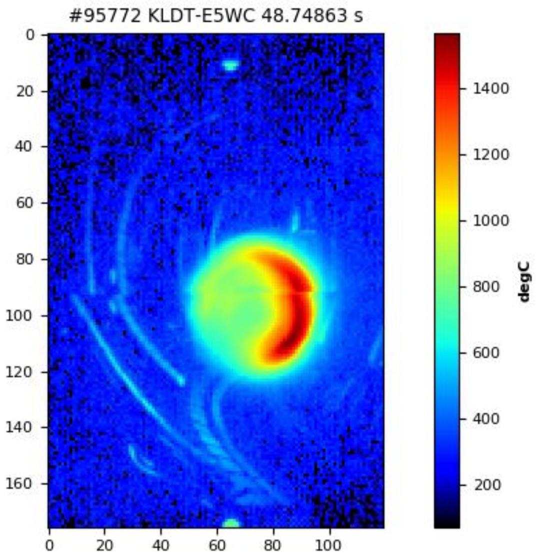
- Same High-Z fraction, same argon amounts, same deuterium amounts, but scan in pre-disruption current: 1.5 MA (base), 2.0 MA, 2.5 MA
- The runaway beam is harder to “catch” in position as the current increases
- RE beam starts at a higher current.
- Neutrons remain higher
- Recombination takes slightly longer.
- More intense RE regeneration during the final collapse

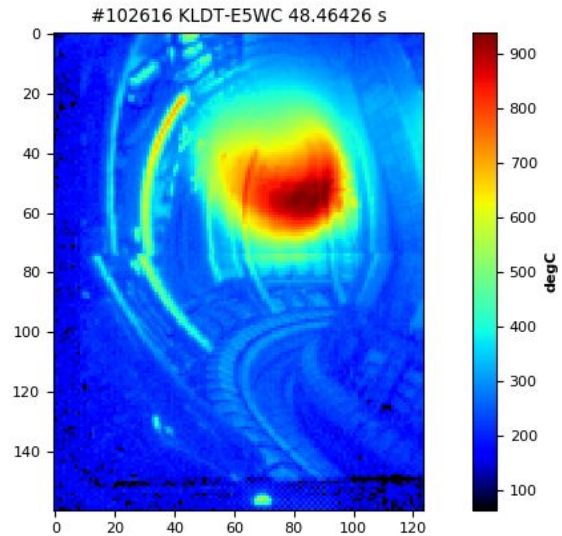


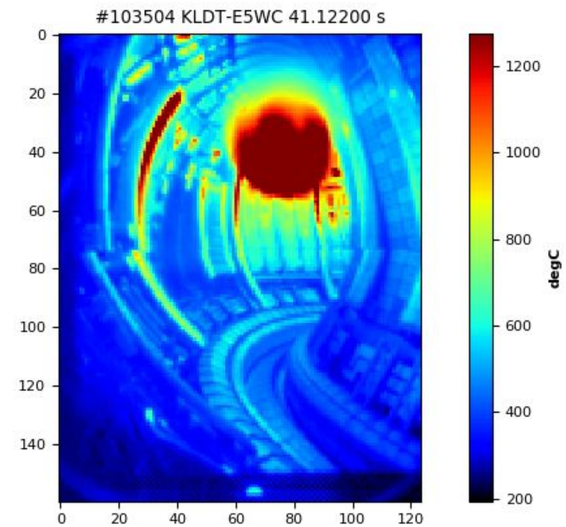
Pre-disruption current makes benign termination more difficult.

Effect of the pre-disruption current

- IR synchrotron images of 3 various pre-disruption currents







- 1.5 MA: only a small beamlet
- Very faint heat loads
- Very fast disappearance

- 2.0 MA: larger beamlet

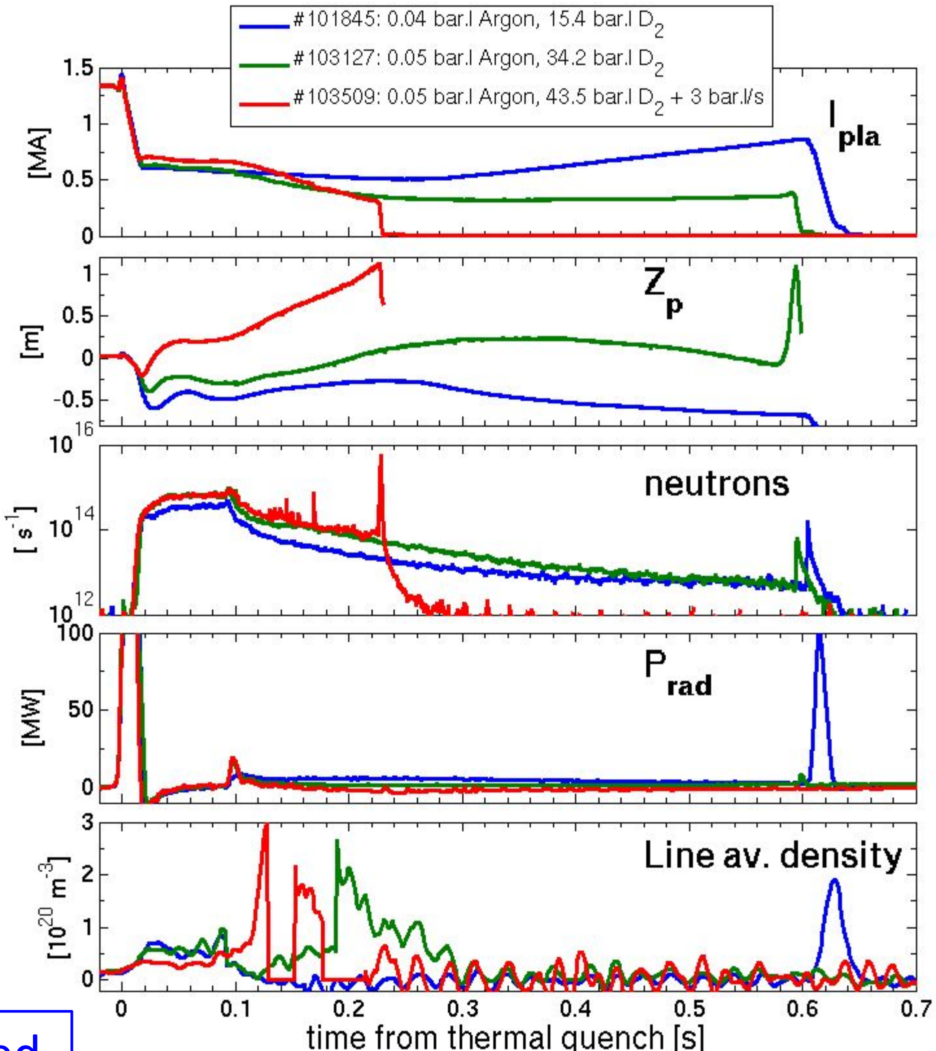
- 2.5 MA: longer beamlet, larger heat loads.
- Slow dissipation

Very high D_2 amounts

- DIII-D has observed an upper limit in the amount of deuterium to achieve benign termination (0.43 bar.l)

- Large injection cases struggle to keep the RE current up.
- Not entirely benign termination

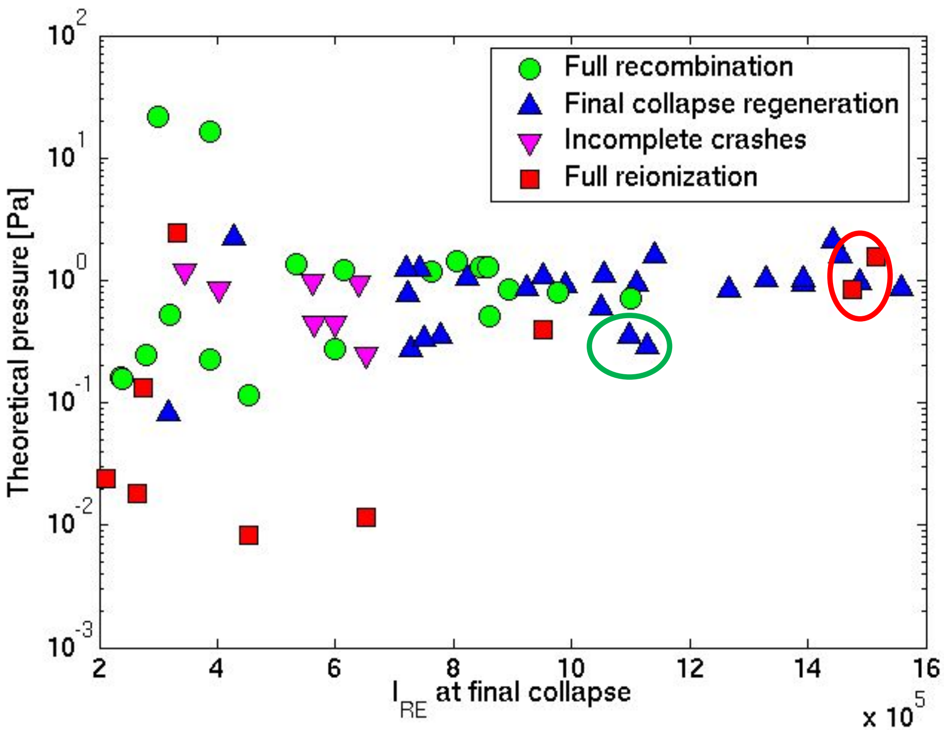
- Largest injection at JET is 16 times larger than the one at DIII-D (normalized to VV volume), but only yields minor reionization



Very high low-Z amounts lead to enhanced RE-plasma collisionality, making the beam less benign at termination

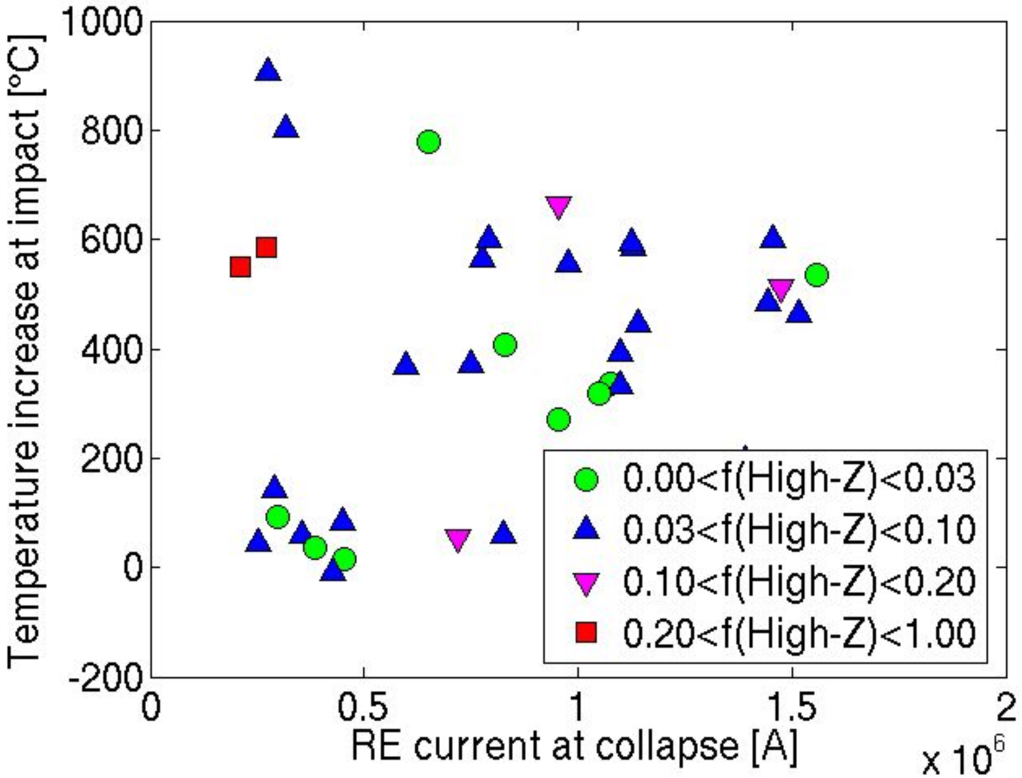
Neutral pressure

- No obvious separation between the fully recombined plasmas and the others solely based on neutral pressure
- Some reionizations happen at high pressure while some recombinations work at lower pressures
- Pressure thresholds could be understood as a sharp boundary limit, while the high-Z ratio makes the rest of the continuum



Scaling of the impact temperature

- Two major parameters: high-Z ratio and runaway or pre-disruption current
- Is it possible to combine them together to get a scaling of the damage (temperature rise) at impact?
- Not obvious. Other confusion factors probably remain.



Major parameters for the benign termination are the current and the high-Z ratio but are not the only ones

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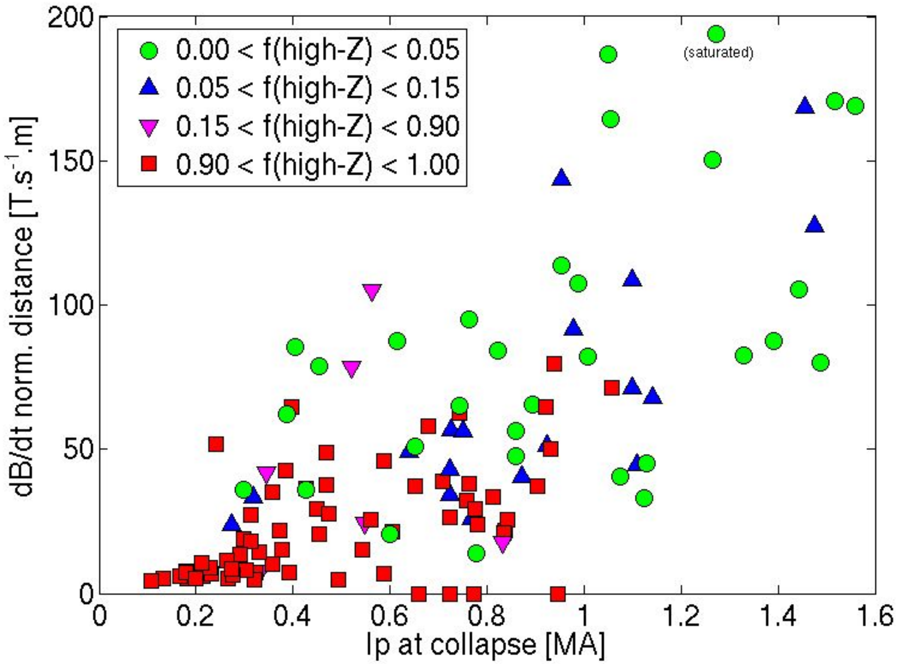
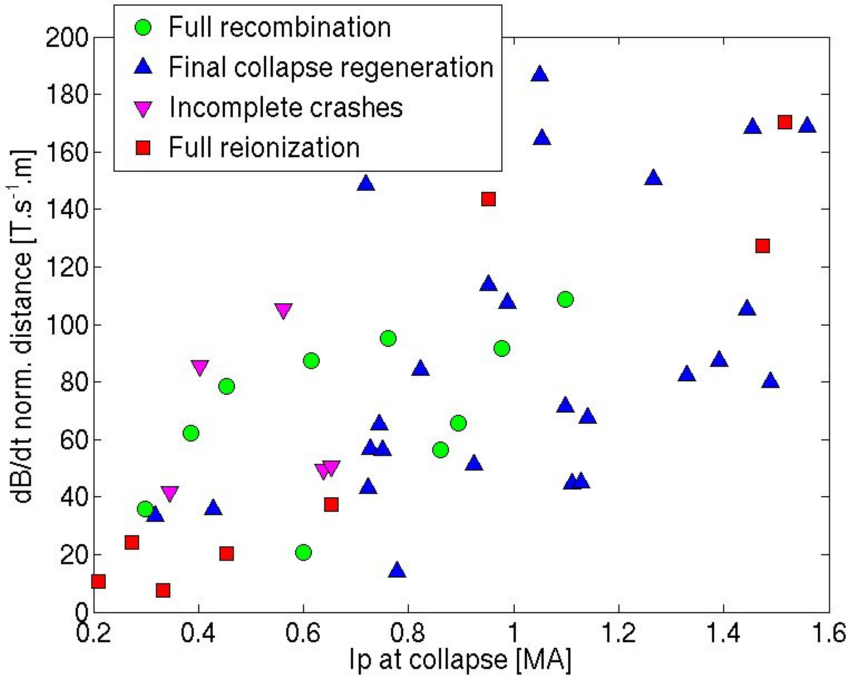
Final MHD mode growth rate

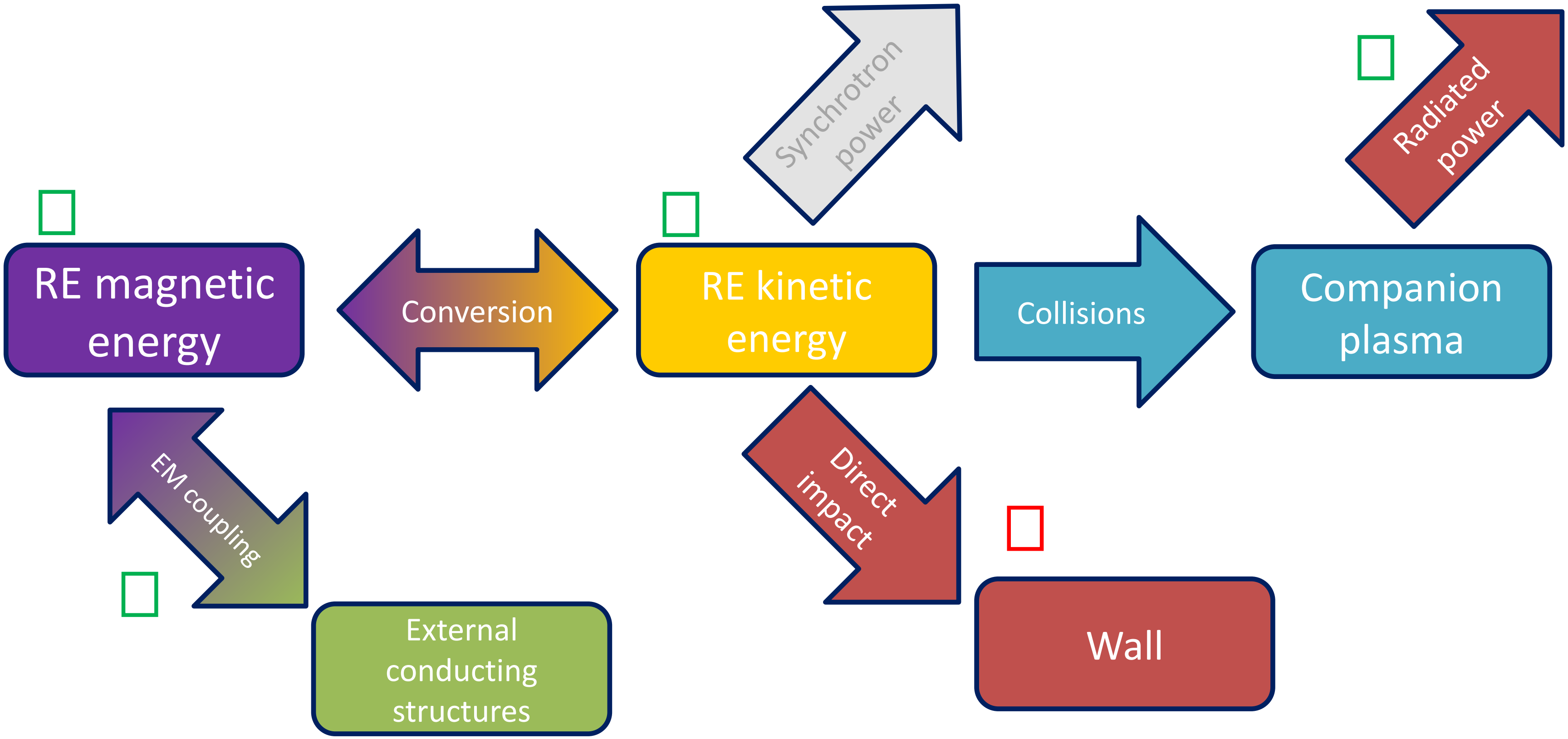
- A lot of the “clean” plasmas i.e. with a very low ratio of high-Z, end their RE beams with large MHD growth rates
- But not all of them: some clean plasmas produce benign termination without a large MHD event.
  - MHD plays a role, but not exclusive.
- No clear correlation between the type of plasmas (recombined, with reacceleration, reionized) with the final MHD growth rate





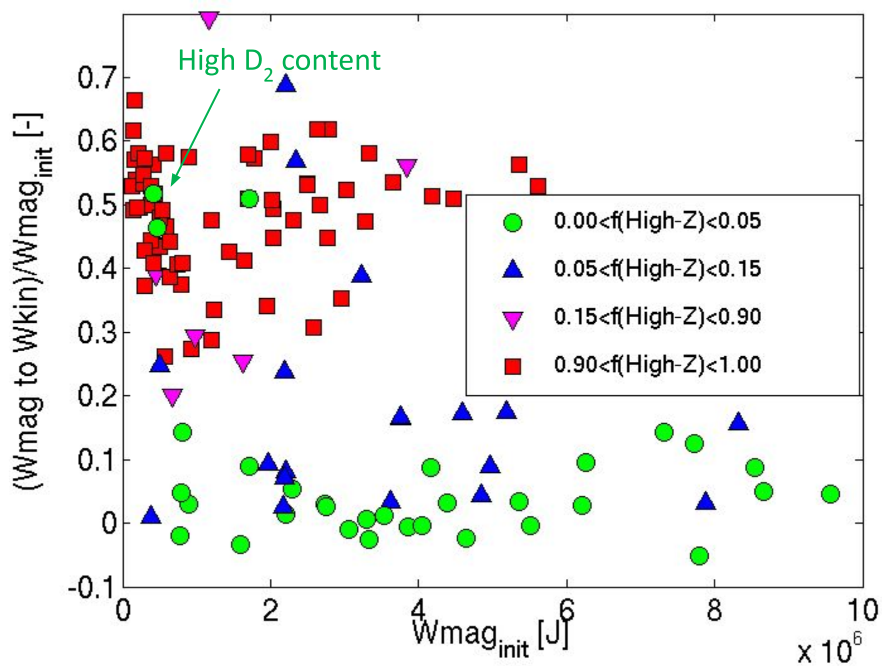
Conversion from magnetic to kinetic energy: how to reaccelerate runaways during the final collapse

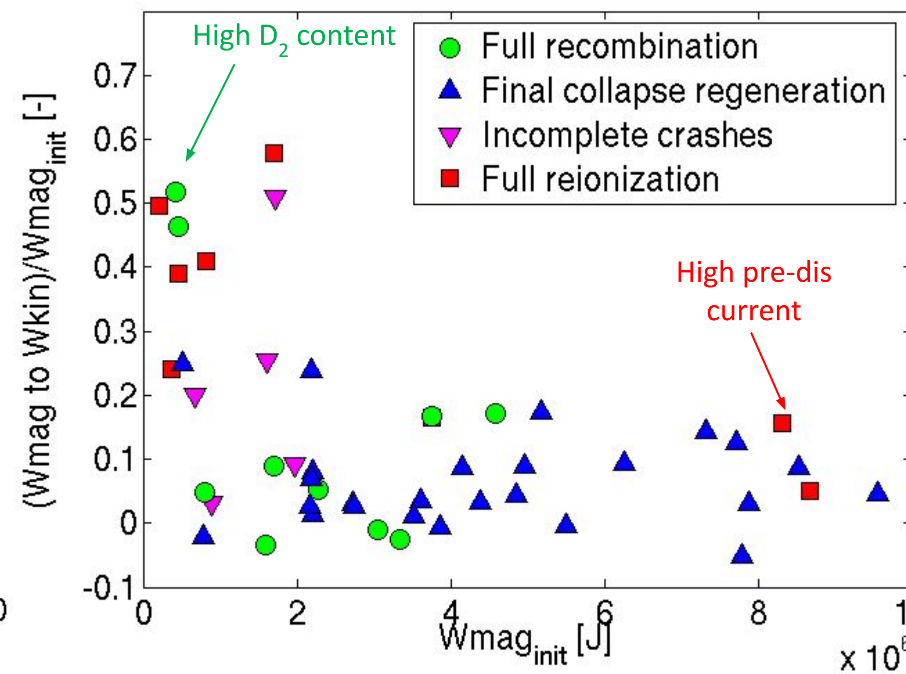
- Calculation of the fraction of the initial runaway magnetic energy converted into kinetic energy
- Elaborated from the method proposed in *[Loarte NF 2011]*
- Conversion happens when HXR bursts are recorded while current decreases



Conversion from magnetic to kinetic energy

- The ratio of conversion of magnetic to kinetic energy is well correlated with the high-Z fraction: “clean” plasmas tend to convert less magnetic energy into RE kinetic energy, saving some damage.
  - Some outliers: high D2 content converts a lot
- Scaling holds when classified by types: fully recombined plasmas tend to convert less





Additional thoughts

- Time may be an important parameter.
- Recent recombined beams have been created using an SPI very close to the beginning of the runaway plateau in order not to miss them.
- Evidence that the runaway energy decreases with time:
  - Do early injections influence the termination dynamics by making recombination harder?
- Evidence on JET that the RE energy decreases with time

- At least one pulse deposits heat from a regenerated beam while moving downwards. As a result, the RE heat flux is spread over a larger area another potential method to further mitigate the beam.

Conclusions and perspectives

- Important parameters to achieve benign termination are
  - the high-Z fraction in the companion plasma
  - The current either pre-disruption or at collapse
  - Possibly neutral pressure through a threshold effect, within which the high-Z fraction plays the major role.
- No sharp limit to the efficiency at higher D_2 amounts, although the efficiency degrades.

- The MHD growth rate is one of the features of benign termination, although not entirely necessary nor sufficient.
- Conversion of magnetic energy into RE kinetic energy is still well correlated with the high-Z fraction and the type of companion plasma

- New round of experiments on next Monday at JET (3.0 MA)
- A lot of data analysis on the way:
  - RE energy from HXR spectrometers, more detailed IR impact analysis
- Modelling to be started.