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Nuclear Fusion 64 112012

+See the author list of "Overview of the EUROfusion Tokamak Exploitation programme in support of ITER and DEMO" by E. Joffrin et al 2024 Nuclear Fusion 64 112019

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INTRODUCTION.

Disruptive terminations of plasma discharges pose severe threats to the device integrity in future operations of International Thermonuclear Experimental Reactor (ITER). Disruptions can cause dangerous excessive electromagnetic forces, heat loads and generation of the intense beams of relativistic runaway electrons (RE). Localized interaction of such beams with surrounding plasma facing components (PFC) inevitably will result in their unacceptable damage. To avoid/suppress RE generation and mitigate other disruption detrimental consequences the Disruption Mitigation System (DMS) is under design in ITER. It is based on impurities injection in the form of solid shattered pellets (SPI). Development of DMS requires advanced understanding of the physics of RE and their interaction with plasma, solid pellets and neutral gases (fuel and impurities). For this purpose, the parameters of disruption generated RE collected during disruptions till to the end of JET operations in 2023 were compiled into joint database. It includes parameters of more than 2000 RE generation events in major disruptions before (JET with Original Plasma Shape, JET OPS, $S_{plasma} \leq 7.8 \text{ m}^2$) and after divertor installation, with metal and carbon limiters and with ITER-like Wall (JET-C and JET-ILW, $S_{pl} \leq 4.7 \text{ m}^2$), see table 1, in spontaneous disruptions and those triggered by slow gas puff, MGI and SPI. This report presents a survey and present status of RE data analysis in JET.

HISTORICAL SUMMARY ON RE GENERATION DURING JET OPERATIONS

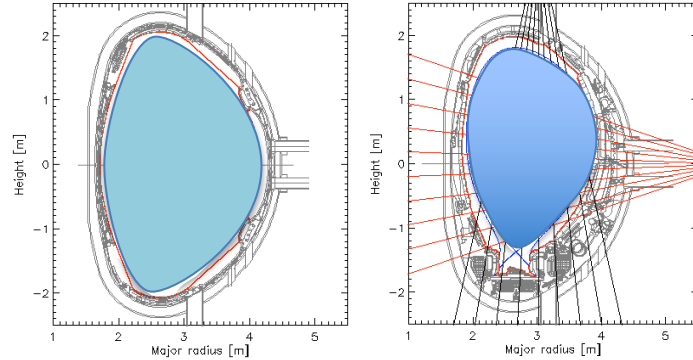


FIG. 1 The JET plasma cross-sections with original shape before divertor installation (JET OPS, $S_{plasma} \leq 7.8 \text{ m}^2$, left chart) and with divertor coils installed inside of the vacuum vessel (JET divertor, $S_{pl} \leq 4.7 \text{ m}^2$, right).

Operational phases & plasma configurations, PFC materials and divertor configurations	Period	Last shot number	Detected RE generation events
JET- Original Plasma Shape (JET-OPS)	Operations till to August 1987	#12106	~ 320 events
JET-OPS, Limiter, X-Point (SN, DN)	August 1987 - February 1992	#28791	~ 560 events
JET-C – Divertor MKI + CFC tiles	March 1994 - June 1995	#35778	~ 130 events
JET-C – Divertor MKIIA, AP + CFC tiles	May 1996 – Feb 1998 – Sept 1998	#45155	~ 220 events
JET-C – Divertor MKIIB +CFC tiles	July 1998 - March 2001	#54549	~ 250 events
JET-C – Divertor MKIIB SR + CFC tiles	Jul 01 - Mar 04; Aug 05 - Apr 07	#63445	~ 150 events
JET-C – Divertor MKII HD + CFC tiles	Carbon wall ends 23-Oct-2009	#79853	~ 150 events
JET with ITER Like Wall (ILW) + Divertor	ILW Experiments – from July 2011	#105929	~ 340 events

TABLE 1. A survey of JET operation stages and number of RE generation events detected during each period

- ~ 340 disruptions with REs at disrupted currents up to 3MA during JET-ILW SPI-MGI experiments have been dedicated to studies of interaction of RE beams with MGI or SPI of D₂ and He, Ar, Ne, Xe, Kr or their mixture with D₂.
- All other unintentional RE in JET-ILW have been mitigated with MGI (10%Ar+90%D).

INSTRUMENTATION

RE interacting with plasma particles and PFC lose energy and produce the X-ray emission in a wide energy range: from soft X-rays (SXR) till to multi-MeV energies: $E_{HXR} \leq E_{RE_MAX} - m_e c^2$; Photo-neutrons (nY) are also produced when γ 's interact with PFC and plasma particles and when the photon energy is higher than the neutron bound energy of target nuclei ϵ_n : $E_n = E_{HXR} - \epsilon_n$. $E_n = 2.2 \text{ MeV}$; $E_n = 1.7 \text{ MeV}$; $E_n = 18.7 \text{ MeV}$; $E_n = 9.9 \text{ MeV}$; $E_n = 12.0 \text{ MeV}$; $E_n = 10.6 \text{ MeV}$; $E_n = 7.4 \text{ MeV}$, $E_n = 8 \text{ MeV}$.

Figure 2 presents layout of diagnostics sets used for measurements of RE parameters in the JET experiments: 5 scintillation time-resolved HXR monitors for neutron rates fission chamber monitors (235U and 238U) at 3 different locations (N1, N2 & N3 - Oct. 2,6,8) operating in a current mode with 0.0001 sec time resolution (Figure 2, left chart).

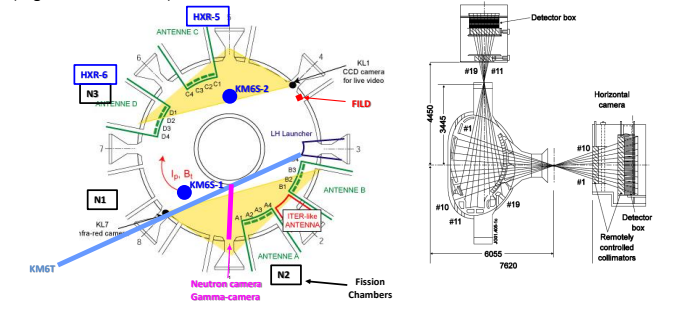


FIG. 2 Layout of JET diagnostics used in RE studies (left chart) and JET neutron/gamma-profile monitor setup (right chart): 2 cameras, vertical and horizontal, with 9 and 10 detectors (corresponding Lines of Sights (LoS) are shown).

Horizontally and vertically viewing NaI(Tl), Bi₄GeO₁₂ (aka BGO, Oct. 8) and LaBr₃ spectrometers; JET neutron/gamma-rays profile monitor in Oct.1 (Figure 2, right chart). Each camera has 2 detectors: NE213 – for neutron and HXR measurements, and CsI detector for HXR registration. Fan-shaped array of remotely adjustable collimators with two apertures (Ø10 & 21 mm) provide the space resolution: ~8 (or ~15) cm (in the centre). CsI(Tl) scintillators (for HXR/gammas) ~40 (or ~15) cm data acquisition system: t ≈ 1 ms. HXR 2D imaging system enables the reconstruction of evolution in time and space of the RE beam; Several sets of SXR cameras have been used to produce SXR tomography of the RE beam in-flight.

MAIN SCENARIOS OF DISRUPTIONS IN JET AND REFERENCE MODEL FOR ANALYSIS

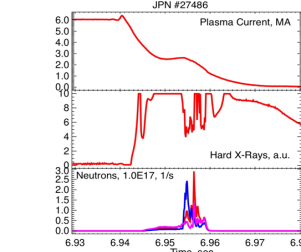


FIG. 3. High current JET-OPS disruption: $I_{pl} \approx 6.0 \text{ MA}$, $I_{plateau} \approx 2.62 \text{ MA}$, RE fraction is $I_{RE} \leq 1.5 \text{ MA}$.

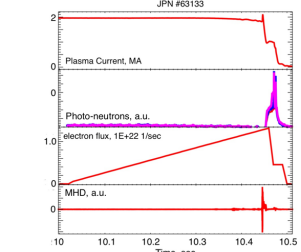


FIG. 4. Slow Ne puff disruption in JET-C, RE current fraction is $I_{RE} \leq 1.2 \text{ MA}$.

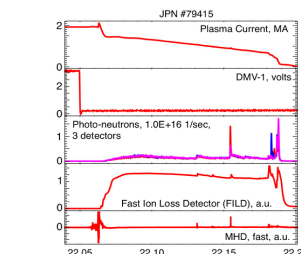


FIG. 5. MGI Disruption in JET-C, $I_{plateau} \approx 1.45 \text{ MA}$, RE current fraction is $I_{RE} \leq 1.25 \text{ MA}$.

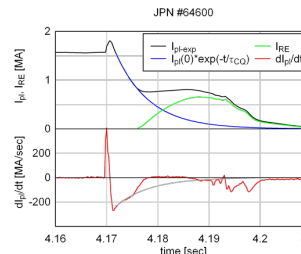


FIG. 6. Reference model for analysis of RE generation dynamics (right).

MEASUREMENTS OF RE ENERGY AND REDF IN JET DISRUPTIONS

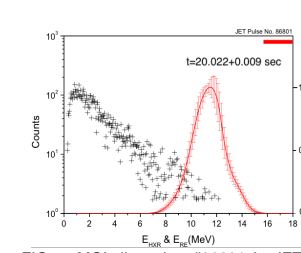


FIG. 7. MGI disruption #86801 in JET-ILW, HXR spectrum: NaI(Tl) detector (raw data, black crosses); reconstructed RE energy spectrum using de-convolution procedure (red).

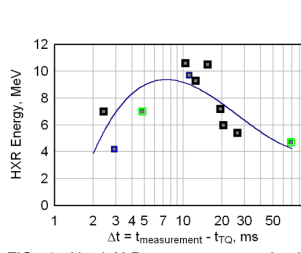


FIG. 8. Hard X-Ray spectrometry in JET-C disruption. NaI(Tl) detector, fast DAQ, integrated signal from Vertical Line-of-Sight. Maximal RE energy E_{MAX} vs. time from the beginning of CQ.

MAIN TRENDS IN RUNAWAY ELECTRON PARAMETERS MEASURED IN ALL SCENARIOS OF MAJOR DISRUPTIONS IN JET

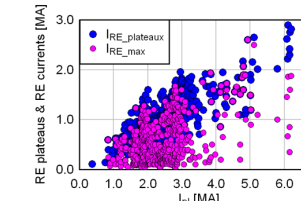


FIG. 9. Values of RE plateaus and inferred RE current fractions plotted vs. disrupted plasma currents in all disruption scenarios+.

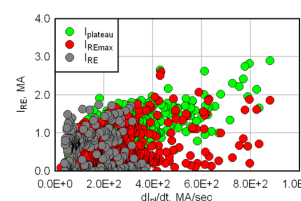


FIG. 9. Dependence of RE current plateaus and RE currents vs. plasma current time derivative dI_p/dt in all disruption scenarios.

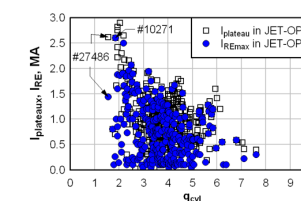


FIG. 11. JET-OPS data on generated RE plateaus and calculated runaway current fractions plotted vs. $q(a)$.

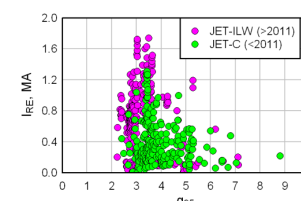


FIG. 12. Data on RE currents generated in JET-C and JET-ILW disruption scenarios plotted vs. q_{95} (EFIT data).

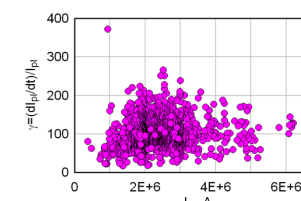


FIG. 17. Analysis of CQ rates in all JET disruption scenarios for RE studies.

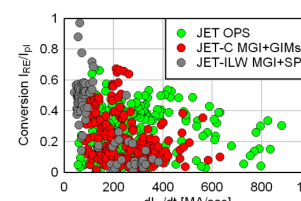


FIG. 18. Conversion of the resistive plasma current into RE one vs. on plasma current time derivative in all disruption scenarios.

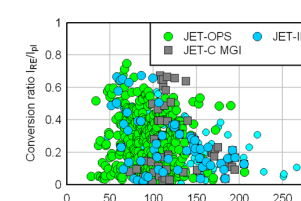


FIG. 15. Conversion ratio I_{RE}/I_{pl} vs. CQ rates for all stages of JET operations.

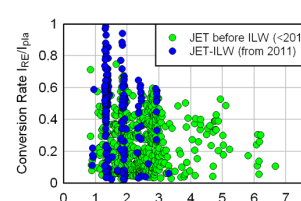


FIG. 16. Conversion rate I_{RE}/I_{pl} dependence on disrupted plasma currents plotted for all JET operation stages.

⇒ The measured energies ($E_{MAX} \leq 10 \pm 12 \text{ MeV}$) are too low in comparison to values expected from: $\gamma = \sqrt{1 + \left(\frac{e}{m_e c} \int E_{||}(t) dt \right)^2} \sim 50-60$ (for electric field $\sim 50 \text{ V/m}$, which is acting during $0.002-0.004 \text{ sec}$).

⇒ **Observed controversy requires an additional analysis described dynamics including controversial data processing and modelling.**

⇒ Evaluation of RE density from measured or deduced runaway current fractions. In particular, assessment of RE density values provided necessary data on evaluation of RE distribution function. Fig 15 presents data on RE density evaluated from given values of RE currents for different values of critical energy of runaway process (represented by Lorentz parameter γ_0): $I_{RE} = \frac{e c}{\gamma_0} \sqrt{\gamma_0^2 - 1} \frac{N_{RE}}{2\pi R_0}$.

ROLE OF B_0 AND ITS DIRECTION IN RE GENERATION.

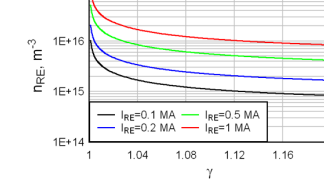


FIG. 15. RE density in runaway beams with different currents depending on estimated runaway critical energies. I_{RE} has been assessed from $N_{RE} = 2\pi R_0 I_{RE} / (e c \gamma_0)$.

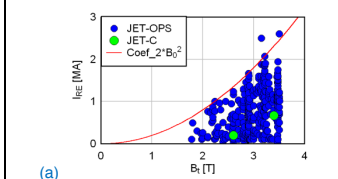


FIG. 16. RE currents plotted as maximal I_{RE} vs. B_0 for different directions (a) – positive; (b) – negative; (c) – photoneutrons data in JET disruptions.

EFFECT OF CURRENT QUENCH DYNAMICS AND PLASMA GEOMETRY EVOLUTION ON RE GENERATION: JET EXPERIMENTS AND SIMULATIONS

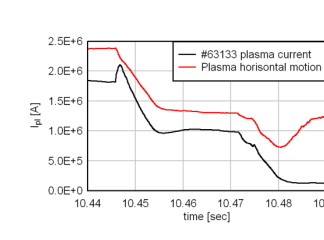


FIG. 17. Evolutions of plasma centroids (PPOX) and runaway current in JET disruption: JPN #63133.

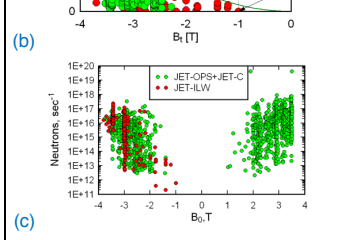


FIG. 18. Effect of the plasma centroid dynamics in horizontal direction ($V_{horizontal} = d a_p/dt$) on RE generation efficiency in tokamaks.

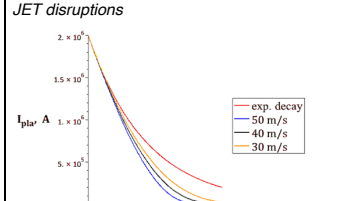


FIG. 19. Evolution of CQ calculated with Eqs.(2-3) for different velocities of horizontal plasma toroid motion.

Disrupted plasmas move fast in space (vertical and horizontal) with changes in many parameters: radius, total inductance, magnetic flux, etc. These evolutions revealed definite effect on RE generation dynamics.

Simulations on disruption evolutions were carried out using following model:

$$\frac{dI_{RE}}{dt} = \lambda_p (Y_{AV} - \frac{1}{\tau_{RE}}) \cdot n_{RE} \quad (1),$$

$$I_{pl}(t) + \frac{L_p(t)}{R_p(t)} \frac{dI_p}{dt} + 0.5 \cdot I_p(t) \frac{dL_p}{dt} = 0 \quad (2),$$

$$\rho \frac{dv}{dt} = \sum_i F_i \quad (3);$$

Where $F_1 = 2\pi R(t) I_p(t) \cdot B_V$, $B_V = \mu_0 \frac{I_p(0)}{4\pi R_0} \left(\ln \frac{R_0}{a_p(0)} + \beta_p(0) + \frac{I_i(0)}{2} \right)$,

$F_2 = \mu_0 \frac{I_p^2(t)}{2} \left(\ln \frac{R(t)}{a_p(t)} + \beta_p^2(t) + \frac{I_i^2(t)}{2} \right)$; $\beta_p^2(t) = \beta_p(t) + \beta_{RE}(t)$; $N_{RE} = 2\pi R_0 \frac{I_{RE}}{e c \gamma_0}$;

$L_p(t) = \mu_0 R_0(t) \left(\ln \frac{R_0(t)}{a_p(t)} + \beta_p^2(t) + \frac{I_i^2}{2} \right)$, $I_i = \ln(1.65 + 0.89c)$

$Y_{AV} = \frac{e}{m_e c} \frac{1}{\ln \left(\frac{3}{2} Z_{eff} + 5 \right)} \cdot \left(E_0(t) - E_{CR, \infty} \cdot \frac{\gamma_0^2}{\gamma_0^2 - 1} \right)$ $\beta_{RE}(t) = 8\pi^2 a_p^2 n_{RE} \frac{m_e c^2}{2 \mu_0 I_p^2} \frac{\gamma_0^2}{\gamma_0^2 - 1}$

$\frac{dL_p}{dt} = \mu_0 \cdot \left[\frac{dR_0(t)}{dt} \cdot \left(\ln \frac{R_0(t)}{a_p(t)} - 2 \right) + R_0(t) \cdot \left(\frac{dR_0(t)}{R_0(t)} - \frac{da_p(t)}{a_p(t)} \right) \right]$, $\frac{dR_0(t)}{R_0(t)} < 0$, $\frac{da_p(t)}{a_p(t)} < 0$;

$2\pi R_0 E_{||}(t) = -(L_{tot}(t) \frac{dI_p}{dt} + 0.5 I_p(t) \frac{dL_{tot}}{dt})$, $\gamma_0^2 = 1 + \left[\frac{e}{m_e c} \int E_0(t) dt \right]^2$

SUMMARY

Collected data on RE generation events (>2000 in total) in JET disruptions covers all stages of JET operations. Runaways have been generated during spontaneous or deliberate disruptions in different plasma configurations: circular or elongated, limiter or divertor, etc. Extended analysis of RE database established key dependencies of main post-disruption RE parameters, such as, RE densities, currents and current conversion ratios (I_{RE}/I_{pl}) on pre-disruption plasma currents, plasma current time derivatives, CQ rates, safety factor $q_{95}/q(a)$, pre-disruption density, temperature, etc. In several experiments with MGI and SPI the HXR/γ and photo-neutrons diagnostics measured maximal energies of runaways $E_{MAX} \leq 10 \pm 12 \text{ MeV}$. Analysis of SPI experimental results and data from experiments with MGI using different DMVs revealed different influence on disruption dynamics and RE generation. One of the important results from the data-base analysis is observation of clear threshold in RE generation on CQ rates. A decreasing trend in conversion ratio I_{RE}/I_{pl} has been established vs. main parameters, such as pre-disruption plasma currents, plasma current time derivatives and CQ rates. Presented data-base on RE in JET requires further extended study including analysis of the disruption phenomenology and numerical simulations of runaway generation dynamics.

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