Latest Progress in Studies of Runaway Electrons in JET

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*See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US

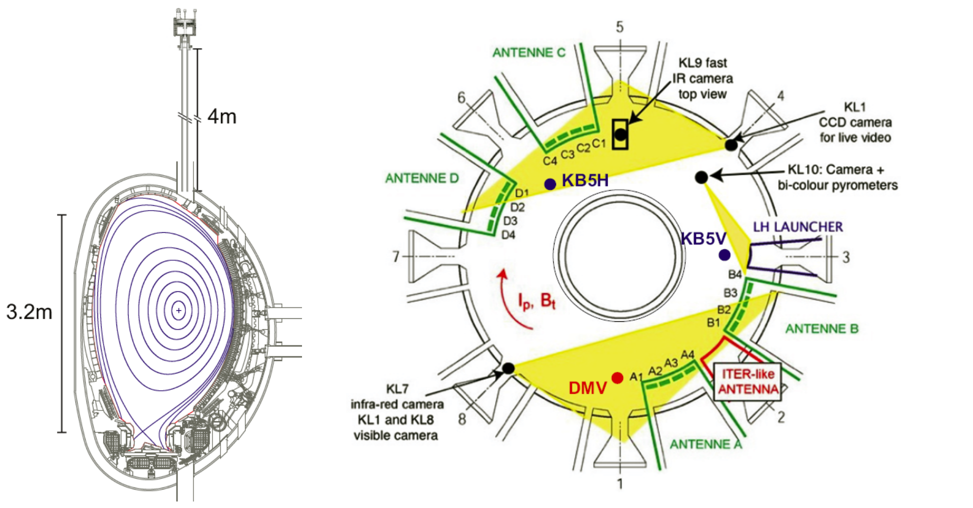
INTRODUCTION

Major disruptions are one of the critical issues for ITER operations due to their severe consequences:

- Excessive electromagnetic forces;
- Large heat loads;
- Runaway electrons (RE).

- ❖ Efficient methods for disruption mitigation and suppression of runaway generation are essential.
- ❖ Detailed understanding of the physics of disruption generated RE is a key issue for the development of RE suppression techniques in present day tokamaks and in ITER.
- ❖ This report is focused on characterization of RE generation processes in disruptions triggered either by the Massive Gas Injection or constant gas puff in experiments with carbon-fibre-composite (CFC) plasma facing components in JET.
- ❖ Data on disruptions occurring after installation of the ITER-like wall (ILW), with the beryllium as the main material, has been collected to obtain a first insight into the impact of PFC material on the processes that generate RE.

MASSIVE GAS INJECTION SYSTEM AND EXPERIMENTAL SETUP



Disruption Mitigation Valve (DMV) Setup for Massive Gas Injection at JET and layout of diagnostics related to MGI and RE experiments [LEHNEN M. et al. 2011 NF 51 123010]:

DMV parameters:

- Injection volume - 650 ml, maximum pressure – 36 bar;
- Injected Particles = 2.5×10^{23} ~ 100x N_{e_tot};
- Injected species: Ar, Ne, He, D_2, Ar/D_2, Ne/D_2

In the experiments: the number of injected argon or neon atoms (or their mixtures with deuterium) has been varied from $(4\text{-}6)*10^{22}$ to $(21\text{-}24)*10^{22}$.

DISRUPTIONS SCENARIOS FOR RE STUDIES

Two scenarios for RE studies at disruptions in JET [RICCARDO V. et al. 2010 PPCF 52 124018]:

- Massive Gas Injection (MGI) using a fast valve (Disruption Mitigation Valve – DMV), usually the disruption occurred 7-10 ms after the DMV activation;
- Constant puff of impurity gas, required a significantly longer time (up to 500 ms) to trigger the disruption;

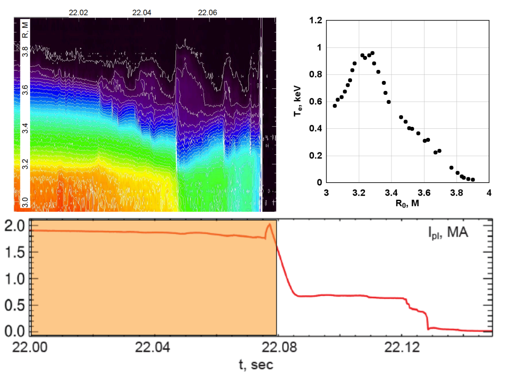
➢ Effect of different gases and mixtures used in MGI onto RE generation:

- Argon: any amount causes RE generation with currents sometimes >1 MA and duration over 0.1 s at B_0 >1.8 - 2 T, with traces of RE (photo-neutrons bursts) even at B_0 = 1.2 T;
- Neon: low probability and efficiency.
- No RE at pure D_2, He and mixtures of Ar/Ne with D_2.

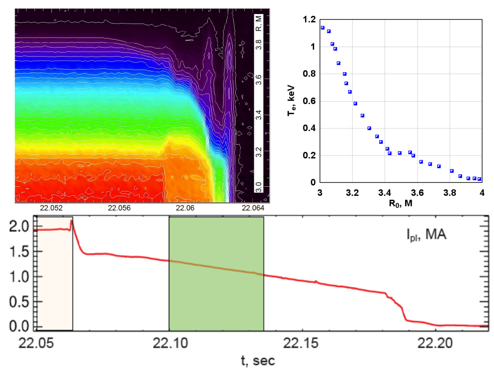
RUNAWAY ELECTRONS DIAGNOSTICS AND METHODS

- 5 scintillation time-resolved HXR monitors and neutron rate fission chamber monitors (^{235}U and ^{238}U) at 3 different locations (Oct. 2,6,8) operating in a current mode with 0.1 ms time resolution.
- Horizontally and vertically viewing NaI(Tl), Bi_4GeO_{12} (BGO, Oct. 8) and $LaBr_3$ spectrometers.
- JET neutron/gamma profile monitor comprises 2 cameras, vertical and horizontal, with 9 and 10 lines of sight, respectively (Oct.1). Each camera has 2 detectors: NE213 – for neutron and HXR measurements, and CsI detector for HXR registration.
- HXR and SXR tomography enabled the reconstruction of RE beam evolution in time and space.
- Numerical processing of the measured HXR spectra allowed reconstruction of the RE energy spectra with characteristic values E_0 of in visible volume and provided the data on maximal energy E_{MAX}.

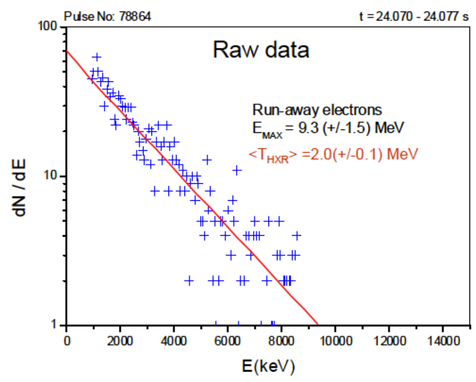
PLASMA PARAMETERS EVOLUTION AND RE GENERATION

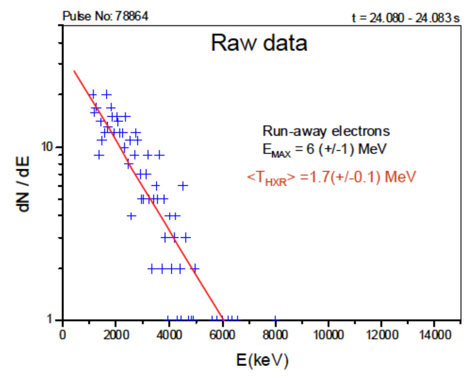


Disruption of #79425. Slow argon injection (activation time at ~21.5 sec). T_e profile measured at t=22.0758.



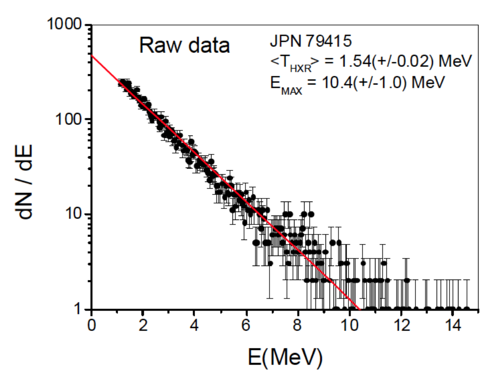
Disruption of #79415. MGI / argon. (DMV at t=22.05) T_e at 22.0625 s.



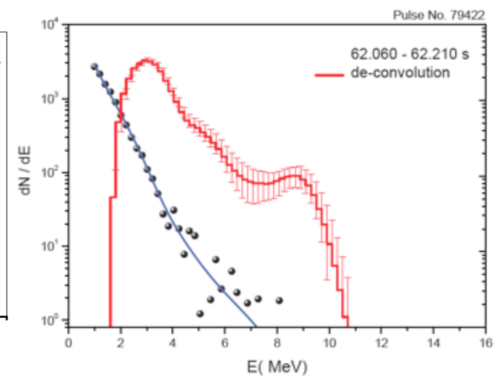


HXR spectrometry: Time resolved measurements of HXR spectra using vertically viewing NaI(Tl)-detector with fast data acquisition

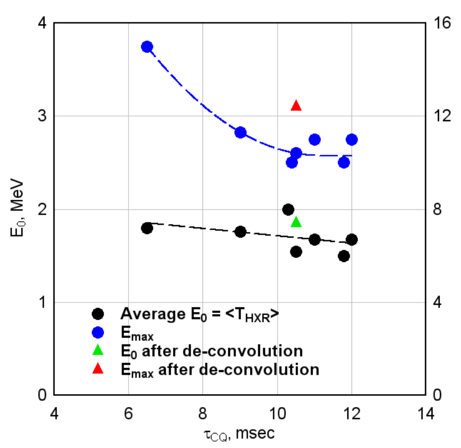
➢ The HXR raw data processing (BGO spectrometer) - de-convolution procedure (in detail see [SHEVELEV A. et al. This conference, report ITR/P5-36])



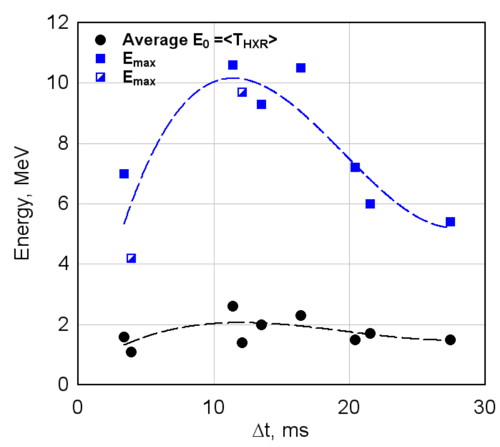
HXR spectrometry: Integral spectrum of HXR recorded using BGO spectrometer in MGI induced disruption



Reconstructed spectrum of RE (red) from raw HXR spectrum data (black) after de-convolution procedure (MGI disruption #79422)



HXR spectrometry. BGO detector. Maximal E_{MAX} and average $E_0 = <T_{HXR}>$ energies vs. characteristic e-folding time of CQ

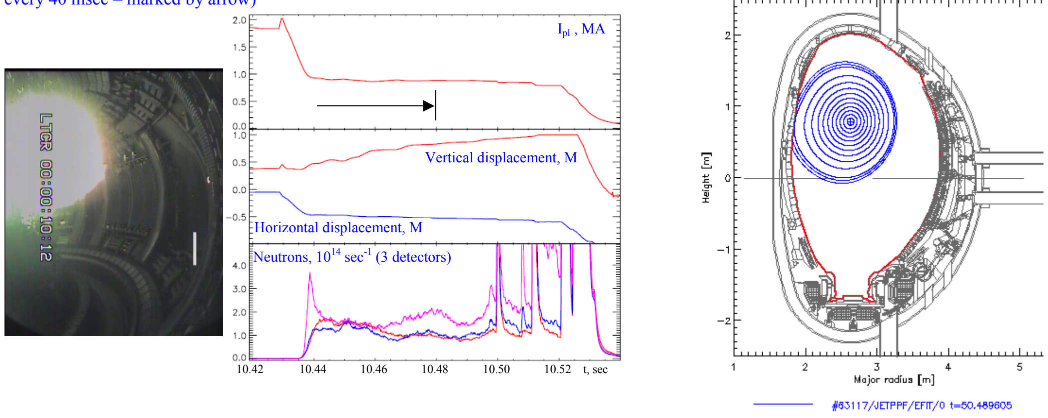


HXR spectrometry. NaI(Tl) detector, fast DAQ, vertical LoS. E_{MAX} and average $E_0 = <T_{HXR}>$ energies vs. time from the beginning of CQ

Time-resolved measurements: E_0 ~ 1-2 MeV, E_{MAX} ~ 5-10 MeV, less than expected from free fall acceleration: $\gamma = \sqrt{\left(1 + (e/mc \cdot \int E_{//0}(t)dt)^2\right)}$ > 50 for $E_{//0}$~50 V/m (at dI_{pla}/dt~200 MA/sec), which is acting during 0.002 sec or longer (E_{MAX}=0.511*(γ −1) > 25 MeV). Complicated trend in E_0, E_{MAX} with the increase of the time after the beginning of CQ found

CQ DYNAMICS, PLASMA GEOMETRY EVOLUTION AND RE GENERATION

JET #63117 Data
VCR frame is taken at t=10.480 s of the JET discharge time (each frame is created every 40 msec – marked by arrow)

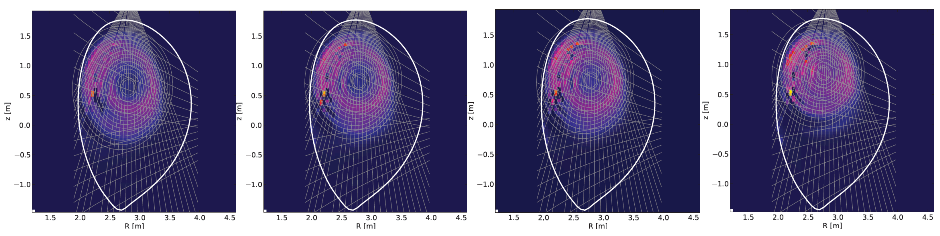


RE beam image and EFIT reconstruction (PLYUSNIN V. V. et al, FEC2004, 2006 NF 46 271)

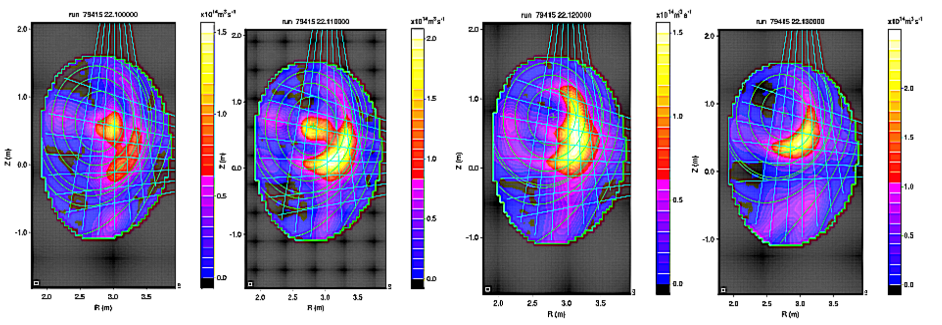
Disrupted plasma is not in equilibrium and it moves horizontally and/or vertically. Total plasma inductance $L_p=\mu_0 \cdot R_0 \cdot (ln(8R_0/a_p)+l_i/2-7/4)$ - not constant, if fast changes => dL_p/dt is not small (!) in energy conservation equation $2\pi R_0 E_{||}(t) + L_p \frac{dI_p}{dt} + 0.5 * I_p \frac{dL_p}{dt} = 0$. Velocity of plasma motion is ~90 m/s in disruption #63117 => dL_p/dt ~4·10^{-4} with opposite sign to dI_{pla}/dt => obvious decrease of accelerating electric fields. In contrary, prompt RE generation in #77983 is observed at low motion. After local maximum, further evolutions of E_0 and E_{MAX} follow to current substitution effect:

$$E_{||}(t) = E_{||0}(t) \times (1 - j_{RE}(t)/(j_{pl}(t) + j_{RE}(t))$$

HXR AND SXR CHARACTERISITICS OF RE BEAMS

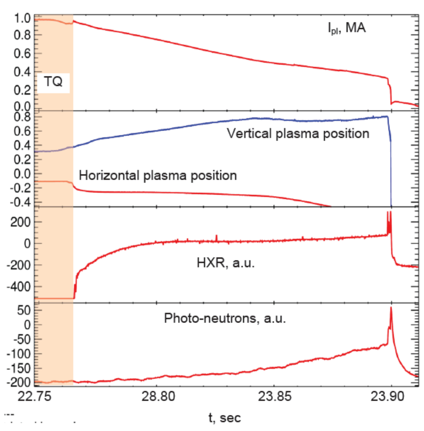


Disruption #79415 SXR tomography of RE plateau; Images produced at t=22.104, 22.114, 22.124 and 22.134 sec (e.g. 4 ms later than HXR images).

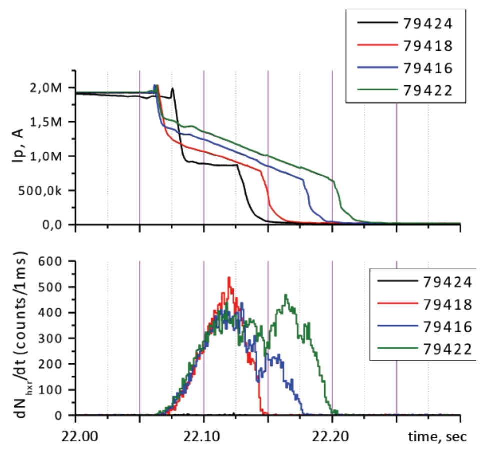


22.10 sec 22.11 sec 22.12 sec 22.13 sec

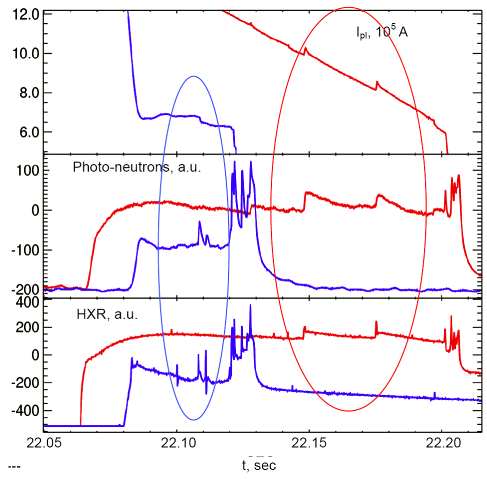
Hard X ray tomography reconstruction of MGI disruption 79415



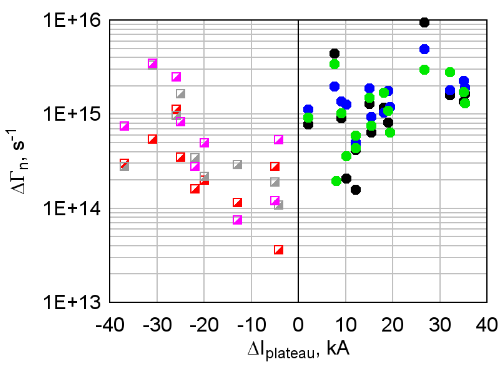
Disruption #77982 (MGI) – low current (<1MA) and prompt RE generation – detected immediately after TQ (end of coloured area)



HXR measurements during RE plateaux induced by MGI (##79416,18,22) and slow gas injection (#79424)



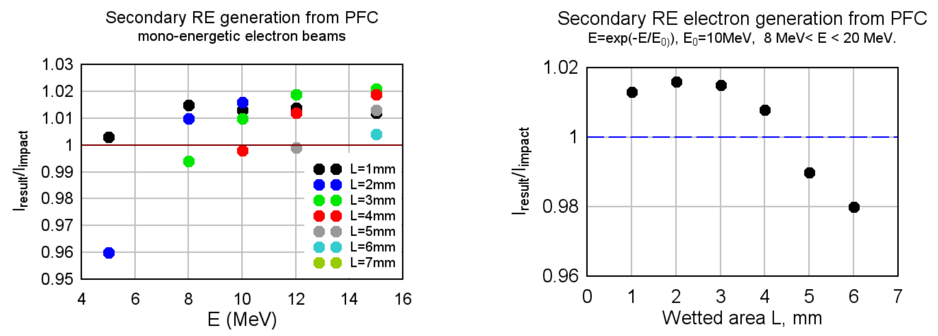
RE plateau current loss and step-like increases of RE currents



Statistics on neutron bursts observed during RE plateau current loss and step-like increases of RE currents

RE BEAM IMPACT ON PFC IN JET

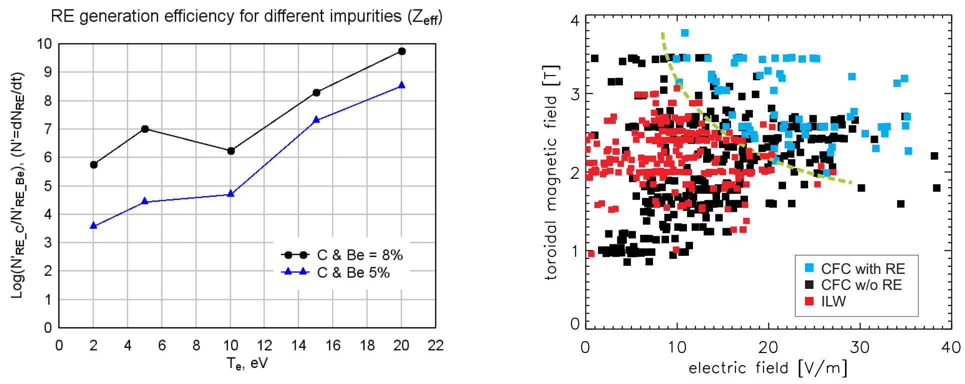
- Monte-Carlo code ENDEP: Interaction of RE with PFC and yield of secondary electrons [BAZYLEV B. et al. 2011 JNM 415 S841].
- Processes: Compton and inverse Compton effects, Auger and photoelectric effects are included.
- Ratio I_{result}/I_{impact} for typical CFC tile in JET is calculated. L is the wetted area along the tile surface. E_{tr}/E = 0.002. For E_{tr}/E>0.005 and for mono-energetic RE with E=4 MeV absorption is larger. At a certain range for parameters of plasma-born RE an additional generation is possible.



Monte-Carlo simulations for mono-energetic beams (left chart), and for RE flux with E=exp(-E/E$_0$)) E$_0$=10 MeV for energy range 8 MeV < E < 20 MeV (right)

FIRST ANALYSIS OF DISRUPTIONS IN JET WITH ILW

The first JET operations with ITER-like Wall (ILW) have demonstrated that this new environment does not favour to the RE generation after major disruptions.



Ratio of RE generation rates calculated for C and Be as main impurities (left). Data map on electric fields generated at CQ in disruptions with CFC and ILW is presented. Data range of RE generation events is bounded by green line (right).

SUMMARY

❖ The enhanced capabilities of JET diagnostics provided new contributions to the physical model of runaway electrons generated by disruptions, in support to development of disruptions mitigation techniques for ITER.

❖ 2D tomography of hard and soft-X emissions enabled detailed study of the spatial structure and time evolution of RE beams on plateau stage. The maximal energies of RE populations in some disruptions achieved 15 MeV.

❖ A new phenomenon is discovered: appearance and gradual increase of the HXR emission secondary maximum with the increase of RE current plateaux duration.

❖ Monte Carlo simulation have confirmed the possibility of the secondary RE generation at interaction of the existing RE fluxes with plasma facing components in JET

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