EUROfusion

Runaway electron beam suppression using impurity flushing and large magnetohydrodynamic instabilities

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Introduction

- Runaway Electrons (RE) are created in thunderstorms and during disruptions of tokamak devices
- They may reach energies up to several 10s of MeV and pose threats to Plasma Facing components
- Shattered Pellet Injection (SPI) as the present disruption mitigation system for ITER aims at:
  - Suppressing the primary RE generation mechanisms (Dreicer & Hot Tail)
  - Suppressing the avalanche multiplication early in the disruption
- But most of state-of-the-art models predict finite primary populations subsequently avalanched *[Vallhagen JPP 2020, Fülop IAEA 2016]*

- ➔ A second line of defense is needed: in-flight suppression of a fully-accelerated RE beam

Mitigation of mature runaway beams

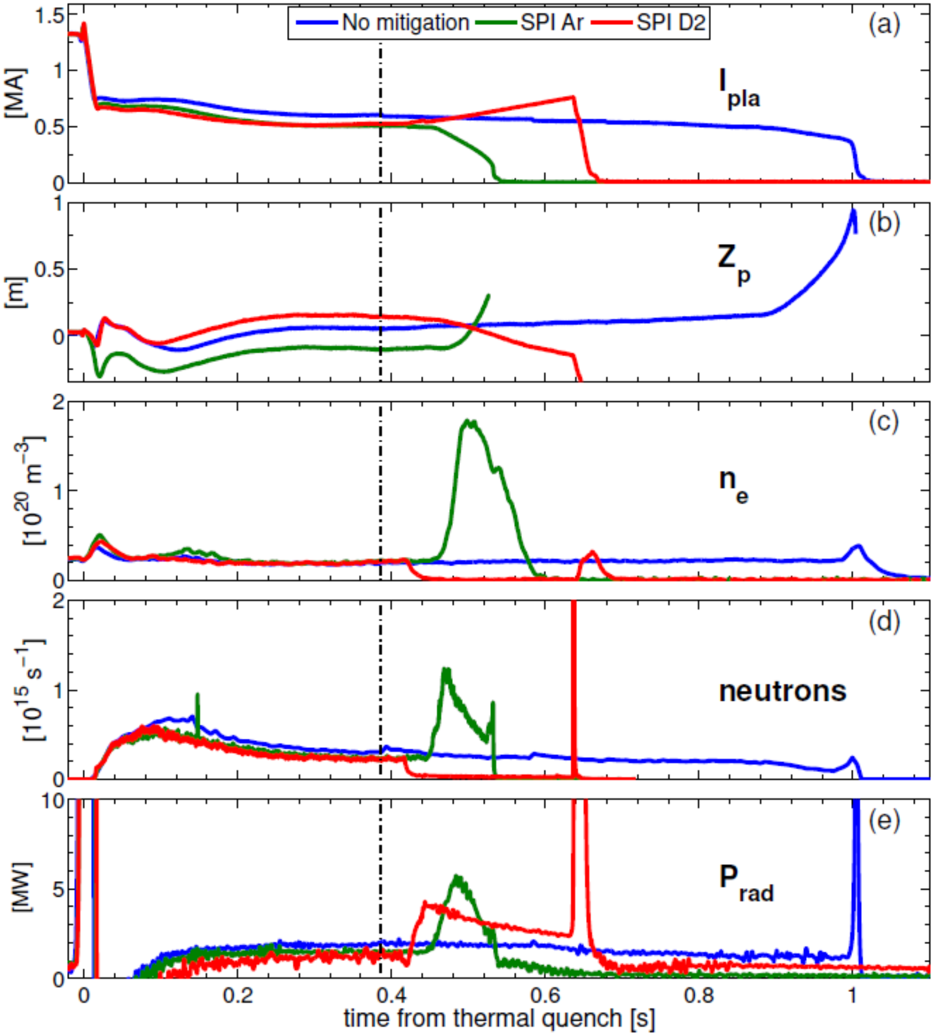
- High-Z SPI (or MGI) species have been tested for RE beam mitigation in the past on DIII-D, JET, AUG, Tore Supra
  - Some success on DIII-D, Tore Supra, AUG, *[Whyte PRL 2002, Shiraki NF 2018, Saint-Laurent EPS 2009, Pautasso NF 2020]*
  - Very limited success under certain conditions in JET *[Reux NF 2015]*

- Increasing evidence from theoretical models that high-Z mitigation is not enough for large ITER-class RE currents *[Martin-Solis NF 2017, Vallhagen JPP 2020, Hesslow NF 2019]*

- Main topic of the present article: use of deuterium to mitigate a RE beam
  - Up to 1.27 MA of runaways dissipated **without measurable heat loads**
  - Builds upon similar deconfinement events observed at DIII-D *[Paz-Soldan PPCF 2019]*

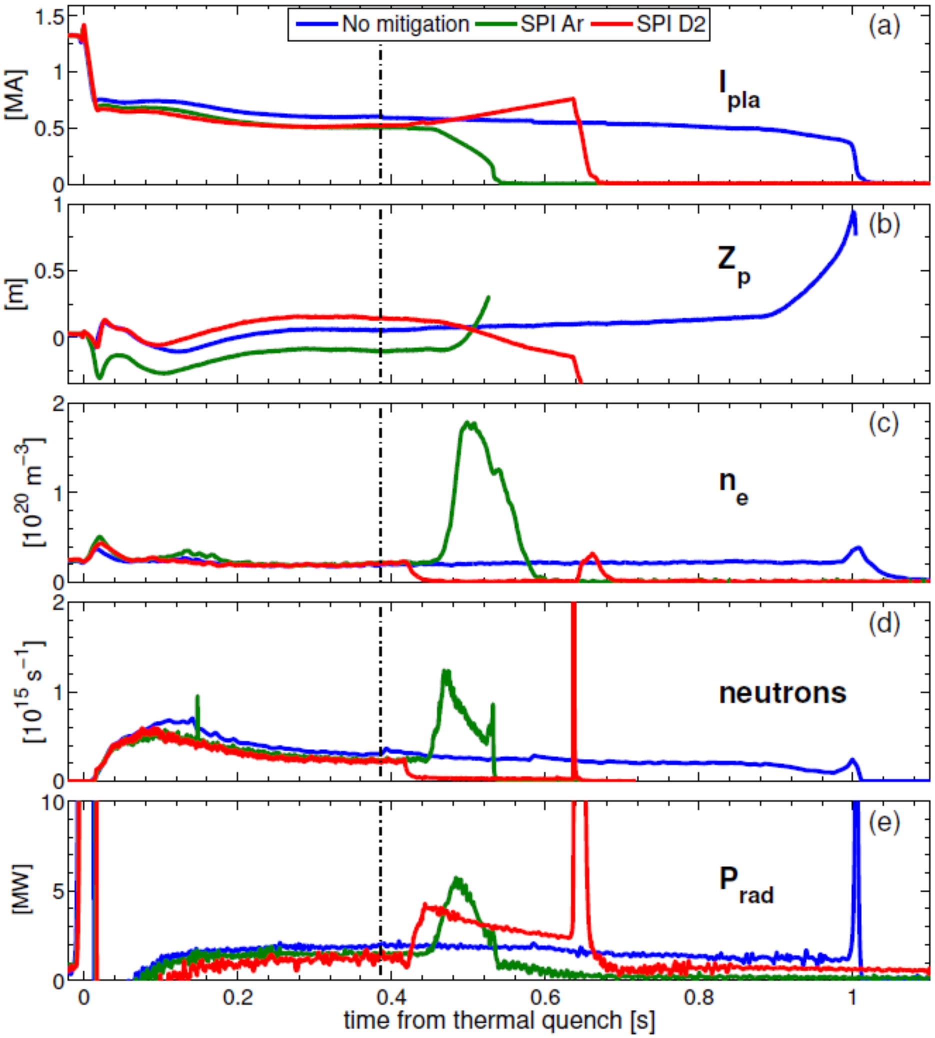
Runaway beam scenarios : no mitigation

- JET « no-mitigation » beam: **(blue curve)**
- Limiter configuration @1.5 MA/3.0 T
- 2.38 10^{21} atoms of argon used to trigger the disruption
- 750 kA RE beam slowly decaying in current.
- $n_{e,line\text{-}av}$ ~ 10^{19} m^{-3}, T_e~ 5-15 eV *[Sridhar NF 2020]*
- P_{rad} ~ 2 MW due to the argon companion plasma
- Impact at termination on localized areas, with measurable heat loads



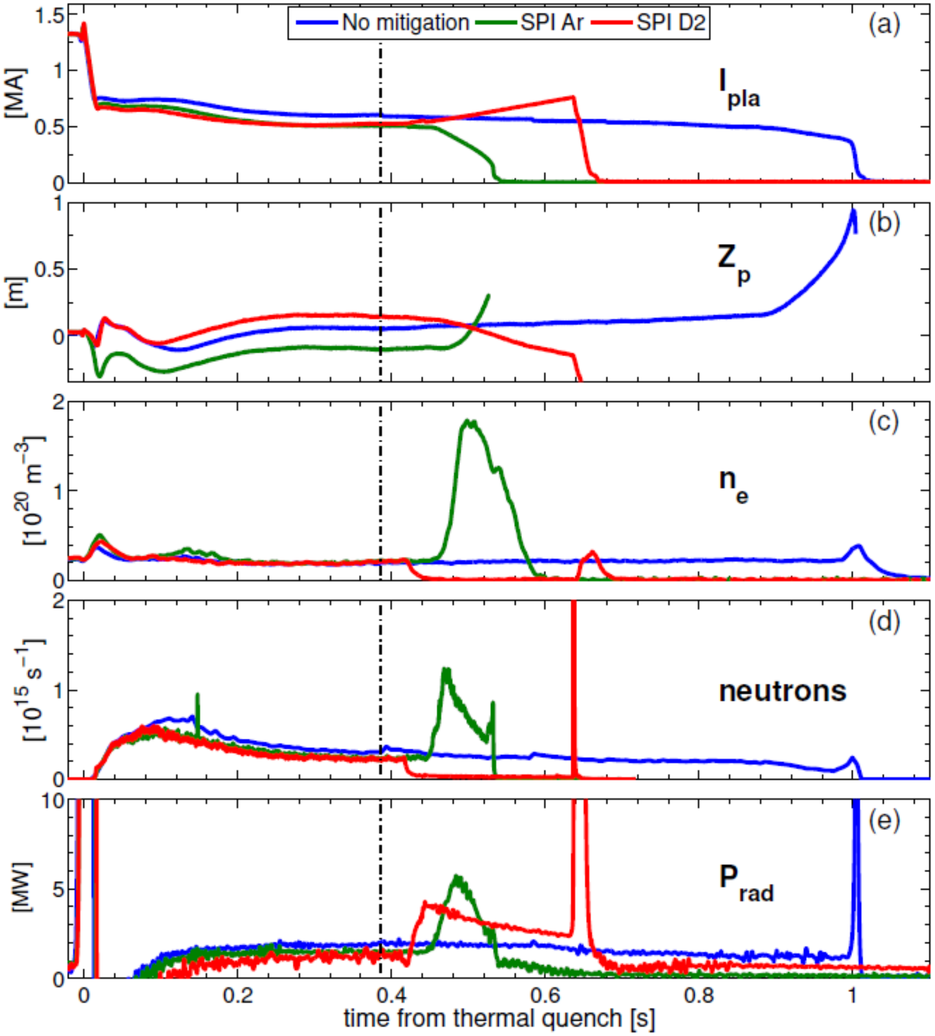
Runaway beam scenarios: high-Z mitigation

- JET Argon SPI scenario **(green curve)**
- Faster current decay
- Increase of free electron density, P_{rad} increase due to the density and impurity content increase
- Vertical destabilization
- Localized impact on the wall, with significant heat loads



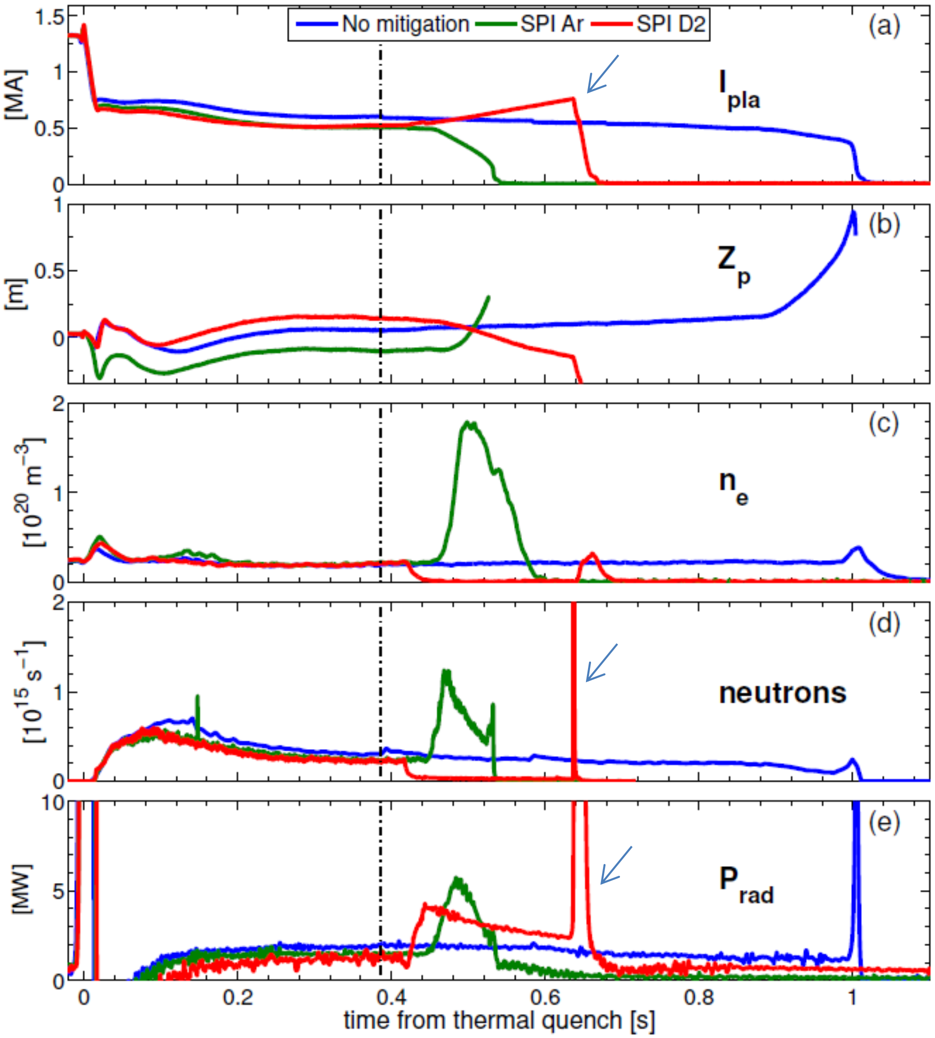
Runaway beam scenarios: D_2 mitigation

- JET D_2 SPI scenario **(red)**
- 1.6 10^{23} atoms injected by SPI
- Current increases ➔decrease of the RE+companion plasma resistivity
- n_e drops to non-measurable values (<10^{18} m^{-3}) ➔ Plasma recombination
    - Argon expelled from the plasma (VUV spectroscopy)
    - Process not yet clear
- Neutron rate drops by a factor 10 P_{rad} increases to 4 MW.
- Measured loop voltage in good agreement with voltage derived from Bethe Stopping power for a neutral gas

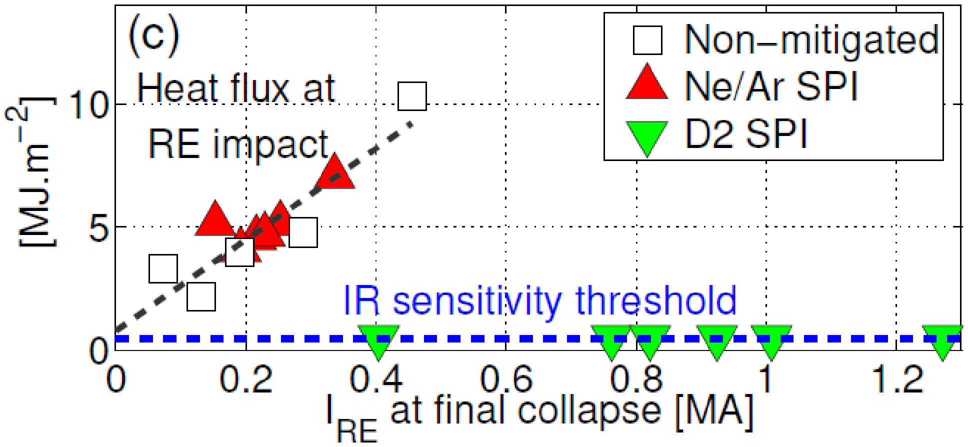


Runaway beam scenarios: D_2 mitigation

- 220 ms after the D_2 shard plume arrival (I_{RE} ~770 ms)
- neutron spike indicating RE losses
- Complete disappearance of RE synchrotron emission (IR cameras) in < 3 ms
- Current decays over ~12 ms
- Radiated power spike
- Rest of the current decay: purely ohmic
    - In some cases: current spike similar to the one from a normal disruption



D_2 mitigation scenario – heat loads

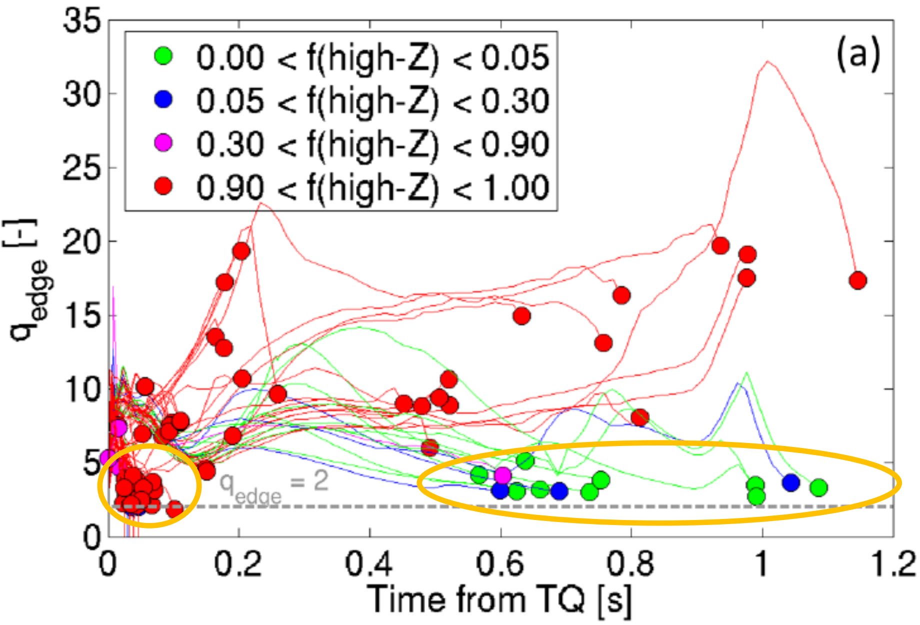


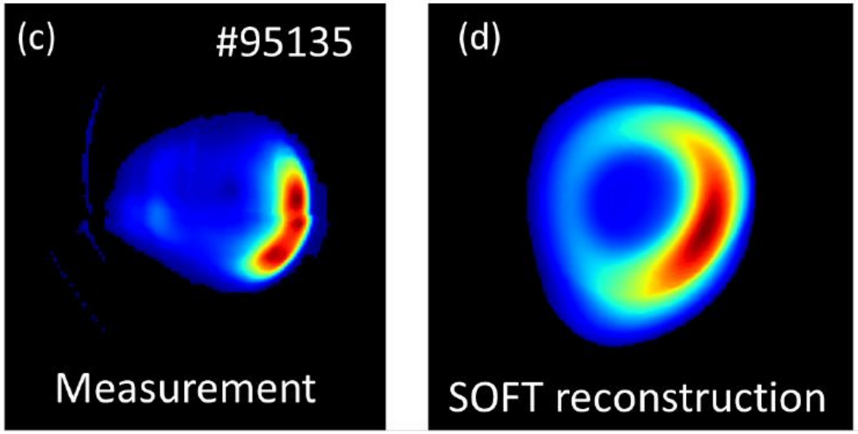
- Most prominent feature: absence of measurable heat loads at beam termination
  - <0.5 MJ.m^{-2}
  - High-Z heat loads up to 10 MJ.m^{-2} despite lower currents

- **Two mechanisms at play:**
  - **A large and brief MHD instability dissipating the runaway electrons**
  - **The absence of RE regeneration (absence of conversion from magnetic to kinetic energy) during the final collapse**

Developement of the MHD instability : j-profile

- Current rise leads to low q_{edge}.
- For D_2-mitigated scenarios, final collapse happens when q_{edge} reaches 2-5
- Not specific to D_2 cases
- Probably not a current-limiting instability as suggested in *[Paz-Soldan PPCF 2019]*
- Reconstruction of the synchrotron emission using the SOFT code *[Hoppe NF 2018]*
- Best match obtained when current profile is hollow (peak at a/2). Energy <15 MeV, pitch angle 0.1-0.3. No f(E) and pitch can match the observation with a peaked profile

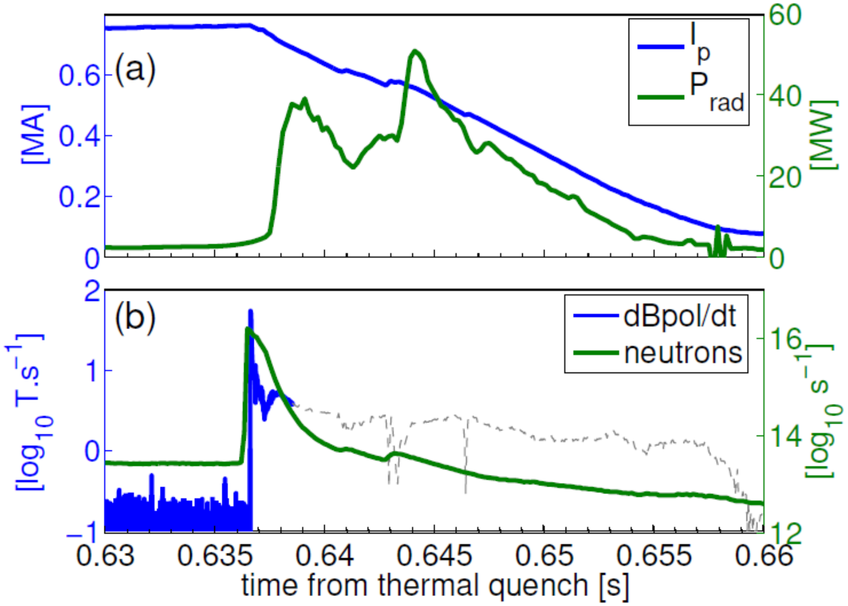


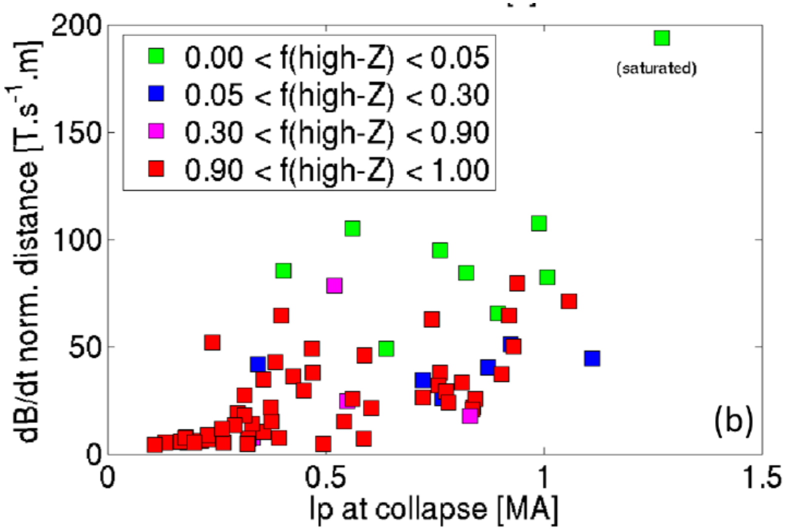


MHD Instability characterization

- Islands visible in the IR pattern
  - m=4 visible at a/3
- n=1 from Mirnov coils (toroidal array) ➔ q=4 ➔ further evidence for a hollow profile
- The instability itself develops on a 10-20 µs timescale (peak dB/dt)
- Experimental magnitude of the instability:
  - $(dB/dt)_{max}$ weakly correlated with the high-Z fraction (D_2 cases vs. High-Z cases): all D_2 cases have large $(dB/dt)_{max}$, but some high-Z cases too.
  - dB/B even less correlated

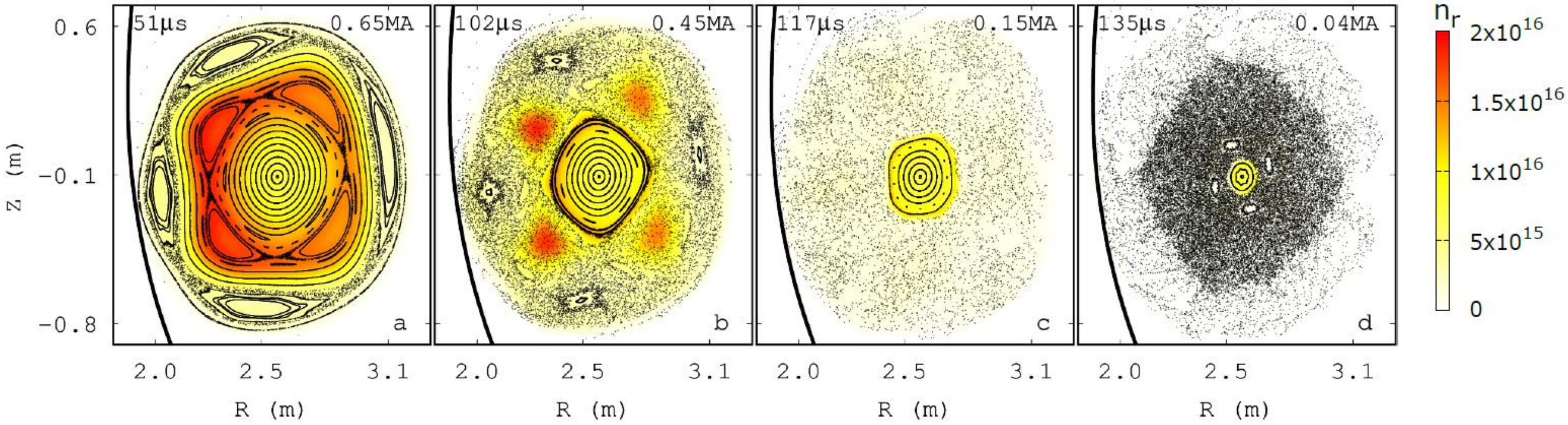
  ➔ growth rate rather than dB/B appears to be the key feature.





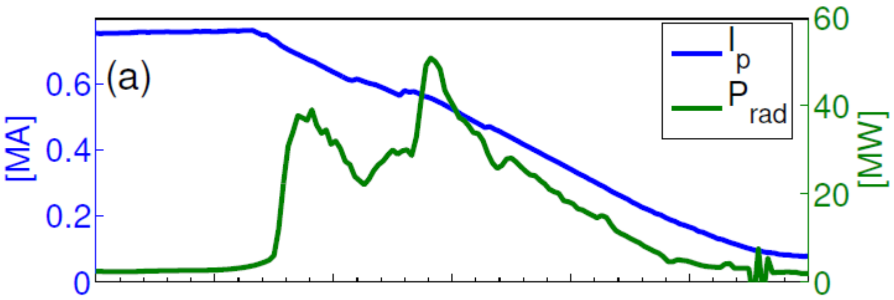
JOREK simulations

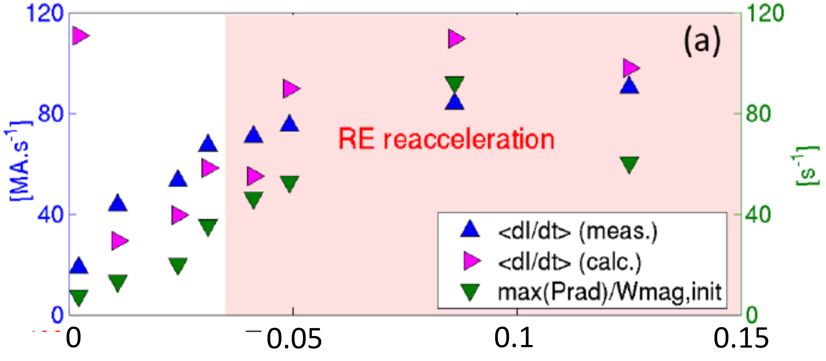
- JOREK simulations have been made using a RE fluid model *[Bandaru Phys Rev E 2019]*
- Initial current profile determined from SOFT simulations
- Result: MHD dominated by tearing mode from the outside q=4 surface.
  - Stochastization starts in the edge
  - Confinement destroyed in 100 µs ➔ timescale compatible with measurements
  - 95% of runaways are lost. RE losses deposited near the limiter contact point but over a wider area.

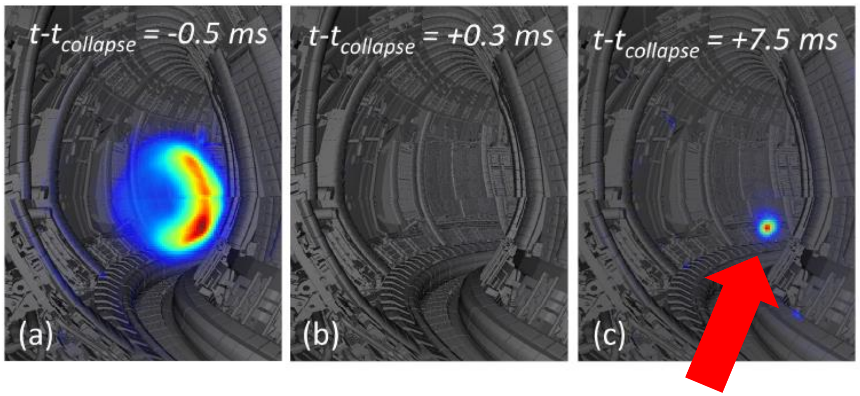


RE regeneration during the final collapse

- After the collapse : current carriers shift from RE to thermal bulk
- Radiated power and free density increases
- Argon line emission is back ➔ argon not completely « purged »
- Maximum radiated power and current quench rate during final collapse correlated with the Ar/D_2 ratio in the neutral species injected into the vessel (triggering MGI + mitigating SPI) ➔ further evidence of the incomplete purge
- When Ar fraction gets higher: reappearance (regeneration) of a small RE beam during collapse







RE regeneration modelling

- Behaviour investigated using a 0D model (lumped circuits + RE population evolution)

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

Energy balance for the companion plasma.

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

Ohm's law for the plasma

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

Ohm's law for passive conductive structures

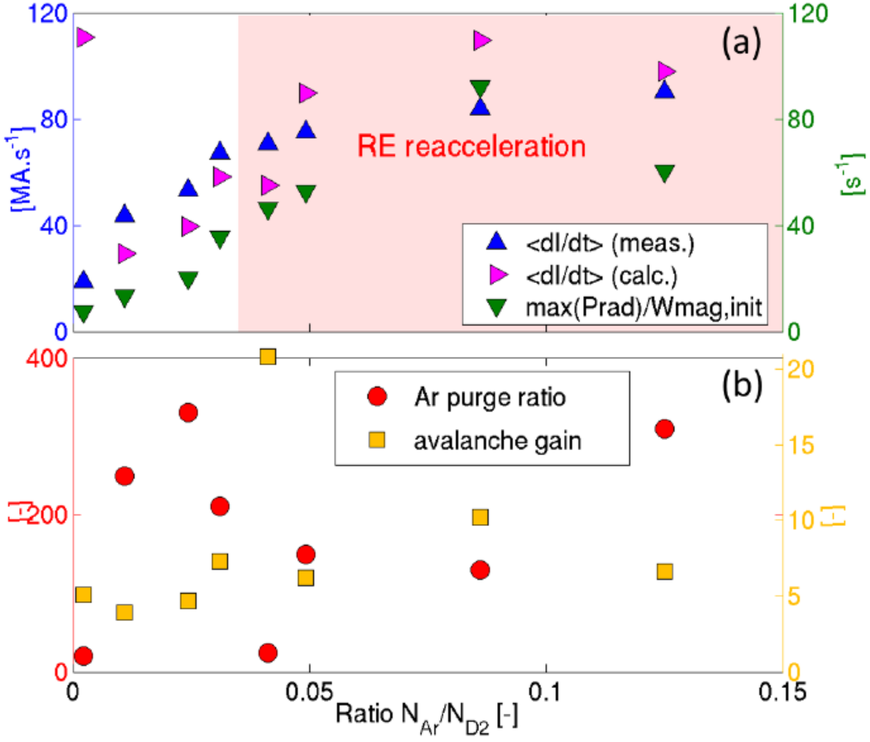
$$\frac{1}{I_{RE}}\frac{\partial I_{RE}}{\partial t} \approx \frac{n_f + n_b}{n_f \ln\Lambda_f(p_c) + n_b \ln\Lambda_b(p_c)} \frac{1}{\sqrt{Z_{RE}(p_c) + 5}} \frac{e\left(E - E_{crit}\right)}{m_e c}$$

Ruanway population evolution (avalanche) [Aleynikov NF 2017, Martin-Solis PoP 2015, Hesslow NF 2019, Breizman NF 2019]

  - Takes into account partial screening of impurities
  - Critical momentum obtained from acceleration-friction force balance
- Computes how fast the plasma reheats compared to the avalanche timescale ➔ self consistent temperature, current and RE generation

RE regeneration modelling

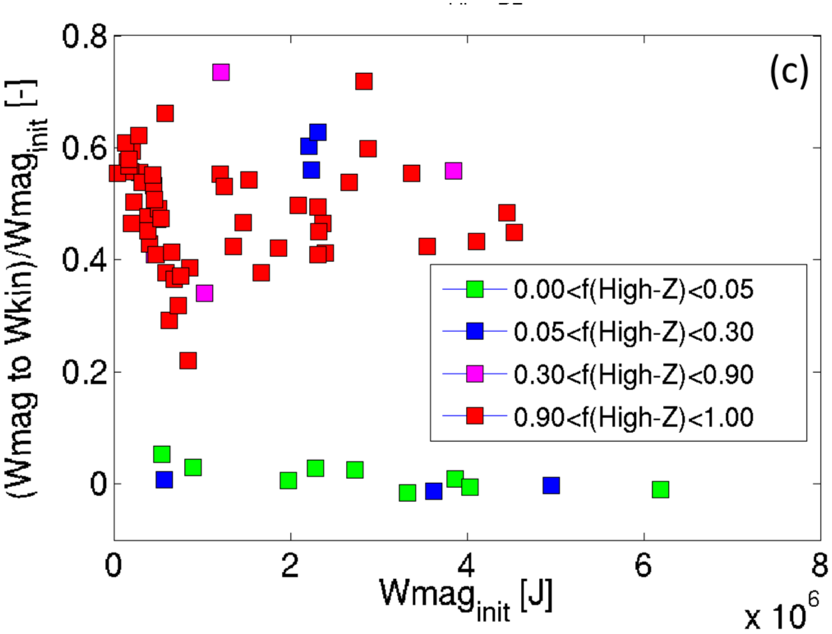
- Numerical parameters:
  - Vessel resistive time L_V/R_V = 5 ms, L_V = 2µH as in *[Strauss PoP 2017]*
  - L_z taken from ADAS
  - l_i = 0.5, Spitzer resistivity
  - Plasma cross section and pre-collapse current from measurement
- Results: dI/dt in good agreement with the experiment
- Argon purge rate between 50 and 300, confirming the purge mechanism
- Avalanche gain too low to regenerate a full RE beam, but small correlation between avalanche gain and Ar/D_2 ratio.
- If Ar/D_2 ratio higher: continuous reacceleration during collapse



Global dynamics of final collapse well captured by the model

Conversion of magnetic into kinetic energy

- Continuous RE regeneration during the collapse: plays a role in the conversion from magnetic to kinetic energy of the runaway beam.
- Typical case: W_{mag} = 2.2 MJ, W_{kin} = 0.4 MJ.
  - ➔ much larger damage if W_{mag} is converted into W_{kin}
- Conversion rate calculated using the method proposed in *[Loarte NF 2011]* and adding radiated power
- Conclusions: conversion rate close to zero for cases where high-Z material < 30%
- High-Z and low-Z cases clearly distinguished



Conclusions

- D_2 RE beam mitigation was found to be efficient and reproducible at JET provided that the companion plasma is pure enough
  - Large enough D_2/High-Z ratio
  - More experiments planned to better assess the boundary conditions

- Extrapolability to ITER and future devices is now the main question
  - Is a large and brief enough MHD instability accessible on ITER?
    - More MHD simulations (JOREK)
  - Modeling predicts the avalanche gain will be larger for ITER
    - Can an arbitrarily high companion plasma purity level be reached?

- Even if runaways are re-accelerated: only a fraction of the initial RE current can be regenerated
  - ➔ Repetitive D_2 SPI could be used to do a stepwise reduction of the RE current down to a tolerable level

- So far: one of the best hopes for RE beam mitigation on large machines