Runaway Electron Beam Suppression Using Impurity Flushing and Large Magnetohydrodynamic Instabilities

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*see affiliations in last slides

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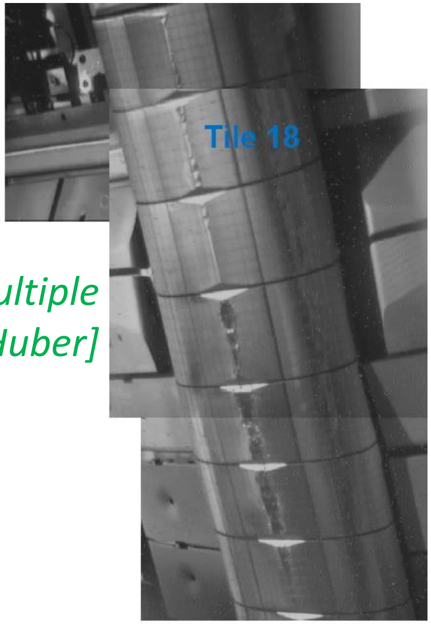
Runaway electrons during disruptions

- One of the most difficult consequences of tokamak disruptions
- Large uncertainties on RE generation on ITER
  - Due to the avalanche amplification factor *[Rosenbluth NF 1997], [Vallhagen JPP 2020]*
  - Some primary mechanisms still subject to uncertainties: tritium seed, Compton scattering, etc.
- Currents of several MA at 10-20 MeV may be reached
  - ➔ Significant damage on PFCs if left unmitigated

Runaway impact on Tore Supra



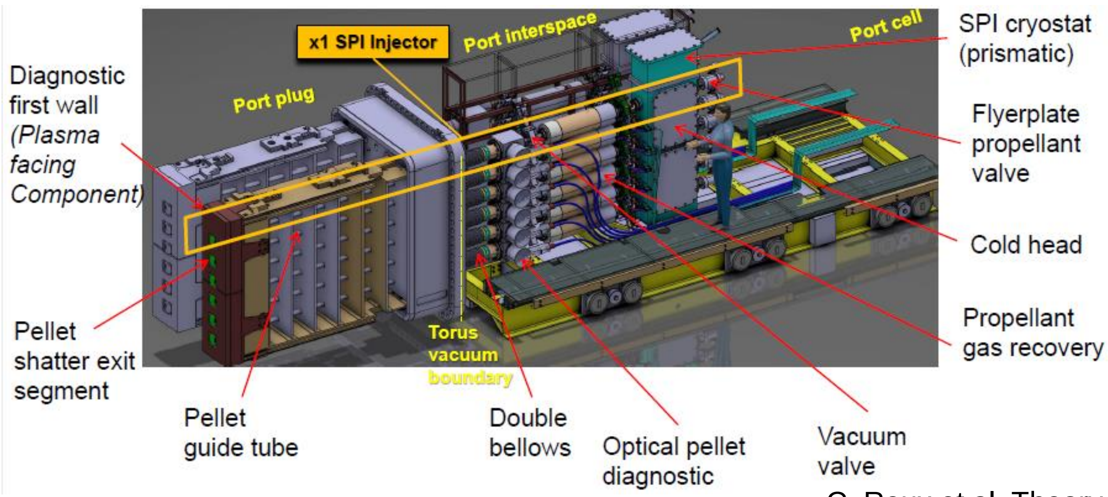
JET in-vessel inspections – multiple runaway impacts [V. Huber]

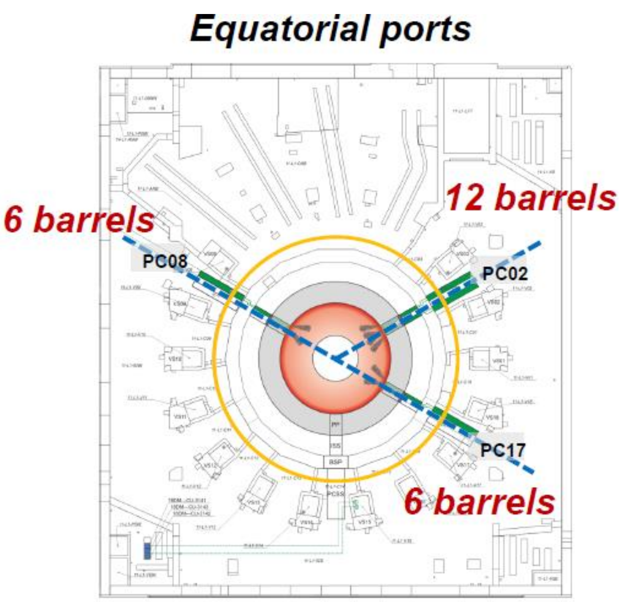
The ITER disruption and RE mitigation scheme

- Based on Shattered Pellet Injection (SPI)
- 24 barrels in equatorial ports + 3 barrels in upper ports
- **First line of defense:**
  - TQ & CQ heat loads mitigation
  - CQ EM load mitigation
  - RE avoidance

  ➔ Which gas mixture and quantities should be used?

  ➔ Are all goals attainable simultaneously?
- **Second line of defense:**
  - In-flight RE beam energy dissipation



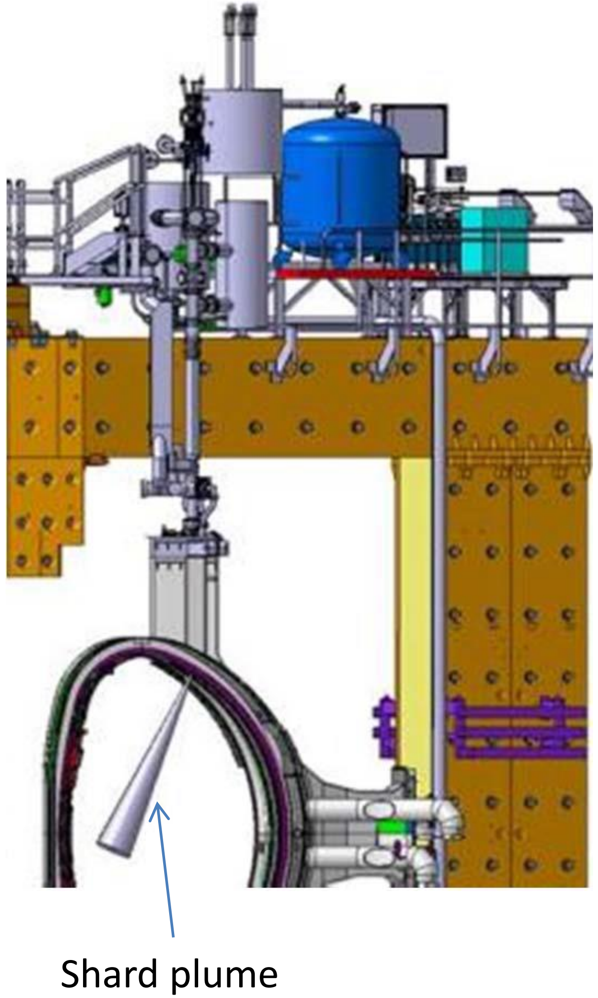


[M. Lehnen, IAEA FEC 2018]

The JET SPI system

- Installed in 2018-2019 through an international Eurofusion-US DOE-ITER-JET Operator collaboration *[Baylor NF 2019]*

- 3 barrels: 12.5, 8, 4 mm pellet diameters
- 10^{21}-10^{23} atoms per pellet (10-600 Pa.m^3)
- Pellet composition:
  - D_2, Ne, Ar, D_2+Ne, D_2+Ar mixtures
  - Mechanical punch for Argon pellets
- Pellet speed: 100-500 m/s, depending on size, species
- Flight time 20-50 ms
- Independent firing of all barrels (+/- 0.2 ms)



Outline

- Introduction
- Mitigating a RE beam
  - High-Z SPI
  - D_2 SPI
- The “D_2 effect” : development of the MHD instability
  - Pre-collapse conditions
  - Mode characterization
- The “D_2 effect” : runaway regeneration during collapse
  - The final collapse: analysis and modelling
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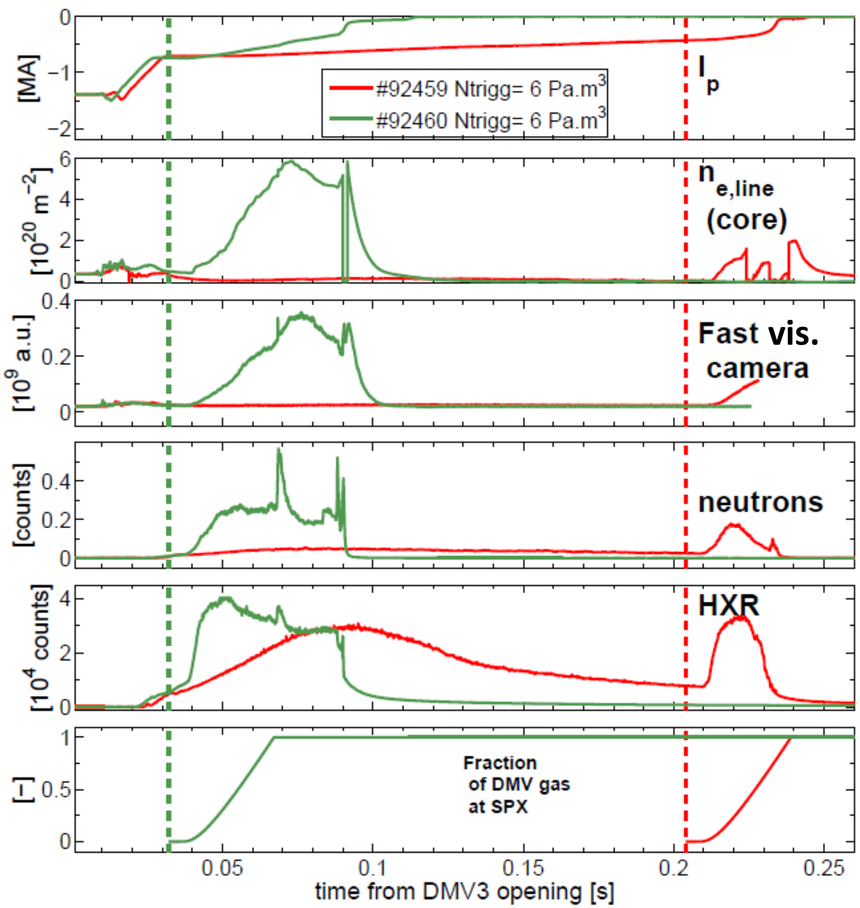
Previous results on runaway mitigation at JET

- Typical runaway scenario:
  - argon injection from a disruption mitigation valve (6 Pa.m³)
  - Limiter plasma
- High Z massive gas injection **accelerates the RE current decay**
  - Free electron density increases
  - HXR/neutrons increase ➔ enhanced collisions/dissipation
  - Destabilizes the beam vertically
- Only works when the **companion plasma electron density is low**
  - Higher density companion plasma: no effect due to penetration shielding and density saturation

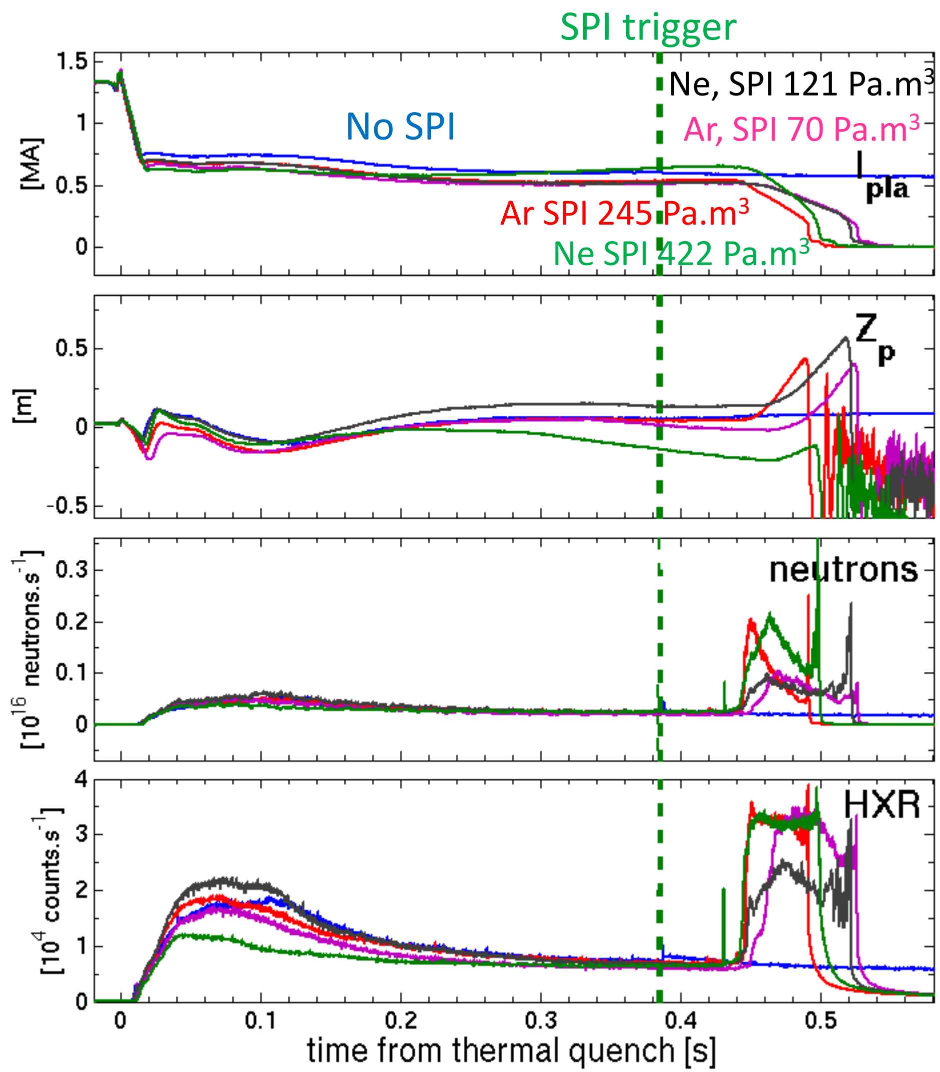


[Reux APS 2017]

High-Z MGI accelerates beam current decay, up to a certain companion plasma electron density

Runaway suppression: high Z injections

- Mitigation experiments: fire a Shattered Pellet in the middle of a runaway beam
- Target: ~ 600 kA runaway beam, **low density companion plasma** ($n_{e,l}$ ~ 2×10^{19} m^{-2})
- Tested:
  - SPI 245 $Pa.m^3$, argon
  - SPI 70 $Pa.m^3$, argon
  - SPI 422 $Pa.m^3$, neon
  - SPI 121 $Pa.m^3$, neon
- In all cases:
  - Beam successfully **shortened** (500 ms instead of 1 s)
  - Linear ramp-down rate 4.8-9 MA/s (larger with bigger pellets)
  - Increase of HXR & neutron rate
  - **Vertical destabilization**
  - **Final impact with PFC heating**



High-Z SPI accelerates the RE current decay but does not prevent impacts

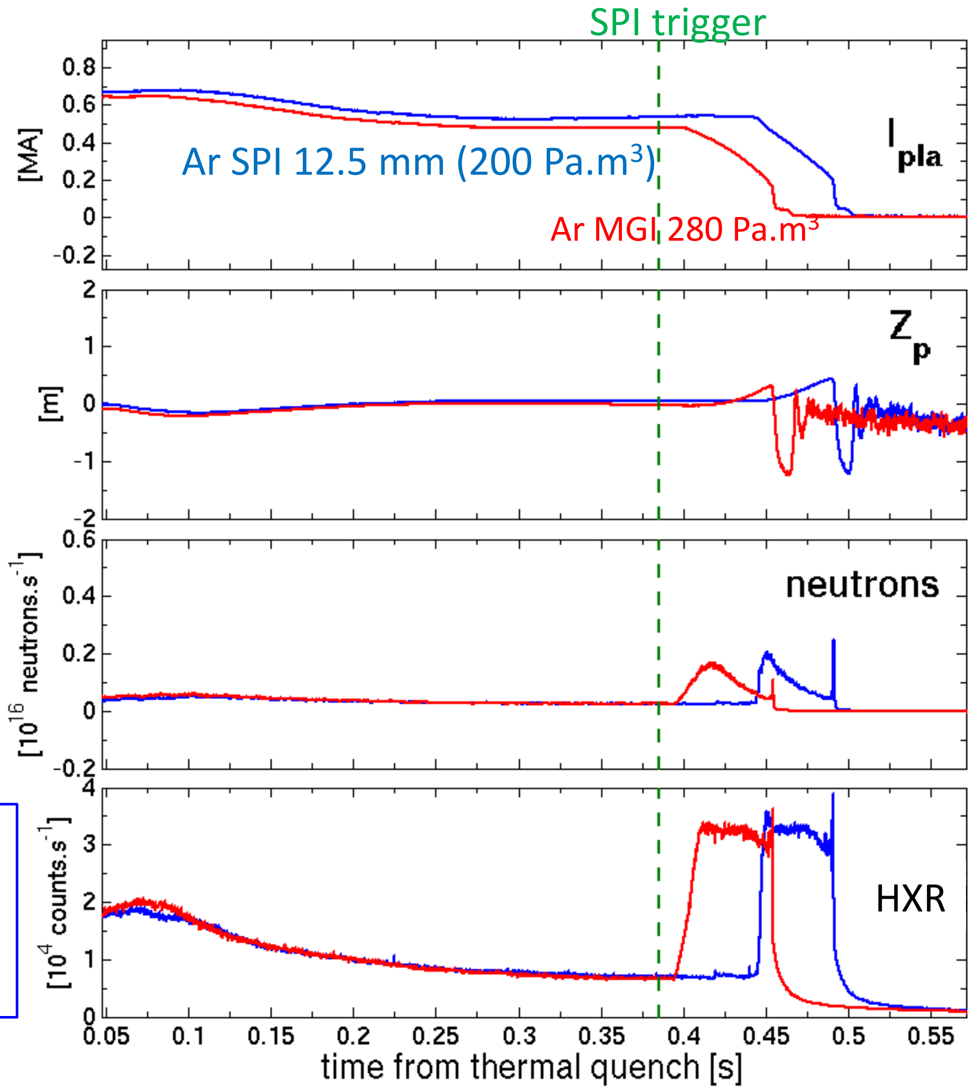
Runaway suppression : SPI vs. MGI

- On the same target runaway beam: compare MGI and SPI in similar conditions.

- SPI 12.5 mm (200 Pa.m^3), argon:
  - Beam successfully shortened. (~500 ms instead of 1.0 s).
  - Linear ramp-down rate 6.3 MA/s
- MGI 280 Pa.m^3, argon:
  - Beam successfully shortened
  - Linear ramp-down rate ~ 5.2 MA/s.

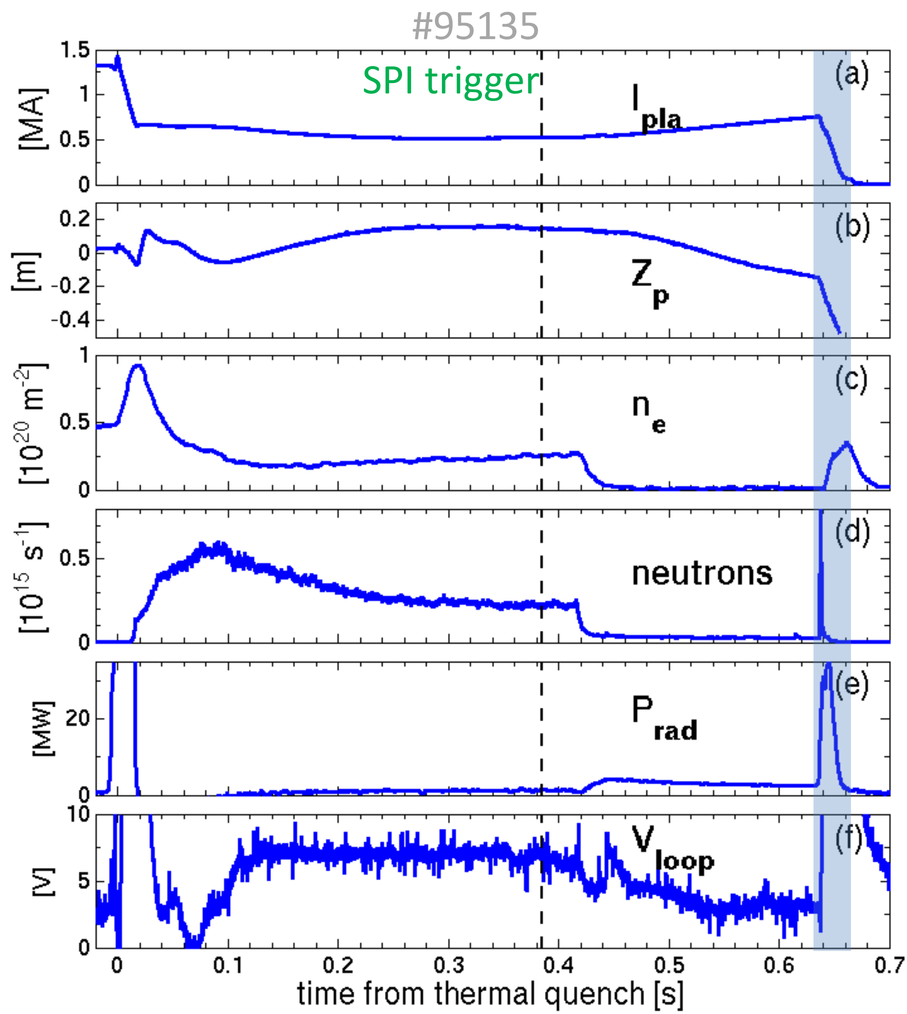
- In **both** cases: increase of neutron rate & HXR, vertical destabilization, heat loads on PFCs

No large difference between MGI and SPI in beams with low-density companion plasmas



Runaway beam suppression :D_2 SPI

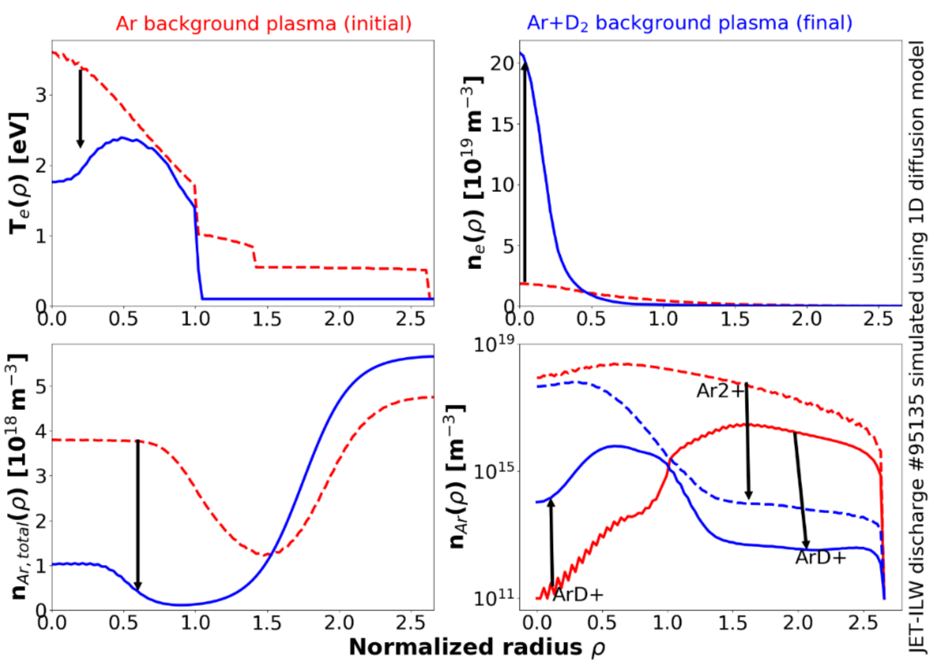
- **Current increases** shortly after SPI
  - Similar observations on DIII-D *[Paz-Soldan PPCF 2019],* Compass *[Mlynar PPCF 2019]*, AUG *[Pautasso NF 2020]*, FTU
- Neutrons and HXR drop
- Electron density drops to <10^{18} m^{-2}
  - Plasma **recombination**
- V_{loop} decreases
  - **Argon flushed-out**
  - VUV dominated by D lines *[Sridhar PhD]*
- P_{rad} increases
- **Runaways disappear in a few ms**
  - Synchrotron emission stops
  - Large neutron/HXR spike
  - Huge **MHD** burst
  - **No visible localized damage**
- Current decay similar to an **ohmic CQ**



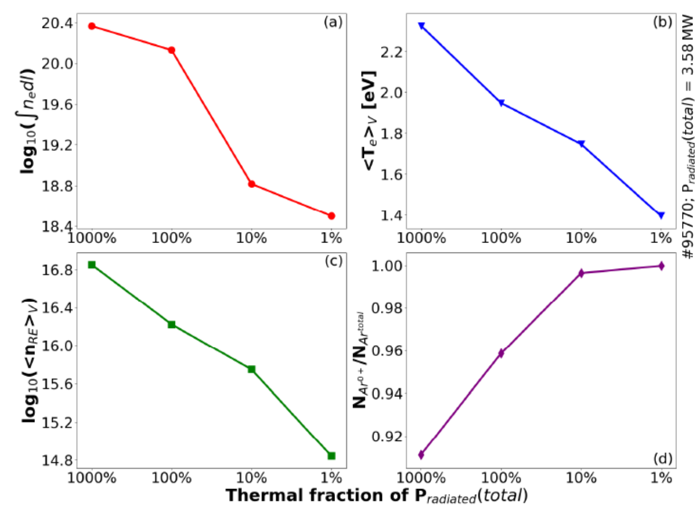
D_2 SPI leads to a benign termination of the RE beam.

Modelling the effect of D_2 SPI on the companion plasma

- Modelling the D_2 effect using a 1D diffusion model *[Hollmann NF 2019]*
  - Computes densities and temperatures with radiated power as an input
- Decrease of temperature is confirmed by the model, but not down to recombination
- The measured density (recombination) can only be matched if 99% of the radiated power comes from non-thermal sources (i.e. runaways)
- Ongoing effort to understand the power balance of the purged beam/plasma system: ECE radiation, synchrotron losses…

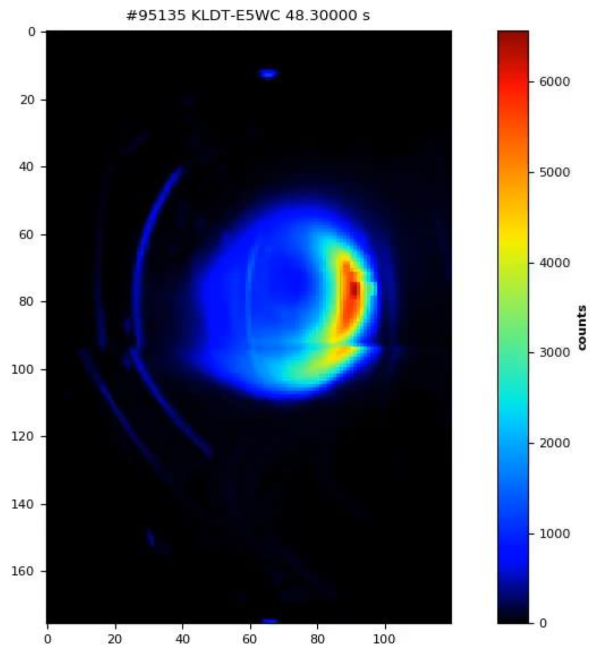


[S. Sridhar PhD thesis 2020]

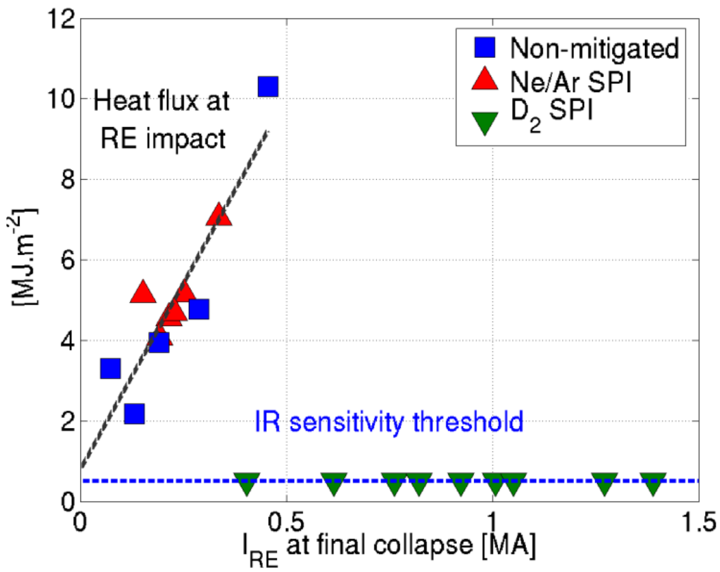


Runaway beam suppression: heat loads

- **Complete and fast (~1ms) dissipation of the runaway beam**
  - But **no visible heat loads**
- Heat loads of D_2-mitigated runaway beams below the measurement threshold of the IR camera (0.5 MJ.m^{-2} vs up 10 MJ.m^{-2} for high-Z or non-mitigated)



IR camera (3-3.5 µm)
- synchrotron emission



[Reux et al., PRL 2021]

Two mechanisms at play:
- Large MHD instability
- Absence of RE regeneration

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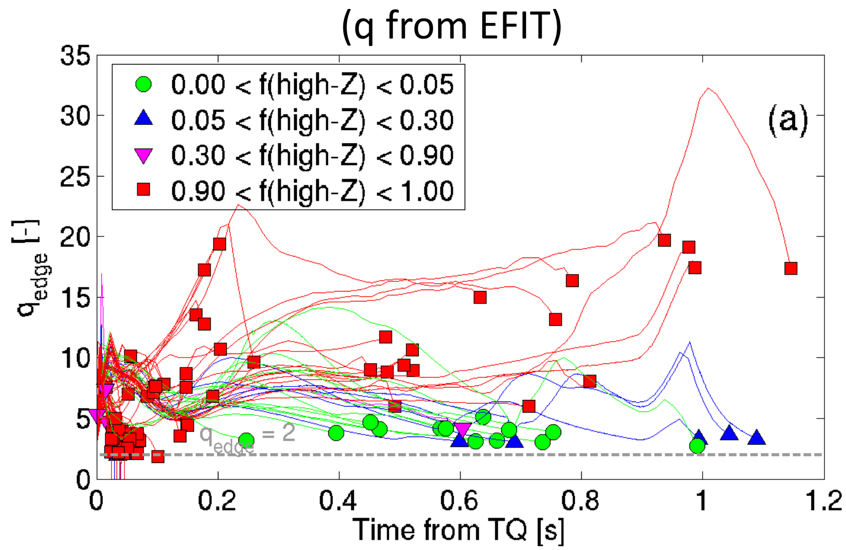
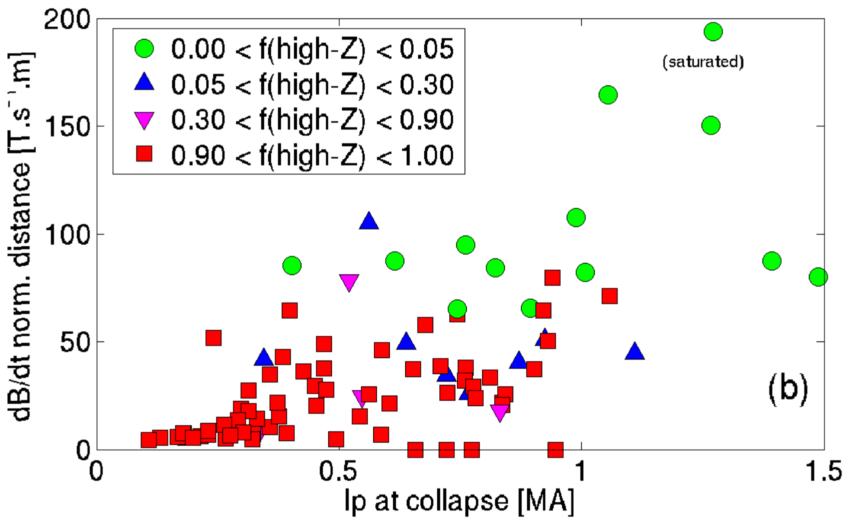
Triggering the instability



- **Current rises up to low q**, but not necessarily q=2 as in previous studies *[Paz-Soldan PPCF 2019]*
- **Benign** terminations associated with **q_{edge} between 2 and 5.**
- **Bad** terminations happen at **any q_{edge}.**
- Large MHD burst probably not always a current-limit instability

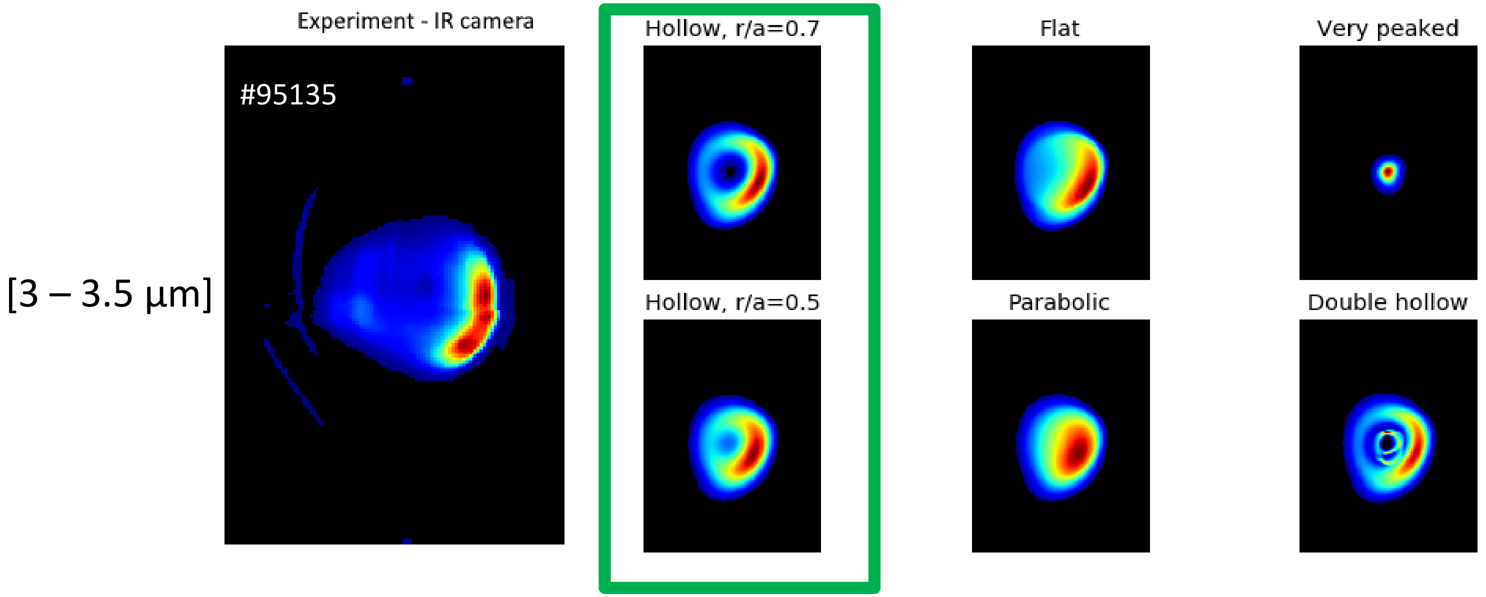


- The **normalized growth rate** of the instability dB_{pol}/dt is better correlated to the **impurity content** or the impact severity compared to the magnitude of the instability $\delta B_{pol}/B_{pol}$

A fast, rather low-q MHD instability is correlated with benign terminations.

Hollow current profile

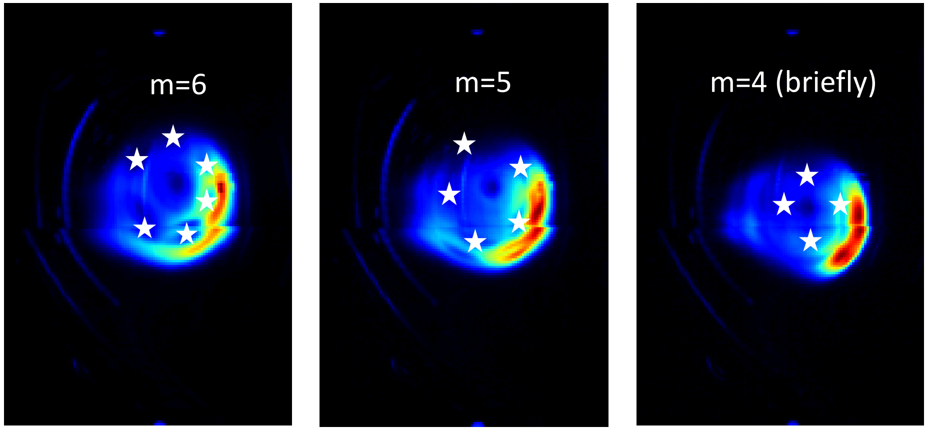
- Current profile before the final collapse: evidence of **a hollow profile** from **SOFT** simulations
- Reconstructions of the measured IR synchrotron emission
- Best match between the measurement and the simulations:
  - Pitch angle between 0.1 and 0.3
  - RE energy < 15 MeV
  - **Hollow current profile**

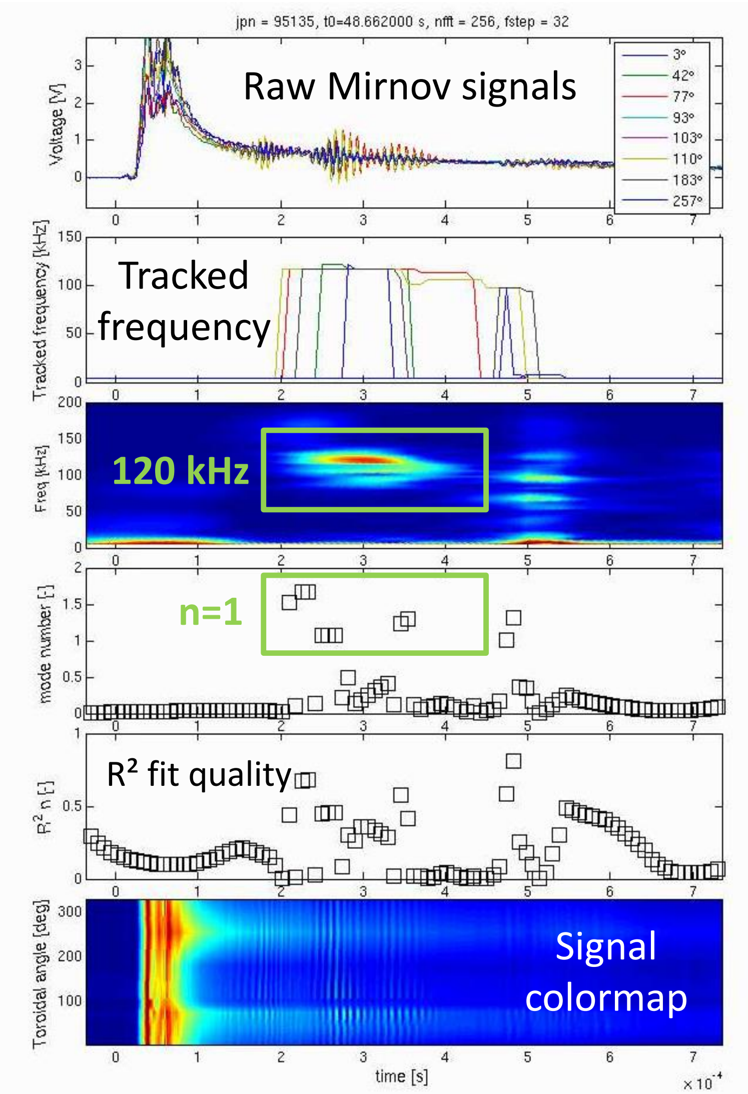


Hollow profile: key ingredient to benign terminations?

Characterization of the instability

- Magnetic islands are visible in synchrotron pictures before the collapse

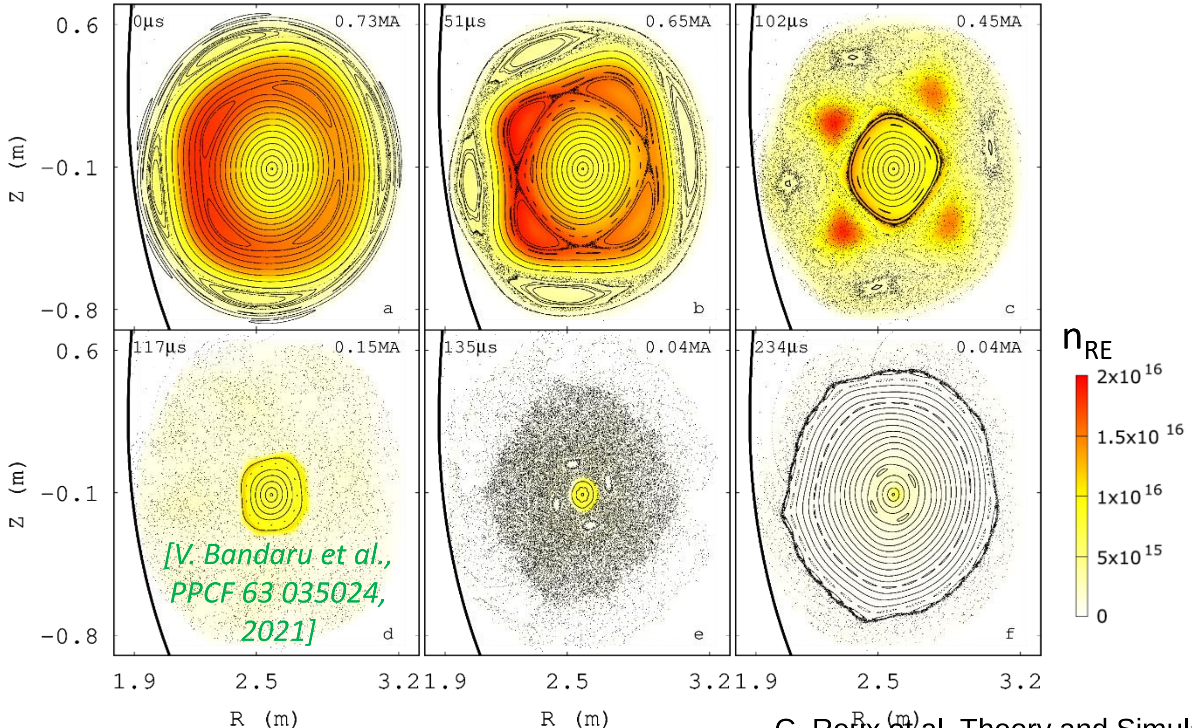


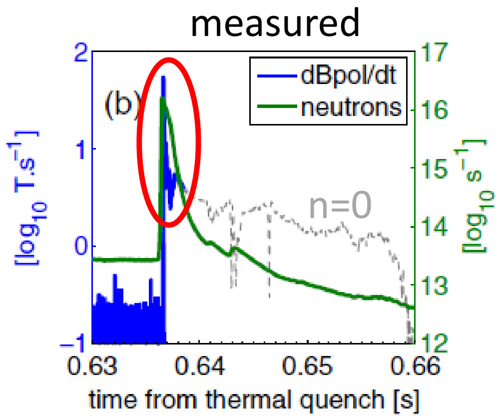


- **Two m=5 patterns visible**, one moving inwards
- m=4 pattern at 0.35 normalized radius ➔ very likely to be the inner m=4 island
- **n=1** most probable mode from Mirnov analysis

Jorek MHD simulations

- Using the q-profile determined above, MHD simulations of the final instability were made with **Jorek.**
- Instability governed by a **double tearing mode** on both q=4 surfaces
- **Destruction of the entire confinement in ~100 µs**
    - Compatible with the experimental timescale (10-20 µs)
- **95% of REs lost** to the wall through stochastization.





Jorek simulations confirm RE losses and the timescale of the collapse

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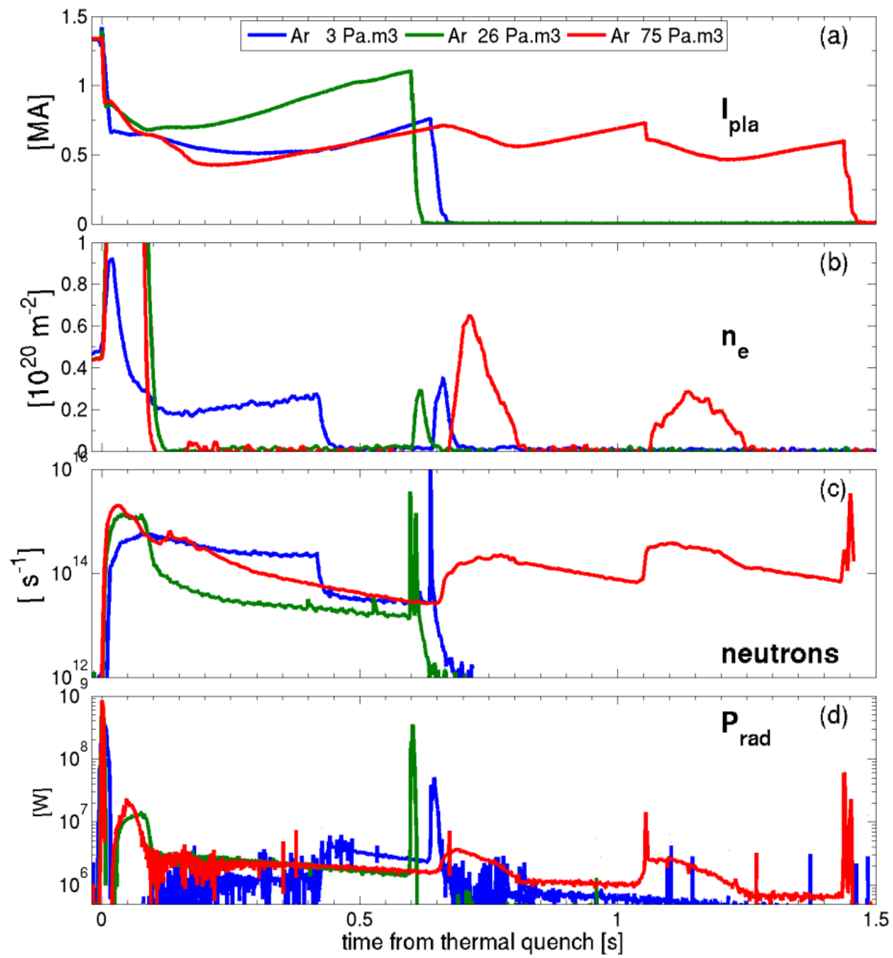
Mitigation using D2: W_{mag} to W_{kin} conversion

- Following the instability, current carried by dissipated runaways is **converted back to ohmic**.
- But in some conditions: REs are **regenerated**
- The features of the subsequent CQ depend on the companion plasma impurity content
- 3 situations:
  - Complete dissipation and no regeneration
  - Regeneration of a small beam
  - Incomplete dissipation and continuous regeneration of a runaway beam

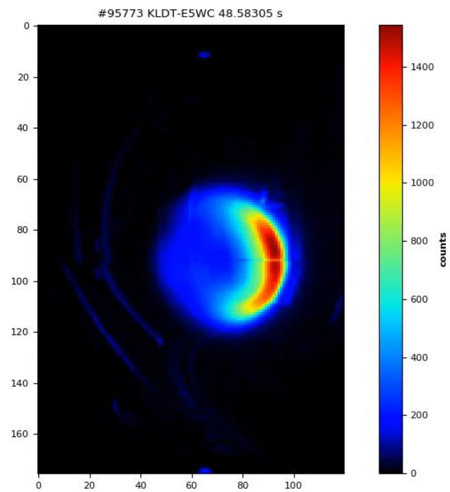
The D_2 effect only works with a clean enough companion plasma



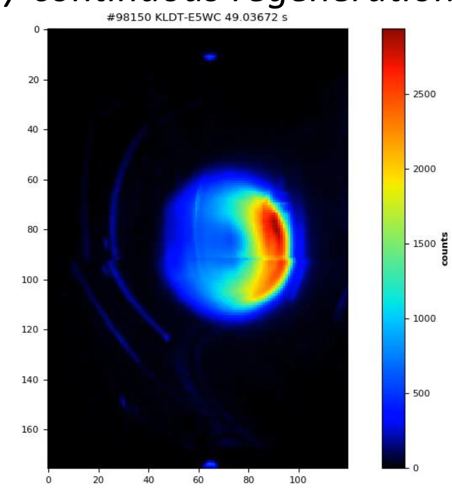
Mitigation using D2: W_{mag} to W_{kin} conversion

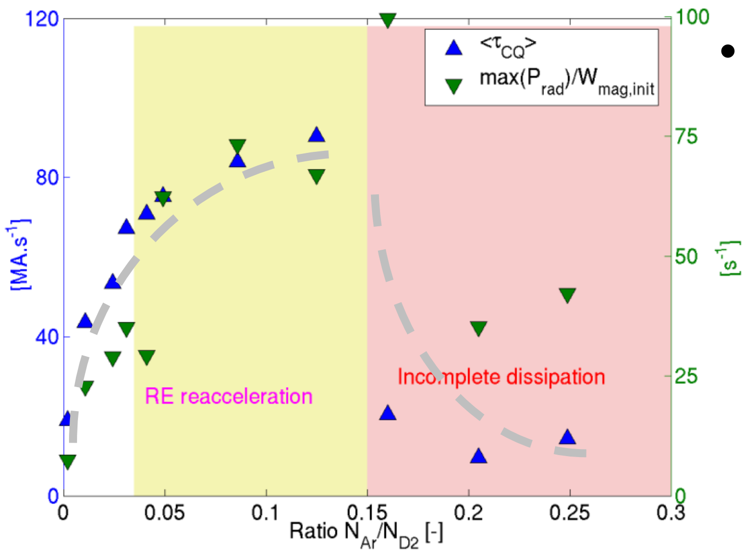
- Focus on the two imperfect dissipations:

Regeneration



Incomplete dissipation / continuous regeneration





- Experimental indications that the remaining argon is responsible:
  - Small regeneration: Correlation between the **Ar/D_2 fraction and the max P_{rad}** or dIp/dt during the final collapse ➔ Higher $E_{//}$
  - When incomplete dissipation occurs: no complete CQ ➔ rollover in P_{rad} and τ_{CQ}

Runaway regeneration model

- A model was developed to estimate the RE avalanche rate following the collapse

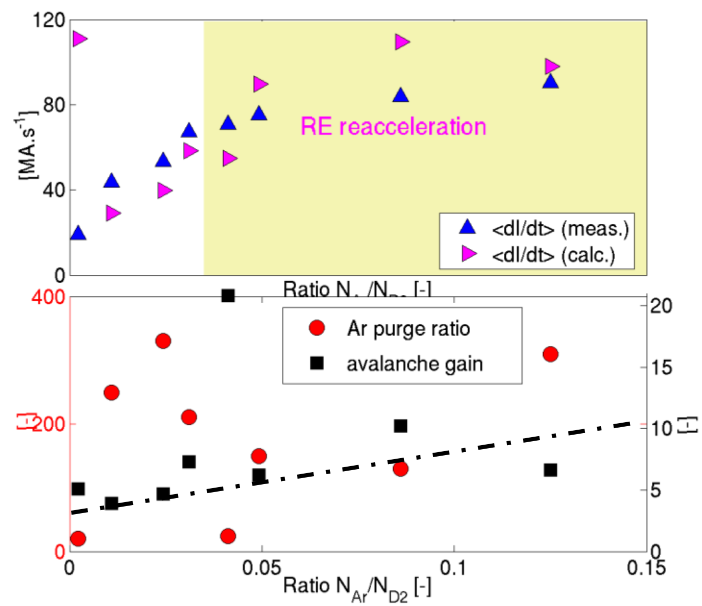
$$\frac{3}{2}\frac{\partial}{\partial t}n_f T_e = \frac{(I - I_{\rm RE})^2}{\sigma S^2} - n_f n_Z L(T_e)$$

$$\frac{d}{dt}(LI + L_v I_v) = -2\pi R E$$

$$\frac{d}{dt}(L_v I + L_v I_v) = -I_v R_v$$

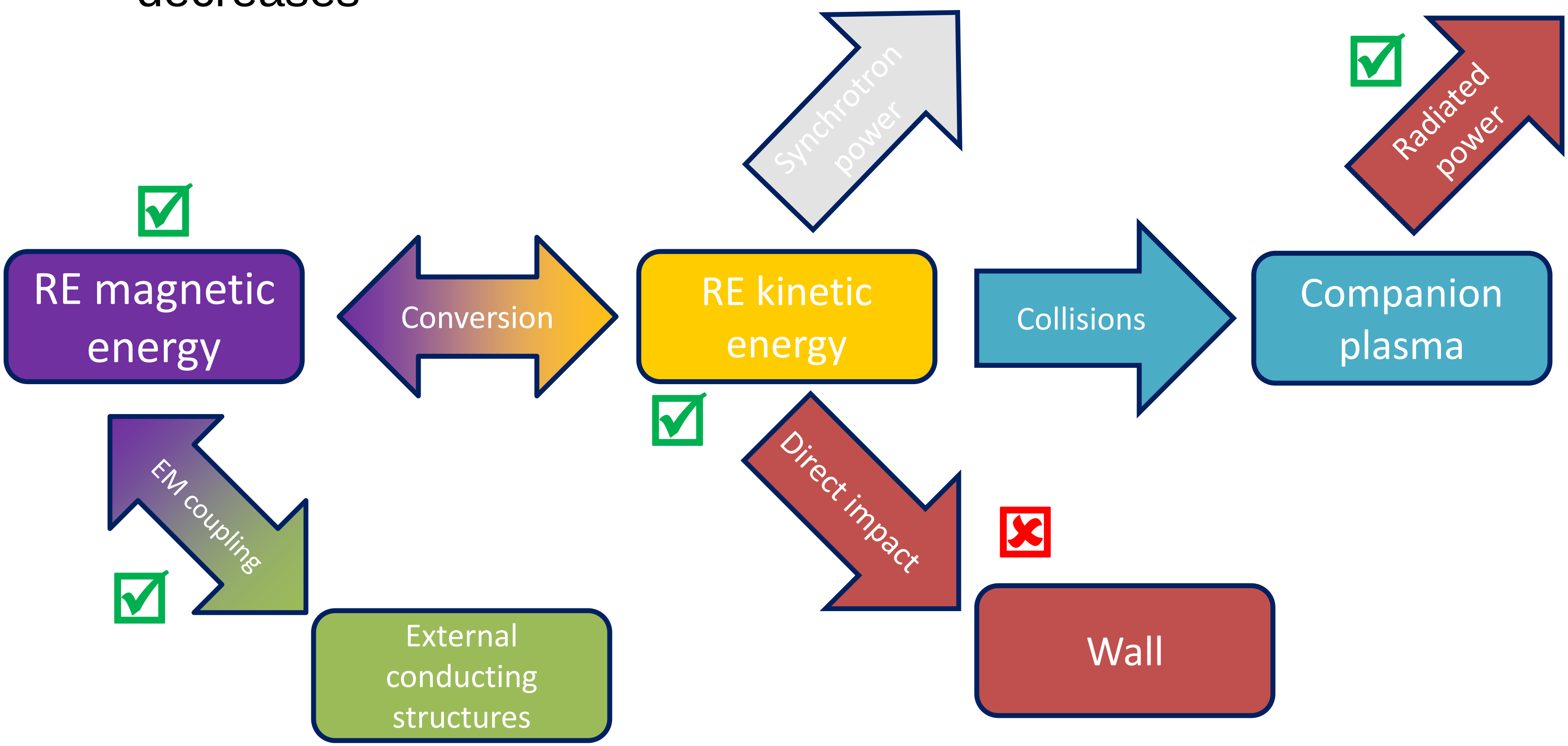
$$\frac{1}{I_{\rm RE}}\frac{\partial I_{\rm RE}}{\partial t} \approx \frac{n_f + n_b}{n_f \ln\Lambda_f(p_c) + n_b \ln\Lambda_b(p_c)} \frac{1}{\sqrt{Z_{\rm RE}(p_c) + 5}} \frac{e(E - E_{\rm crit})}{m_e c}$$

- The model solves the evolution of the plasma temperature, plasma, vessel, runaway currents and electric field
- The impurity concentration is determined by matching calculated/measured P_{rad}
- Results:
  - dI/dt in good agreement with measures
  - Argon « purge » ratios of a few 10s to 300 needed. ➔ mechanism confirmed



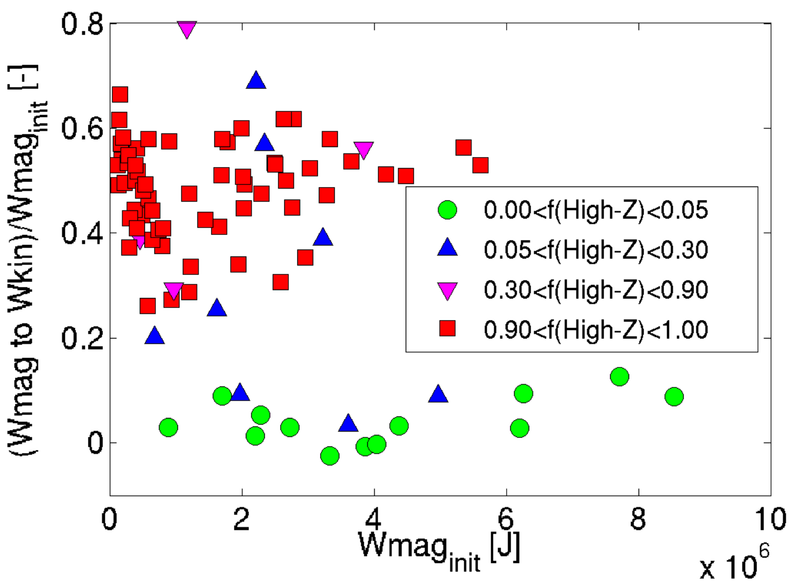
Conversion from magnetic to kinetic energy: how to reaccelerate runaways during the final collapse

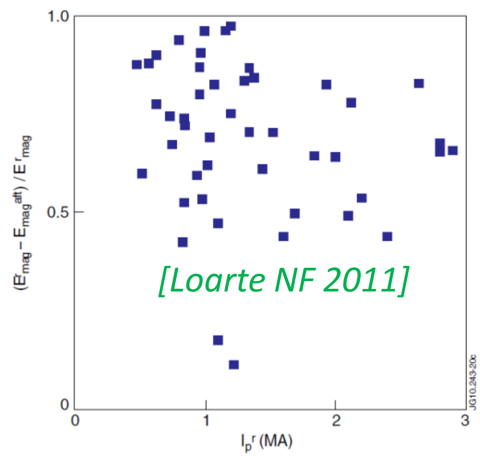
- Calculation of the fraction of the initial runaway magnetic energy converted into kinetic energy
- Elaborated from the method proposed in *[Loarte NF 2011]*
- Conversion happens when HXR bursts are recorded while current decreases



Mitigation using D_2: W_{mag} to W_{kin} conversion

- Fraction of magnetic energy converted (method in *[Loarte NF 2011]*)
  - 25% < f_{conv} < 80% for high-Z
    - Similar range as in [Loarte NF 2011]
  - f_{conv} <10% for low-Z
- Note: regeneration of small RE beams not taken into account : too small RE currents ➔ probable reason for the gap between pure D2 and pure High-Z: non-continuous regeneration not here





The absence of conversion from W_{mag} to W_{kin} is a key ingredient

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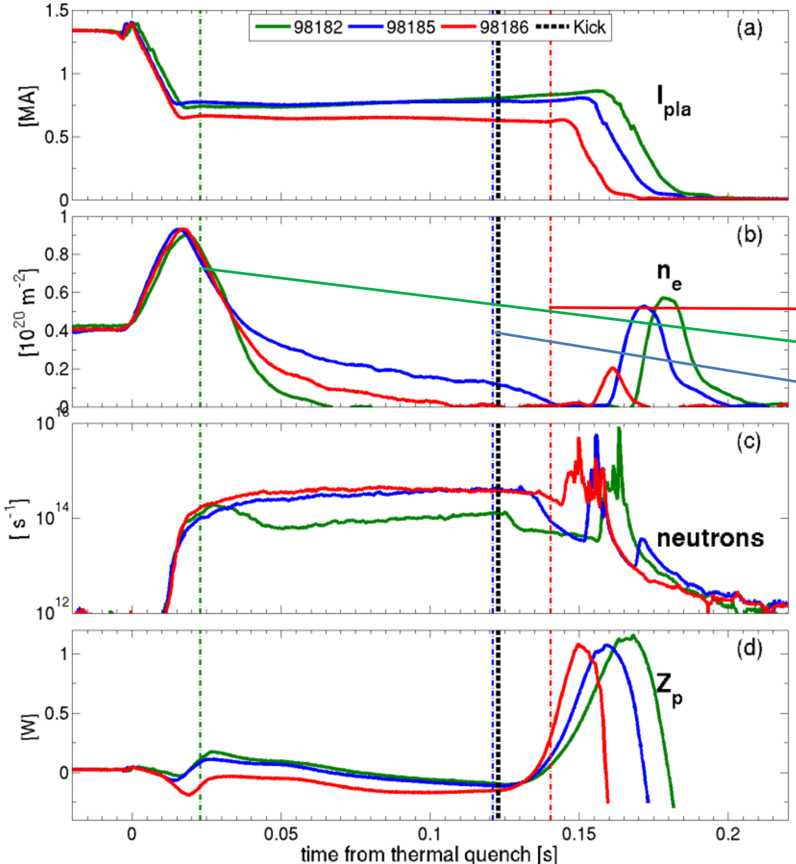
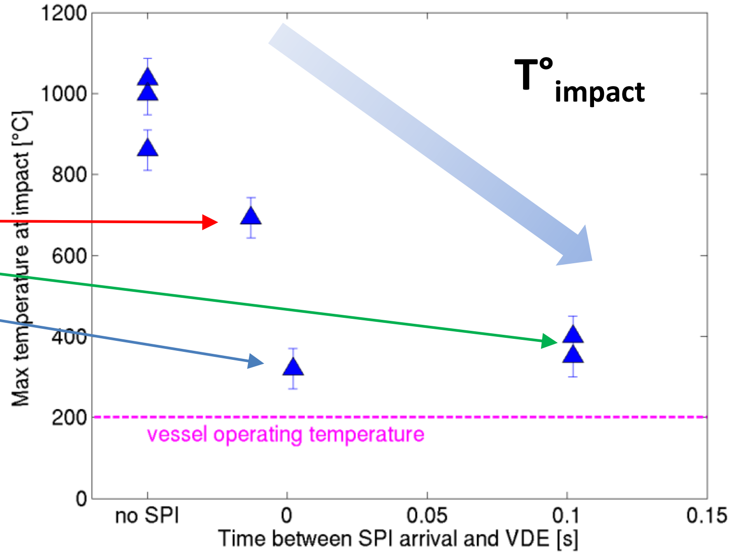
The D_2 effect in Vertical Displacement Events

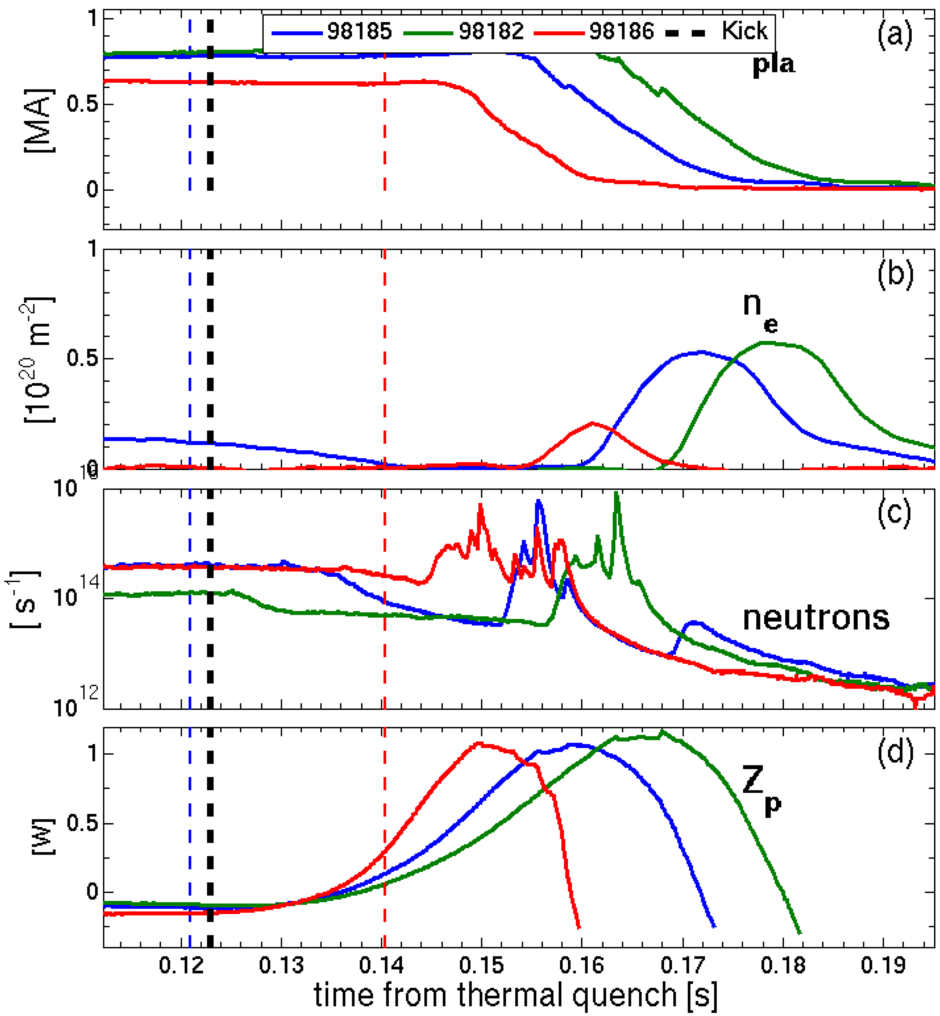
- **Lack of vertical position control**: potential limit of the scheme on ITER
- D_2 effectiveness in a « scraping-off » beam? *[Konovalov IAEA FEC 2016]*
- Fire the SPI into a vertically moving plasma (VDE duration: 15 ms – purge duration ~ 20 ms)
- Result: **D_2 still efficient if the pellet arrives at the plasma edge at the beginning of the fast displacement**





The D_2 effect still works if fired early into a VDEing RE beam

Close-up on termination

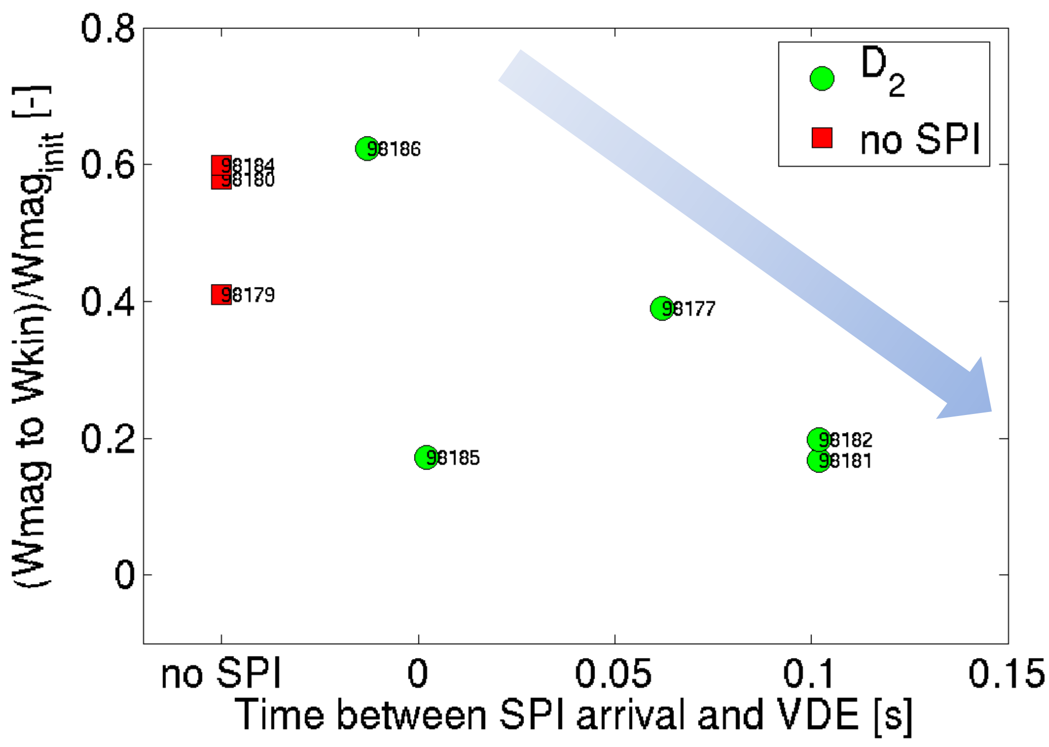


Continuous transition between mitigated/unmitigated VDE REs

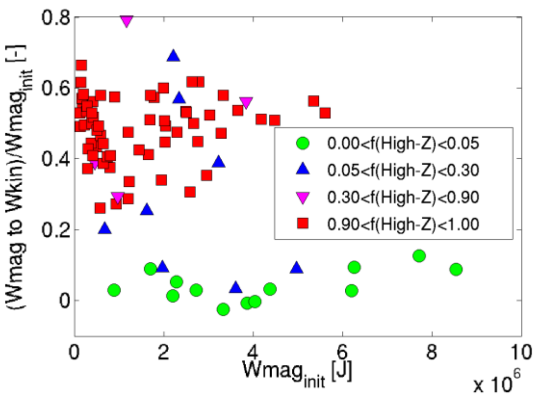
- The D_2 pellet slows the VDE down.
- Several spikes on neutrons even in the « early SPI » case benign termination ➔ runaway regeneration or effect of the movement?
- Density spike higher with early efficient mitigation
  - Higher conversion from W_{mag} to ohmic and then radiation?
  - Higher assimilation in the full mitigation case?
- Not shown here: density spike even lower in the non-mitigated case

The D_2 effect in Vertical Displacement Events

- Weak decreasing trend in W_{mag} to W_{kin} conversion as the SPI is fired earlier and earlier
- But even at a distance of the VDE, some conversion is still there (consistent with multiple spikes)
- 98185 not consistent with the trend, but also shows very low heat loads. (no camera on 98177)



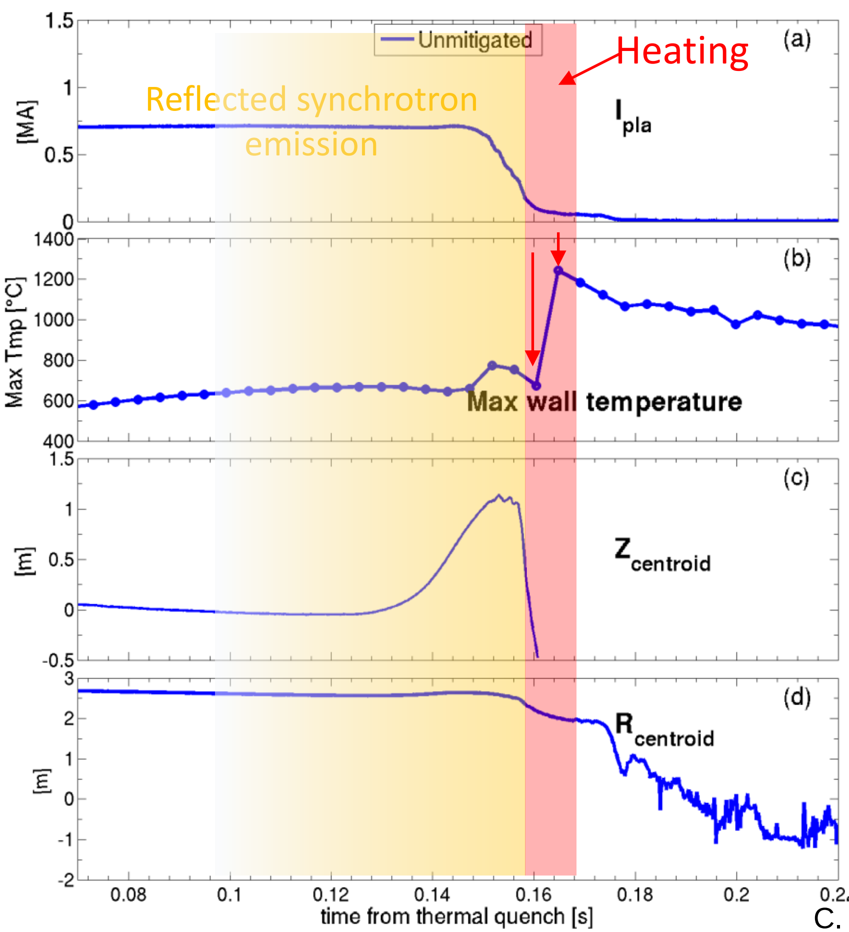
Non-VDE database

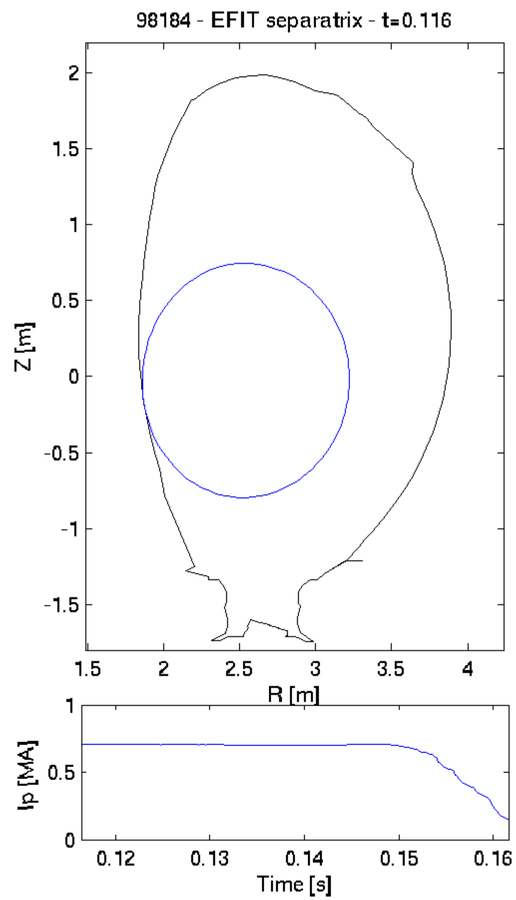


Lower W_{mag} to W_{kin} conversion if the VDE is taken on time

Heat loads timing – unmitigated case

- Heating time span: 2 frames ➔ ~ 10 ms.
- No significant energy deposition on plasma facing component touched by the beam while moving up ➔ Only very weak scraping off
- Heating only starts when the plasma shrinks at the end of the collapse.



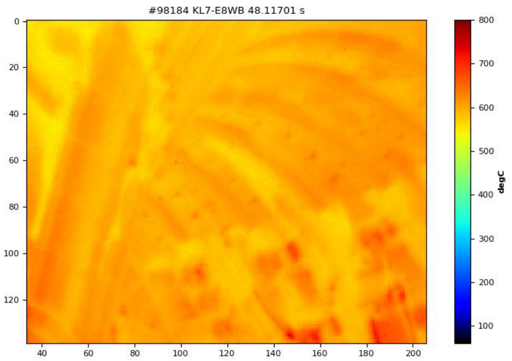


- Possibly linked to RE regeneration only happening during collapse

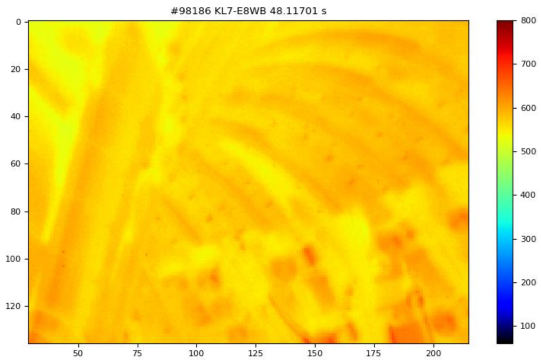
Heat loads linked to RE regeneration?

Spatial footprint

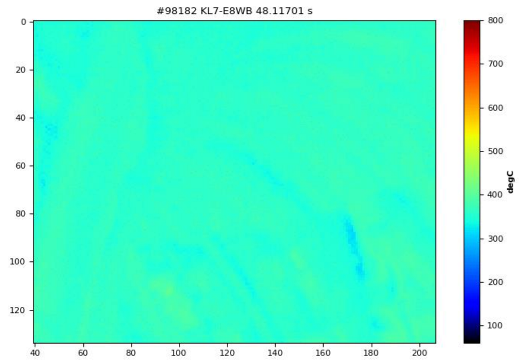
- Very localized impact point for non-mitigated cases
- Gets broader for half-mitigated case and even broader for the fully-mitigated case
- Side note: reflected synchrotron radiation is clearly visible



No mitigation

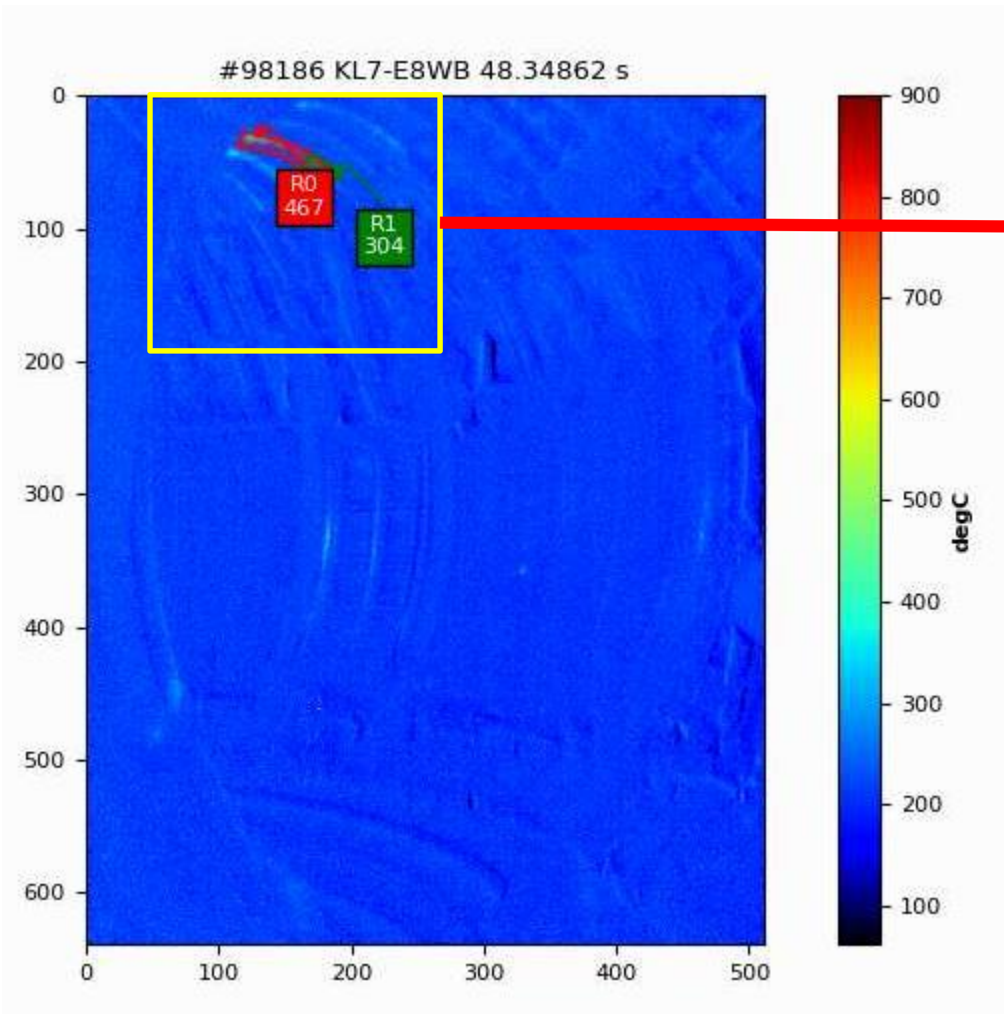


Half-mitigated

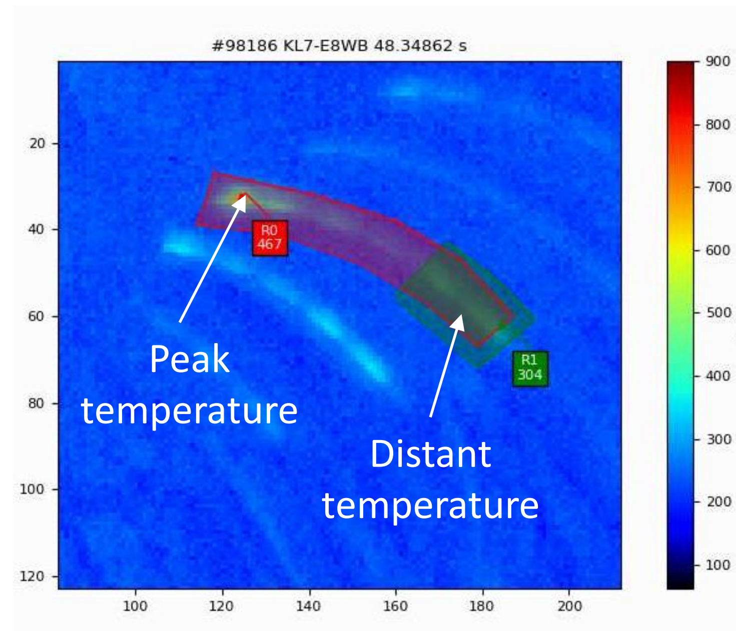


Fully mitigated

Spatial footprint

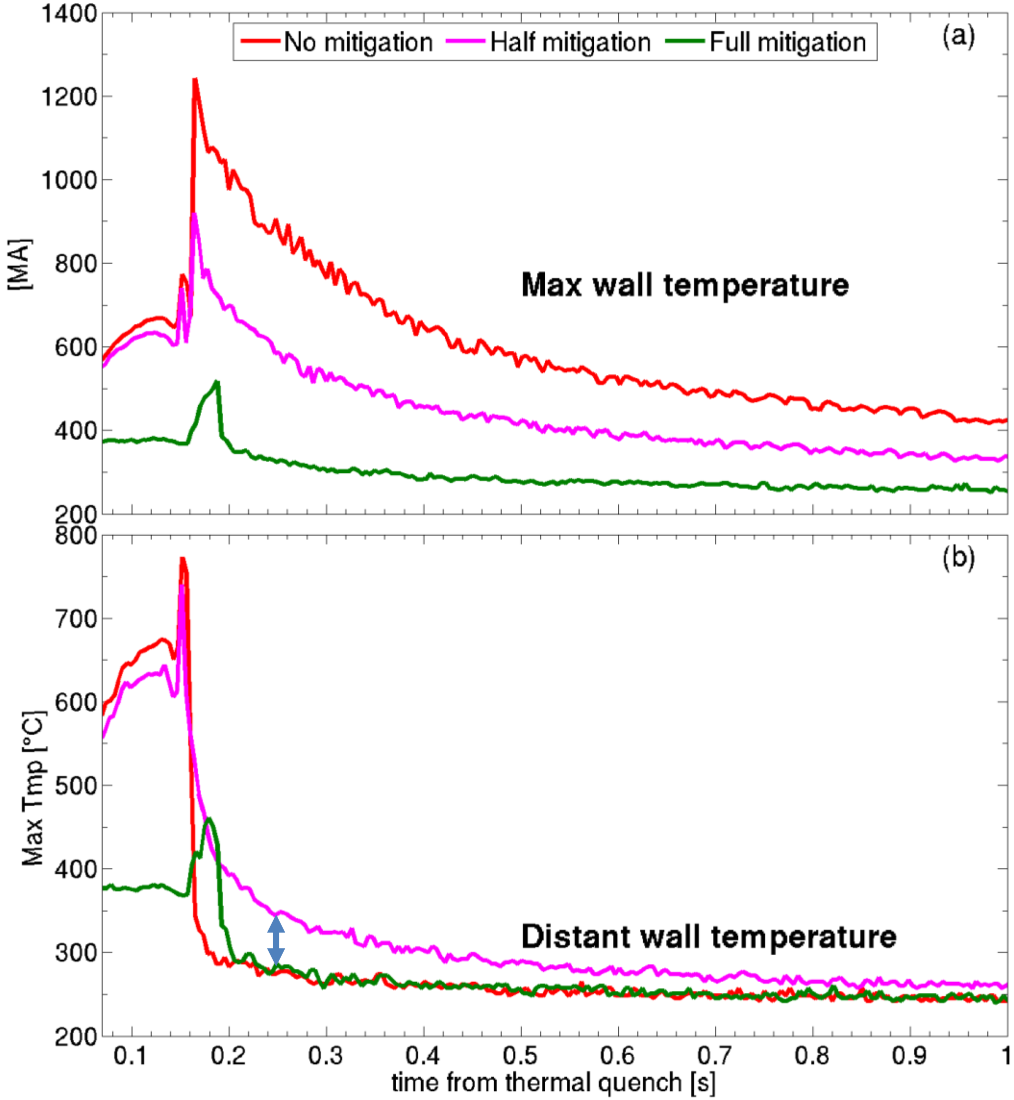


[3.65 µm – 5.05 µm]



- 2 Regions of interest:
  - Main deposition area
  - Rest of the dump plate rib (away from the main point)

Heat load peaking

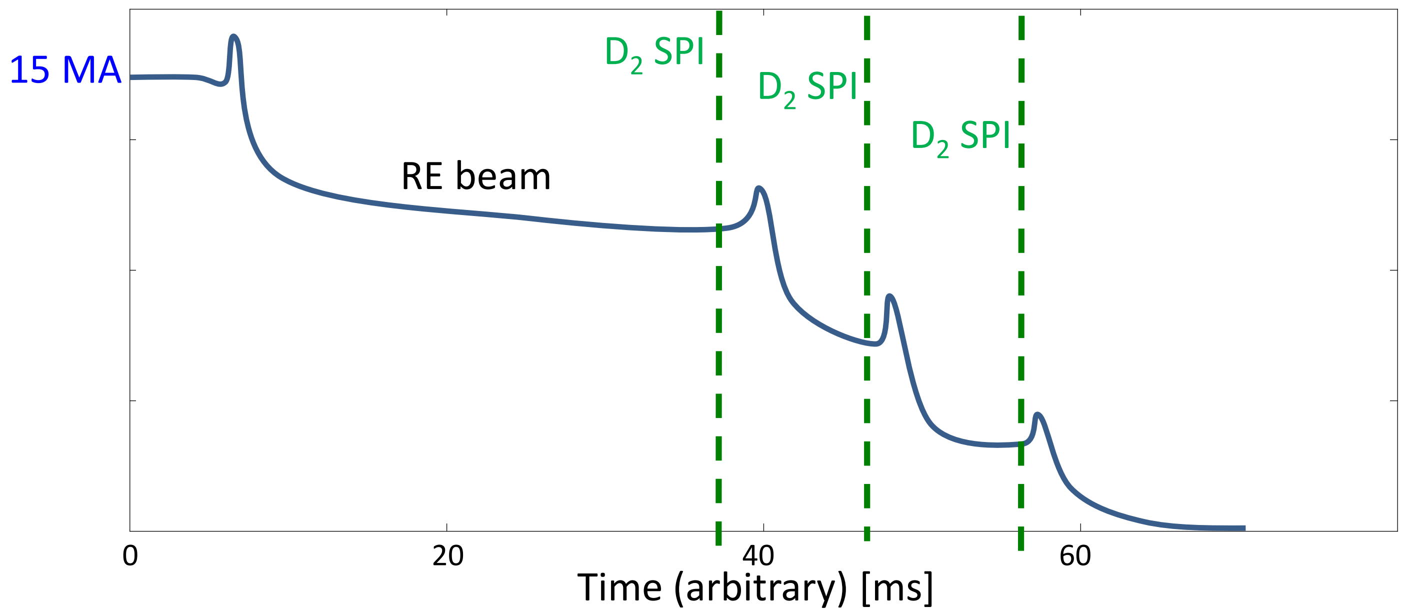


- More peaked heat loads for unmitigated cases
- More spread heat load pattern for the half-mitigated case
  - Consequence of the slower movement, with the plasma « rolling » on the upper dump plate?
  - « Mid-size » MHD instability?
  - Small regeneration of runaways during the collapse?

Better mitigation = more spread heat loads

Prospects for ITER

- The level of companion plasma purity needed to prevent RE reacceleration needs to be assessed
  - Very likely to be high, as the avalanche is very strong on ITER
- The accessibility of the large MHD instability is also to be assessed
  - More Jorek simulations planned
- Even if complete dissipation is unsuccessful, each intermediate collapse shaves off a fraction of the total current
- ➔ **Repetitive D_2 SPI** until the current reaches a safe level



Conclusions

- High-Z SPI not efficient at killing completely a RE beam (~ MGI)
- D_2 SPI suppresses RE beams up to 1.4 MA without heat loads
- MHD instability in a hollow current profile leads to complete dissipation of runaways
- No regeneration of runaways occurs in the final collapse thanks to the absence of high-Z impurities
- Works in a vertically moving beam
- Very promising for ITER and beyond

Perspectives

- Better understand the power balance in the purged beam/companion system

- More studies on the current profile following the D_2 pellet arrival (island patterns)

- Better characterization of RE energy with HXR.

- More advanced modelling on the runaway behaviour after D_2 arrival (Jorek? DREAM?)

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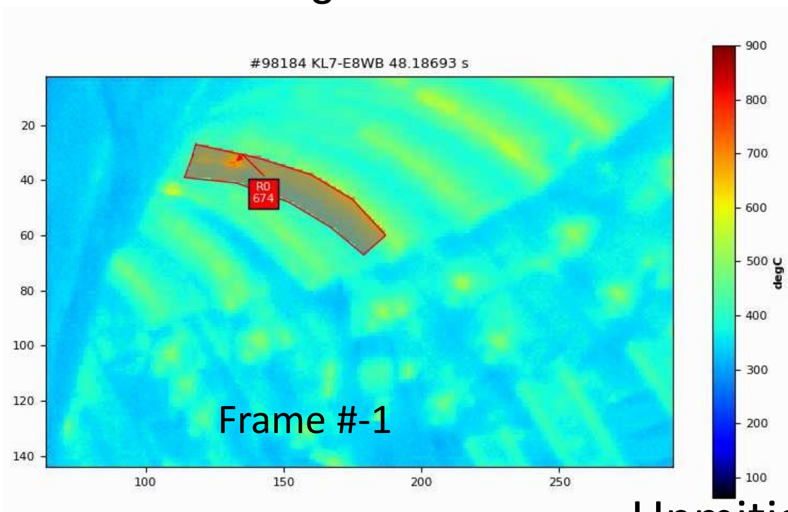
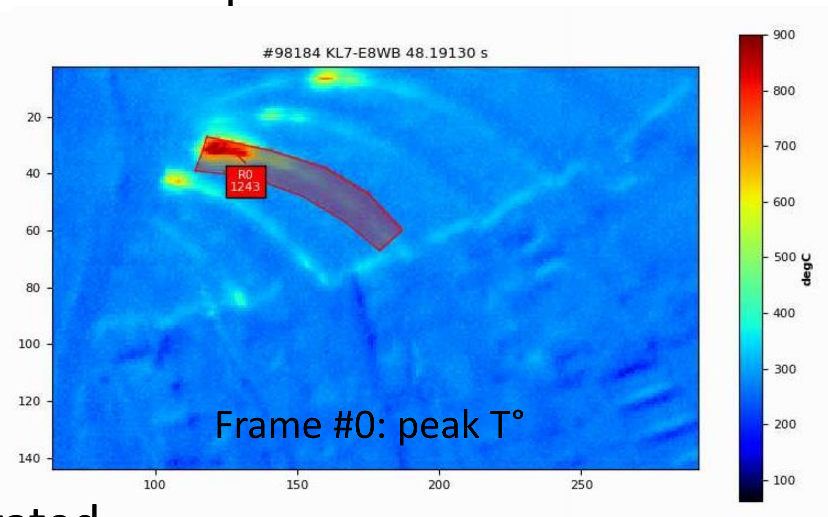
Additonal material

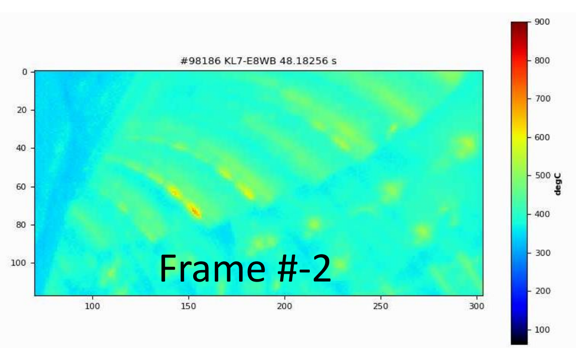
Heat loads timing

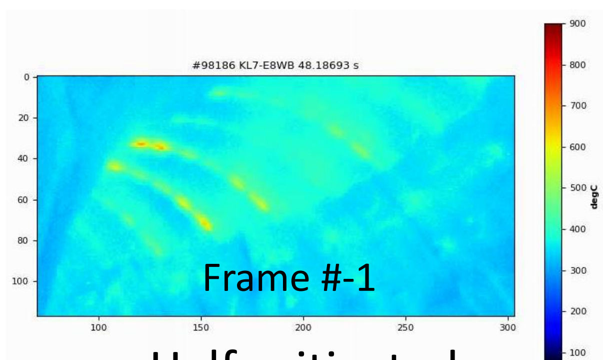
- Camera pictures: when does heating start?
  - Unmitigated case: only one frame (5 ms) before temperature max.
  - Half-mitigated case: 2 frames before the spike

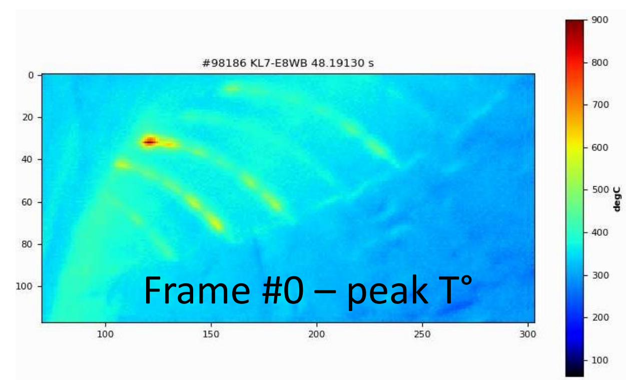




Unmitigated

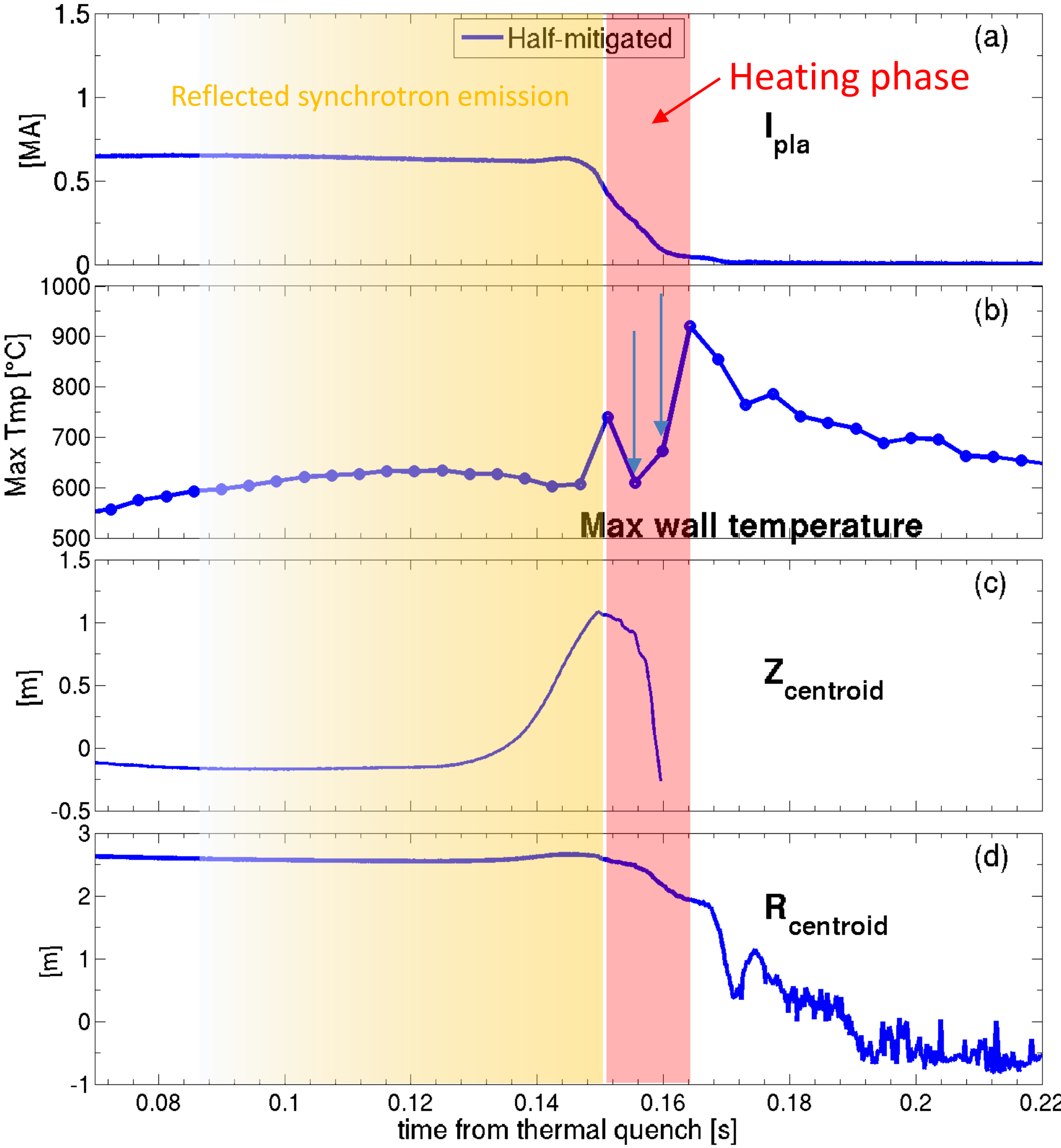






Half-mitigated

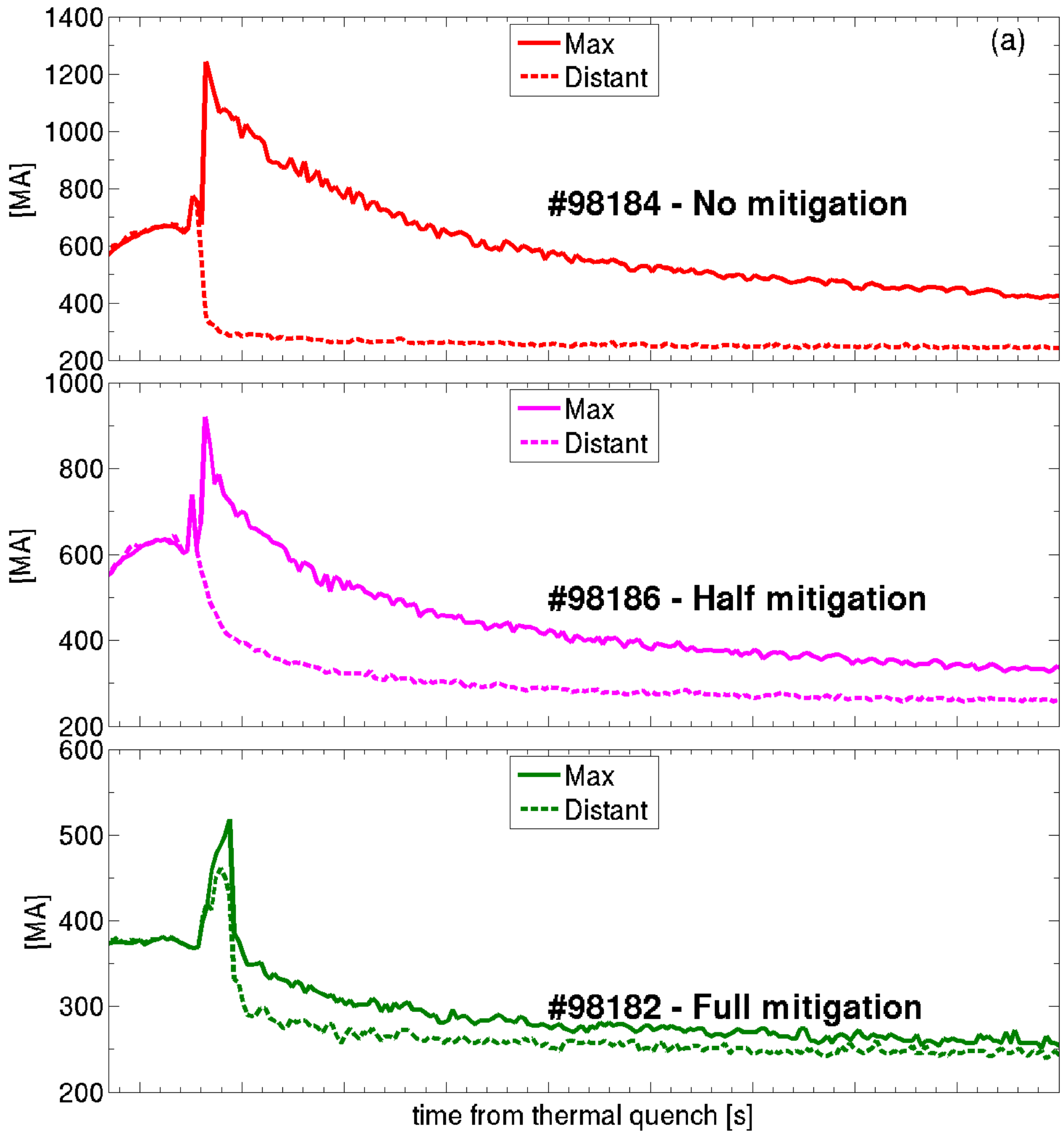
Heat loads timing – half-mitigated case



- Same situation with the half-mitigated case.
- No heating before the middle/end of the final collapse
- ➔ Very limited scraping off again?
- Possibly linked to RE regeneration only happening during collapse

Heat loads linked to regeneration rather than initial RE impact?

Peaking factor for various cases



- Heat load pattern much more peaked for non-mitigated cases.
- Much flatter for the half-mitigated case.
  - Spatial broadening by a « mid-size » MHD instability?
  - Beam movement?