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Abstract

Measurements are presented of the properties of the runaway beams generated in JET following disruptions. Radiation is emitted by the runaways, both when they are in flight and when they hit the vessel walls. Because radiation protected soft x-ray cameras were developed for the JET DT campaign, it has been possible to make the first direct observations of the runaway beam in flight from the x-ray line radiation produced by the beam excitation of K-shell vacancies in the metallic impurities of the residual plasma. These observations give clear images of the runaway beam and provide detailed information on its time development, size, position and stability. The current density and q-profile have also been determined. It has been found that there is a delay between the disruption and the start of runaway generation and this offers a possibility of instigating runaway control methods. Detailed determination of the runaway-wall interaction suggests that the runaways have a braided structure.

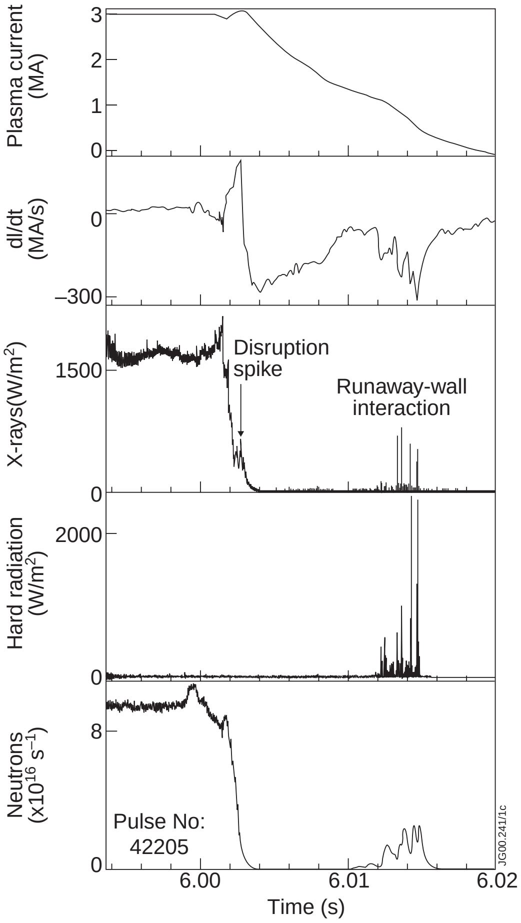
1. Introduction

Tokamak discharges that disrupt often generate a current of runaway electrons, with energies of many MeV, that is a significant fraction of the total ohmic current. Substantial damage can occur when the runaway beam hits the limiters or torus wall, and this may cause serious problems in the next generation of large tokamaks. It is therefore worthwhile to study the runaways in existing machines with an aim of trying to find ways to control or reduce the undesirable effects. The generation of runaways has received considerable theoretical attention, and the general principles are well understood, although there has been little detailed comparison with experimental measurements, partly due to the lack of adequate diagnostics. The prevalence of runaway generation in JET has varied in response to the different machine configurations. In the original configuration, with carbon wall tiles, disruptions were frequently followed by the generation of large runaway currents of more than 1MA that persisted sometimes up to several seconds [1].

Since the carbon tiles were changed to beryllium, and the divertor was introduced, the long runaway tails were no longer found and only a small fraction of disrupting plasmas generated substantial runaway currents. These changes may be due to the lower Z_{eff} with the Be tiles and the poorer vertical stability in the divertor configuration, resulting in a more rapid transfer of the current to the torus walls. A rather complete description of the events leading to a plasma disruption has been established and it seems clear that there is a large, rapid, influx of impurities at the time of the thermal quench. The characteristic signature of the runaways is a plateau that develops on the current decay trace about 10ms after the disruption, followed by a burst of hard radiation when the beam hits the walls (Figure 1). The hard radiation is correlated with rapid the changes in the current.

2. Runaway Generation

During major tokamak disruptions the original hot plasma is rapidly cooled to temperatures of the order of 10eV and this results in the generation of very large electric fields (10 V/m and more) exceeding the Dreicer field, and allowing for the rapid generation of substantial runaway currents. The loss of plasma pressure at disruption causes a rapid inward movement of the current column. In addition, the vertical stability is generally lost, resulting in the current carrying column being rapidly driven into the vessel wall, quenching the current, which by then is partly carried by the runaways. When the runaways are in flight two distinct radiation effects are important: strongly forward peaked bremsstrahlung, and very weak line radiation produced by excitation of residual plasma impurities, principally Cr, Fe, and Ni..



In contrast to the bremsstrahlung, the line radiation is radiated in all directions. The forward peaking of the bremsstrahlung makes it difficult to use for diagnostic purposes [2]. However, the intensity and other properties of this radiation give some information on the beam, and show that there is a delay in JET between the disruption and the generation of the runaways. This delay could be used to instigate runaway control methods. Generally radiation from the runaways is seen only when they interact with the walls, when very high intensities are seen, as a considerable fraction of their energy is dissipated in hard radiation and photo-produced neutrons. This radiation is generally considerably scattered and appears as a large signal in almost all unshielded detectors.

Figure 1: Aftermath of a disruption. The current trace develops a plateau until the runaways hit the wall which produces hard radiation.

3. Runaway Beam Characteristics and Stability

For the JET DT campaign, radiation protected soft x-ray cameras were developed (their sight lines are shown in Figure 2) that were shielded from all but the direct radiation from the tokamak. These view the plasma at 70^o to the current and, following a disruption, therefore detected none of the forward peaked bremsstrahlung. However a weak but very clear image of the beam is seen (Figure 3) and the movement of this image is always very clearly correlated with movement of the current channel determined from the plasma position signals. Detailed examination of the data from many discharges has led to the conclusion that a direct image of the runaway beam is being seen. It is formed as a result of the runaways producing K-shell vacancies in metallic impurities in the residual plasma gas mixture left after the disruption [3]. Calculations show that the expected intensity of this radiation is of the correct magnitude to explain the observed images. These images offer the possibility of determining several new properties of the runaway beam, and its vertical dimensions can be determined as a function of time. The beam is observed to start in a small volume at the plasma centre and grow in diameter from 0.2m to about 0.8m as it moves towards the wall. It always moves radially inwards and is generally also vertically unstable resulting in its interaction with a small region of the inner upper or lower part of the vessel wall. It never occupies more than a small fraction of the total volume. A delay of about 5ms is seen between the negative voltage spike and the start of radiation emmission. The image is extremely smooth, proving that the runaway beam is in a stable configuration until it hits the wall. There is absolutely no hint of beam instability in this period of the beam's development. One way to reduce the damage caused be the runaways hitting the wall would be to try to stabilise their position while they are well centred in the vessel. Their energy would be gradually lost by radiation and this could be enhanced by the admission of high Z gases.

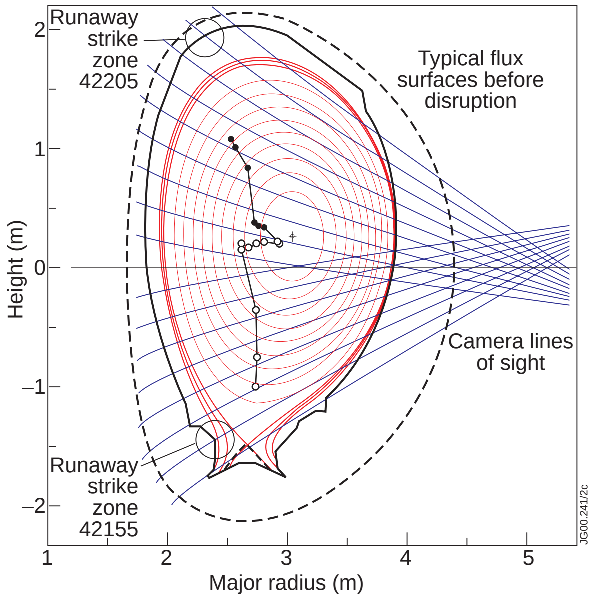


Figure 2: Camera lines of sight. Trajectories of current centre are shown for two disruptions at 2 ms intervals. The areas of wall interaction are indicated.

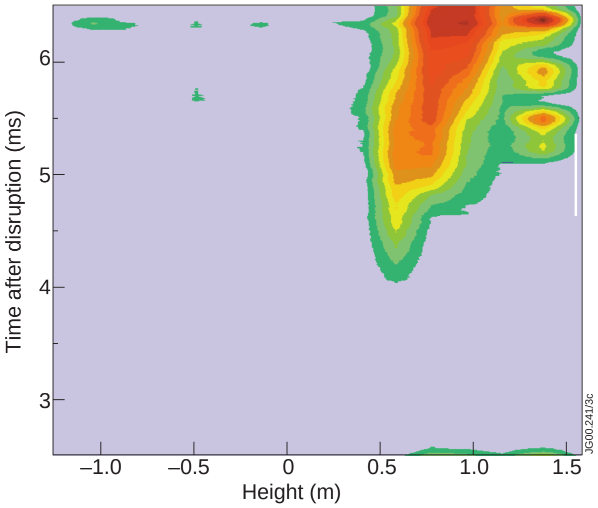


Figure 3: Runaway beam in flight. The motion of the beam, its size, and freedom from instability are seen. (Time taken from start of negative voltage spike).

A variety of different mechanisms for the formation of the beam image has been considered, but the only plausible one is that of K-shell vacancy production by the runaways in the metallic impurity ions of the plasma remnants. The cross-section (σ_z) for this is large and rather independent of runaway energy. The K x-rays will be detected by our cameras with almost 100% efficiency. If the runaway current density is j_r then the power produced by this process per unit volume for mono-energetic electrons is

$$P_K = \Sigma n_r n_z \eta_z \sigma_z v_e E_{Kz} = j_r \Sigma n_z \eta_z \sigma_z E_{Kz} / e$$

where n_r, n_z are the runaway and impurity densities. η_z is the K-shell fluorescence yield (approximately 0.4 for nickel), v_e is the electron velocity and E_{Kz} is the x-ray energy.

4. Safety Factor

The observed signals, S_K, are the integral over a line of sight of P_K , are therefore a direct determination of the line integrated runaway current density.

$$S_K = \int j_r dl \, \Sigma n_z \eta_z s_z E_{Kz} / e$$

If the assumption is made that the radial distribution of the impurities does not vary very greatly and that σ_z may be taken as a constant, then $S_K = K \int j_r dl$ and the current density and hence the q-profile can be found from inversion of the measurements. The beam is too small to obtain a direct profile of the line of sight emission, but a profile has been obtained in some discharges when the beam moves rapidly across a single line of sight. Assuming a circular runaway beam and taking the total current from the plateau value of the current trace, the current density and q-profile have been calculated (Figure 4). q rises from about 0.5 at the centre to 3 at the edge of the beam. This distribution is similar to that found in a normal tokamak discharge and may account for the stability of the beam. A consistent value of the edge q of the runaways has also been obtained from the beam size and current as it starts to interact with the vessel wall

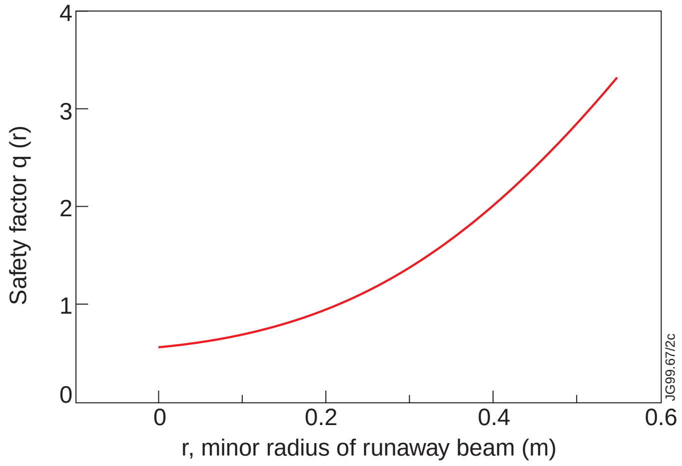


Figure 4: Radial profile of the q-value of the runaway beam.

5. Wall Interaction.

When the runaways hit the wall, high levels of hard radiation are produced. This is detected by Si diodes in the radiation protected cameras that have a direct view of the machine but are shielded to give them a low but adequate efficiency above 1MeV. The measurements with the cameras localise the interaction zone of the runaways as a small region with a poloidal width of less than 10cm of the upper or lower inner vessel wall vessel depending on the vertical movement of the beam (Figure 5). The runaway-wall interaction varies very rapidly with a series of very fast spikes, some with a half width of less than 12μs, within a time window of a few ms.

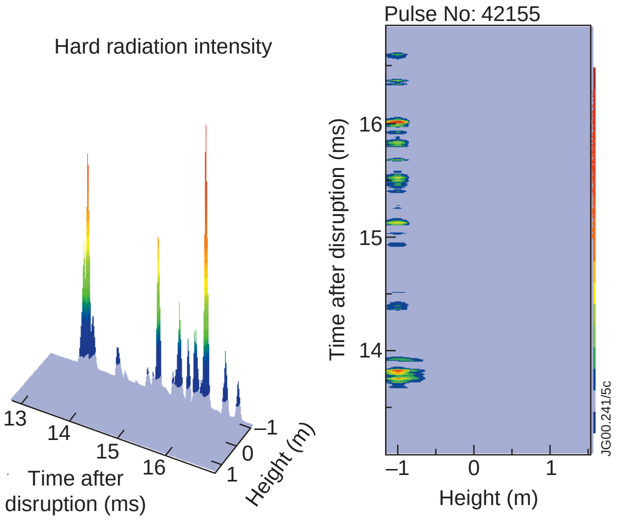


Figure 5: The runaway-wall interaction showing a series of rapid spikes localised on a small area of the lower inner wall. A large signal is seen in only one channel.

These fast spikes have often been ascribed to the development of instabilities in the runaway beam causing ejection of part of it onto the vessel wall. Examination of our data would suggest the much simpler mechanism that the wall interaction is just a consequence of the beam being driven into the wall at a uniform speed. The radial velocity of the centre of the current distribution, determined by magnetic measurements, together with the diameter of the runaway beam, give a wall interaction time during which the entire beam is lost that is quite close to the observed time window. The most probable explanation for the fast spikes is that the runaways have a very uneven spatial distribution on a series of concentric tori. This could be caused by the extreme sensitivity of the production process to the ratio of the applied electric field to the Dreicer field. Also, the production rate may be enhanced on rational q surfaces if avalanche effects are important in the production processes. In addition, the structure of the spikes is not always completely toroidally symmetric, suggesting poloidal runaway current density variations on each flux surface. The runaway beam therefore appears to have a complex ribbon structure associated with the underlying poloidal field structure. This is not inconsistent with the smooth x-ray profiles that are observed as the camera has a resolution of about 12cm and will therefore average over the small-scale features.

6. Summary

- A detailed image of the disruption generated runaway beam has been determined from K-shell x-rays produced by the beam in the residual post disruption plasma.
- The generation of the runaways is delayed 5ms after the negative voltage spike giving opportunities for instigating control measures, possibly by stabilising the runaway column near the vessel centre, or by more drastic methods such as killer pellets.
- The q-profile of the beam has been determined.
- The wall interaction has been shown to be very localised and its rapid variation suggests a braided structure for the runaway beam.

Acknowledgements

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