EUROFUSION CP(15)05/86

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(22nd June 2015 – 26th June 2015)
Lisbon, Portugal

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 under grant agreement No 633053.

Parameters and Stability of Runaway Electron Dominating Discharge in JET with ITER-Like Wall

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**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

Introduction Potentially severe generation of high-energy runaway electrons (RE) in tokamaks could occur on any stage of discharges: during breakdown and plasma current ramp-up, during stationary stages and during disruptions. Uncontrolled generation of RE currents up to several MA during disruptions is considered as most dangerous for the device first wall [1]. Usually the RE generation is detected with the aid of HXR diagnostics and photo-neutrons. Relativistic RE interacting with background plasma, neutrals or surrounding plasma-facing components (PFCs) produce a bremsstrahlung hard X-ray emission (HXR) in the MeV energy range and photo-neutrons. Measurements of these radiations provide the information on energy characteristics of RE. For the device protection and RE studies 5 scintillation time-resolved HXR monitors and ^{235}U and ^{238}U fission chamber neutron rate monitors at 3 different locations operate in a current mode with 0.1 ms time resolution. The HXR emission has been measured with the set of horizontally and vertically viewing NaI(Tl), Bi_4GeO_{12} (usually referred as BGO) and $LaBr_3$ spectrometers. The data on spatial distribution of HXR emission sources in the plasma has been obtained with the JET neutron/gamma profile monitor routinely used for neutron and gamma rays measurements. The HXR raw data measured by BGO spectrometer has been processed with de-convolution procedure using the DeGaSum code [2]. This procedure allowed reconstruction of the energy spectra of generated RE populations. The RE distribution function (REDF) is important characteristic describing the RE generation process. Evolution of REDF can characterize different stages of this process such as acceleration of electrons and their scattering on background plasma and neutrals, interaction with first wall, etc. Sometimes the RE were detected in-flight during the transient stages of discharge breakdown and plasma current ramp-up in JET with ITER-Like Wall (JET-ILW) [3]. Events of RE generation during flat top stages of discharges in JET constitute a subject of highly rated interest, first of all due to the rare possibility to study the onset, growth and reasons for loss of relativistic electrons (REs) [4]. In this report we present a study of RE parameters generated and detected during quasi-stationary stage of the JET-ILW discharge following the large plasma density decrease. In order to avoid an ambiguous interpretation of the processes occurring on this stage the evolution of measured plasma parameters (density, electron temperature, loop voltage, plasma current) have been numerically processed in frames of conventional theory for RE generation.

Experimental data and discussion During the flattop stage of ordinary JET-ILW pulse (JPN #86078) a sudden loss of control on inlet of working gas resulted in decrease of plasma density to extremely low value: $<n_e> \leq 2.E18\ m^{-3}$ (from approx. t = 18.4 sec in Figure 1). This regime with low density has been sustaining approximately 8 seconds. The neutron diagnostic registered almost complete disappearance of fusion neutron yield from the deuterium plasma following this density decrease. Plasma current during this low-density stage was kept almost constant ($I_{pl} \cong 1.8$ MA) till to discharge termination (Figure 1). The measured loop voltage (V_{loop}) at the beginning of density decrease was $V_{loop} \cong 0.65$ V, that corresponds to $<T_e> \cong 1.5$

keV calculated from classical resistivity with neo-classical correction on fraction of trapped particles. Obtained <T_e> value is very close to T_e data provided by other JET diagnostics. In low-density phase the mean (drift) current velocity increases up to $u_0 = (I_{pl}/\pi a_{pl}^2)/(en_e) \leq$ 3.0E6 m/sec, where a_{pl} is plasma radius (from EFIT) and <n_e> is measured plasma density. Large drift velocity ($u_0 \cong 0.1 v_{Te}$) inevitably will lead to asymmetry of the electron distribution function ($f_e(v_e) \sim n_e * exp(-(v_e - u_0)^2/v_{te}^2)$). Simple calculation shows that appeared asymmetry causes a significant increase of the number of electrons (up to ~10%) moving in the direction of acceleration. It results in increase of number of electrons with velocities higher than the critical one: $v_e > v_{Dr} = \sqrt{\frac{e^3 n_e \, ln\Lambda \, (2+Z_{eff})}{4\pi\varepsilon_0^2 m_e E}}$, where v_{Dr} is a critical velocity for generation of primary (Dreicer) runaway electrons (RE). According to the theory of RE generation two mechanisms are responsible for generation of RE. The primary mechanism, when acceleration of electrons by external E-field is higher than frictional drag of Coulomb collisions with plasma particles. And the secondary avalanching, when existing RE (collisionless on their origin) transfer a significant energy (higher than threshold for runaway acceleration) to surrounding thermal electrons via close distance collisions thus enabling multiplication of the number of RE. It is clear that secondary avalanching could occur only if the primary generation will provide the substantial RE flux with sufficient energy. Note, that the close distance collisions are less frequent by the factor $8*ln\Lambda$ than usual Coulomb (distant) collisions. Dynamics of both processes is determined by the runaway growth rate, which is mainly depending on the ratio of externally applied electric field (E_0) to the threshold field, above of which a free acceleration is possible: $\alpha = E_0/E_{DR}$, where $E_{DR} = \frac{e^3 n_e \, ln\Lambda \, (2+Z_{eff})}{4\pi\varepsilon_0^2 m_e v_{Te}^2}$ – is a threshold field for Dreicer process, and $\beta = E_0/E_{CR}$, where $E_{CR} = \frac{e^3 n_e \, ln\Lambda \, (2+Z_{eff})}{4\pi\varepsilon_0^2 m_e c^2}$ - is the critical field for avalanching.

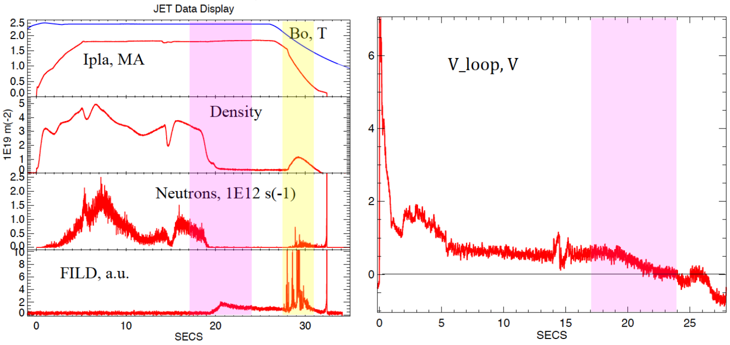


Figure 1. JPN#86078: General view of discharge parameters evolution (left chart). Right chart - loop voltage time evolution till to beginning of pulse termination. Studied stage (RE) is highlighted in pink (both charts), in yellow – RE instability phase

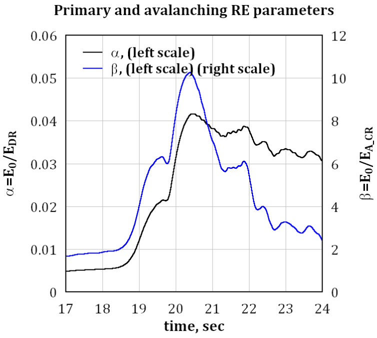


Figure 3. Evolution of RE generation parameters ($E/E_{DR/CR}$) for primary and avalanching processes in JPN#86078

Figure 3 presents evolutions of α and β during low-density stage. RE generation has been modelled with conventional equation for evolution of RE density $\frac{dn_{RE}}{dt} = \lambda_R - \frac{n_{RE}}{\tau_R} + \frac{n_{RE}}{t_0}$, where $\lambda_R = C(Z_{eff}) \cdot n_e v_e \varepsilon^{-\frac{3(Z_{eff}+1)}{16}} \cdot \exp\left(-\frac{0.25}{\varepsilon} - \sqrt{\frac{Z_{eff}+1}{\varepsilon}}\right)$ is the primary generation rate, and $t_0 = \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e} \sqrt{\frac{3}{\pi}(Z_{eff}+5)} \cdot (\beta - 1)^{-1}$. So, that $1/t_0$ is the secondary avalanching growth rate and confinement time τ_R is infinity. Modelling revealed large increase of runaway growth rate and simultaneous decrease of runaway critical energy (W_{cr}) when density decreased below 1E19 m^{-2}, i.e. at t ≥ 19.5 sec (Figure 4). It is important to note, that contribution from runaway avalanching source to total RE population was less than expected from theory since the Dreicer acceleration and EDF asymmetry provided nearly total contribution into RE population (n_{RE}~1.E15 m^{-3} at t=24 s), that corresponds to RE current fraction $I_{RE} \leq 200$ kA/m^2. Evolution of REDF indicates that further sustainment of RE stage is provided by avalanching. Gradual decrease of loop voltage indicates not only increase of $<T_e>$, but also increase of RE fraction in total plasma current I_{pl} ~1.8 MA. Loop voltage becomes negative at large RE current fraction. After t = 24 s the numerical analysis of experimental data fails due to inversion of loop voltage signal. Simultaneously to increase of runaway growth rate the vertical and horizontal HXR detectors registered the increase of HXR signals from the plasma centre (Figure 5). The scintillator of the FILD detector (Fast Ions Loss Diagnostics, Figure 1) also registered increase of the signal, which is associated with the presence of HXR emission caused by RE in plasma. RE produce electromagnetic radiation in collision with plasma particles and when they hit the surrounding PFC. In both cases the predominant radiation production mechanism is bremsstrahlung. Figure 6 presents the measurements of HXR radiation performed using the JET γ-camera with vertically and horizontally viewing sets of detectors in direction perpendicular to the direction of RE motion (along the toroidal field lines).

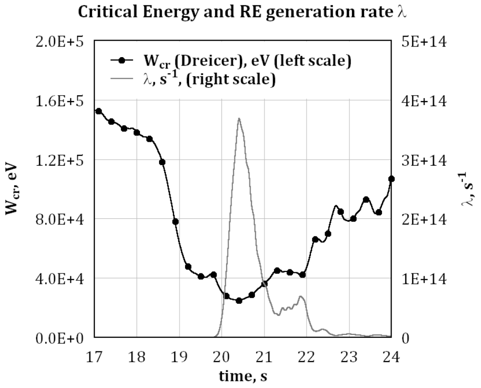


Figure 4. Evolution of critical energy W_{cr} for runaway process and RE generation rates.

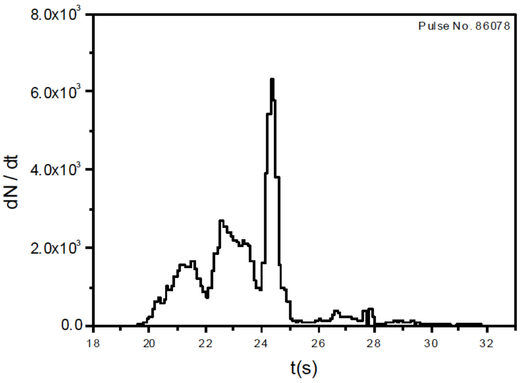
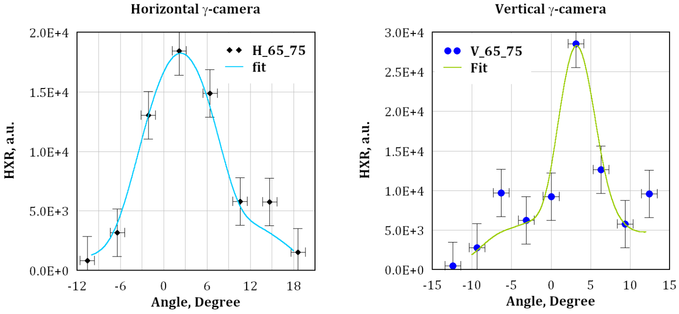


Figure 5. Signal from HXR detector during low-density phase of JPN#86078

HXR spectrometry has been used to study the dynamics of RE generation process. Energy spectra of RE have been measured. A study of RE energy spectra revealed the generation of electrons with maximal energies up to 7 MeV and characteristic energy 2.5 MeV (Figure 7).



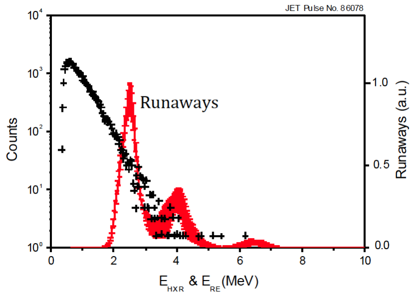


Figure 6. HXR bremsstrahlung measured by different channels of gamma camera. Each channel is characterized by unique angle of inclination to vertical of horizontal plane.

Figure 7 JPN#86078: HXR spectrum and reconstructed REDF at beginning RE stage (t=20.2-22 s)

2D map of HXR emissivity source in Figure 8 is created by a combination of data from two gamma cameras. Taking into account that HXR bremsstrahlung is radiated in direction of RE motion during scattering and it has very narrow forward radiation pattern with angular half-width $\theta \sim {}^{1}/_{\gamma}$, γ–relativistic parameter [5], one can conclude that RE are scattered by ions during one act of scattering and this scattering is by large angles $\geq \pi/2$ (close distance collisions). Analysis of HXR radiation patterns for vertical and horizontal cameras plotted in polar coordinates (Fig. 9) reveal the correspondence of RE energy determined with HXR spectroscopy. Two narrow patterns with $\theta \sim 0.1$ have been detected in the vicinity of q=1.

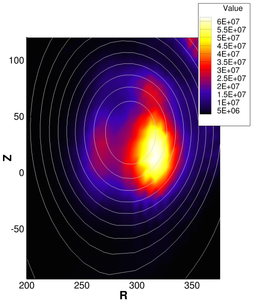


Figure 8. JPN#86078: 2D map of HXR emission sources during RE stage

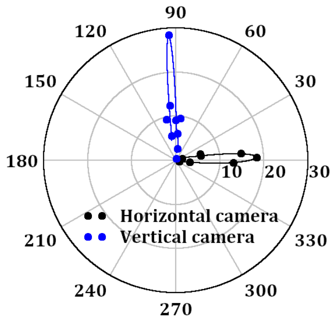


Figure 9. HXR radiation intensity patterns in polar coordinates for vertical and horizontal γ-cameras: pole – is a point of maximum of emission in Fig. 8.

The kinetic instability driven by RE (fan instability) arises due to the anomalous Doppler effect [6]. The magnetized Langmuir oscillations in plasma could be generated if the certain conditions on runaway beam velocity and density are satisfied: $V_{beam} > 3V_{cr}*(\omega_{ce}/\omega_{pe})^{3/2}$, where $V_{cr}=V_{Te}\alpha^{-1/2}$ $(\alpha=E_0/E_{DR})$; and $\nu_{eff} > \nu_e$, where $\nu_e=2.91*10^{-6}\ln\Lambda*n_e Z_{eff}T_e^{-3/2}$ and ν_{eff} is the effective collision frequency, which characterizes the enhancement of collisions due to electrostatic oscillations: $\nu_{eff}\approx\pi^{1/2}\omega_{pe}(\omega_{pe}/\omega_{ce})K(Zeff)*\varepsilon^{-3(Z+1)/16-1.5}\exp\{-1/4\varepsilon-((Z+1)/\varepsilon)^{1/2}\}$.

First analysis shows that this instability is the first candidate to explain intense burst of photo-neutrons and signal from FILD (Fig. 1, time range is highlighted in yellow). This data will be studied more in detail to provide the information on possible methods for destabilization of RE beams.

Summary

- RE generation process was detected on flattop stage of JET discharge using HXR diagnostics and identified. Main parameters of RE generation (critical fields, energies etc.) have been evaluated. Temporal, spatial and energy characteristics of RE generation process were studied.
- HXR spectrometry measured the HXR spectra, and RE with maximal energies up to 7 MeV and mean energy of 2.5 MeV were detected.
- It is found that RE current fraction could achieve half of the total plasma current, while the lower energy electron population (with several tens keV) could carry the other current part.
- Scattering of RE on plasma ions due close distance collisions was identified using the analysis of HXR bremsstrahlung.
- The evidence for kinetic instability (characteristic HXR bursts) has been observed only during plasma discharge ramp-down and significant decrease of magnetic field. Parameter space for instability has been analyzed.

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 under grant agreement No 633053. IST activities also received financial support from "Fundação para a Ciência e Tecnologia" through project UID/FIS/50010/2013. A.E. Shevelev and E.M. Khilkevitch are grateful for financial support from the Ministry of Education and Science of the Russian Federation (Agreement No.14.619.21.0001, 15.08.2014, id RFMEFI61914X0001). The views and opinions expressed herein do not necessarily reflect those of the European Commission."*

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