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ABSTRACT.
Generation of runaway electrons (RAEs) is often observed at disruptions in JET. RAEs are usually detected with the soft and hard X-ray and neutron diagnostics [1]. At the current quench stage a large population of the high-energy RAEs (typically with several MeV) can often create a current plateau achieving sometimes more than 50% of the pre-disruptive plasma currents. For the future reactor-scale devices this phenomenon constitutes a serious problem since the localized deposition of several Mega-Amperes multi-MeV RAEs current to the components of the first wall may cause severe damage to the device [2].

This paper presents recent progress on studies of the disruption generated runaways and their main dependencies on plasma parameters and disruption conditions. The evolution of the primary RAEs [3] generated at the thermal quench and their role in further development of the runaway process has been examined. It is found that primary runaway beam can exist at an early stage of the disruptions even with strong re-arrangement of the magnetic structure. Runaway current plateaus were usually not detected at disruptions with a relatively high electron temperature (T_e~100 eV) immediately at the beginning of the current quench phase. There are indications that auxiliary plasma heating also may affect the creation of continuous plateau, even in cases when hard X-rays and neutron emission have been observed. Data on disruption generated RAEs obtained in JET prior and after divertor installation has been analysed in order to study possible trends for runaway generation during disruptions at the nominal experimental parameters in ITER [4].

1. DISRUPTIONS AND RUNAWAY ELECTRONS

A series of the experiments on major disruptions provoked by intense gas puff, as well as detailed analysis of spontaneously occurring disruptions have been carried out to further understanding of the trends of disruption induced runaway process. Helium, argon and neon were used to achieve the density limit conditions and disruption initiation. Other reasons for disruptions in JET were a consequence of the device operation near instability thresholds on safety factor, plasma pressure or plasma inductance [5]. RAEs generation has been observed in disruptions that occurred in a wide variety of different experimental conditions, namely, various triangularities and elongations, current rise stage, gas puff, VDE, etc.

Figure 1 presents typical examples of disruption induced runaway process. Discharge Pulse No: 58363 (B_0 = 3.2T, I_{pl} = 2.7MA) disrupted due to locked mode (left chart), while disruption in Pulse No: 58603 (right chart) occurred at intense CD_4 puff and **V**ertical **D**isplacement **E**vent. All characteristic features of the runaway process including runaway current plateau (Pulse No: 58363) and semi-plateau (Pulse No: 58603) and intense bursts of the hard X-rays and neutron emissions are presented in this Figure. The evolution of these signals is shown along with the contour plots of soft X-ray emission registered during disruptions by the horizontal camera. Loss of the vertical position control at disruptions resulted in a very fast vertical movement of the runaway current channel with subsequent beam deposition to the plasma facing components. Such an evolution is clearly seen in soft X-ray image (Pulse No: 58363). Spots of soft X-ray radiation and intense bursts of hard X-ray and neutron emission highlight the event of the beam deposition to the bottom (Pulse No: 58363) and top (Pulse No: 58603) parts of the vacuum chamber.

A very limited number of disruptions resulted in relatively long runaway plateaus after divertor installation. For example, runaway current plateau IRA = 0.5 MA was observed during ~0.1s after major disruption at the current rise stage in Pulse No: 46892 (B_0 = 2.9T, I_{pl} = 1.5MA), when the runaway current channel was stabilized by the plasma position control system soon after disruption (Fig.2). In this pulse the fast inward movement of the current-carrying channel was stabilized (curve X), but due to slow vertical displacement (curve Z) the runaway current was eventually lost.

Creation of runaways due to the primary mechanism at disruption thermal quench depending on the quench duration has been modelled in [6]. Also it was suggested that these runaways could serve as seed population for further secondary avalanching process at current quench stage in JET [7]. In this case the evolution of the primary RAEs at strong changes of the magnetic configuration during disruption plays an important role. Analysis of the soft X-ray image evolution has been carried out to investigate this problem. Runaway beam produces an observable soft X-ray image exciting the plasma impurity ions. Contour plot of the soft X-ray emission obtained during disruption in Pulse No: 53784 (I_{pl} = 1MA, B_0 = 3T) highlights the creation of the runaway beam channel at the of the current quench stage following the broadening of the emission profile at disruption (Fig.3). Soft X-ray images of disruptions with higher currents are less observable in early stages due to the higher energy of runaway electrons. In this case runaways can only be detected when they interacting with heavy impurities released from the device wall (bright soft X-rays spots in Fig.1).

In a majority of recent experiments the runaway plateaus were usually not observed at disruptions with a relatively high electron temperature (T_e ~100eV) immediately at the beginning of the current quench phase. This data is in an adequate agreement with the earlier observations made in JET disruptions prior to the divertor installation [8], when the probability of the RAEs generation in beryllium-bounded disruptions was significantly lower in comparison to that in carbon-bounded cases due to higher electron temperature immediately before the plasma current quench, i.e. carbon release during disruption caused much stronger cooling effect in comparison to beryllium. Large number of disruptions has been occurring at the presence of auxiliary plasma heating: Ion Cyclotron Resonance (ICRH), Low Hybrid (LHCD) or Neutral Beam Injection (NBI). Application of the heating can be considered as one of the main reasons for relatively high T_e. The result of disruption data analysis can be formulated as following: if for some reasons the auxiliary plasma heating still has effect on electron temperature during disruptions the probability of the runaway current plateau creation decreases despite the observation of hard X rays and neutron emission (Figures 4 and 5).

Figures 6-8 summarize the recent experimental data on disruption generated runaway electrons in JET with addition of some early information on high-current disruptions prior to divertor installation in JET. In the recent experimental data (pulse numbers after 50000) the highest disrupted currents, at which runaway generation has been observed, were I_{pl} < 3.5MA, while prior to the divertor installation higher plasma currents were 6MA disruptions with 2-3MA runaway current plateaus were obtained. The experimental data on disruption generated RAEs in JET demonstrates fairly linear dependence of the runaway current on plasma current derivative and pre-disruptive plasma current values (Fig.6). This dependence should be considered as essential in studies of operational limits on plasma current at which runaway generation can be expected during disruptions in future larger devices. The increase of operational limits on toroidal magnetic field values obviously leads to enhancement of the confinement of the runaway electrons and runaway current values, respectively (Fig.7). Taking into account stronger dependence of the runaway process on the plasma current values and summarizing the data on runaways observed at disruptions prior and after divertor installation the experimental data on disruptions with and without runaways can be plotted in the Q_{95}-I_{pl}-diagram (Fig.8). This data together with results of numerical modelling suggest that significant runaway currents can be generated in disruptions, which might be occurred at the ITER nominal experimental parameters [4]: $I_{pl} = 15MA$, $n_e = 10^{20}\ m^{-3}$, MHD safety factor (Q_{95}) = 3.

SUMMARY.

Low energy runaway electrons have been detected using soft X ray diagnostic on early stage of disruption, when they have been creating the narrow runaway beam channel.

Relatively high electron temperature ($T_e \sim 100eV$) during disruptions affected the runaway generation rate preventing the creation of long runaway current plateaus.

Application of auxiliary plasma heating in order to slow-down the plasma cooling during disruption can considered as one of the candidates to decrease the runaway be generation efficiency in disruptions.

Increase of runaway currents with increase of the pre-disruptive currents and plasma current derivative together with better confinement of runaways at higher toroidal magnetic fields B_0 suggests significant values of the runaway currents may be generated during disruptions at the nominal ITER operating parameters.

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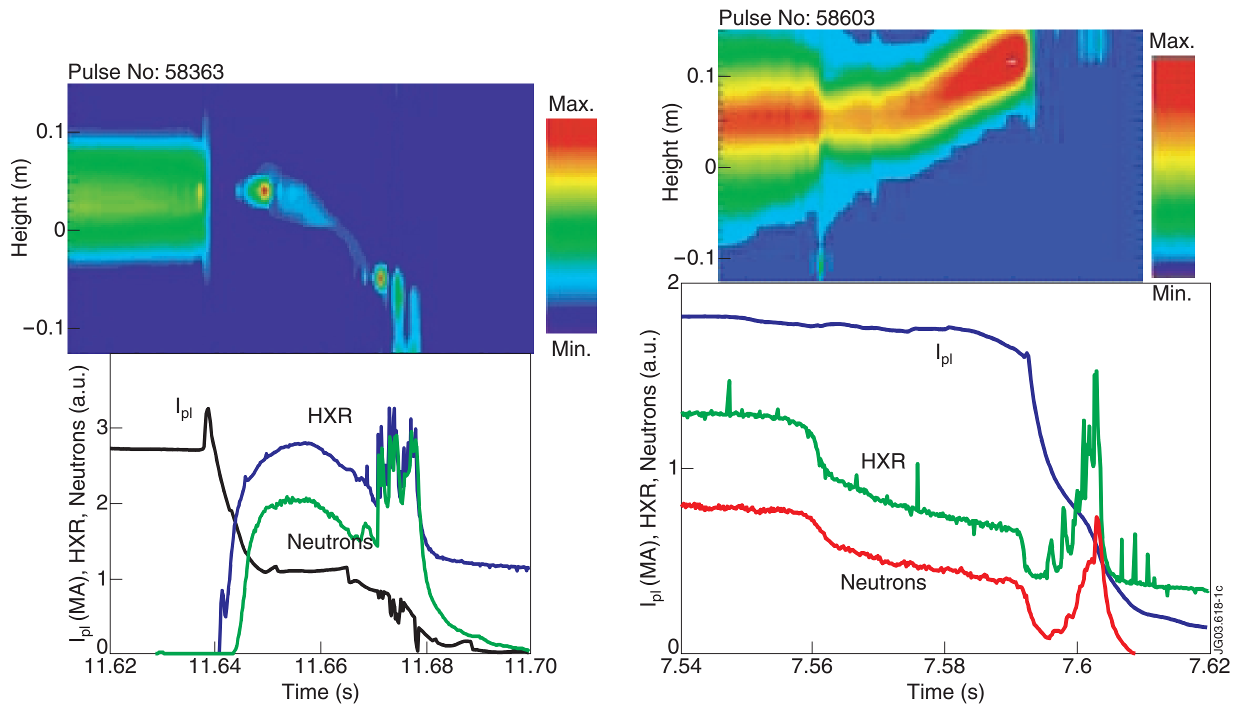


Figure 1: Time-traces of plasma current, hard X-ray (HXR) and neutron emission signals are presented together with soft X ray images of the locked mode disruption in Pulse No: 58363 and disruption with VDE and CD_4 puff in pulse Pulse No: 58603.

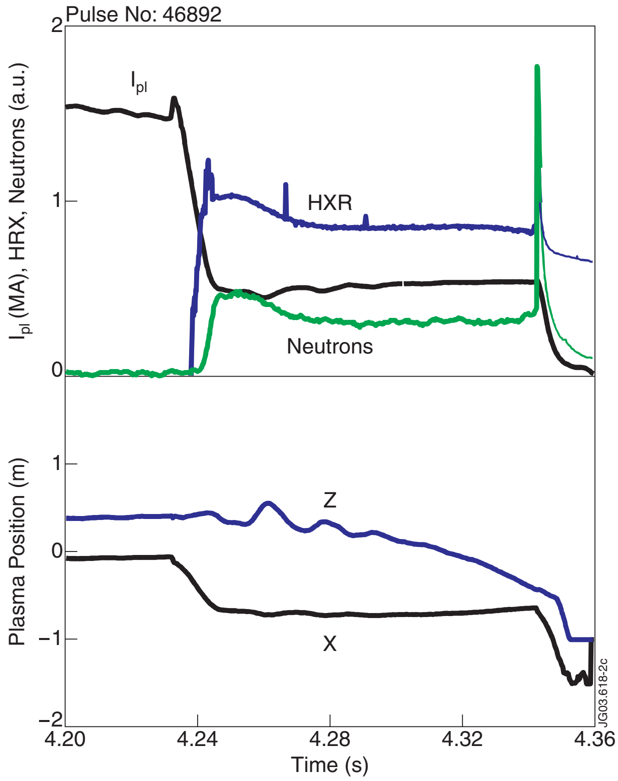


Figure 2: Stabilisation of current channel movement in the spontaneous current-rise disruption.

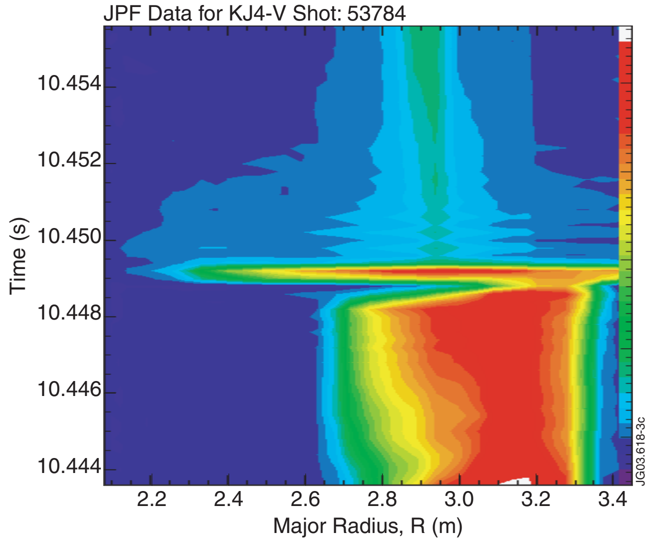
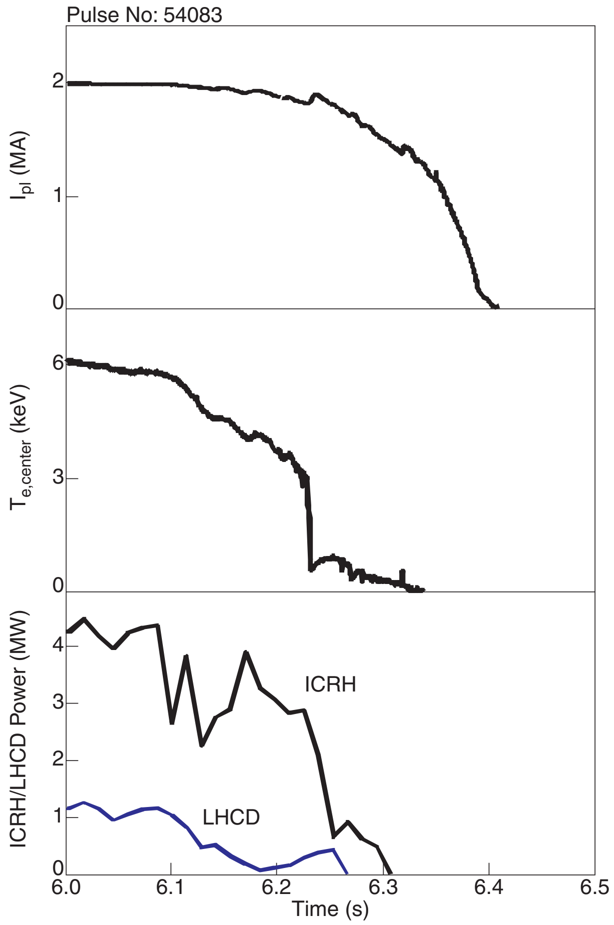


Figure 3: 1 MA disruption in Pulse No: 53784 and post-disruption beam image presented as a contour plot of soft X-ray emission detected by vertical camera.



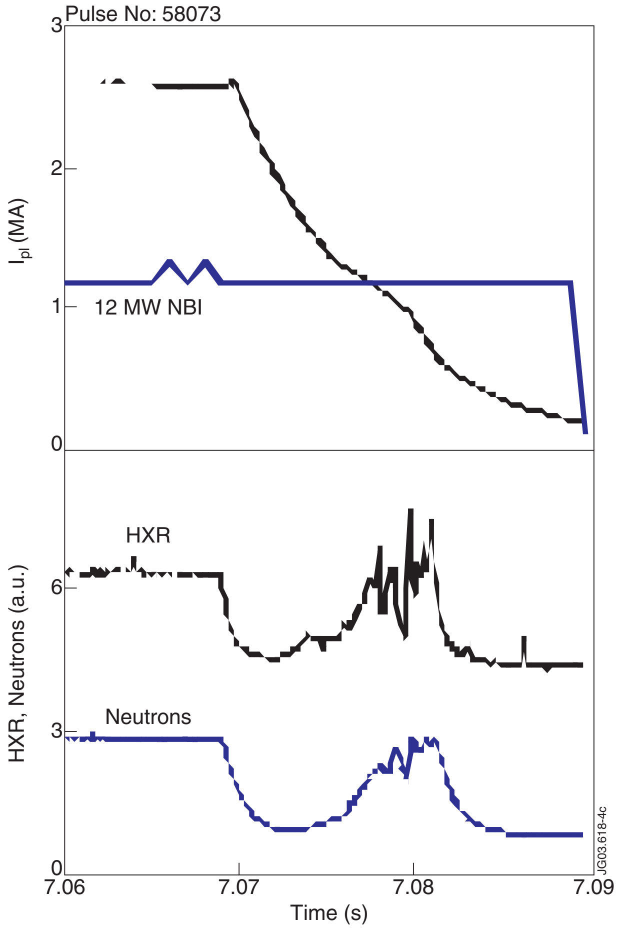


Figure 4: Effect of the auxiliary plasma heating (ICRH, LHCD, NBI) on the Te and runaway generation during disruptions. There is no any HXR or neutrons in Pulse No: 54083 and only small runaway semi-plateau is present in Pulse No: 58073.

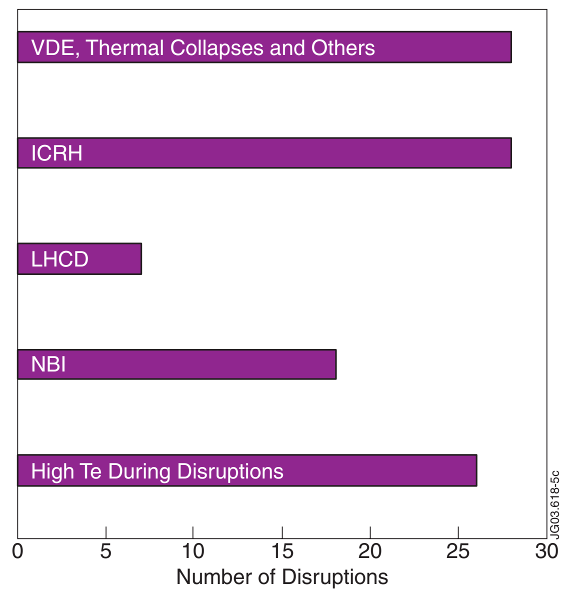


Figure 5: Statistics on 107 disruptions without runaways. Disruptions with presence of plasma heating (in some cases their combination), T_e~100 eV and other known events, like VDEs, "cold disruption", etc are presented.

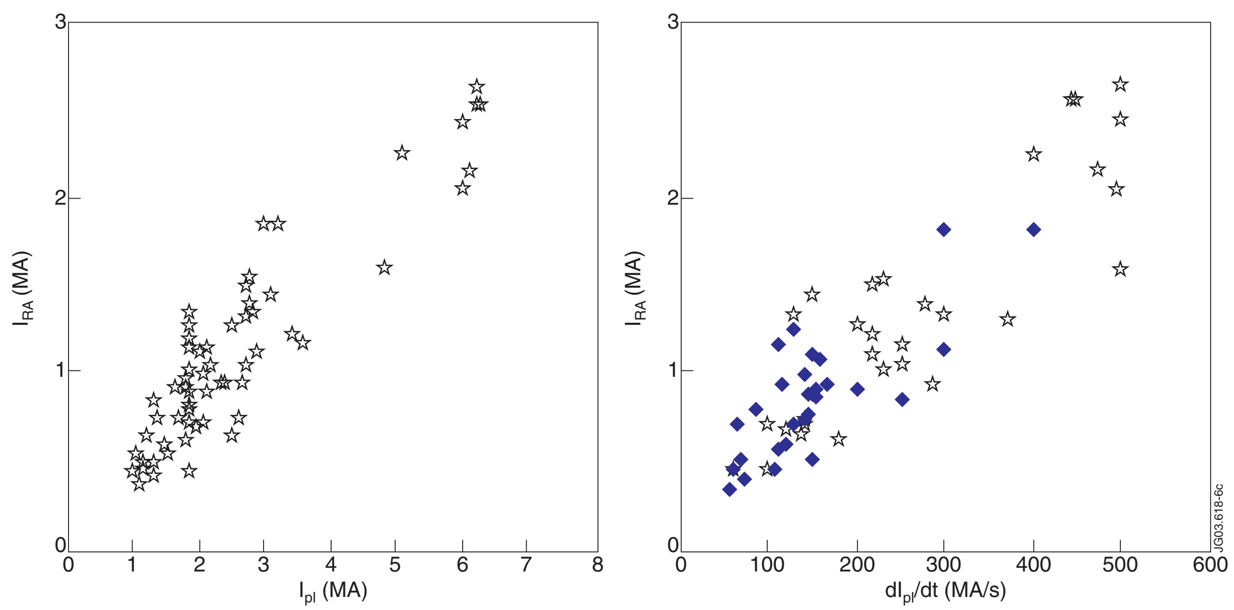


Figure 6: Dependencies of runaway current values on pre- disruptive plasma current values (left) and on plasma current derivative (right) at the quench stage prior (grey stars) and after (blue diamonds) divertor installation.

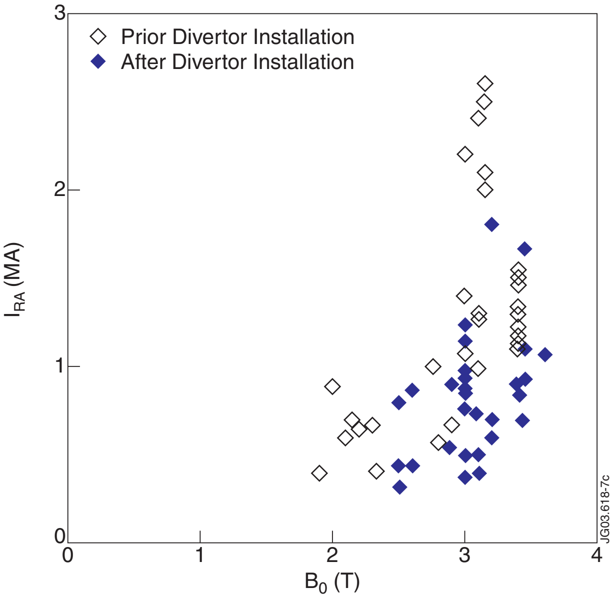


Figure 7: Dependence of runaway current plateau values on toroidal magnetic field in experiments prior and after divertor installation.

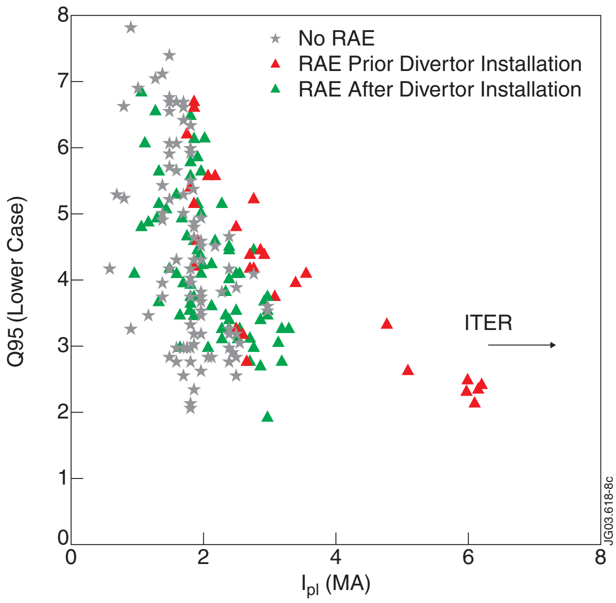


Figure 8. Data on disruption generated runaways and disruptions without runaways in JET plotted on Q_{95}-I_{pl} diagram. Direction to ITER operational parameters: I_{pl} = 15MA, Q_{95} = 3 is indicated by arrow.