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Runaway Electron Generation in JET Disruptions

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Abstract

There is concern about secondary runaway electron generation, or runaway avalanche, and the effect it may have on the structure following disruptions in Next Step devices such as ITER. The behaviour of runaways generated during deliberately induced disruptions in JET is examined for evidence of secondary runaway generation.

Introduction

There have been many observations of runaway electron generation resulting from the large electric fields induced during rapid current decays in disruptions of tokamak plasmas [1-7]. This is of concern because of the potential damage to the first wall that such a beam of relativistic electrons may cause on striking a material surface. There are two descriptions of runaway generation usually given: primary generation, in which individual electrons diffuse through velocity space until they exceed the critical velocity, above which their collisional drag is lower than the acceleration due to the electric field [8-12], and secondary generation, in which close collisions between existing runaways and slow electrons knock the slow electrons above the critical velocity leading to an exponential avalanche of runaway electrons [13-16]. There is experimental evidence that such secondary generation of electrons does in fact occur in non-disruptive plasmas [17].

During fast disruptions it is not clear whether the conventional descriptions of runaway generation hold. The cooling of electrons can be very fast, due, for instance, to an influx of impurities [18] and may generate a non-Maxwellian distribution function. The generation of runaway electrons during the cooling process would not then be properly described by the calculations of primary runaway generation because the highly transient nature of the problem becomes important. Once runaways have been generated secondary runaways are expected to be produced but the relative importance of the initial generation and the avalanche process is uncertain. Secondary runaway generation tends to be more important in larger machines with their higher currents. The maximum runaway energy and the number of e-foldings is larger, both depending on the change in poloidal flux during the disruption current decay. Here the decline in runaway current following disruptions in JET is studied for evidence of secondary runaway generation.

Disruption Current Decay

It is primarily in the very fastest JET disruptive current decays that large numbers of runaway electrons are generated since the voltages required to drive runaways are large. A typical fast current decay, taken from a plasma in which a density limit disruption was deliberately induced, is shown in figure 1. This experiment was carried out with the plasma resting on a carbon limiter. After the initial current spike, associated with the negative voltage spike, there is a rapid decay of current down to a level of about one third of its initial value. This residual current is carried by runaway electrons as can be seen from the low resistance as well as the observations of high levels of hard X-rays, non-thermal ECE and photo-neutrons [1,3,5].

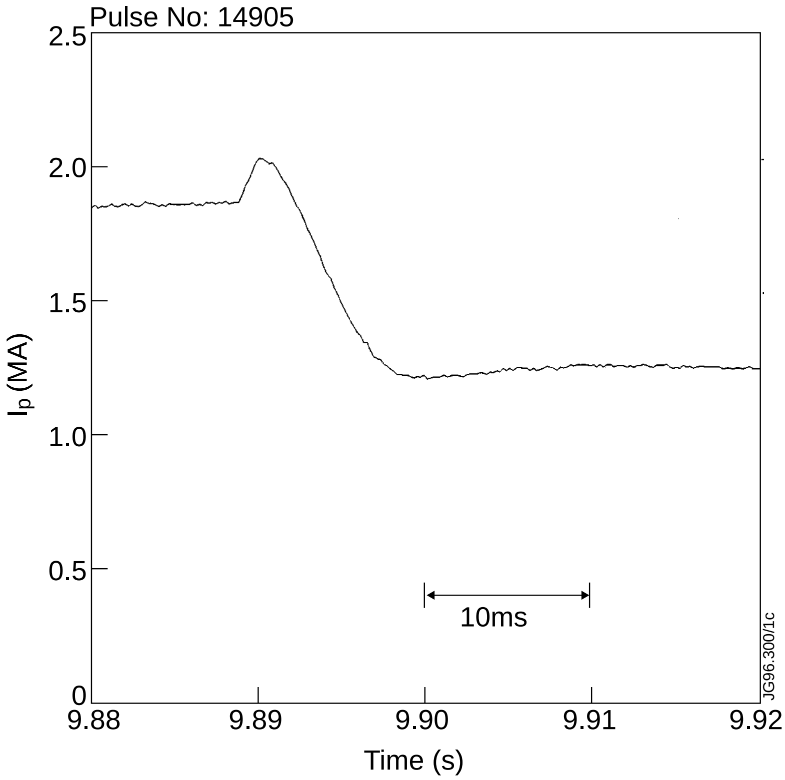

Figure 1: Current behaviour during a deliberately induced density limit disruption. Following the current spike there is a rapid decay of the current down to a plateau level. This plateau current can persist for many seconds and is carried by runaway electrons.

In many cases there is a sudden loss of the runaway current after only a short time, although in other cases, the runaway column is controlled and held in equilibrium for many seconds. Here the interest is in runaway beams which are held in equilibrium in order that the natural decay of the runaway current, once the large driving electric fields induced in the disruption have subsided, can be studied. It is believed in this case that the majority of the runaways remain confined in the current-carrying channel and only a minority are lost from near the edge of the current channel by collision with the first wall.

Before looking in detail at the observed current decay it is useful to consider what might be expected in a plasma where secondary generation has played an important role. If the secondary generation process were important in determining the number of runaway electrons then, below a cut-off given by the maximum energy reached, the energy distribution of runaways should be an exponential, reflecting the exponential avalanche process, (runaways generated at early times are in the minority but have picked up most energy from the electric field). Assuming that energy loss due to collisions, radiation or instabilities can be neglected during the generation of the runaways, the energy distribution would be of the form

$$f \propto \exp(-\frac{\gamma}{2\ln\Lambda})$$

where $\gamma = \frac{1}{(1-v^2/c^2)^{1/2}}$, [e.g. 15]. This exponential energy distribution is rather different from the more uniform energy distribution expected if primary generation has dominated, resulting either from a steady generation rate or from unstable broadening of the energy distribution if the electric field attempts to drive a mono-energetic runaway beam.

Having generated runaway electrons during the disruption, they will lose energy through collisions, radiation, instabilities or interaction with field ripple. It is important here that for relativistic electrons the collisional drag on electrons of the background plasma is independent of momentum [10,19], unlike non-relativistic electrons. In the simple case of a slowing down process which doesn't depend on energy or time, for instance collisional energy loss to a given density of background electrons, the exponential energy distribution expected from secondary runaway generation would give an exponential decay of the number of runaways and consequently of the runaway current. Assuming a normalised energy loss rate, $g = -d\gamma/dt$, constant in time and independent of energy the runaway energy distribution maintains an exponential shape but with an amplitude decreasing with time

$$f \propto \exp(-\frac{gt}{2\ln\Lambda})\exp(-\frac{\gamma}{2\ln\Lambda})$$

where $\ln\Lambda$ is the Coulomb logarithm. The resulting runaway current is then given approximately by

$$I = I_0 \exp(-\frac{gt}{2\ln\Lambda})$$

This assumes the upper limit cut-off to the energy distribution is not important which will be approximately true if the avalanche process dominates the runaway generation. The experimental result to look for, then, is an exponential decay of the runaway current.

Figure 2 shows the runaway current following a deliberate density limit disruption, plotted on a logarithmic scale. After an initial period of 300ms during which the position control of the runaway column is regained, the decay is a clear exponential for 6s, decaying with a characteristic time of 2.5s, until approximately 16s, at which point the control of the runaway beam position is lost. The exponential nature of the current decay appears to indicate that secondary runaway generation has played an important role in the disruption runaway process.

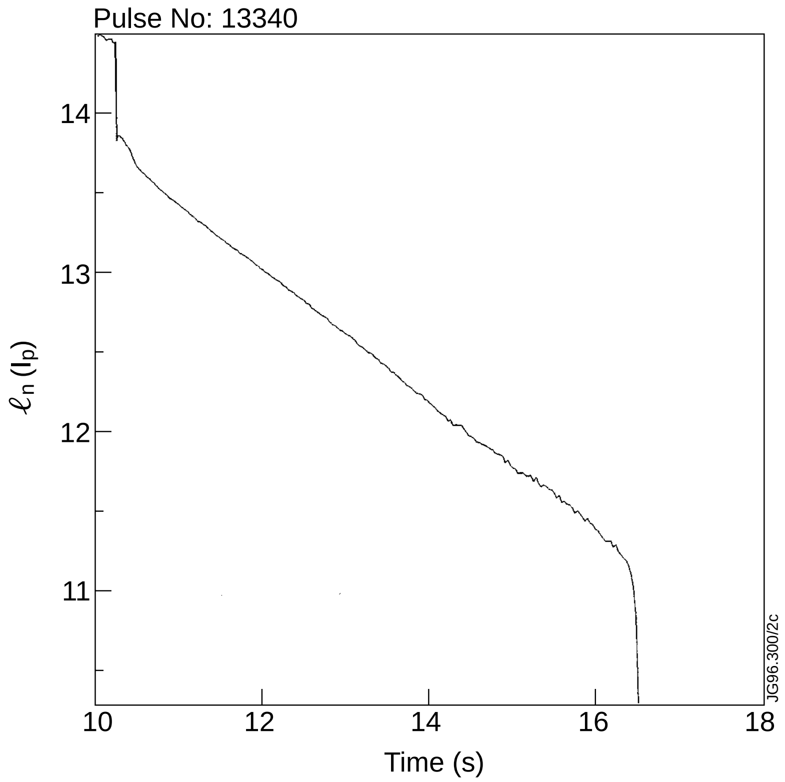

Figure 2: Runaway current decay following disruption in a case where the runaway column was well controlled. The scale is logarithmic showing the exponential nature of the decay up to 16.4s at which point the column becomes vertically unstable. The plasma current is less than 100 kA at this time.

There is an alternative explanation of the exponential runaway current decay, however, if the energy distribution is uniform rather than exponential, but the drag force decays as the runaway current diminishes. This could occur if the runaway beam slows down on a density of background electrons which in turn is decaying with time. The drag term would then diminish with time and, if the runaway energy distribution were uniform up to a cut-off energy, an approximately exponentially decaying current may result. To distinguish between these two possible explanations of the exponential current decay it is necessary to look at the energy of the runaway beam.

To summarise then, the two possibilities are:

1) With a constant drag on the runaway electrons the exponential current decay results from the exponential energy distribution of the runaways set up by the secondary generation process. The energy would decay approximately in proportion to the current because the average energy of the exponential runaway distribution remains approximately constant.

2) With a drag decaying with time resulting, for instance, from a decaying density of background electrons, an approximately exponential current decay results if the initial runaway energy distribution is uniform. The energy in the runaway beam would decay exponentially on a timescale half that of the current decay, as both the number and the average energy of runaways diminish.

The discussion here is concentrated initially on slowing down due to collisions because they provide the irreducible minimum drag force. We will see that the results can be explained by collisional drag so we do not need to consider the additional drag from instabilities. In addition, the energies are too low for synchrotron radiation or strong resonant interaction with the toroidal field ripple [20,21] to be important.

Although the plasma is difficult to diagnose in the period following disruptions, after the initial 300ms period it is possible in this case to determine the line integrated density from an interferometer and the energy from the magnetic measurements. The errors in determining both of these quantities are likely to be larger than before the disruption so the exact values may be in error. We will concentrate first on the general time behaviour and look later at the quantitative comparison with expectations.

Runaway Energy and Electron Density

Figure 3 shows the ‘plasma’ energy inferred from magnetic measurements during the decay of the runaway current. The energy decays exponentially as expected but decays on a timescale of 1.2s, approximately half that of the runaway current (implying that the poloidal beta remains approximately constant). This supports possibility 2) rather than possibility 1). Closer investigation suggests that, as expected, the energy is primarily in the direction parallel to the magnetic field, the diamagnetic beta being close to zero.

Figure 4 shows the electron density measured during the decay of the runaway current. Close to the disruption the density is subject to fringe jumps and the value before 11 seconds is unreliable. Data taken after that time are continuous and consistent. The electron density decays exponentially on a timescale of 2.2s, approximately the same timescale as the runaway current, again consistent with possibility 2) rather than possibility 1).

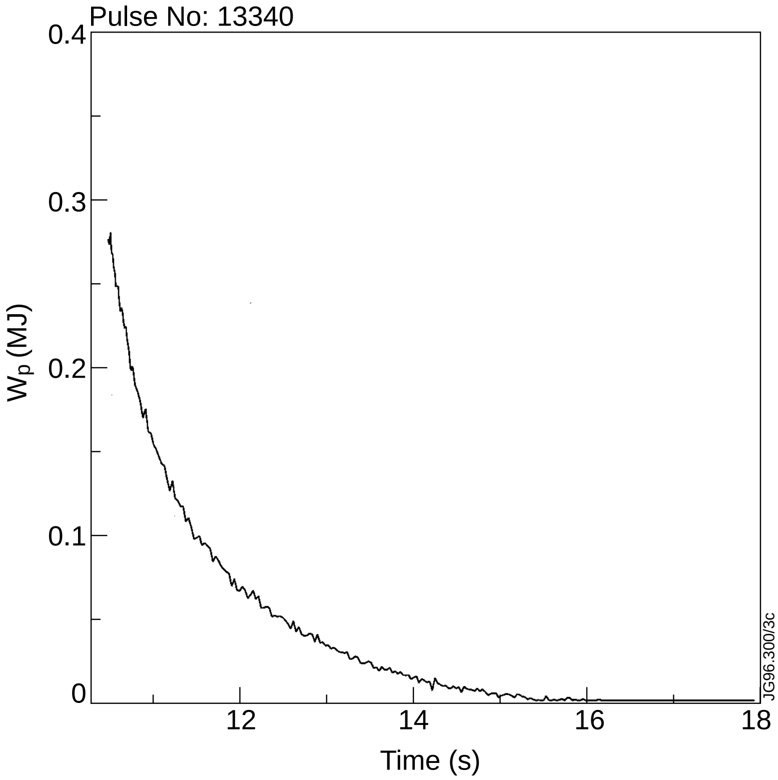

Figure 3: Measured stored energy during the decay of the runaway current for the shot shown in figure 2. The energy is derived from magnetic measurements assuming an isotropic plasma so must be corrected for this case in which the runaway energy is primarily associated with motion parallel to the magnetic field.

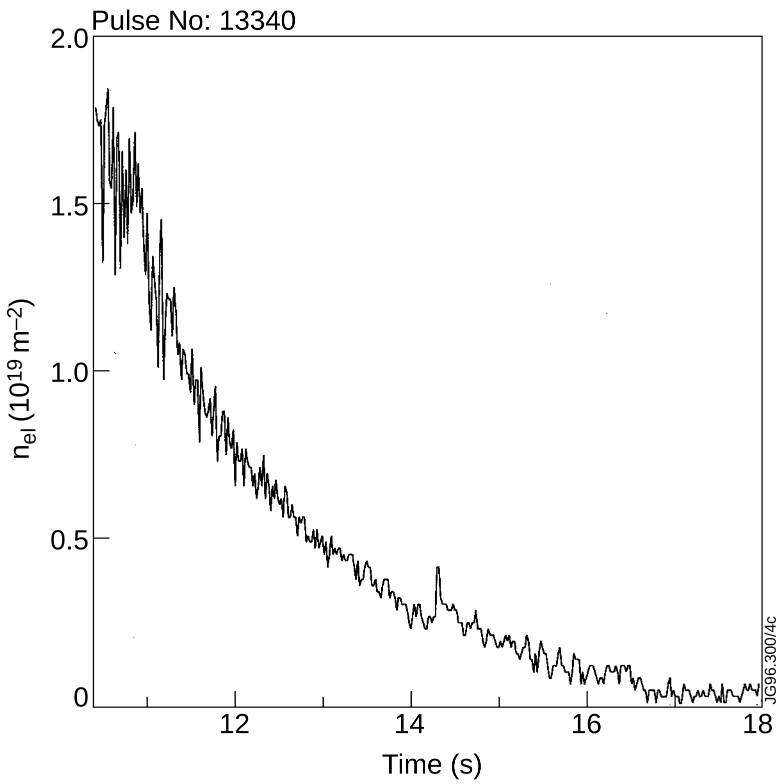

Figure 4: Measured electron density during the decay of the runaway current. The density of bulk electrons is several hundred times higher than the density of runaway electrons.

It appears that the most probable explanation of the observations is that there is a uniform runaway energy distribution and a slowing down rate which is proportional to the background electron density which, in turn, is decaying with time. To check the consistency of this explanation, a runaway energy distribution is derived and then its decay simulated and compared with experiment. The runaway current is assumed to be uniformly distributed over the inner half of the plasma radius, consistent with the inferred value of internal inductance. The path length used to derive an average background electron density from the line integral density is then assumed to be twice the inner half radius.

The initial number of runaway electrons and their average energy derived from the experimental values of current and energy at 10.5s. These are

$$N_r = \frac{2\pi IR}{ec} \text{ and } \gamma = \frac{Wec}{2\pi IRm_0c^2}$$

giving 3.3×10^{17} runaway electrons with an average energy of γ=7.5. A correction factor of 2/3 has been applied to the energy since it is derived assuming an isotropic plasma whilst the runaway energy appears, as expected, to be parallel to the magnetic field. The low value of average energy is interesting since it is substantially less than that expected if secondary runaway generation has dominated, $\gamma = 2 \ln\Lambda$, approximately $\gamma = 40$. It is also much less than the maximum expected energy resulting from free fall acceleration in the large electric fields following the disruption. Given the flux swing of approximately 3Wb, an energy of $\gamma = 90$ would be expected. This discrepancy is discussed in the next section.

To derive the behaviour of a runaway beam under the assumption 2) above, the background electron density is taken to be proportional to the runaway electron density $n_e = \beta n_r$ and the only drag on the runaway electrons is assumed to be due to the collisions with the background electrons with a drag given by $\frac{d\gamma}{dt} = \frac{-n_e}{\alpha}$. The additional parameter of interest is the energy distribution of runaway electrons, f, where $n_r = \int f d\gamma$. Here f is assumed to be uniform, up to the maximum energy, at a value of

$$f = \frac{4{I_0}^2 Rm_e}{a^2e^2W_0},$$

where the initial runaway current and energy are indicated by the subscript 0, R is the major radius and the factor 4 arises from the assumption that the electrons are confined to the central half of the minor radius.

The result of the assumed proportionality between electron density and runaway density is a current that decays exponentially as

$$I = I_0 \exp\left(\frac{-f\beta t}{\alpha}\right)$$

The constants f and β are derived from the experimental observations of initial current, initial energy and initial electron density. The constant α is calculated from standard theory to be 1.7×10^{18} $m^{-3}s$ assuming lnΛ = 20. This gives all the information required to calculate the decay of the runaway current, runaway energy and electron density. Figure 5 shows the result of this calculation compared with the experimental observations. The main point of interest is that the timescale for the decays is approximately correct because this is fixed by the initial values as well as the assumption that the plasma is confined to the inner half radius. The very close agreement between the calculated and observed timescales is coincidental since several of the quantities used in the calculation are uncertain, particularly the width of the runaway beam. Nonetheless the agreement on timescales suggests that the runaways are indeed losing energy primarily as a result of collisions with background electrons. It is of further interest to note that no transport of the runaway electrons over the 6 second period studied has been included, the runaways appear to slow down rather than being lost by transport processes. There is also no need to invoke the additional losses that would be associated with a large density of neutral particles within the plasma.

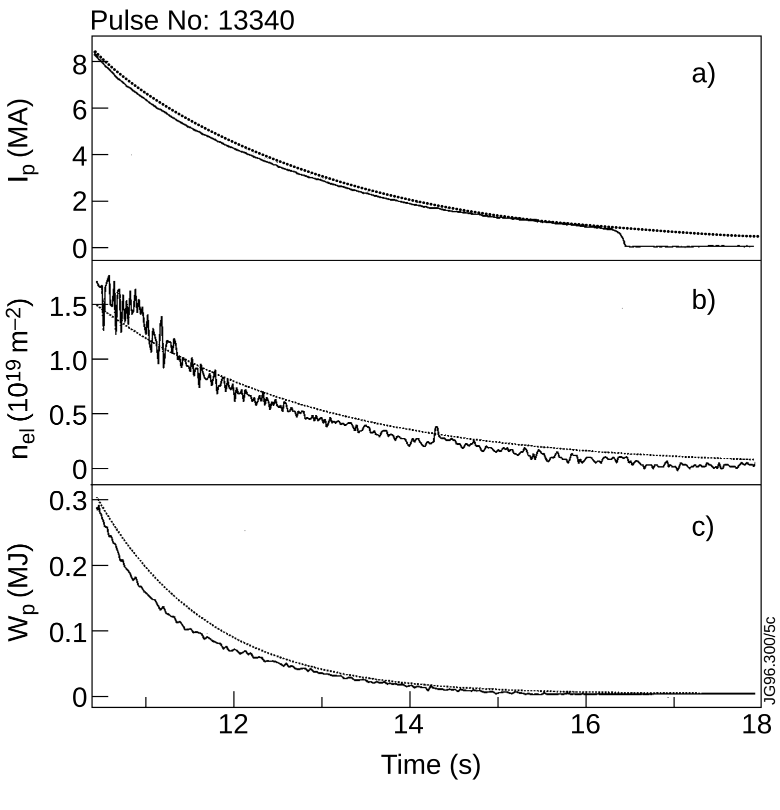

Figure 5: Comparison between measurements and calculations which assume a uniform runaway energy distribution slowing down on the background electrons.

a) Runaway current.

b) Line integrated electron density.

c) Stored energy.

In each case the observations are shown by solid lines whilst the calculations are shown by dotted lines.

Initial Phase of Runaway Current

Although the decay of the runaway current and energy from 300ms after the disruption appears to rule out the importance of secondary generation, there remains the question of what happened in the first 300ms, in particular why the average energy of the runaways is so much lower than would be expected from free fall in the large electric field. There are several possible explanations of the behaviour. For example the energy could have been lost to (a high density of) background electrons in the early phase, or radiation losses could have played a role, particularly if there were scattering of energy into the direction perpendicular to the magnetic field as a result of instability of the runaway column. Alternatively the runaway current studied here may not have been generated at the time of the disruption but only after a significant flux swing had already taken place. This could arise if the initial density were very high but fell rapidly during the current decay.

The loss of energy from synchrotron radiation as the runaways orbit the tokamak is not important at the energies considered here, however if there is scattering of energy into the perpendicular direction, arising from instabilities driven by the anisotropic nature of the electron distribution function, the power loss is increased substantially because the Larmor orbit is much smaller than the major radius. The resulting drag is given approximately by $\frac{d\gamma}{dt} = \frac{-B^2\gamma^2}{5}$. At the energies expected from free fall acceleration in the disruption electric fields, the drag is very large leading to a slowing down from γ of 90 to 30 in 15ms at 3T. Because this slowing down process is dependent on γ, the low energy runaways are little affected, reducing the energy of runaways without substantially reducing the total number. A candidate instability for this mechanism is the anomalous Doppler instability [23] which can be stabilised by collisional damping if the electron temperature is sufficiently low [24]. It is possible that the runaway column is unstable shortly after the disruption but is stabilised later, during the time studied here, because the electron temperature is lower. If this were the case, the observation that the distribution function is not as predicted by secondary generation would be explained. Even if the runaway distribution were initially an exponential function of energy, this would be considerably altered by an energy loss process which acted preferentially on the higher energy electrons.

The loss of energy due to collisions with background electrons could explain the difference between the free fall energy and the observed energy if the electron density immediately after disruption were approximately 4×10^{20} m^{-3}. Whilst this value of density seems high, it is consistent with the large density increase expected from a rapid cooling due to an impurity influx [18]. The measured density is unreliable close to the disruption in this case although substantial density increases observed during disruptions have been reported [22]. This does not seem a good explanation of the early phase, however, since if the electron density were this high, the generation of runways would probably be suppressed altogether.

The possibility that the runaways were generated only during the later part of the initial disruption current decay would resolve the problems both that the energy is low and that secondary generation has not played an important role, since both depend on the total flux swing experienced by the runaways. This would arise if the electron density were very high immediately after the disruption but decayed more quickly than the plasma current, allowing the generation of runaways only 5-10 ms after the disruption. There is evidence that for the disruption discussed here the runaway generation is delayed, as shown in figure 6 taken from [5]. Following an initial burst of hard X-rays, there is an increase of hard X-ray emission which persists and reflects the runaway behaviour. The hard X-ray emission, however, rises only after half of the initial current decay has already taken place. The delayed generation of the runaways is the most plausible explanation of the observations.

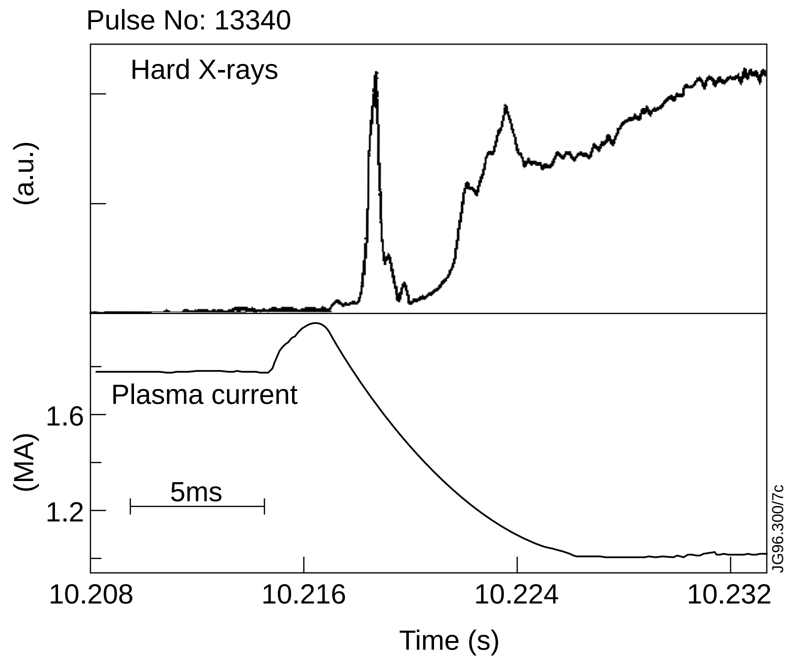

Figure 6: After an initial burst of hard X-rays there is an increase to a level that persists reflecting the runaway behaviour. The second increase begins approximately halfway through the disruption current decay.

Conclusions

The secondary generation of runaway electrons, predicted to lead to a runaway population increasing exponentially with time, may be a serious problem following disruption in a Next Step device such as ITER. A substantial fraction of the current could be transferred to a beam of runaway electrons which, if not well controlled, may lead to localised heating of the first wall.

The exponential runaway energy distribution predicted by secondary generation of runaways is expected to lead to an exponential decay of runaway current when the driving term is removed, on the assumption that the drag is a constant.

The observed decay of current carried by controlled runaway beams following disruption in JET is indeed an exponential decay but closer investigation shows that this is due to a decaying damping force, apparently as a result of a decaying density of background electrons.

The combined evidence of the decay of current, energy and electron density suggests a uniform, rather than exponential, energy distribution of the runaway electrons.

In situations where runaway avalanche is likely to be important in Next Step devices, that is following a disruption, there is no evidence that avalanche has occurred. It is suggested that this may be because instability of the anisotropic electron distribution function has masked the effect or, more likely, because the runaways were not generated immediately at the disruption because the electron density is too high. Only once the density has fallen are the runaways generated, so leading to lower runaway energies and little runaway avalanche. This would lead to a much less significant problem in a Next Step device and merits further investigation.

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