RUNAWAY ELECTRONS IN JET – SUMMARY ON RE DATA AFTER THE END OF JET OPERATIONS

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Main efforts of nuclear fusion research are focused on the mastering of complex technology of a fusion reactor, which will enable the generation, heating and confinement of plasmas in the "burning regime". It should result in a creation of the energy source, based on use of energy of controlled fusion reactions for electricity generation and, simultaneously, allowing to sustain the plasma hot enough requiring no external energy for heating. Recent experiments have demonstrated that one of the most advanced types of such devices for controlled fusion is a tokamak. International Thermonuclear Experimental Reactor (ITER) being currently under construction in Cadarache in southern France is based on the tokamak concept.

Plasma major disruptions pose severe threats to the device integrity in future operations of ITER. They can cause dangerous excessive electromagnetic forces, heat loads and generation of the intense beams of relativistic runaway electrons (RE). Localized interaction of intense RE beams with surrounding plasma facing components (PFC) inevitably will result in inacceptable PFC damage. To avoid/suppress RE generation and mitigation of other disruption detrimental consequences the Disruption Mitigation System (DMS) is under design for ITER. DMS will be based on injection of impurities in the form of solid shattered pellets (SPI) with support of Massive Gas Injection (MGI). Despite significant progress in studies relevant to the ITER DMS design, the set of physical and technology problems remains un-resolved. Development of DMS requires further advances in understanding of the physics of RE and their interaction with plasma, solid pellets and neutral gases (fuel and injected impurities).

Operational phases & plasma configurations	Period	Last shot number	Detected RE generation events
JET- Original Plasma Shape (OPS)	Operations till to August 1987	#12106	≈ 320 events
JET-OPS, Limiter, X-Point (SN, DN)	August 1987 - February 1992	#28791	≈ 560 events
Divertor – MKI + CFC tiles	March 1994 - June 1995	#35778	≈ 130 events
- MKIIA, AP + CFC tiles	May 1996 – Feb 1998 – Sept 1998	#45155	≈ 220 events
- MKIIGB +CFC tiles	July 1998 - March 2001	#54549	≈ 250 events
- MKIIGB SR + CFC tiles	Jul 01 - Mar 04; Aug 05 - Apr 07	#63445	≈ 150 events
- MKII HD + CFC tiles	Carbon wall ends 23-Oct-2009	#79853	≈ 150 events
- MKII & ITER Like Wall (ILW)	ILW Experiments – from July 2011	> #80000	> **340** events

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

Apparent progress in RE characterisation was achieved after the parameters of RE generated in disruptions during all periods of JET operations have been compiled into comprehensive data-base with inclusion of latest results obtained just before the end of JET operations in December of 2023 (Table 1). From the beginning of JET operations there were several limited attempts to review the data on RE generation during JET disruptions [1-3].

This report summarizes the analysis of experiments on RE generation in spontaneous disruptions, during those triggered by constant gas puff, and using MGI and SPI, including latest experiments on benign RE termination. RE parameters have been measured in JET disruptions with original plasma shape – JET-OPS ($S_{plasma}< 6.6$ m^2), in a series of dedicated experiments during period of JET operations with divertor ($S_{plasma}< 4.7$ m^2) and carbon fiber composite tiles (CFC, till to 2009) and with ITER-like Wall (from 2011).

The mapping of disruption and RE parameters has been carried out to study the dependencies of post-disruption plasma parameters on pre-disruption ones. Despite the plasma parameters are poorly known immediately during and after disruptions, this approach enabled establishing certain links between plasma parameters before thermal quench and during current decay (T_e and n_e, l_i, and current quench (CQ) rates, data from EFIT, etc.). Obtained data was used to study the trends in RE parameters for a wide range of disrupted JET currents (up to 6.7 MA). Using widely known models for RE generation: primary mechanism (“Dreicer-Gurevich-Connor/Hastie...”), secondary avalanching (“Sokolov-Putvinski/Rosenbluth...”) [3-6] and results of study of plasma ion charge depending on T_e [7] the parameters of RE were calculated and compared to those measured in experiments. Note, that in certain cases the simulations yielded the data, which was in contrary to experimentally observed trends. Study of current quench (CQ) stages revealed different, accelerating and constraining effects of initial plasma configurations (circular (limiter) or X-point) on CQ rates, RE generation and value of current conversion ratio (I_{pl}/I_{RE}). Analysis of MGI effect from different Disruption Mitigation Valves and SPI data revealed different effects on disruption dynamics and RE generation. One of the important results from the data-base analysis is observation of lower threshold in generation and a decreasing trend in conversion ratio I_{RE}/I_{pl} depending on CQ rates. Figures 1-3 demonstrate the separated results from the JET RE database analysis highlighting some counter-expectation trends. In particular, similarly to dependencies on CQ rate, conversion ratio I_{RE}/I_{pl} experiences significant decreasing trend with increase of disrupting plasma currents and plasma current time derivative.

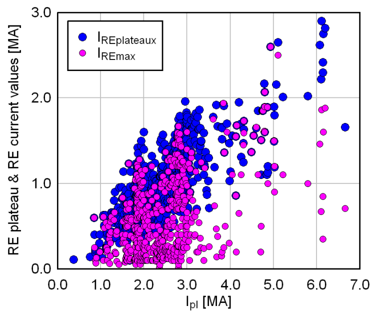

Figure 1. *Maximal values of RE plateaus and RE current values inferred from the measured plateaus in JET disruptions.*

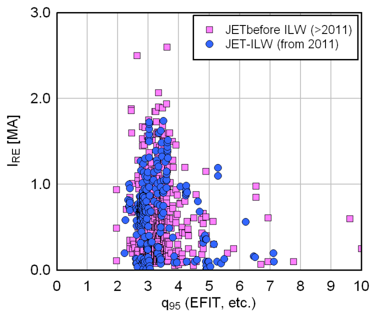

Figure 2. *Maximal values of RE currents in all types of disruptions in JET plotted vs. safety factor q_{95}*

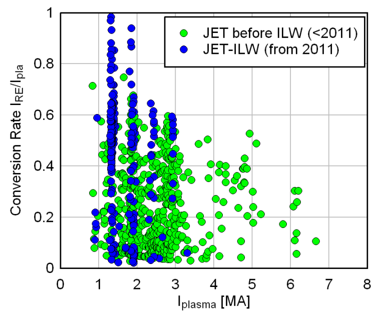

Figure 3. *Conversion of the resistive plasma currents into RE ones in disruptions during all JET operations*

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] R. D. Gill et al. 2002 Nuclear Fusion **42** 1039
[3] V. V. Plyusnin et al. 2006 Nuclear Fusion **46** 277
[4] H. Knoepfel, D.A. Spong 1979 Nuclear Fusion 19 785
[5] Yu. A. Sokolov. 1979 JETP Letters 29/218
[6] M. N. Rosenbluth and S. V. Putvinski 1997 Nuclear Fusion 37, 1355
[7] D. Kh. Morozov, E. O. Baronova, I. Yu. Senichenkov, 2007 Plasma Physics Reports, V33, No 11, p.906

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