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EUROfusion

# Data on Runaway Electrons in JET (II)

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**Previous results on RE data analysis in JET were presented in report "Data on Runaway Electrons in JET (I)", V.V. Plyusnin et al. 46th EPS Conference on Plasma Physics, 2019, Milano, report P4.1046**

**First summaries on RE generation events in JET have been given in:**

**[1] Harris G.R.1990 Preprint JET-R(90)07**
**[2] O.N. Jarvis et al. 1988 Nuclear Fusion 28 1981**
**[3] R.D. Gill Nuclear Fusion 33 (1993) 1613**

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# Background & Motivation

- <u>Motivation:</u> Development of ITER DMS requires an understanding of the physics of generation of relativistic electron beams and their interaction with the massive quantities of matter, as well as the beam interactions with applied external magnetic perturbations.
- <u>Background:</u> Plasma parameters and their evolutions during disruptions (TQ and CQ stages) are poorly known. As a consequence, numerical simulations of RE generation use very often the input data in a form of model functions, evolution of which during TQ and CQ could be far away from reality due to, for example, effects of substantial parameter asymmetry.
- <u>Purpose:</u> Formulation of input data for simulations of RE generation based on key physical processes at conditions close to experimentally observed and capable to study the processes of suppression/avoidance of disruption generated RE in ITER.
- <u>Actions:</u> Collect and perform an analysis of the experimental data during JET disruptions which have an effect on RE generation dynamics in JET. Compare the evolution of these parameters and establish the trends in their influence on RE generation. Perform numerical processing of experimental data taking into account established differences and similarities (phenomenological and numerical) in spontaneous or triggered by GIMs, MGI and SPI disruptions.

# Work structure

1) Analysis and selection of parameters, which influence on acceleration process could be set as reference ones in RE dynamics parametrisation, for example, li, safety factor, etc.

2) Establishing trends in parameters of "natural" RE generated in spontaneous disruptions during all operational phases in JET (original, JET-C & JET-ILW) depending on characteristics of disrupting plasmas with a different size. The purpose: possible extrapolation of existing experimental RE data up to ITER scale.

3) Analysis of pre-disruption plasma parameters in GIMs/MGI/SPI experiments for establishing the links between pre-disruption and pos-disruption plasma parameters and study RE generation trends in X-point and circular plasmas, with and w/o heating.

# Summary on time history of operational regimes and plasma configurations in JET

| Limiter Name | First Shot | Last Shot |
|---|---|---|
| Mk2HD | 63446 | |
| Mk2GB-SR | 54550 | 63445 |
| Mk2GB | 45156 | 54549 |
| Mk2A | 35779 | 45155 |
| Mk1 | 28792 | 35778 |
| Limiter | 1 | 28791 |

Sources used for DB elaboration & analysis:

1). JET Logging system & session report generator

2). Monk et al 1998 IAEA FEC Yokohama.

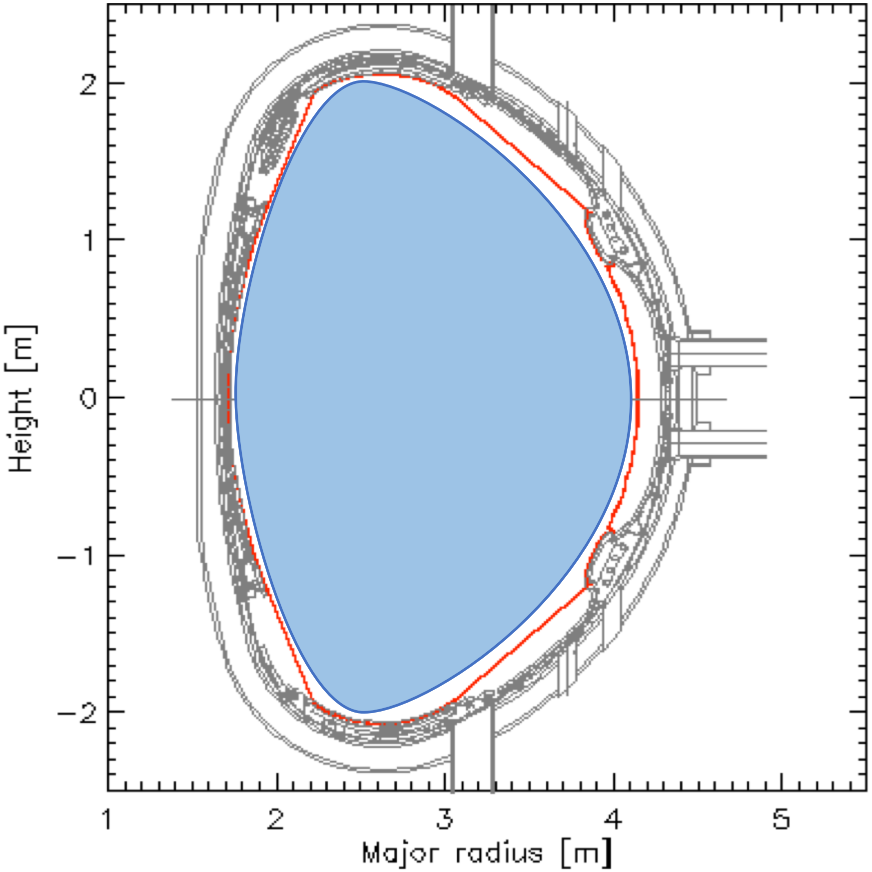
3). A. Loarte 2001 PPCF

4). W. Fundamenski et al 2008 Fus. Sci & Technology

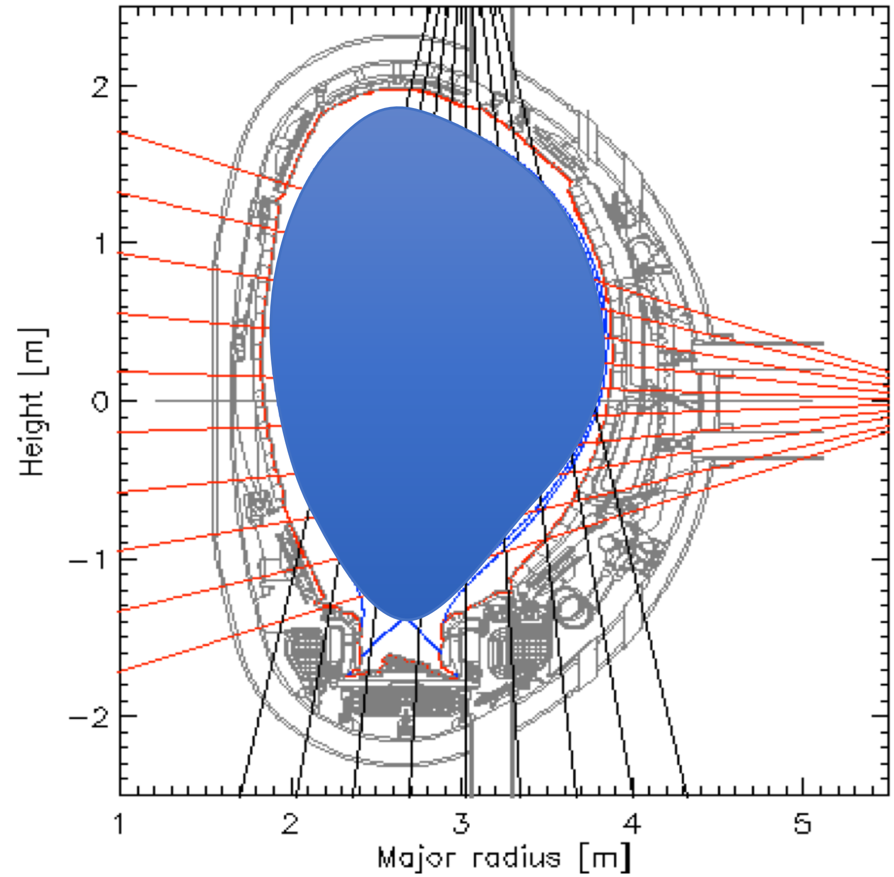
5) P.C. de Vries, Nucl. Fusion 49 (2009) 055011

| Operational phase & configurations | Period | Last shot number | Data on RE generation events |
|---|---|---|---|
| 1. Limiter only | Operations till to August 87 | #12106 | ≈ 320 events |
| 2. Limiter + X-Point (SN, DN) | August 87 - February 92 | #28791 | ≈ 560 events |
| 3. Divertor - MKI | March 94 - June 95 | #35778 | ≈ 130 events |
| - MKIIA, AP | May 96 – Feb 98 – Sept 1998 | #45155 | ≈ 220 events |
| - MKIIGB | Jul 98 - Mar 01 | #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 |
| 4. MKII ILW | ILW from July 2011 | > #80000 | > 150 [illegible]nts |

# Reference plasma cross-sections before and after installation of the divertor structure in JET and for JET with ITER-like Wall: JET original, JET-C, JET-ILW




JET original: $S_{pl}$=6.6 $m^2$ – operational phases 1-2




JET-C & JET-ILW: $S_{pl}$=4.7 $m^2$ – phases 3-4 (table)

Early data on RE generated in JET disruptions [for example [1-3], or V.V. Plyusnin et al. 2006 Nuclear Fusion] has demonstrated a large difference in RE generation efficiency depending on plasma cross-section size

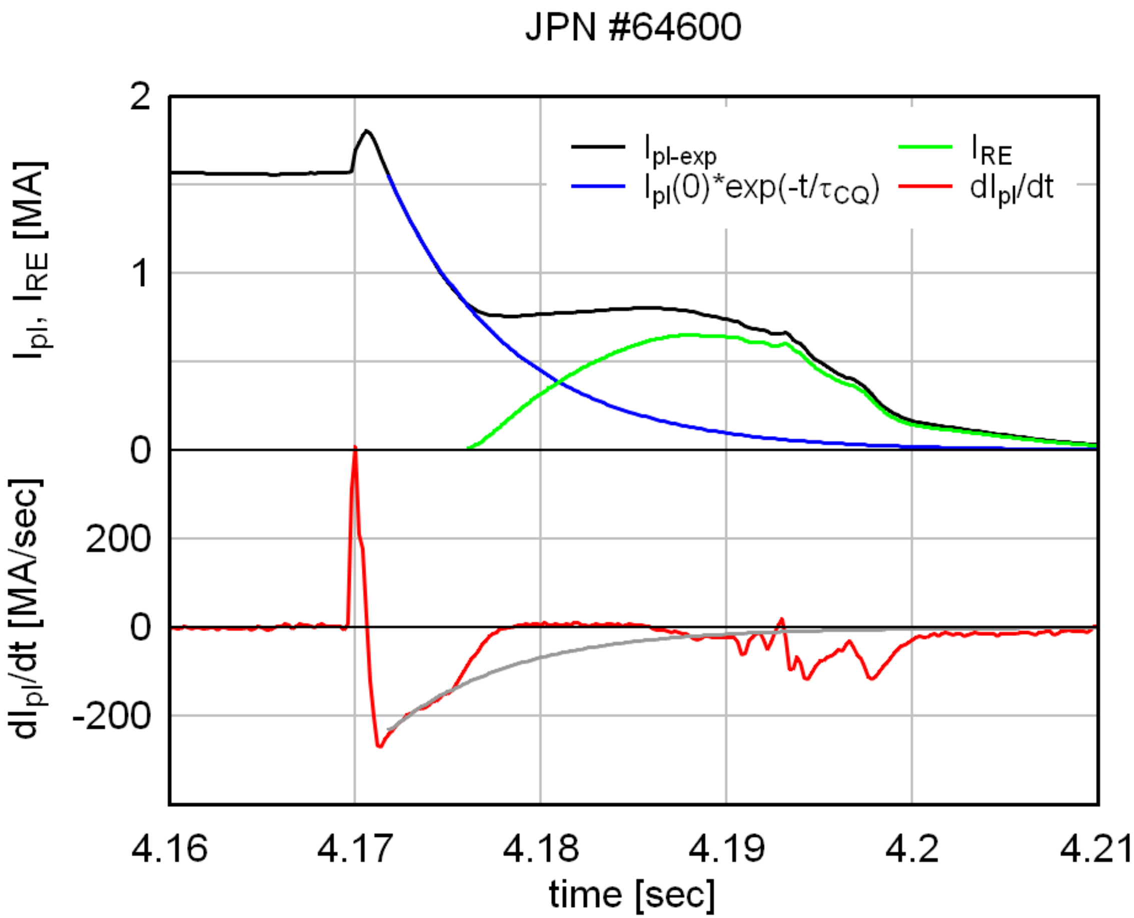
The set of parameters determining the evolution of accelerating electric fields have been choosen for analysis of trends in RE parameters.

1) Plasma internal inductance: $l_i \approx \ln(1.65 + 0.89c)$, where **c** is plasma current profile factor in $j(r)=j(0)*(1-r^2/a^2)^c$; The $l_i$ evolutions allow characterization of the plasma currents re-distributions that result in increase/decay of electric fields [for example, A. Loarte NF2011].

2) Safety factor q(r,t) and its link to evolution plasma current densitity:

$j_{\parallel 0} = \sigma_{\parallel} E_{\parallel 0} = \frac{5 * B_0}{\pi * q(0) * R_0}$ and $q(r) = \frac{5 \cdot B_0}{\mu R_0} \frac{r^2}{\int_0^r j_{\parallel}(0) \cdot \left(1 - \frac{x^2}{a^2}\right) \cdot 2\pi x dx}$, as well allow evaluate E-fields evolution during TQ and CQ.

3) Plasma current quench rate (CQ): $\gamma = 1/I_p*dI_p/dt \equiv R_{pl}/L_p$ – characterizes evolution of pos-reconnection decay of plasma currents. Simplified model presumes that plasmas do not move after stored energy collapse.




Evolution of plasma parameters in reference JET disruption #64600. $\tau_{CQ}$ in figure is exponential e-folding time: $\tau_{CQ} \equiv 1/\gamma = I_p/dI_p/dt \equiv L_p/R_{pl}$. Green curve is inferred evolution of RE current – reference parameter for numerical processing of RE data.

# Key parameters, dependencies & working equations (cont.):

Modified model of CQ: $\gamma = 1/I_p * dI_p/dt = -(R_{pl} + dL_p/dt)/L_p$ - plasmas are moving after stored energy colapse and plasma geometry is evolving in time and space [Y. Shibata et al. Nucl. Fusion 50 (2010) 025015; V.V. Plyusnin and I.M. Pankratov, 38th EPS Conf. 2011 Strasbourg ,(ECA) http://ocs.ciemat.es/ EPS2011PAP/pdf/P4.091.pdf]:

In this modified case the total inductance time derivative is not negligibly small and should be used in the following form:

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

,where $\frac{\frac{dR_0(t)}{dt}}{R_0(t)} \leq 0$, and $\frac{\frac{da_{pl}(t)}{dt}}{a_{pl}(t)} < 0$. Use of this formula reveals constraining effect on electric fields during CQ, when the plasma motions are detected. Moreover, the plasma motions causes the plasma/RE currents peeling effect, which also should be taken into account in E-fields evolution:

$$\Delta I_p(t) = \int_0^{a(t)} (j_{pl}(r,t) + j_{RE}(r,t)) \cdot 2\pi r dr - \int_{r(t)}^{a(t)} (j_{pl}(r,t) + j_{RE}(r,t)) \cdot 2\pi r dr$$

## Key parameters, dependencies & working equations (cont.):

Ongoing analysis of RE generation process depending on established trends in key parameters is based on the set of equations:

$$I_p(t) \cdot R_p\,(t) = -L_p(t)\frac{dI_p}{dt} - 0.5 \cdot I_p\,(t)\frac{dL_p}{dt} \qquad (1)$$

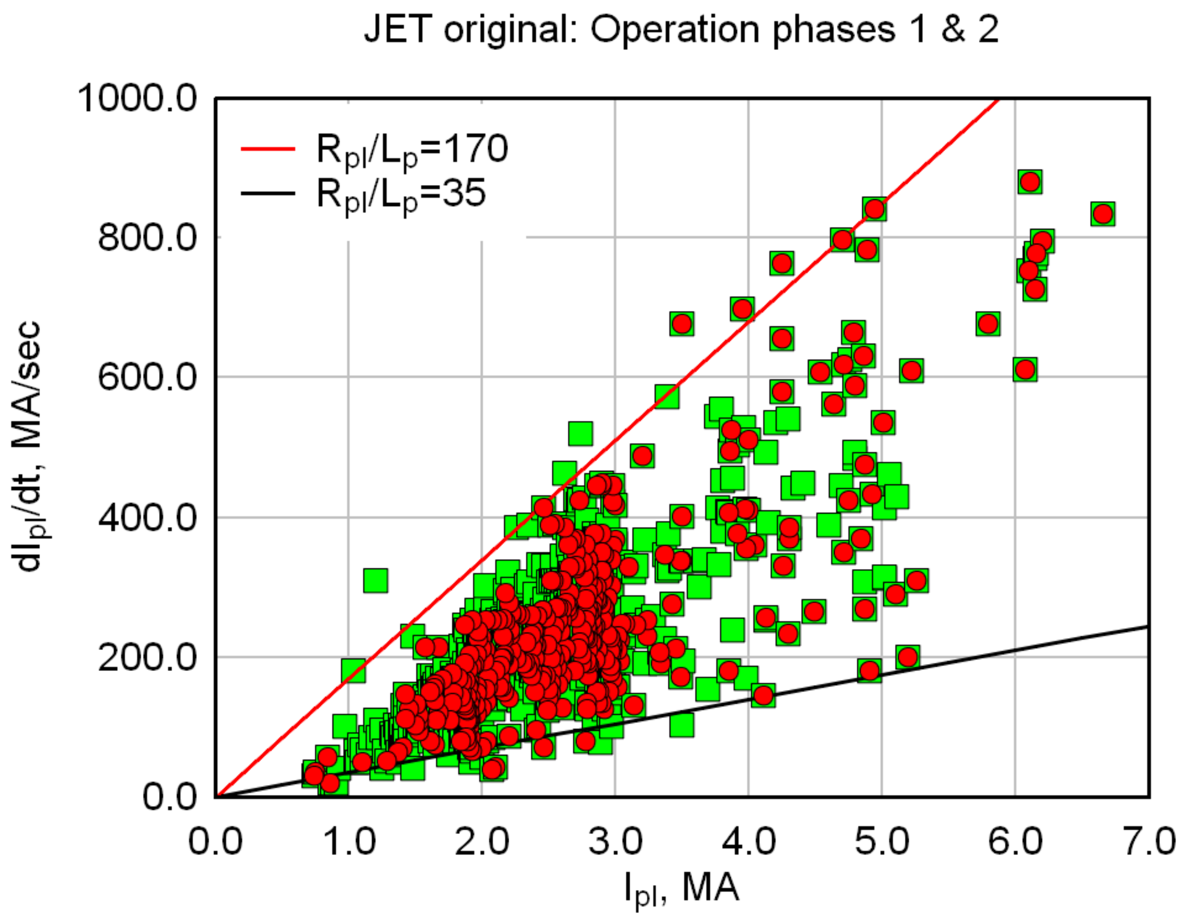
$$\frac{dj_{RE}}{dt} = \lambda_{RE} + (\gamma_{hot}+\gamma_{SA} + \gamma_{ad}) * j_{RE} - \frac{j_{RE}}{\tau_{RE}} \qquad (2)$$

$$\Delta\sigma_{\parallel}\frac{d\psi}{dt} = 2\pi R_0(j_{\parallel}(t) - j_{RE}(t)) \qquad (3)$$

RE current could be calcualted as:

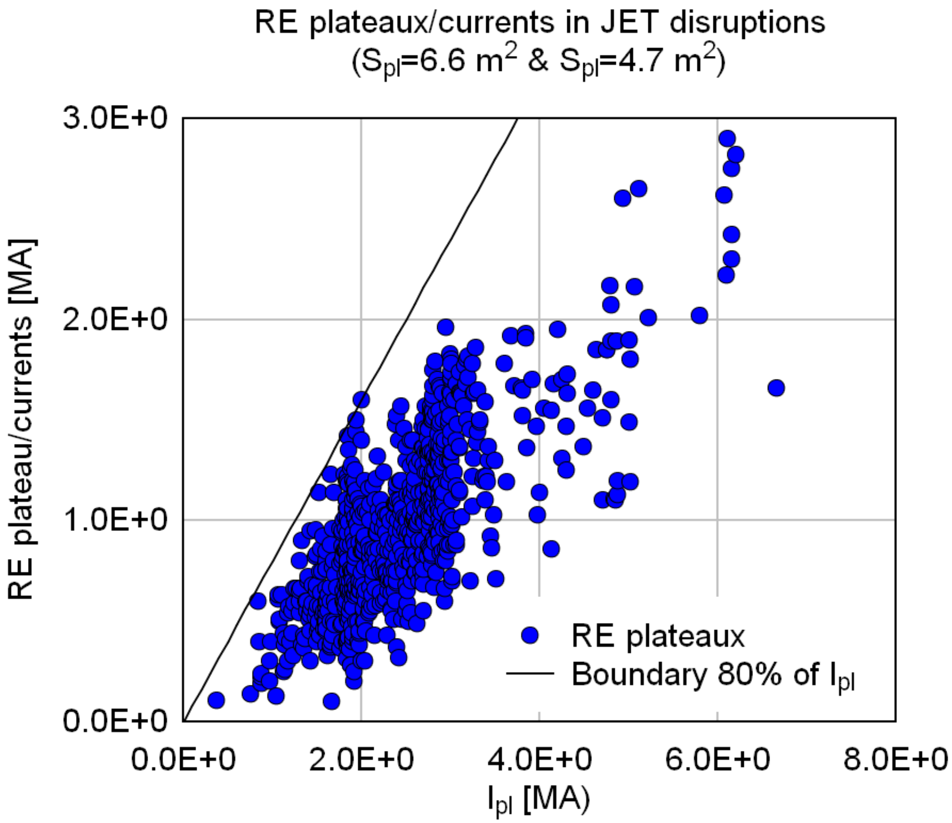
$j_{RE}(r,t) = 2ec\int_0^{t'}(\sum S_{RE}(r,t) * \frac{e*A_{\psi}}{\sqrt{m_e^2c^2+e^2A_{\psi}^2}})dt$, where $\sum S_{RE}(r,t)$ -is sum of all RE sources during disruptions and $A_{\psi}$=$\int E_{\parallel}dt$.

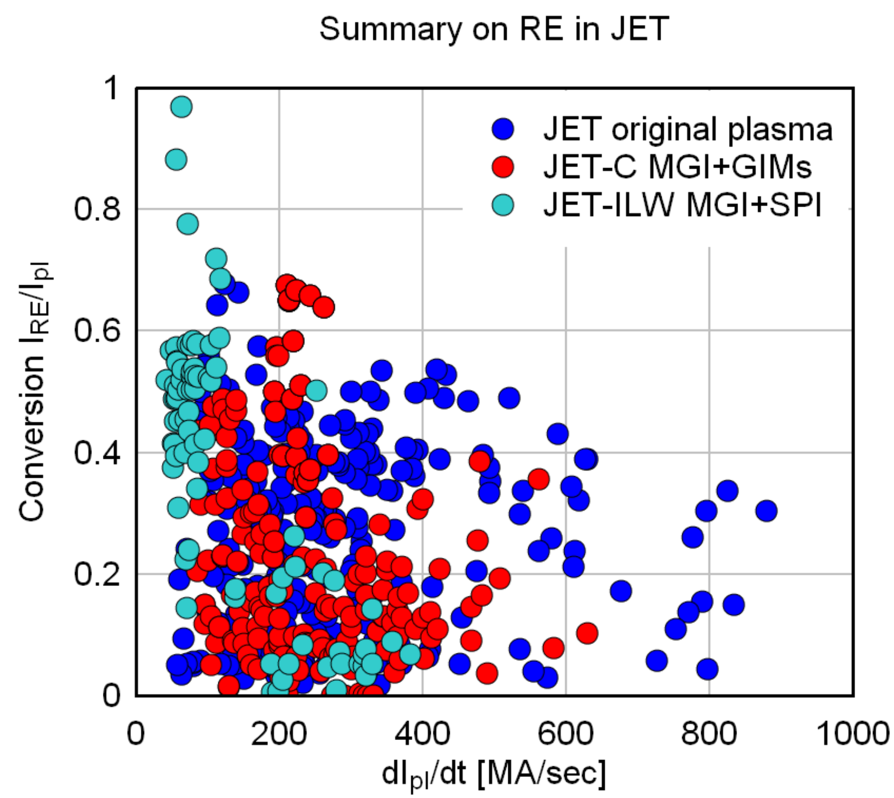
# General characteristics on RE data in JET (original plasmas)




CQ rates in JET original plasmas ($S_{pl}$=6.6 m$^2$): $\gamma = 1/I_p * dI_p/dt = R_{pl}/L_p$ ; green – all RE generation events (HXR and neutron signals detected), red circles - events with RE plateaux/currents. [Ref. [Harris G.R.1990 Preprint JET-R(90)07]

# RE data summarized in JET original, JET-C and JET-ILW plasmas



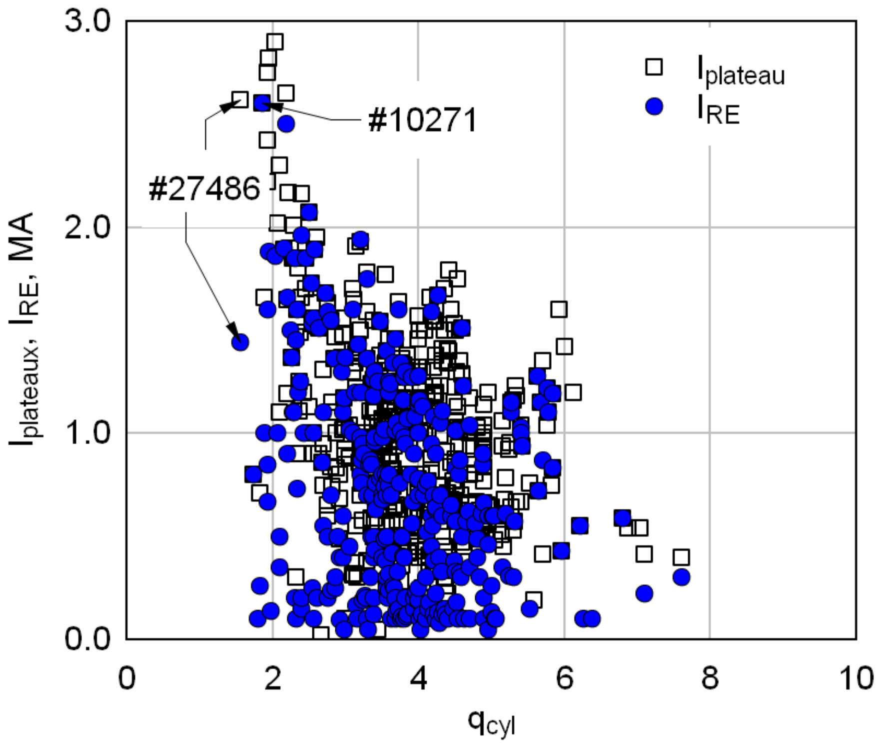




Maximum RE currents in JET achieved 80% of pre-disruption plasma currents (new data), decreasing at higher plasma currents (typical for JET original plasmas)

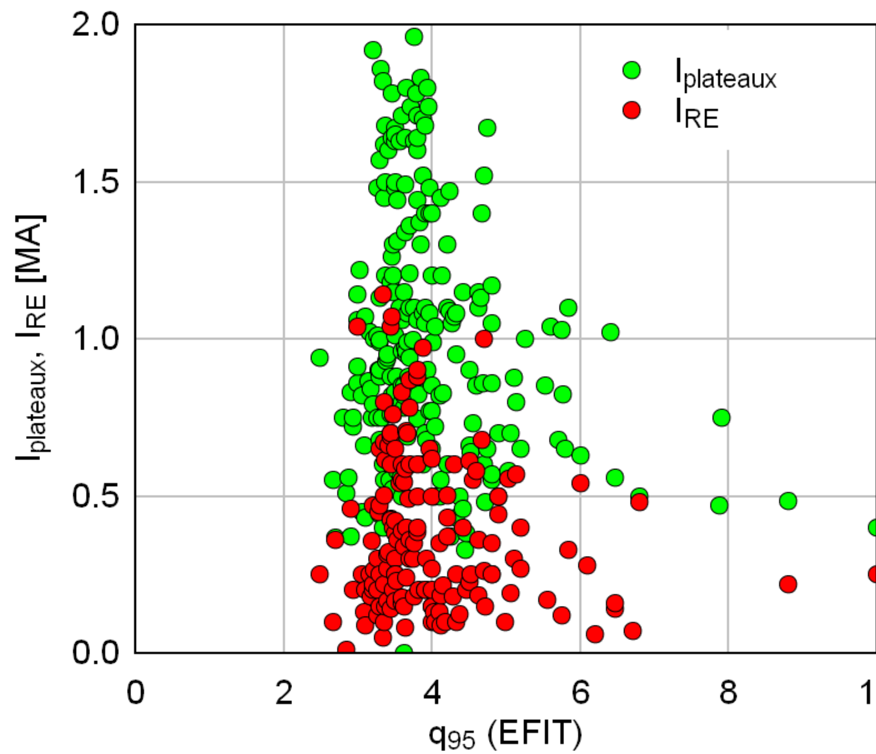
Surprisingly decreasing dependence of conversion ratio $I_{RE}/I_{pl}$ vs. plasma current time derivative (new data). Possible issuses for RE data extrapolation to ITER parameters

# Dependencies of generated RE currents vs. $q_{cyl}$ & $q_{95}$ in JET original, JET-C and JET-ILW plasmas

RE generation in JET (original, before #28791)
$S_{area}$ = 6.6 m$^2$

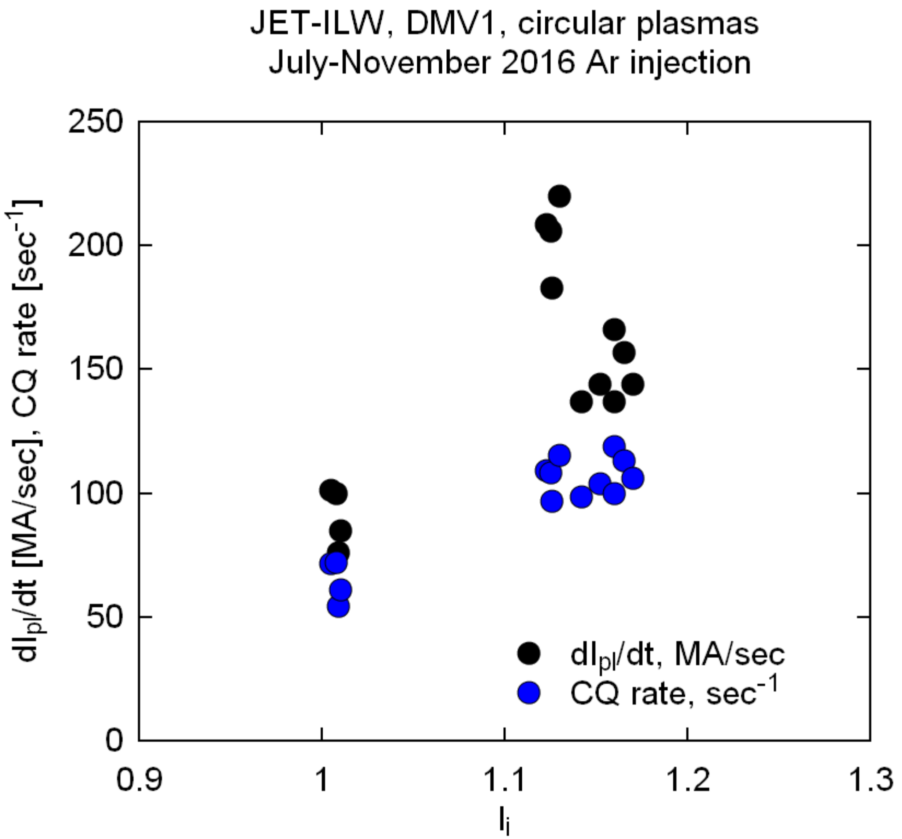


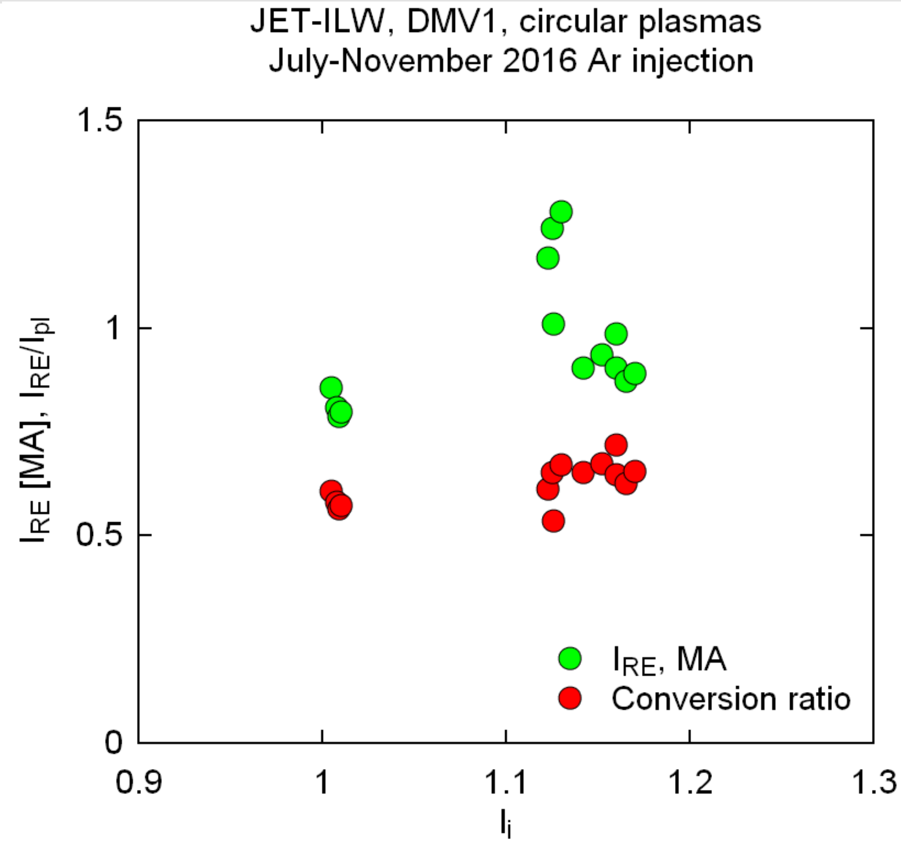

JET-C operations (from JPN#28792)
Limiter and divertor plasmas with $S_{pl} \leq 4.7$ m$^2$




Mapping of RE generation in $q_{cyl}$ and $q_{95}$ space in JET for different operational stages. Obvious increase of RE generation with increase of plasma current-carrying fraction inside the q=2 surface.

# Effect of plasma current profile ($l_i$) on CQ dynamics and RE generation parameters in circular plasmas of JET-ILW:

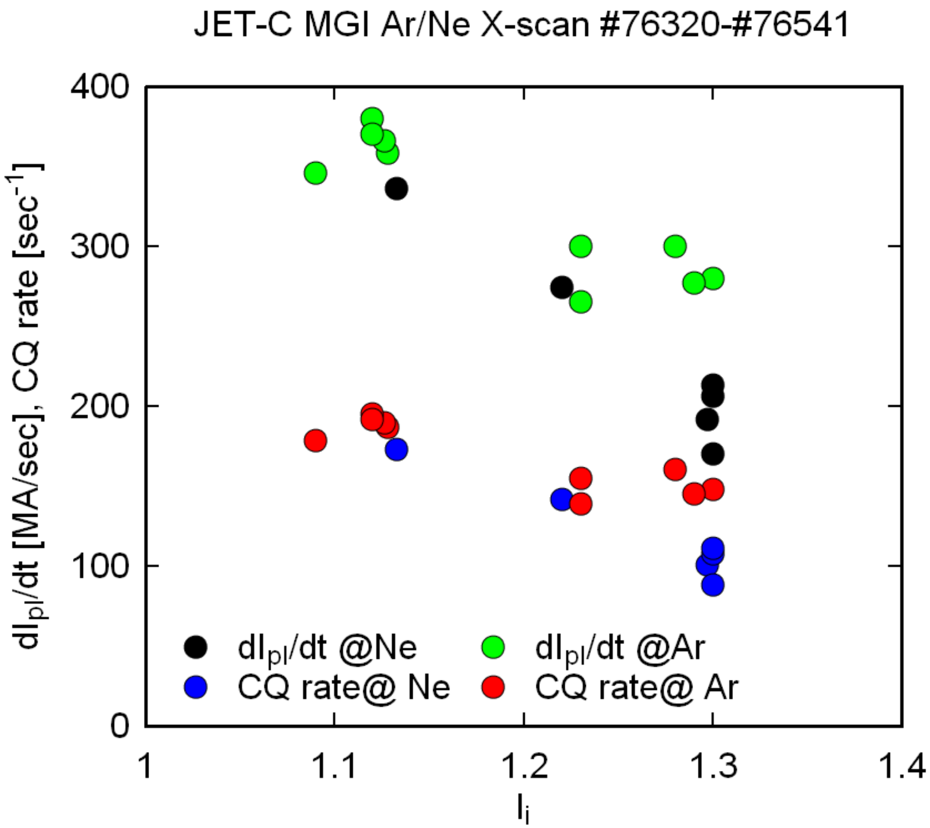


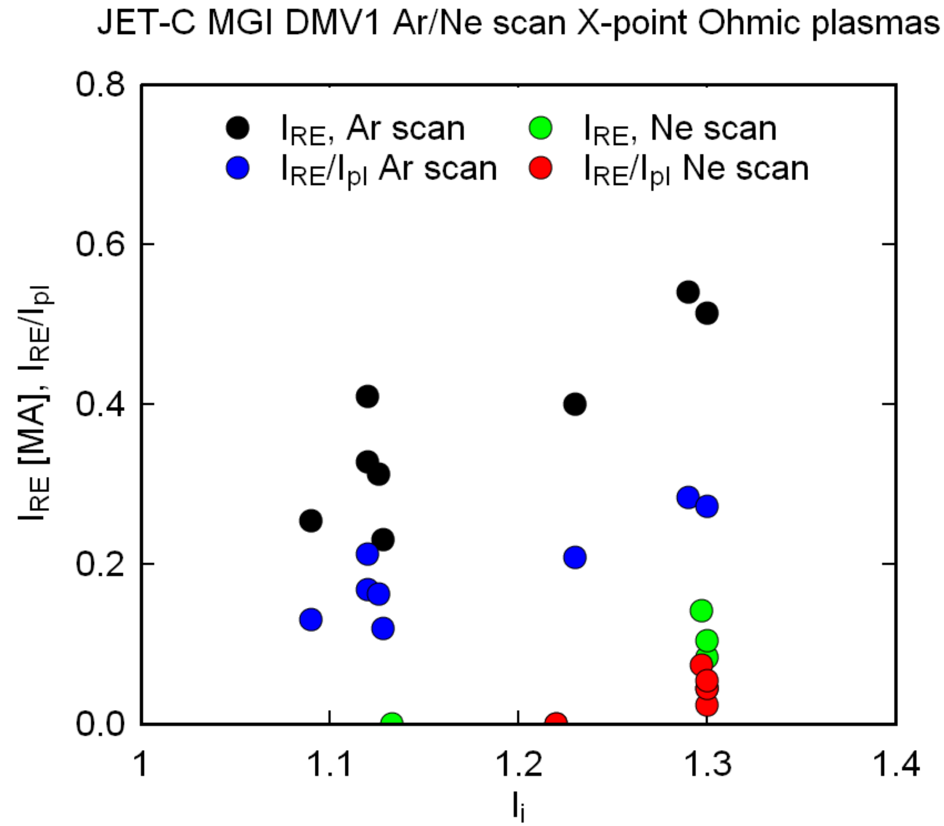




RE generation in circular JET-ILW plasmas: the RE currents generated at Ar injections revealed increasing trend depending on plasma current time derivatives, which, in turn, increased with pre-disruption plasma internal inductance.

**Note, that asymmetry caused by MHD modes may play role.** Analysis is underway.

# Effect of plasma current profiles ($l_i$) on disruptions CQ dynamics and RE generation parameters in JET-C X-point plasmas




In comparison to circular JET-ILW plasmas, Ar/Ne injections into X-point JET-C plasmas resulted in opposite decreasing trends in plasma current time derivatives and CQ rates vs. internal plasma inductance. These dependecies, nevertheless, resilted in increase of generated RE currents. An extended analysis of obtained data is underway...

## Summary

- The data on disruption generated RE in JET is retrieved for entire history of JET operations. RE generation events have been grouped on parameters of disrupting discharges and the RE parameters for further analysis.
- This first analysis of RE database has revealed the wide range of plasma parameters affecting the RE generation or increasing the efficiency of this process.
- The RE generation events have been mapped on pre-disruption plasma parameters (safety factor $q_{95}$, plasma internal inductance, electron temperature, density, etc.).

- RE generation efficiency revealed an increasing trend with decrease of the safety factor of disrupting discharges: $q_{cyl}\approx 2$ or $q_{95}\approx 2.5\text{-}3$ – are lower operation values (new data).
- New data on upper boundary of generated RE current values (≈80%) has been established during the RE data analysis.
- A detailed comparison of RE generation parameters in circular and X-point plasmas revealed strong differences in their CQ parameters and efficiency of RE generation.
- An analysis of the collected RE data will be continued...