Analysis of Variability in Pre-Disruption Plasma Parameters and their Effect on Runaway Electron Generation using the JET data-base on RE

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INTRODUCTION AND BACKGROUND

- In tokamak-reactor, such as International Thermonuclear Experimental Reactor (ITER), the generation of runaway electrons (RE) is unacceptable;
- Development of Disruption Mitigation System in ITER (ITER-DMS) requires a detailed understanding of the physics of RE and trends of their parameters during generation and interaction with injected solid state and gaseous impurities for RE suppression as an input data for numerical simulations;
- 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, [1-3]). However, these attempts are still waiting a compiling into joint database;
- After the review of multi-machine RE experiments on European tokamaks [4], **the first extended summary** on RE generation events in JET [5] and further development of RE data [6] have been elaborated. This data includes about 2000 RE generation events in major disruptions before and after divertor installation, with metal and carbon limiters (JET-C and JET-ILW), in spontaneous disruptions and those triggered by slow gas puff Massive Gas (MGI) and Shuttered Pellet Injections (SPI).

STATISTICS ON RE GENERATION EVENTS IN DISRUPTIONS DURING JET OPERATIONS

Operational phase & configurations	Period	Last shot number	Data on 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
- MKIIA, AP	May 96 – Feb 98 – Sept 1998	#45155	≈ 220 events
- MKIIGB	July 98 - March 2001	#54549	≈ 230 events
- MKIIGB SR	Jul 01 - Mar 04; Aug 05 - Apr 07	#63445	≈ 200 events
- MKII HD	Carbon wall ends 23-Oct-2009	#79853	≈ 340 events
- MKII ILW	ILW from July 2011	> #80000	> **210** events

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

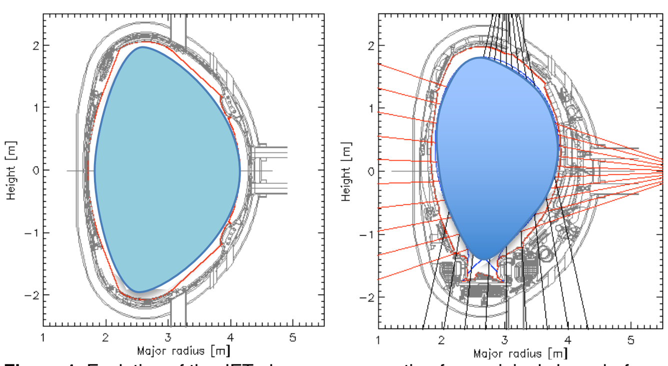

Figure 1. Evolution of the JET plasma cross-section from original shape before divertor installation (left, $S_{pl} \approx 6.6$ m²) to the plasma cross-section with divertor coils installed inside of vacuum chamber (right chart, $S_{pl} \leq 4.7$ m²).

- >210 (update 2022) RE generation events during JET operations with ILW (MKII ILW) have been triggered in studies of RE generation during intentional disruptions occurred after MGI or SPI of impurity gases (He, Ar, Ne, Xe, Kr) or their mixture with deuterium.
- RE data was collected in JET-ILW MGI experiments with plasma currents ≤ 2MA.
- All other unintentional disruptions in JET-ILW have been mitigated with MGI (10%Ar+90%D).

COMMON OBSERVATIONS DURING RE GENERATION IN DISRUPTIONS

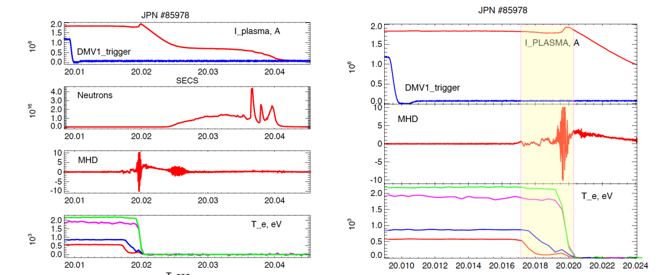

Figure 2. Example of common disruption scenario for RE studies: Disruption of JPN#85978 triggered by MGI with 100% of Ar in DMV1. Left chart – general view of plasma parameters evolution; Right chart – detailed view of plasma parameters evolution during thermal quench stage.

Massive Gas Injection (MGI) from Disruption Mitigation Valve (DMV) was used to trigger a series of major disruptions in JET-C and JET-ILW [4-7]. The number of injected argon or neon (or their mixtures with deuterium) atoms has been varied between (4-6)*10^{22} and (21-24)*10^{22} particles (maximum up to 2.5*10^{23}).

MGI and SPI technique allowed generation of RE in magnetic fields above 1 T, sometimes with the currents larger than 1 MA and duration over 0.1 second for study of RE generation and interaction of RE beams with injected impurities for suppression and mitigation.

INSTRUMENTATION

1) HXR spectra have been measured by γ-ray spectrometers and after numerical processing the RE distribution function has been calculated and applied in study of the dynamics of RE generation.
2) When HXR emission (bremsstrahlung of relativistic RE) passes through the matter, photo nuclear reactions take place resulting in strong activation and the neutron emission occurs. Photo-neutron data used in analysis has been produced with neutron rates fission chamber (^{235}U and ^{238}U) monitors installed at 3 different locations on JET (Oct. 2,6,8) and operating in a current mode with 0.0001 sec time resolution. This data was verified by comparison to the data characteristic for the symmetrical deuterium plasma in conventional discharge.
3)Various magnetic probes and standard plasma diagnostics for T_e, n_e, SXR, etc.

EXPERIMENTAL DATA ANALYSIS: CQ RATE & CONVERSION RATIO STUDY – TO ESTABLISH GENERAL TRENDS

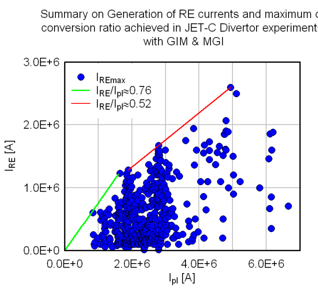

Figure 3 Maximal values of RE currents measured during disruptions triggered by GIM puff and MGI in JET operations with inclusion of some highest plasma current disruptions

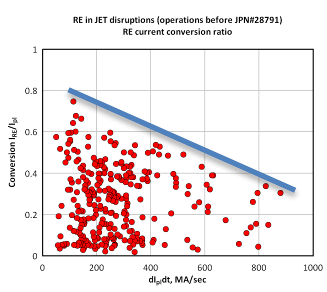

Figure 4. Decreasing trend in conversion ratio vs. plasma current time derivatives in spontaneous disruptions with RE generation in JET with original configuration.

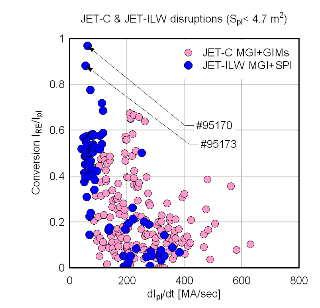

Figure 5 Maximal values of RE currents measured during disruptions triggered by GIM puff and MGI+SPI in JET-ILW RE experiments operations.

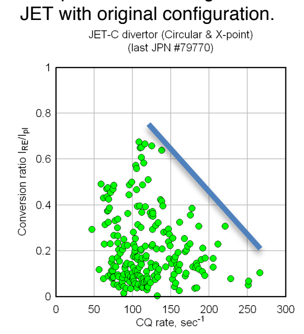

Figure 6. Decreasing trend for conversion ratio vs. CQ rates in disruptions with RE generation at MGI+SPI in JET-ILW.

EXPERIMENTAL DATA ANALYSIS: MAPPING OF RE GENERATION IN SEPARATE EXPERIMENTAL SERIES ON PRE-DISRUPTION PARAMETERS: INDUCTANCE, TEMPERATURE AND DENSITY (ALSO IN [6])

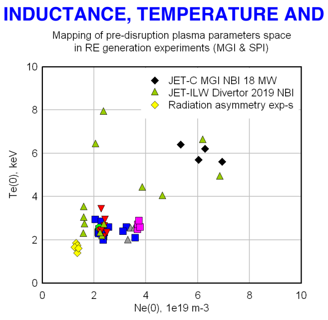

Figure 7 Experimental data map of JET-ILW operations with RE.

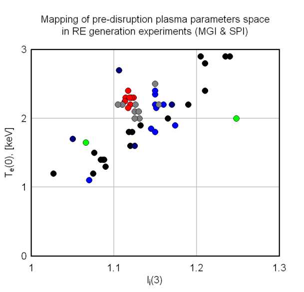

Figure 8. Mutual dependence between pre-disruption $T_e(0)$ and plasma current profile peaking.

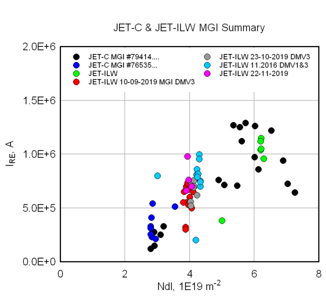

Figure 9 Counter - expectation increasing dependence of generated RE currents vs. pre-disruption density

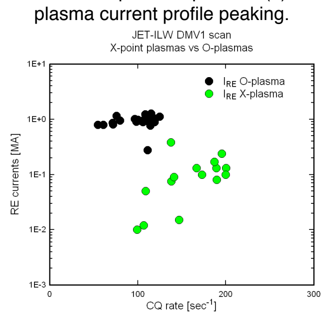

Figure 10. Comparison of RE currents generated in circular and X-point plasmas in JET ILW

EXPERIMENTAL DATA: ESTABLISHING LINKS BETWEEN PRE- AND POST-DISRUPTION PARAMTERS

A study of CQ rates (γ=1/I_p*dI_p/dt) + **energy conservation equation** + calculation of RE current fraction taking into account exponential plasma current decay process

$$V_{loop}(t)I_p(t)+\frac{d}{dt}\left[\frac{L_p(t)\cdot I_p^2(t)}{2}\right]=0 \qquad I_{pl}(t)=I_{pl}(0)\cdot exp\left(-\frac{t}{\tau_{CQ}}\right)$$

$$L_p(t)=\mu_0 R_0(t)\left(ln\left(\frac{8R_0(t)}{a_p(t)}\right)+\beta_p^*(t)+\frac{l_i}{2}-2\right) \qquad I_{RE}(t)=I_{TOT}(0)-\ I_{pl}(0)\cdot exp\left(-\frac{t}{\tau_{CQ}}\right)$$

$$CQ=\frac{dI_p}{dt}/I_{pl}(t)=-\frac{R_{pl}(t)}{L_{ext}(t)} \qquad T_{e,fin}=\left(83.60\ \cdot\frac{ln\Lambda}{CQ*\,a_{pl}^2}\cdot\frac{Z_{eff}N(Z_{eff})}{\left(ln\left(\frac{8R_0(t)}{a_p(t)}\right)-2+\frac{l_i}{2}\right)}\right)^{2/3}$$

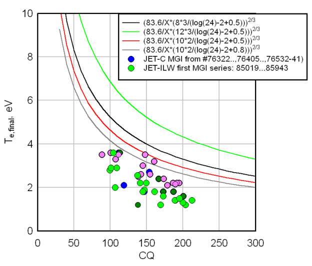

Figure 11. Assessment of post-disruption T_e from the CQ rate analysis: circles - data with RE at corresponding CQ and pre-disruption T_e in keV; lines - results of calculation of pos-disruption T_e at corresponding L_p

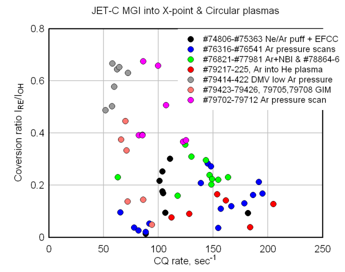

Figure 12. CQ rate threshold for RE generation in different experimental conditions of MGI experiments in JET-C with obvious decreasing trend toward to higher CQ rates

EXPERIMENTAL DATA ANALYSIS: EVOLUTION OF PLASMA GEOMETRY AND RE GENERATION

Disrupted plasmas move fast in space changing many parameters: radius, total inductance, magnetic flux, etc. Equation of energy conservation of plasma current loop (expanded) is:

$$2\pi R_0E_0(t)=-L_p(t)\frac{dI_p}{dt}-0.5\cdot I_p(t)\frac{dL_p}{dt},$$

In which: $\frac{dL_p}{dt}=\mu_0\cdot\left[\frac{dR_0(t)}{dt}\cdot\left(\ln\left(\frac{8R_0(t)}{a_{pl}(t)}\right)-2\right)+\ R_0(t)\left(\frac{\frac{dR_0(t)}{dt}}{R_0(t)}-\frac{\frac{da_{pl}(t)}{dt}}{a_{pl}(t)}\right)\right],$

and $\frac{\frac{dR_0(t)}{dt}}{R_0(t)}<0,\ \frac{\frac{da_{pl}(t)}{dt}}{a_{pl}(t)}<0;$

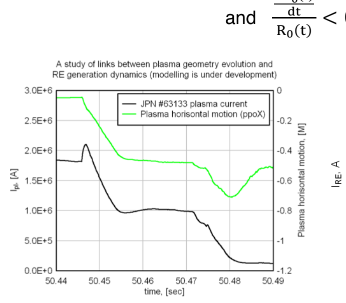

Figure 13. Fast horizontal plasma motion after disruption energy collapse.

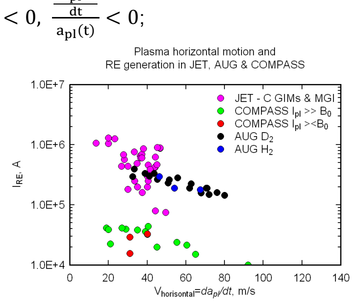

Figure 14. RE currents generated in moving plasmas: I_{RE} vs. da_p/dt.

=> During fast motion the term with $\frac{dL_p}{dt}$ is of order of value for one with $\frac{dI_{pl}}{dt}$. At vertical plasma motions dL_p/dt has largest constraining effect on E_0 and RE generation. From another hand the influence of disrupted plasma current density re-distribution on RE generation efficiency should be expected. Therefore, electric fields and RE generation, as well, depending on plasma temperature and density, should have also a dependence on plasma column geometry evolution. These experimental observations should be taken into account as input parameters in future studies.

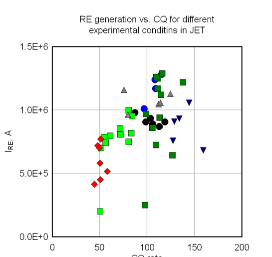

Figure 15. Generated I_{RE} vs. CQ rates in MGI/SPI experiments in JET

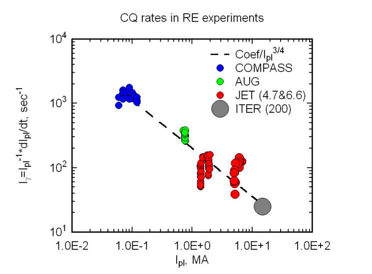

Figure 16. First look onto CQ scan in MGI/SPI experiments in JET and other European tokamaks (including some JET data with original plasma cross-section)

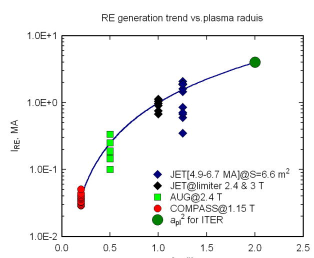

Figure 17. Trend in RE generation depending on plasma radius with extrapolation to ITER plasma radius

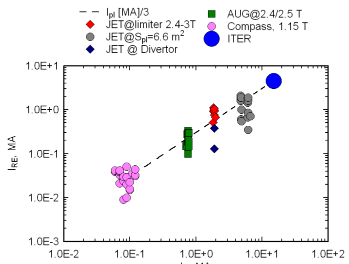

Figure 18. The trend of RE current generated in JET and European tokamaks depending on operation plasma currents.

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