Data on Runaway Electrons in JET

V.V. Plyusnin[1], V.G. Kiptily[2], A.E. Shevelev[3], S. Gerasimov[2] and JET contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
*(1) Instituto de Plasmas e Fusão Nuclear, Instituto Superior Tecnico, Universidade de Lisboa, Lisboa, Portugal; (2) CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK; (3) Ioffe Institute, St. Petersburg, 194021, Russia; * See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)*

E-mail: vladislav.plyusnin@ipfn.ist.utl.pt

1. Introduction

In tokamak-reactor, such as ITER, the generation of runaway electrons (RE) is unacceptable. Disruption Mitigation System (DMS) designed in ITER should be a reliable tool for suppression of RE and mitigate other detrimental consequences of disruptions. Development of DMS requires a detailed understanding of the physics of RE and their interaction with surrounding plasma and neutral gases (fuel and injected impurities). Elaboration of RE database and its comprehensive analysis should stimulate further advances in such understanding. From the beginning of JET operations there were several attempts to review the data on RE generation events (for example, [1]). However, these attempts are still waiting a compiling into joint database.

This report presents the first summary from the analysis of the most extended data on RE generation events in JET disruptions. This data includes more than 1800 RE generation events in major disruptions before and after divertor installation, with metal (Be) and carbon (JET-C) limiters and with ITER-like Wall (JET-ILW), in spontaneous disruptions and those triggered by slow gas puff and Massive Gas Injections (MGI). An analysis of the data has been performed manually on the basis of JET Logging System and results of previous studies [1-6] to avoid ambiguous interpretation of observed RE generation events: HXR/γ radiation and photo-neutron data together with RE plateaux parameters have been used in analysis. All RE generation events in JET could be separated on several groups: RE generation in disruptions, generation of RE at plasma discharge start-up (not included in this report), and, very rare, formation of RE generating stages during normal discharges, when feedback control of plasma density was lost (considered elsewhere [7]). Measurements of HXR/γ and photo-neutrons with time-resolved HXR monitors, neutron rate fission chamber monitors ($^{235}U$$^{238}U$) and HXR/γ spectrometers allowed evaluation energy of runaways (max of $W_{RE\_JET\text{-}C} \leq 30$ MeV and $W_{RE\_JET\text{-}ILW} \leq 5\text{-}10$ MeV).

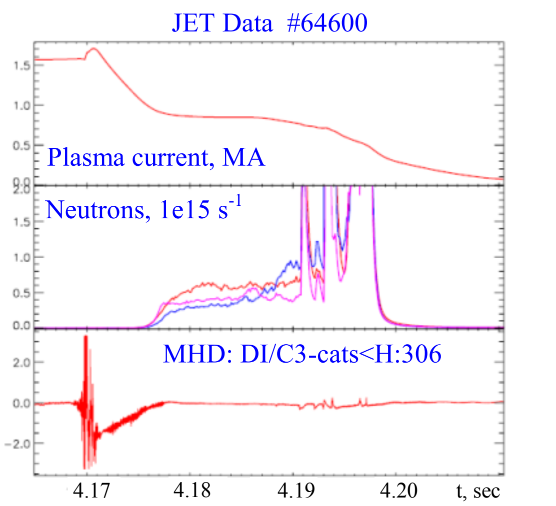

Figure 1. Example of spontaneous disruption with RE generation event in JET #64600

2. Basis description of RE generation scenario during disruptions in JET

Generation of RE during major disruptions have been detected since the beginning of JET operations. Figure 1 presents an example of spontaneous current rise major disruption in JET (#64600) resulted in RE generation. After MHD instability the discharge #64600 entered into current quench

(CQ) stage. After CQ all characteristic features, which highlight the generation of the high-energy RE, including the current plateau with simultaneous increases of the photo-neutron and hard X-ray (not shown here) emissions have been detected. Sometimes the current plateaux with RE populations have been lasting up to 10 sec with current values about 1MA.

2. Statistics on RE generation events in disruptions during JET operations

Table 1 presents the JET operations history. Experiments during first two phases (Limiter only and Limiter + X-Point) have been carried out in JET with original plasma cross-section ($a_{pl} \leq 1.25$ m, $b \leq 2.1$ m). During these operational phases in JET a generation of RE plateaux up to 3 MA was observed at disrupted plasma currents up to 6.6 MA. After divertor installation the current-carrying plasma cross-section has been decreased to 4.7 m^2 ($S_{p\_lim}/S_{p\_div} \approx 1.4$). During divertor operational phases (MKI, MKII, etc.) the largest disrupted current was 3.8 MA at which RE generation was detected in JET.

Operational phase & configurations	Period	Last shot number	Number of RE generation events
Limiter only	*Operations till to* August 87	#12106	≈ 320 events
Limiter + X-Point (SN, DN)	August 87 - February 92	#28791	≈ 560 events
Divertor - MKI	March 94 - June 95	#35778	≈ 130 events
D- MKIIA, AP	May 96 – Feb 98 – Sept 1998	#45155	≈ 220 events
D - MKIIGB	Jul 98 - Mar 01	#54549	≈ 230 events
D - MKIIGB SR	Jul 01 - Mar 04; Aug 05 - Apr 07	#63445	≈ 200 events
D - MKII HD	Carbon wall ends 23-Oct-2009	#79853	≈ 340 events
D - MKII ILW	ILW from July 2011	from #80000	> 100 events

Table 1. A survey of JET operational stages and number of registered RE generation events in disruptions during each phase

Note, that approximately 130 RE generation events have been occurring during experiments on RE studies in JET-C after divertor installation [3-6, 8]. In these experiments slow gas injections and first MGI have been used to trigger the disruptions. Yet another 120 RE generation events during JET operations with ILW (MKII ILW) [9] have been triggered in studies of RE generation during intentional disruptions occurred after MGI of impurity gases (He, Ar, Ne, Xe, Kr) or their mixture with deuterium. In JET-ILW the RE data was collected in MGI experiments with plasma currents ≤ 2MA. All other unintentional disruptions have been mitigated with MGI (10%Ar+90%D). A detailed analysis of the collected database and RE parameters is remaining to be done.

3. Main features of RE generation process observed during disruptions in JET

CQ stages have been characterized using CQ rates ($\gamma = 1/I_p * dI_p/dt$) inferred on the basis of exponential plasma current decay process: $I_{pl}(t) = I_{pl}(0) \cdot exp\left(-\frac{t}{\tau_{CQ}}\right)$, where $\tau_{CQ} = \frac{L_p}{R_{pl}}$, L_p is plasma inductance and R_{pl} is plasma resistance. Analysis of current quench (CQ) rates in JET disruptions with RE during first two operational phases has demonstrated that almost all CQ data points are located between values $35 \leq \gamma \leq 170$ (Figure 2). Several types of CQ behavior have been detected: constant CQ, i.e. $\gamma \equiv R_p/L_p$=const till to RE plateau formation, and CQ with gradually increased and decreased rate values. Therefore, at the beginning of CQ (immediately after negative voltage spikes/current bumps) plasma geometry didn't change significantly and in assumption $L_p \approx$ const, one could determine the boundaries of electron temperatures for these CQ rates from the plasma resistance R_p: 5 eV < T_e < 15 eV. Similar T_e values have been deduced during JET-ILW operations. These results are in close correspondence to assumptions made in different works on RE generation at disruptions.

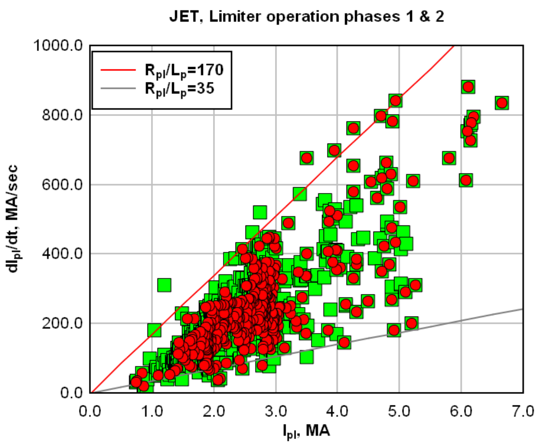

Figure 2. CQ rates in JET before divertor installation: red circles - RE plateau/semi-plateau cases and HXR/neutron signals, green – RE generation (only HXR/neutron signals) without plateau formation.

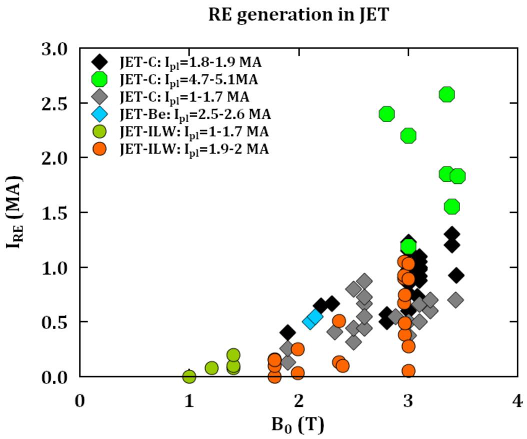

Figure 3. Generation of RE currents depending on B_0 at different plasma currents in JET (Update of Figure 7 from [6]). RE currents are calculated as difference between RE plateau total current and exponentially decaying resistive currents.

Detailed study of RE database revealed RE generation during spontaneous disruptions at low magnetic field ($B_0 \approx 1$ T) in JET even before divertor installation (for example, JPN #11213, etc.). This result is complementing to the data obtained later in MGI experiments [9, 10]. Therefore, systematic analysis of the data on RE in JET-C and JET-ILW with MGI confirms an absence of the "so-called" threshold on magnetic field values (about 2 T) [4, 5] (Figure 3). Extended data on RE confirms previous results from JET-C and JET-ILW on the current conversion rate: max (I_{RE}/I_{pl}) $\leq$ 0.6-0.7 for all JET operational regimes [3-6, 10].

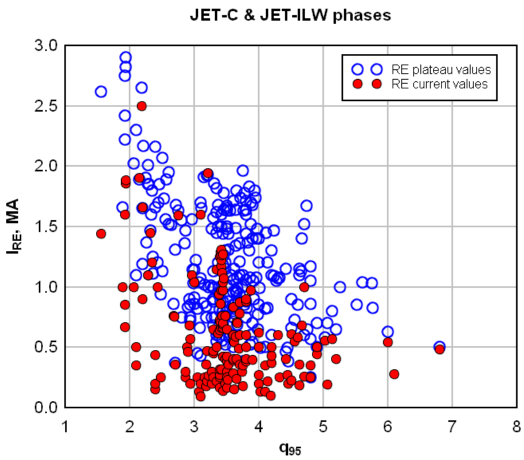

Figure 4. Summary on RE plateau values and deduced RE fraction values depending on q_{95} values in JET discharges [2-6]

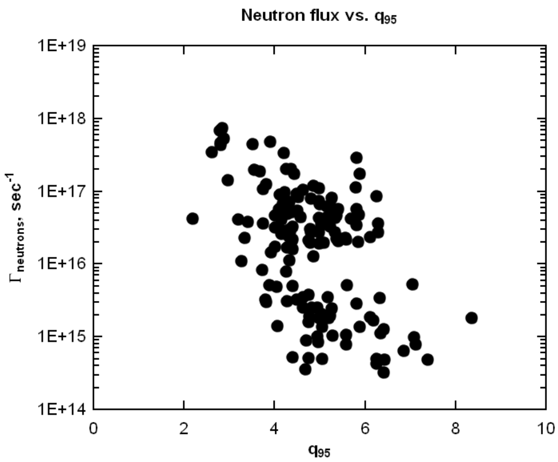

Figure 5. Photo-neutron flux plotted vs. q_{95} values for RE generation events in JET.

However, disrupted plasmas move fast in space changing many parameters: radius, total inductance, magnetic flux, etc. Velocities (da_{pl}/dt) up 50 m/sec were measured during CQ. Term characterizing the plasma motions (da_{pl}/dt) has strong effect on the time derivative of the plasma total inductance: $\frac{dL_p}{dt} = \mu_0 \cdot \left[\frac{dR_0(t)}{dt} \cdot \left(\ln\left(\frac{8R_0(t)}{a_{pl}(t)}\right) - 2\right) + R_0(t)\left(\frac{\frac{dR_0(t)}{dt}}{R_0(t)} - \frac{\frac{da_{pl}(t)}{dt}}{a_{pl}(t)}\right)\right]$ in the energy conservation equation for plasma current loop: $V_{loop}(t)I_p(t) + \frac{d}{dt}\left[\frac{L_p(t)\cdot I_p^2(t)}{2}\right] = 0$. Therefore, electric fields and RE generation, as well, depending on plasma temperature and density, should have also a dependence on plasma column geometry evolution [10]. These experimental observations should be taken into account as input parameters in future studies. In the difference from previous results based on analysis of limited number of RE generation events [4, 5], we can show that RE plateaux were detected even at q(a)≤2.5, sometimes achieving 3 MA on plateau stage and with up to 2.5 MA of the RE current fraction (Figure 4). Apparently, generation of quasi-stable RE beams could be detected in a wide range of q_{95} and any process which constrains RE generation should be linked to other factors, such as high density rise in disruptions or screening effects of electric field by highly conductive plasma layers created during MHD active stages [6, 10]. The data presented in Figure 4 is supported by the increasing trend in the dependence of measured photo-neutron fluxes on inferred RE current fractions (Figures 5) indicating increase of both density and energy of RE populations.

The database on RE in JET is still under development: recent JET experiments allow not only formulation of input data for numerical models, but also to avoid ambiguous interpretation of the early data. Figure 6 presents results on RE generation at low q_{95} [9]: RE beams were generated at different low q_{95} for the same currents 1.4 and 2 MA indicating that possible lowest threshold on q_{95} could be linked to instabilities of JET discharges itself at low q_{95} [3-5, 11]. Obvious boundary of RE at $q_{95}\approx 2$ (Figure 3) as well indicates the approaching to the marginal conditions on general stability for discharges in JET.

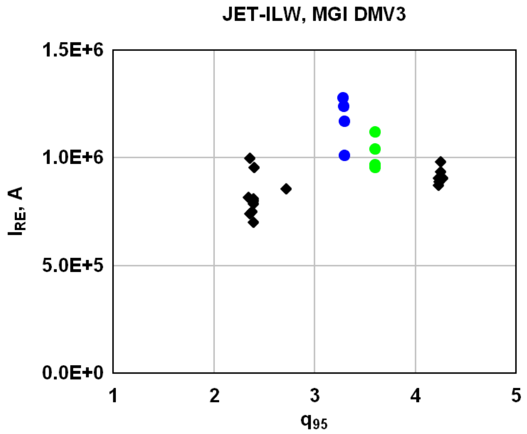

Figure 6. RE generation at low q_{95} 1.4 MA (black diamonds) and 2 MA (green and blue circles) in experiments with MGI in JET-ILW [9].

4. Summary

Collected data on RE generation events in JET disruptions represents an important part of JET experimental data. The first analysis of RE database has shown wide range of plasma parameters affecting the RE generation or increasing the efficiency of this process. Runaways have been generated in different configurations (elongations, etc.). Current rise spontaneous disruptions (times before X-point formation) are the most dangerous from viewpoint of RE generation due to low density and many fast particles from start-up. Presented data on RE in JET requires further extended study including numerical simulations of the disruption phenomenology and runaway generation dynamics.

Acknowledgement

"This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the EURATOM research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. IST activities also received financial support from “Fundação para a Ciência e Tecnologia” through project UID/FIS/50010/2019. The views and opinions expressed herein do not necessarily reflect those of the European Commission."

References

[1] Harris G.R.1990 Comparison of the current decay during carbon-bounded and beryllium-bounded disruptions in JET. Preprint JET-R(90)07
[2] O.N. Jarvis et al. 1988 Nuclear Fusion **28** 1981
[3] R.D. Gill 1993 Nuclear Fusion **33** 1613
[4] R.D. Gill et al. 2000 Nuclear Fusion **40** 163
[5] R.D. Gill et al. 2002 Nuclear Fusion **42** 1039
[6] V. V. Plyusnin et al. 2006 Nuclear Fusion **46** 277
[7] V. V. Plyusnin et al. 42th EPS Conference on Plasma Physics, 2015, Lisbon, ECA **39E** P2.127: http://ocs.ciemat.es/EPS2015PAP/pdf/P2.127.pdf
[8] M. Lehnen et al. 2011 Nuclear Fusion **51** 123010
[9] C. Reux et al. 2015 Nuclear Fusion **55** 129501
[10] V.V. Plyusnin et al. 2018 Nuclear Fusion **58** 016014
[11] D.J. Campbell et al. 2003 Plasma Phys. Control. Fusion **45** 505–520