Runaway electron generation with ITER-like Wall and Efficiency of Massive Gas Injection at JET

25th IAEA Fusion Energy Conference,

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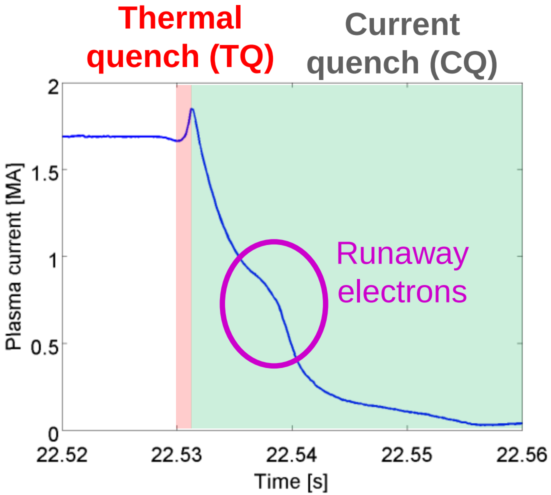
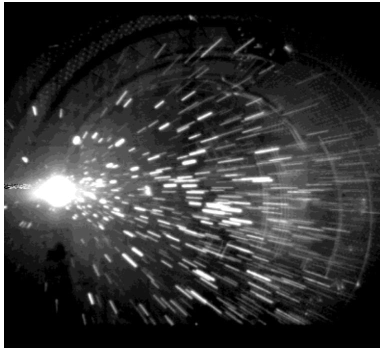
DE LA RECHERCHE À L'INDUSTRIE

Disruptions

- Major operational concern for ITER and future machines
- 3 types of consequences:
  - **Heat loads:** conduction, radiation ➔ TQ,CQ
  - **Electromagnetic forces:** halo/eddy currents ➔ CQ
  - **Runaway electrons** (MAs @ 5 to 20 MeV) ➔ CQ
- **Massive Gas Injection**: one of the disruption mitigation methods foreseen on ITER. Goals:
  - Radiating the plasma thermal energy
  - Controlling the duration of the current quench
  - Prevent/suppress runaway electrons
- Questions to be addressed:
  - Radiation efficiency, radiation asymmetries
  - Ability to suppress runaway electrons in a metal environment





Example of runaway impact on carbon PFCs on Tore Supra

Outline

- **Introduction**
  - Disruptions and MGI
- **Efficiency of Massive Gas Injection**
  - Experimental background and questions to be addressed
  - Radiation efficiency
  - Radiation asymmetries
- **Runaway electrons at JET-ILW**
  - Experimental background and questions to be addressed
  - Dependencies with JET-ILW
  - Runaway beam mitigation
  - Runaway beam impact
- **Conclusions and perspectives**

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Experimental background - MGI

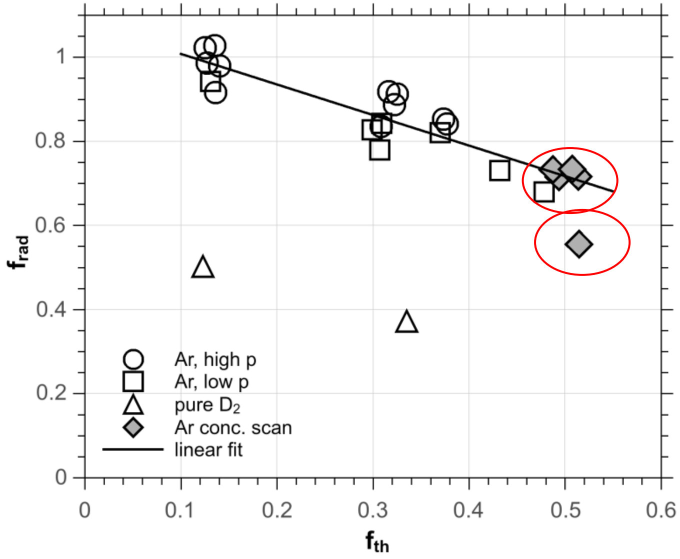
- **Heat loads and radiation - previous observations at JET-ILW:**
  - **Lower radiation** during current quench due to absence of carbon [1]
    ➔Slower current quenches ➔ larger halo currents ➔ **larger forces**
  - Low radiation ➔ larger conducted power: risk for PFC during VDEs
  - MGI with 90%D_2+10%Ar restores some radiation during CQ [2]
  - **MGI radiation efficiency decreases** with increasing W_{th}

- **Questions to be addressed:**
  - Can radiation efficiency decrease be compensated by other injection scenarios?
    - By increasing argon fraction? Pressure?
  - How large are radiation asymmetries?
    - Efficiency of MGI on incoming disruptions with a locked mode

[1] P. De Vries et al., Plasma Phys. Control Fusion. 54 (2012)
[2] M. Lehnen et al., Nucl. Fusion 53 (2013)

MGI efficiency decreases with f_{th}

- MGI aims at radiating the thermal and magnetic energy ($W_{th}+W_{mag}$)
- Most common mixture : 90%D_2+10%Ar
  - Combines fast delivery of D_2 and radiation capabilities of argon
  - D_2 only: radiation efficiency down to 40-50%
- At higher thermal energy fraction ($f_{th} = W_{th}/W_{mag}$): decrease of radiation efficiency down to 70%
- Increasing the argon fraction >10%: no increase of radiation efficiency
- Decrease the argon fraction: first signs of efficiency decrease only at 1% Argon lower pressure

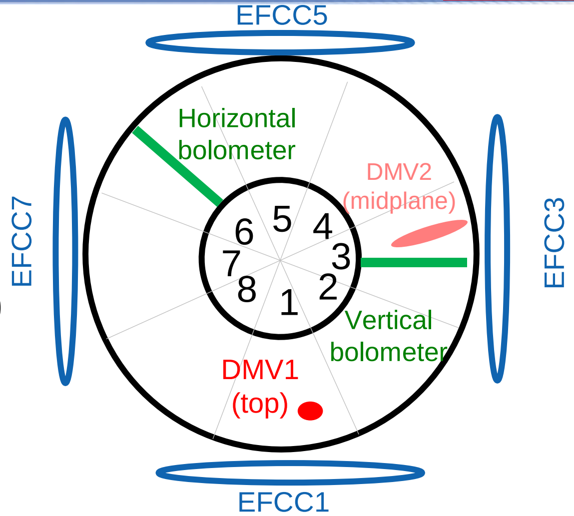


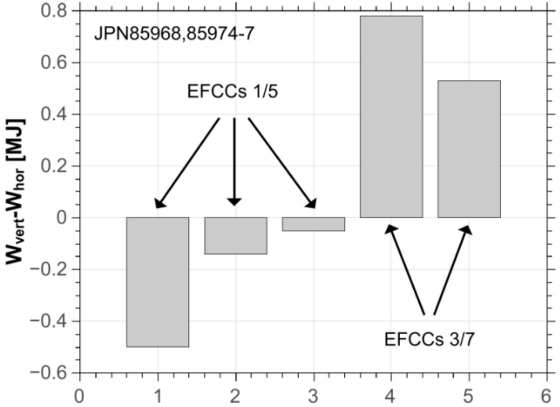
Decrease of radiation efficiency unrecoverable by increasing argon fraction

Radiation asymmetries related to locked mode phasing

- MGI may lead to localized radiation peaking
  ➔radiation efficiency decrease?
- Injection on real disruptions with locked modes may increase peaking
- Mode lock triggered by Error Field Correction Coils (EFCC)
- Radiation measured with two bolometer arrays -135° and 90° away from the valve

- Radiated energy difference changes sign with mode phasing
- Up to 20% deviation to uniformity





Radiation asymmetries depend on mode lock phasing

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  - Dependencies with JET-ILW
  - Runaway beam mitigation
  - Runaway beam impact
- **Conclusions and perspectives**

Experimental background - runaways

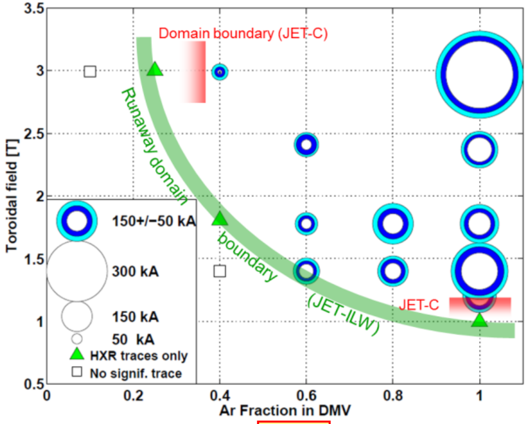
- **Runaway electrons - previous observations at JET-ILW:**
  - Almost no runaways during spontaneous disruptions (>6000 discharges)
  - Slower current quenches ➔ lower accelerating field
  - Argon MGI is still able to generate 5 to 15 MeV runaways [1]

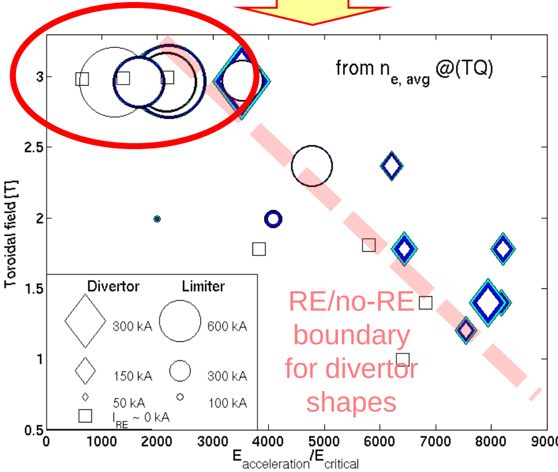
- **Questions to be addressed:**
  - What are the generation conditions for runaways at JET-ILW
    - Argon fraction in MGI?
    - Link to physics parameters?
  - **Can runaways be suppressed by MGI?**
  - Characterize runaway impacts on PFC

[1] C. Reux et al., Proceedings of PSI 2014, accepted for publication in JNM, 2014

RE generation dependencies

- RE generation using D_2+Ar MGI to determine the operational domain
- Domain boundary similar between JET-C and JET-ILW
- Runaway energies 5 to 15 MeV *(see V. Plyusnin poster P5-23, today)*
- Known runaway generation dependencies:
  - Accelerating electric field E_a
  - Critical electric field $E_c = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 m_e c^2}$
  - Toroidal field B_t
- Divertor pulses: clear domain in (E_a/E_c, B_t) space
- At equal E_a/E_c, higher RE currents with limiter pulses

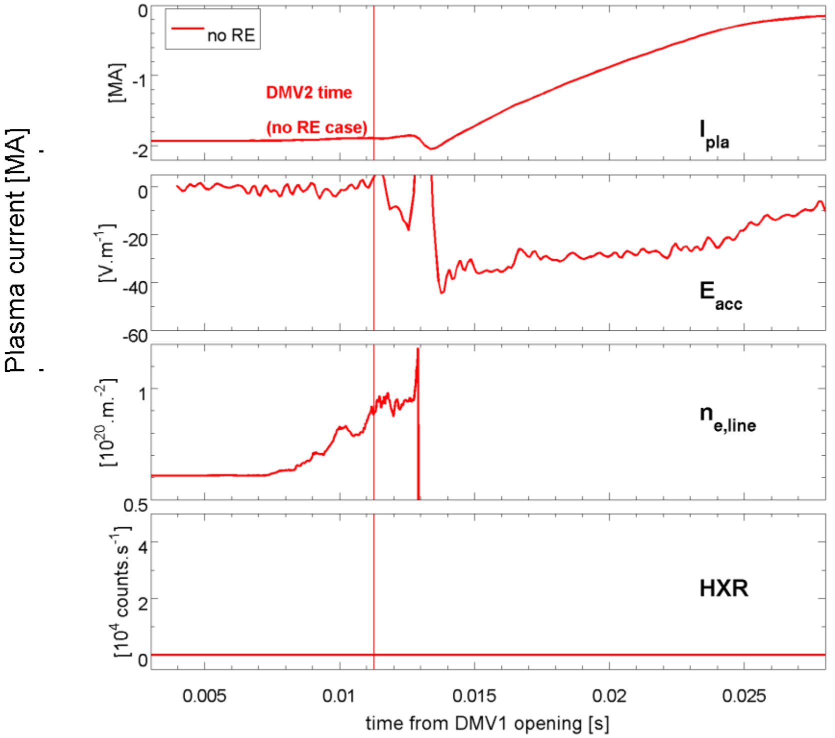




Strong dependence of RE generation on vertical stability

Runaway beam early mitigation: successful if early enough

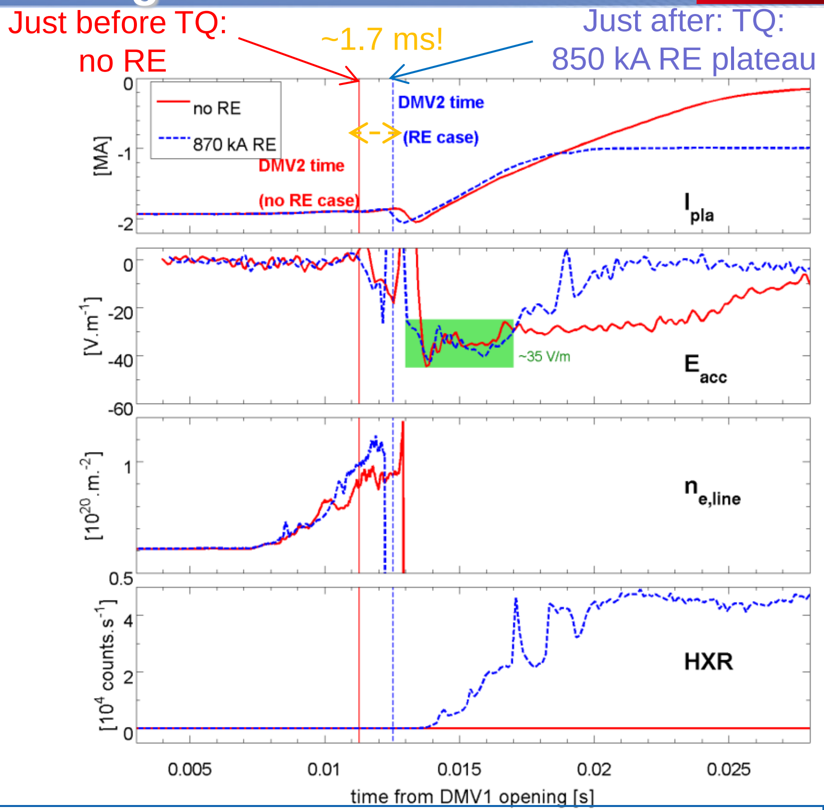
- Scenario: trigger runaway beam with DMV1 100% Argon
  - ➔ ~0.7 MA 50 ms beam
- Experiment: fire DMV2 high pressure D_2 at different times
- Result:
  - – No runaways if DMV2 gas arrives before TQ



Runaway beam early mitigation: successful if early enough

- Scenario: trigger runaway beam with DMV1 100% Argon
  ➔ ~0.7 MA 50 ms beam
- Experiment: fire DMV2 high pressure D_2 at different times
- Result:
  - No runaways if DMV2 gas arrives before TQ
  - Fully unmitigated runaway beam if DMV2 gas arrives after TQ
- dI_p/dt, accelerating electric field E_a almost identical during early CQ
- Density rise before TQ very similar

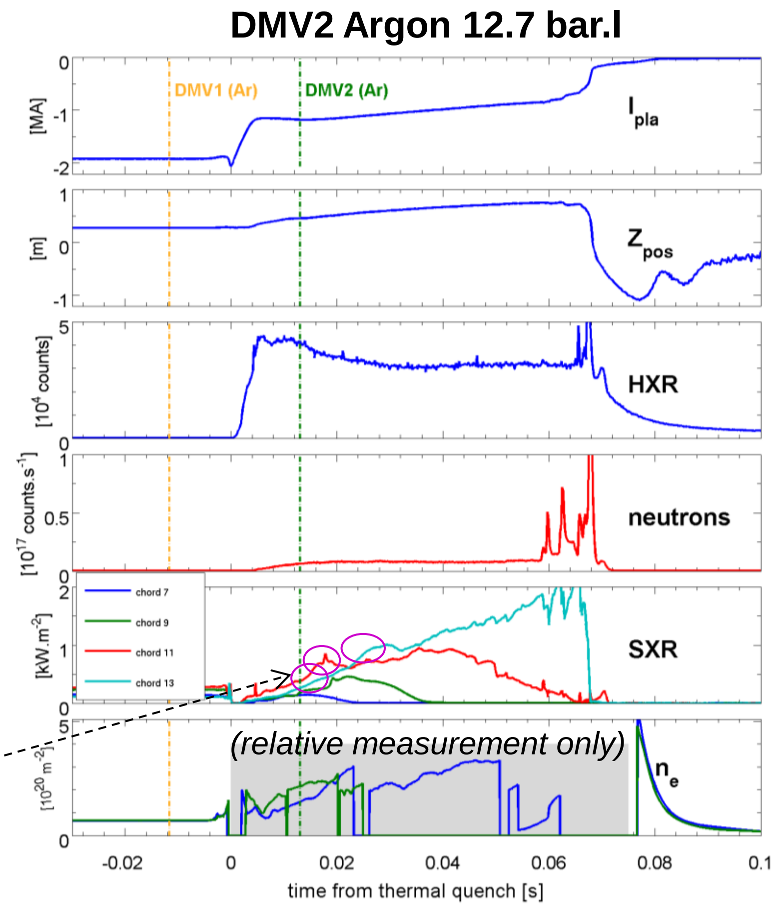
➔ DMV2 D_2 gas mixing regime differs before/after TQ



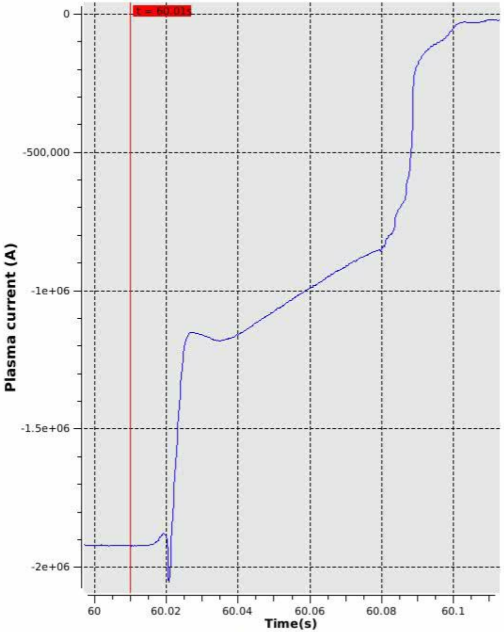
Suppression of an incoming runaway beam feasible if done before TQ

Runaway beam late mitigation: no significant effect

- Same runaway beam scenario (DMV1 100% argon low pressure)
- High-Z injection during the runaway beam (argon, krypton)
- No significant effect on runaway beam current, HXR/neutrons rate, plasma electron density and vertical motion
  - Runaway current slow decay is already present in unmitigated cases (RE/DMV1 gas interaction)
- Transient increase of SXR radiation and visible light



Mitigation gas interacts with runaway beam

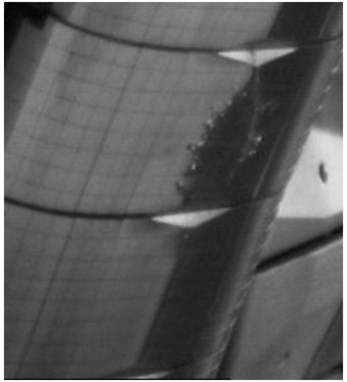


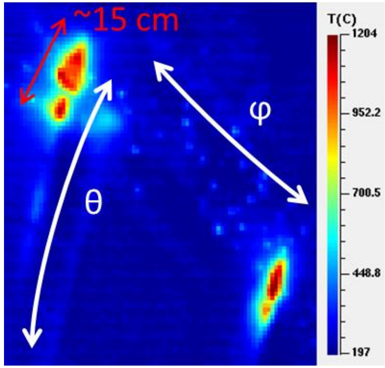
- Interaction between DMV2 gas and RE beam or CQ cold plasma
- Possible explanations on the absence of efficiency:
  - Background neutral gas pressure (DMV1: 3.5 bar.l, DMV2: 7.2 to >20 bar.l Ar, Kr, Xe)
  - Background plasma pressure
  - RE energy too low for significant braking effect
- To be compared with DIII-D, Tore Supra, AUG results

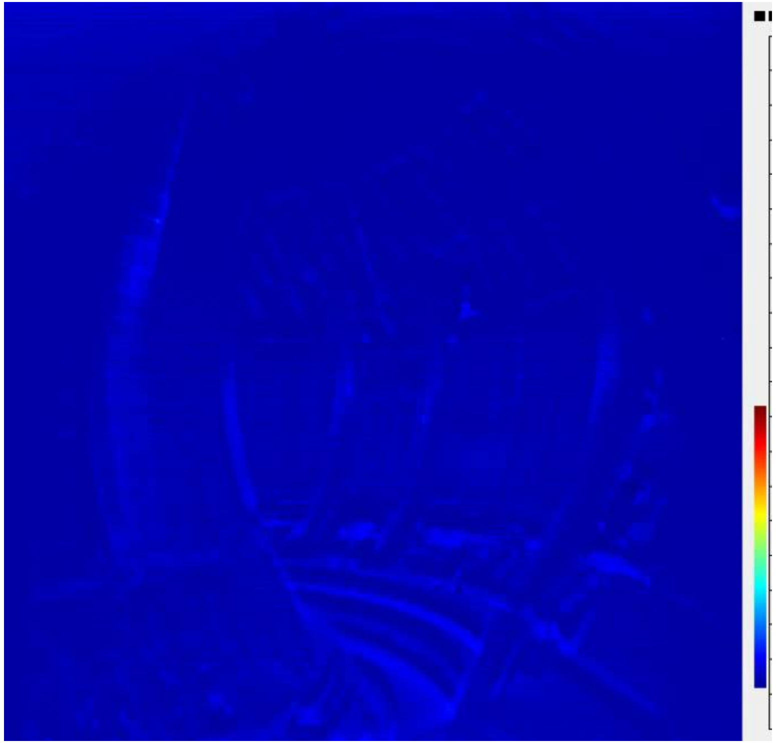
Suppression of an already accelerated beam difficult

Runaway impact on PFCs: asymmetries

- Mild impacts at 50-100 kA reported in [1]
  - Toroidally periodic impacts on the upper dump plate
  - Melting unlikely
- Latest observations:
  - 770 kA RE beam at termination
  - Impact on Inner Wall Guard Limiter







[1] C. Reux et al., Proceedings of PSI 2014

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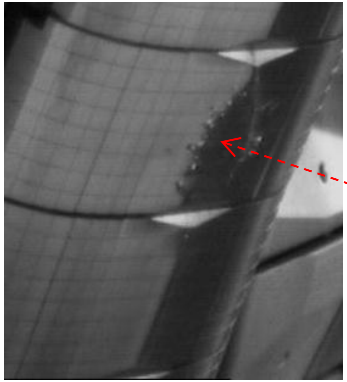
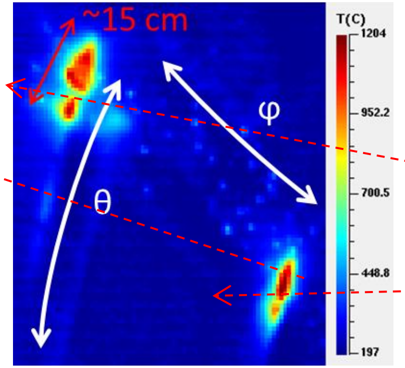
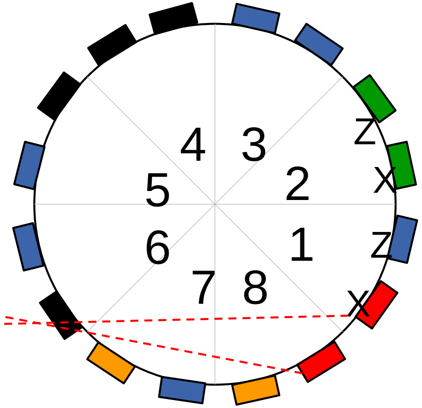
(red)	Significant melting
(yellow)	Traces of melting
(green)	Surface alteration only
(blue)	No damage
(black)	No data



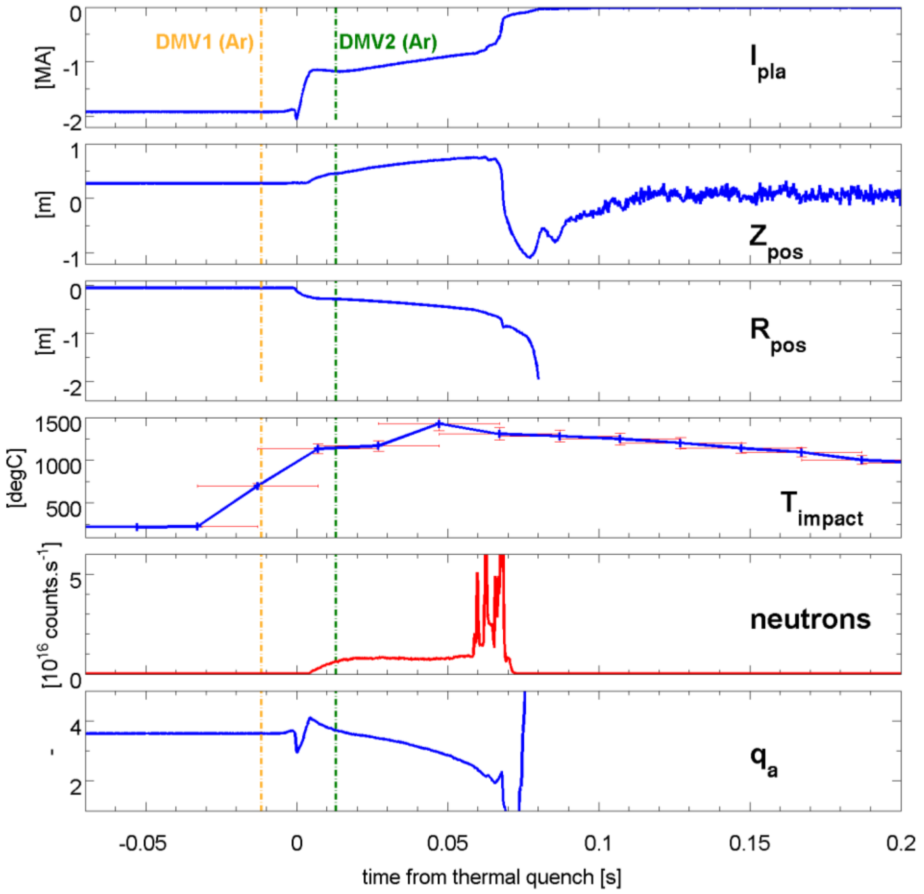


Toroidally asymmetrical impacts



[1] C. Reux et al., Proceedings of PSI 2014

Runaway interaction with the wall: dynamics



- Impact from a failed mitigation attempt (12.7 bar.l)
- Slow upward-inward drift of the beam

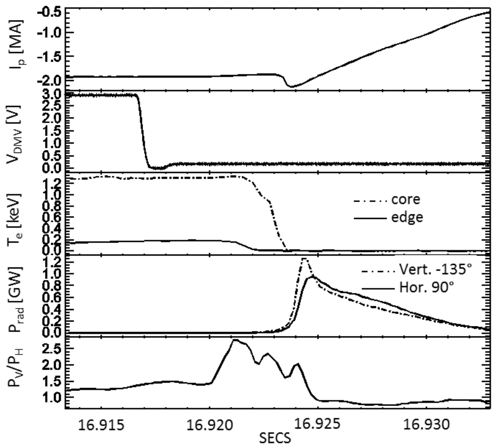
- 0.77 MA to 1.0 MA ➔ ~1400°C on beryllium tile
- Interaction with the wall starts before the final current drop
- Final current drop when q_{edge}=2 is reached

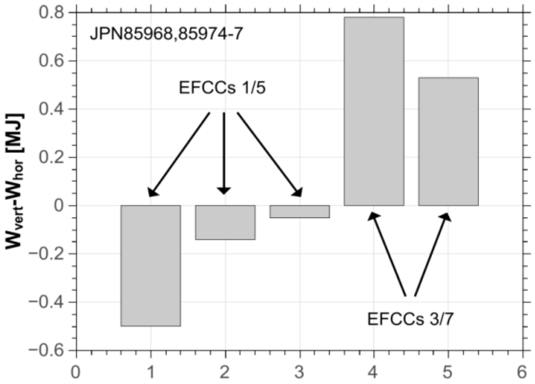
Runaway beams in the MA range: significant melting

- **Conclusions**
  - Radiation efficiency of MGI decreases with increasing f_{th}
  - Toroidal asymmetries in radiation
  - RE generation strong dependence on **vertical shaping**
  - **Mitigation of RE beam feasible before thermal quench, difficult after**
  - Unmitigated 1MA beam at a few MeV: beryllium melting
- **Perspectives**
  - Continue mitigation experiments
  - Use the data to build extrapolation to ITER
    - Enabling research programme for RE modelling (Fokker-Planck codes)
  - Investigate further the link between vertical shaping and RE generation
  - Develop alternative control schemes

Additionnal slides

Radiation asymmetries - 2



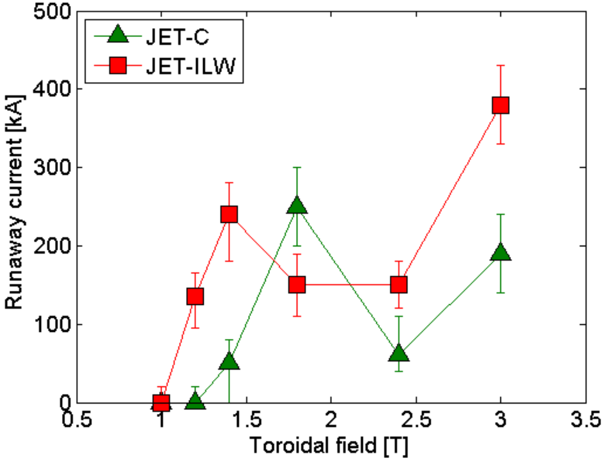


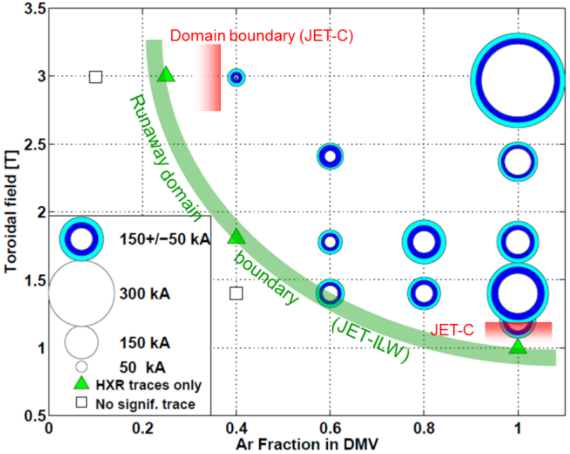
- Increase of the radiated power ratio P_{vert}/P_{horiz} during the first stage of the disruption: pre-disruption, thermal quench and early current quench
- Total radiated energy difference between two arrays changes sign when EFCC phase changes
- Up to 20% deviation to uniformity

Radiation asymmetries depend on mode lock phasing

Runaway electron behaviour

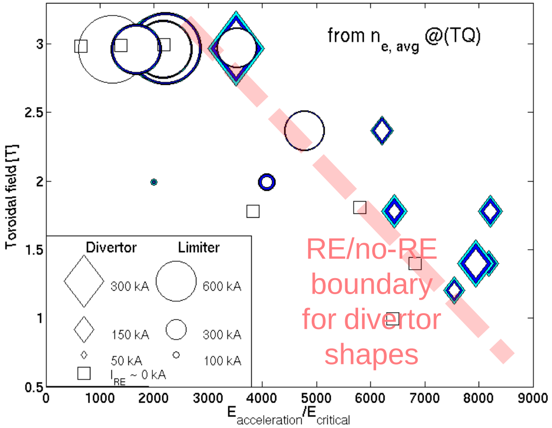
- Runaway electron generation using D_2+Ar MGI to determine the operational domain
  - Scan in argon fraction f_{Ar} and toroidal field B_t
- Domain boundary (entry points) similar between JET-C and JET-ILW (slightlier earlier entry for JET-ILW)
- Inside the runaway domain: higher currents for JET-ILW
  - Possibly due to different background density conditions at the end of the current quench (different outgassing from JET-ILW

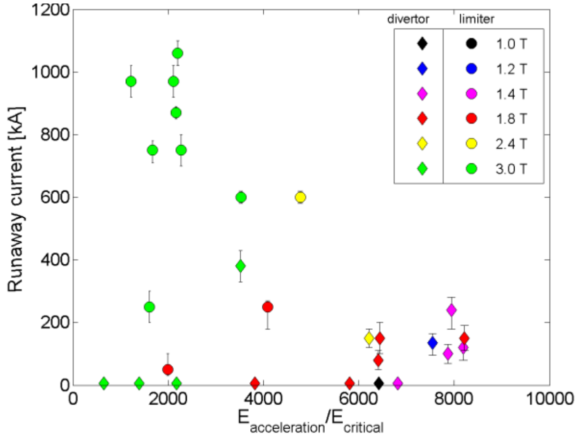




Runaway electron behaviour - 2

- Operational domain has to be transcribed into physics parameters
- Known runaway generation dependencies:
  - Accelerating electric field E_a: partly related to the current quench speed
  - Critical electric field (Dreicer and avalanche mechanisms) $E_c = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon^2 m_e c^2}$
  - Toroidal field B_t
- With divertor pulses: clear domain in (E_a/E_c, B_t) space
- At equal E_a/E_c, limiter pulses generate higher runaway currents





Strong dependence of runaways on vertical position

Runaway generation physics

- 2 main mechanisms for runaway generation
- **Primary generation** : Dreicer mechanism : unconditional generation when accelerating electric field E_a above the Dreicer field E_D

$$E_D = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 m_e v_e^2} = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 T_e}$$

  - Runaway generation also happens above a critical field E_C at a lower rate

$$E_c = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 m_e c^2}$$

- **Secondary generation**: avalanche : thermal electrons are accelerated by collisions with runaway electrons. Requires seed electrons. Depends on E_c:

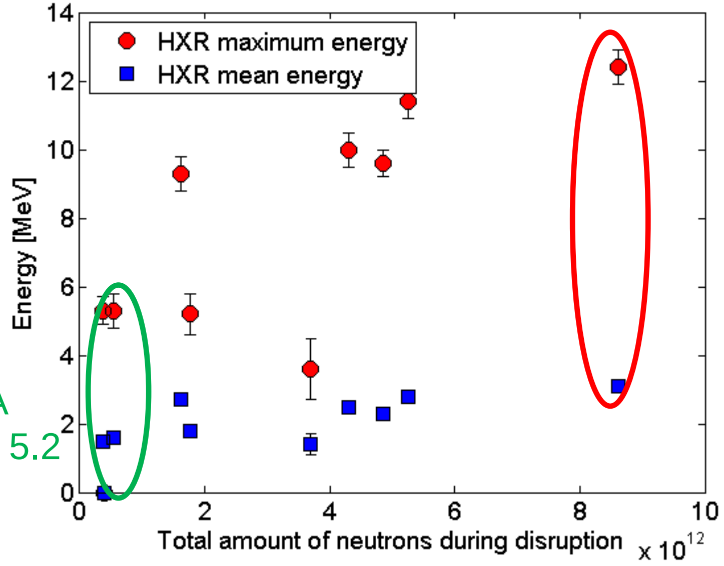
$$\frac{dn_r}{dt} \simeq \sqrt{\frac{\pi}{2}} \frac{(E/E_c - 1)}{3\tau \ln \Lambda} n_r$$

Runaway characteristics (1)

- Runaway interaction with wall and background plasma:
  - Hard X-ray emission (HXR)
    - Indicator for runaway relative energies
  - Photoneutron production:
    - Indicator for total amount of runaway electrons

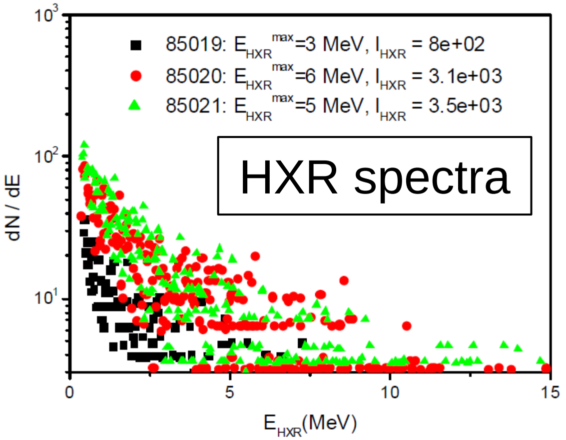
- At low runaway currents, maximum and mean HXR energy increase with increasing runaway current

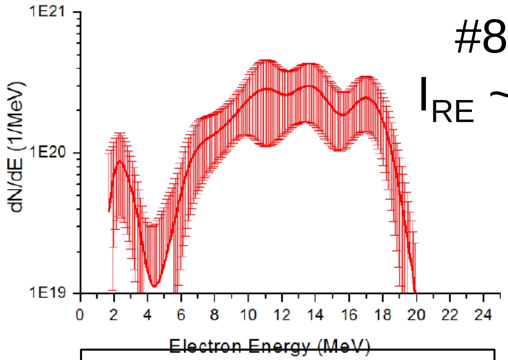
I_{RE} = 240 kA : max(E_{HXR}) = 12 MeV



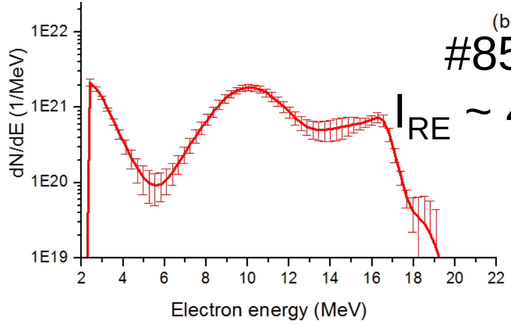
I_{RE} ~ 0 kA
Max(E_{HXR}) = 5.2 MeV

- Runaway energy spectrum deconvoluted from HXR measurements using the DeGaSum code [Shevelev_NF_13]





Runaway spectra



Maximum runaway energy so far: 20 MeV at I_{RE} = 475 kA, consistent with theories

Full critical field calculation

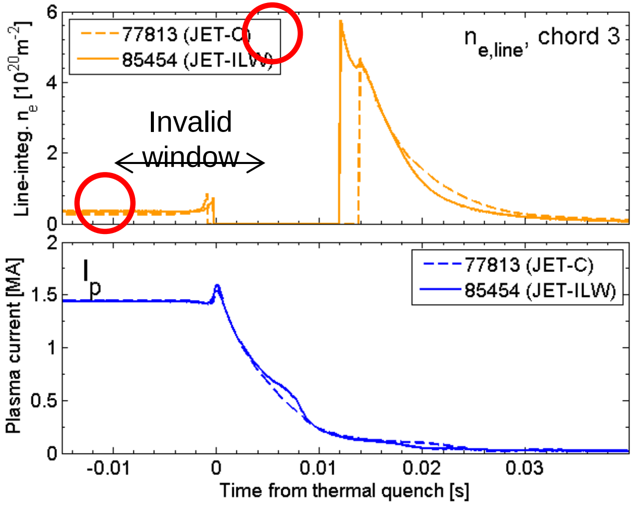
- Second main parameter for runaway generation: critical field E_C

$$E_c = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 m_e c^2}$$

- No density measurement during middle of current quench (interferometer beam refraction)

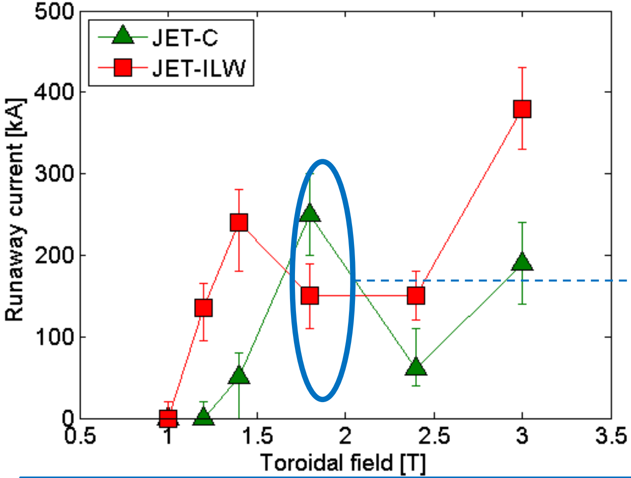
- Two critical field estimates:
  - Start of current quench (last density point)
  - End of current quench (first density point)

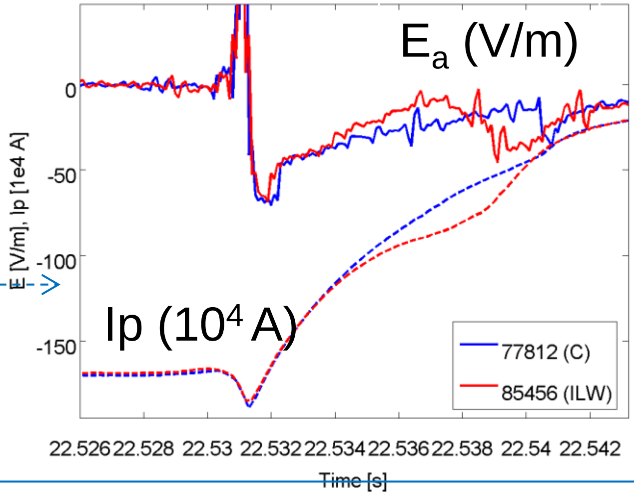
- Used to compute E_a/E_C ratio



Differences JET-C and JET-ILW

- Discharges at f_{Ar} = 100%: direct JET-C/JET-ILW comparisons :
  - Same plasma parameters : density, divertor configuration
  - Same injection parameters: pure Argon, full pressure in DMV
- In both JET-C and JET-ILW, runaway appear around 1.5MA/1.2T
- Inside runaway domain $I_{RE,ILW} > I_{RE,C}$



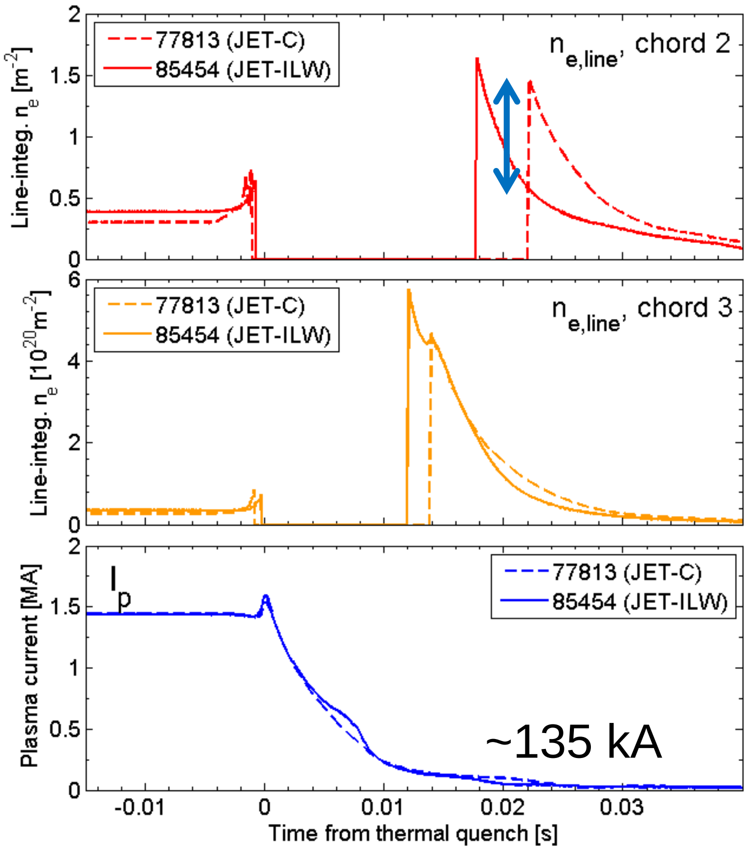


More runaways in JET-ILW in high E_a/E_C, high B_t regimes ?

Differences JET-C and JET-ILW

- Differences JET-C/JET-ILW
  - CQ temperature?
  - Magnetic turbulence?
  - **Density: post-CQ density higher in JET-C cases**

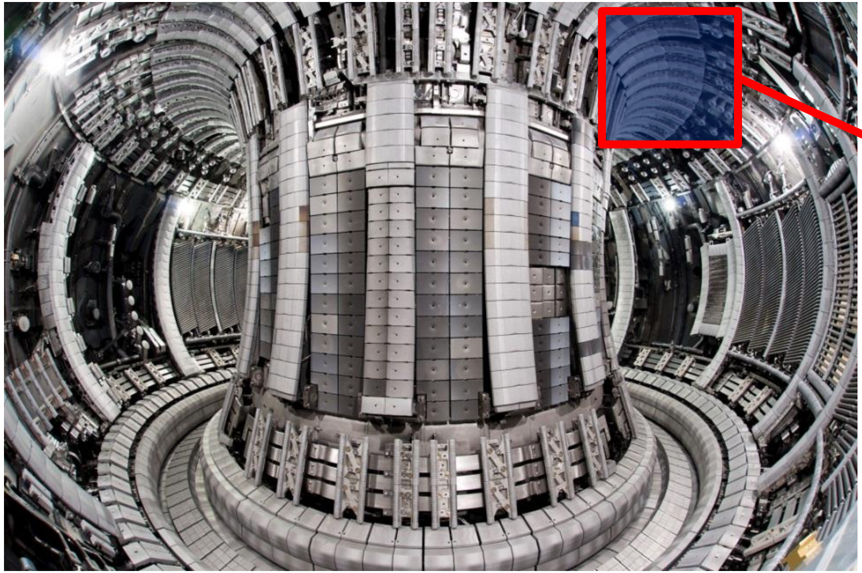
- Different density behaviour due to JET-ILW?
  - Different impurity content leading to different CQ temperature?
  - Different wall outgassing conditions?

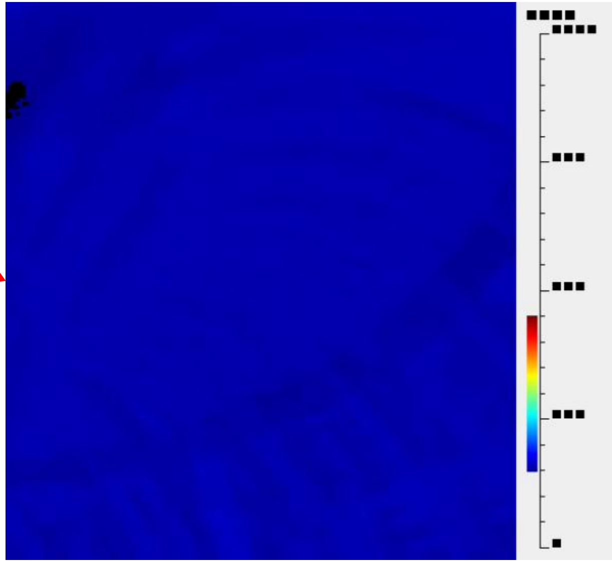


Density at end of CQ different in ILW: impact on runaway generation?

Runaway impact observations

- Runaway electron beams in divertor configuration usually impact the upper dump plate at JET (vertical instability)
- Impact seen by infrared camera (20 ms time resolution) on two representative pulses :#85020 (~50 kA) and #85021 (~100 kA)





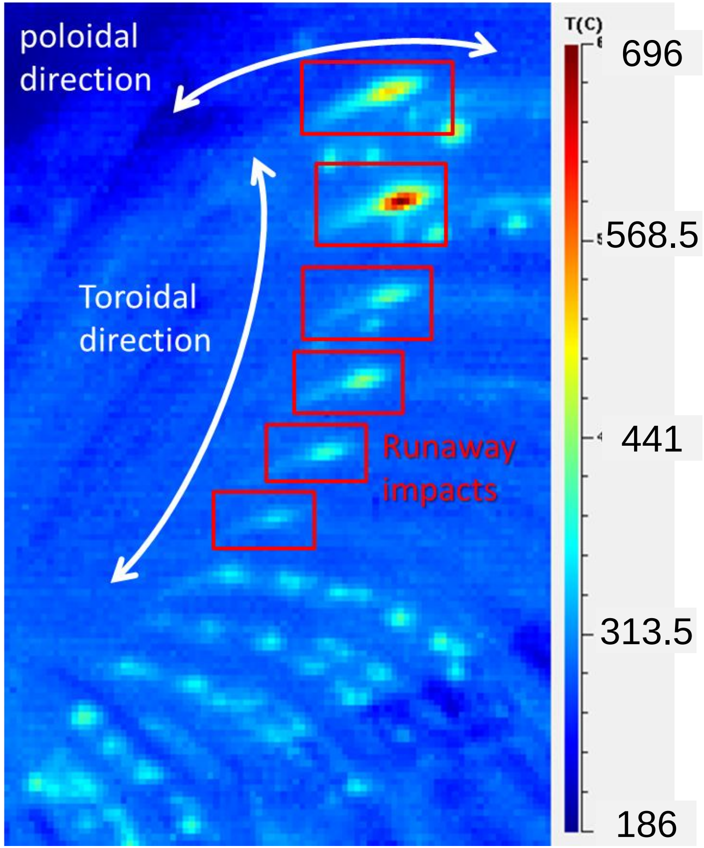
Runaway impact observations

- Footprint on upper dump-plate:
  - Localized hots spots on dump plate ribs
  - Toroidally periodic
  - Poloidally localized

- Apparent poloidal size ~ 32 mm +/- 8 mm, toroidal length 10+/-5 mm

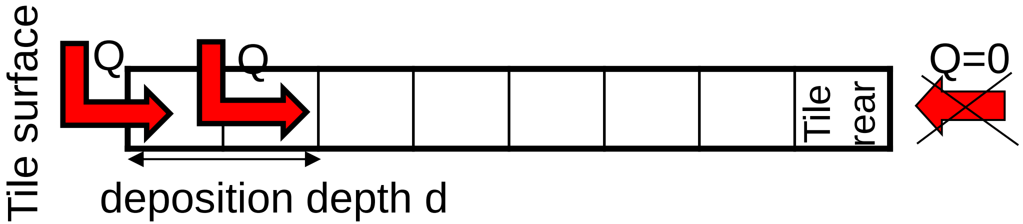
- Consistent with upwards movement of plasma centroid

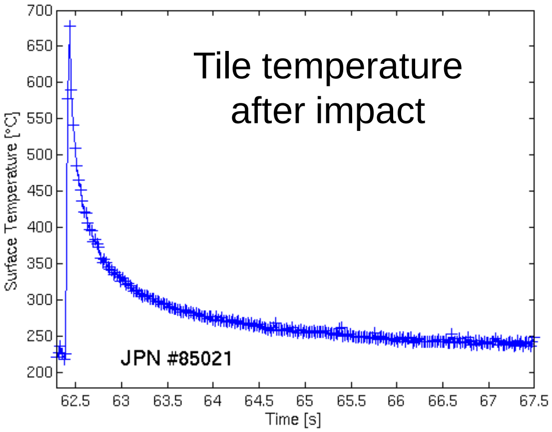
Runaways: localized impacts, small area



Cooling time simulations (1)

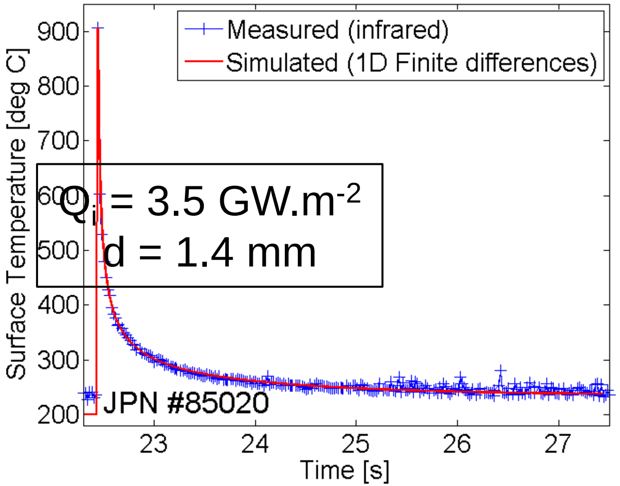
- Low IR time resolution ➔ **peak temperature is subject to caution**
- **Cooling phase** long enough to be fully captured by the camera
- Simulate tile cooling with a simple 1D heat diffusion model
  - Finite difference model, 1D slab
  - Beryllium constant thermal properties
  - No radiative cooling, no conductive heat loss between tile and carrier
- Fit parameters :
  - Incident heat flux Q
  - Heat deposition depth d

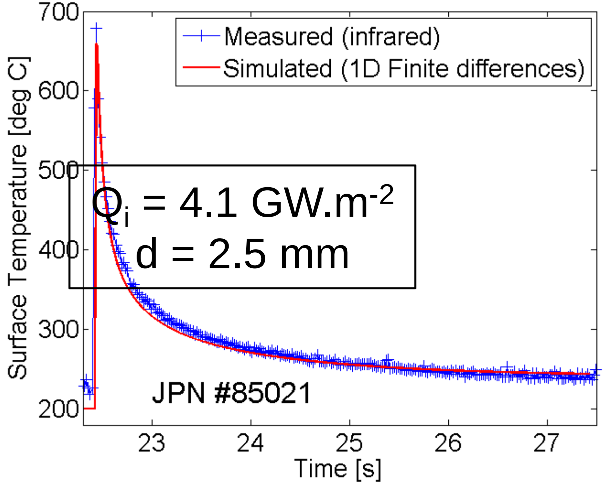




Cooling time simulations (2)

- Results and fits for 85020 and 85021



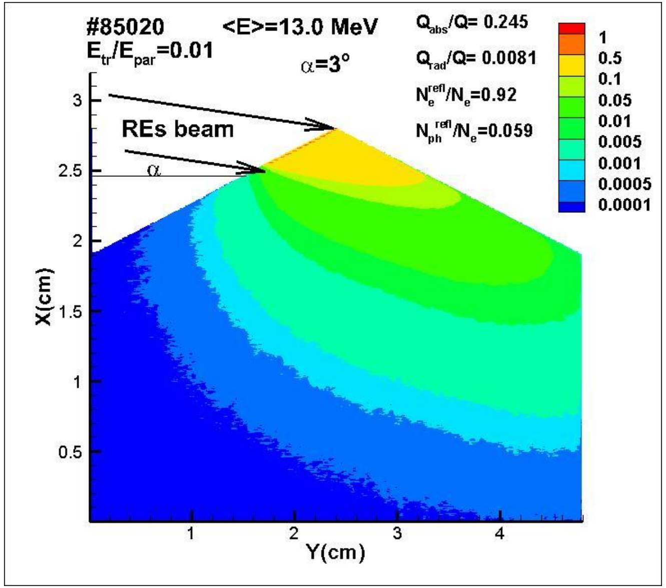


- Fit parameters tuned to match final temperature and initial cooling
- **1 ms** heat deposition time is assumed (neutron peak)
- Deposition depth of 1.4 and 2.5 mm needed
- Higher I_{RE} on #85021➔ higher heat flux and deeper deposition

➔ Volumic heat deposition on beryllium tiles

Runaway absorption simulations (1)

- More refined simulations carried out with the MEMOS/ENDEP suite of codes [Bazylev JNM 2014]
- ENDEP: Monte-Carlo code treating the runaway electron absorption by wall material (3D realistic geometry)



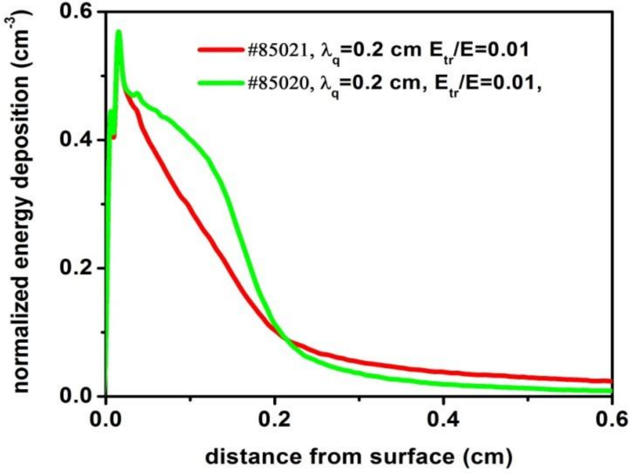
- E_{tr}/E_{par} = 0.01 is assumed. Impact angle 3°. Runaway energy spectra taken from deconvolutions shown earlier

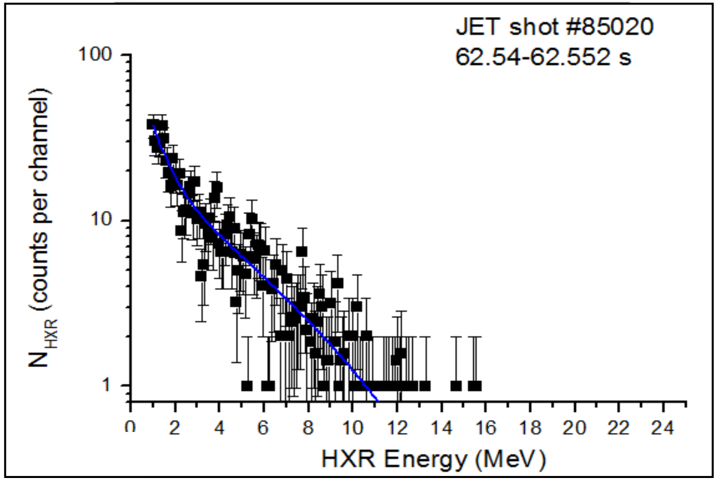
➔ Only part of the thermal and magnetic energy deposited in the tile : rest goes through.

➔In-depth deposition

➔ Volume deposition confirmed

Runaway absorption simulations (2)



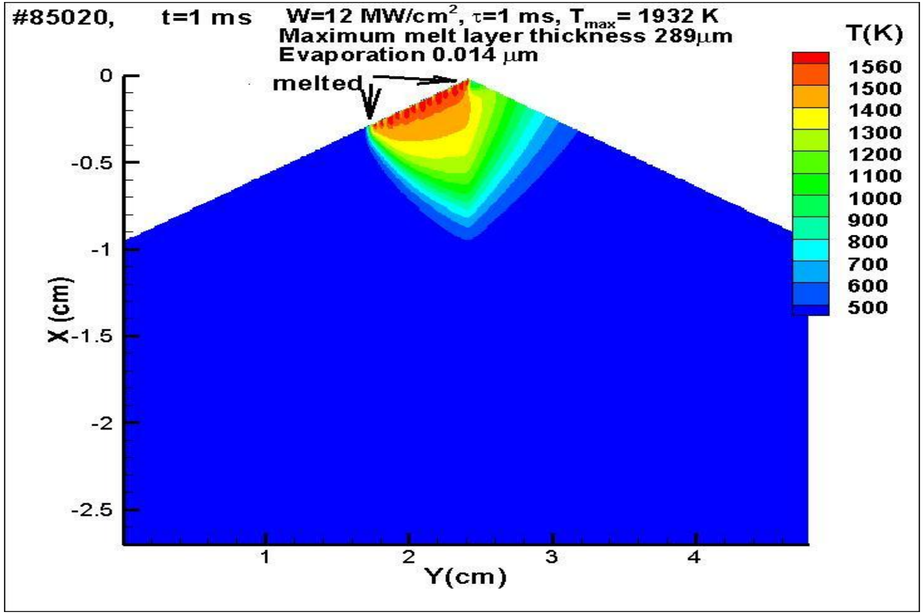


- Energy absorbed in the first 2 mm from tile apex : **consistent with simple 1D diffusion simulations**
- Photon energy spectrum recalculated by ENDEP: **consistent with measured HXR spectrum.**

➔ Good consistency of simulations with measurements

Heat diffusion simulations (1)

- MEMOS code: heat diffusion in 3D geometry, temperature-dependent thermal properties, melt-layer motion
  - Normalized heat deposition maps from ENDEP taken as input
  - Scan parameter: Heat flux: 10 to 120 GW.m^{-2}: **10 to 120 MJ.m^{-2}, 1 ms**



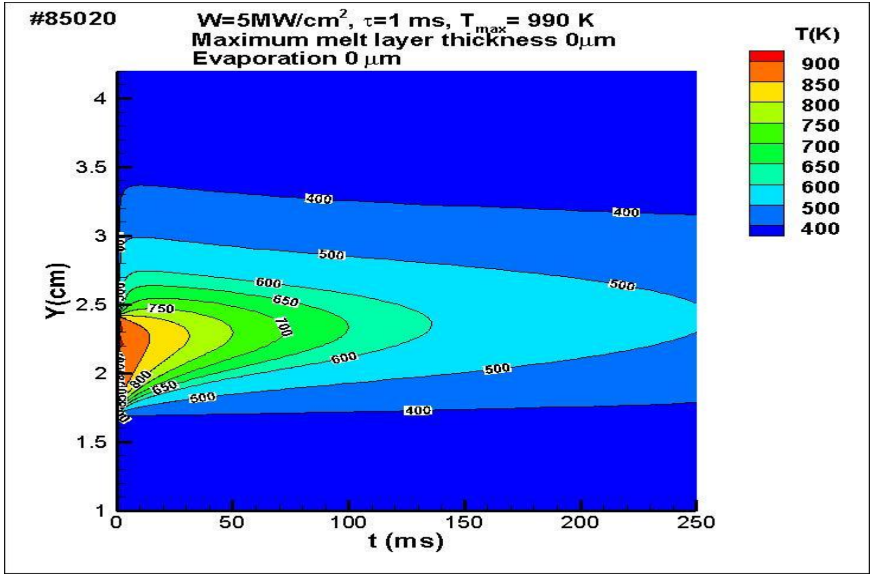
- Melting threshold ~ 100 MJ.m^{-2}

  ➔Not reached during experiments

- Deposition dependent on tile geometry

Heat diffusion simulations (2)

- $P_{incident}$ = 50 $MJ.m^{-2}$ closer to the actual measured surface temperature
- Maximum temperature 1030K for 100 kA discharge, cooling phase in qualitative agreement with IR measurements



- No melting for beryllium tiles at ~50 and ~100 kA runaway beam with E_{mean} = 12 MeV
- Shallow melting might occur with larger runaway currents.

➔ No melting for 50 kA and 100 kA beams at JET-ILW thanks to in-depth deposition

ENDEP simulations (4)

- For a single isolated tile :
  - Only 25% of the beam thermal energy is deposited
  - Less than 10% of the beam magnetic energy is lost in the tile
  - Spectrum is altered after passing through the tile : slightly recentered around mean value
- The rest of the energy is supposed to hit the following tile in the dump plate.