JOINT EUROPEAN TORUS

JET-P(89)69

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Preprint of a paper to be submitted for publication in
Nuclear Fusion

NEGATIVE VOLTAGE SPIKE IN TOKAMAK DISRUPTIONS

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Abstract

In JET disruptions the negative voltage spike appears after the instabilities with which it is usually associated. This unexpected behaviour is explained in terms of an initial trapping of the poloidal flux and its subsequent release, triggered by a sudden cooling of the plasma.

Introduction

A characteristic feature of tokamak disruptions is the appearance of a large negative voltage spike at the surface of the plasma. This negative toroidal voltage is due to an expulsion of poloidal flux caused by a flattening of the current profile. It is reasonable to believe that this flattening of the current is associated with current gradient driven instabilities which also cause the sudden disruptive energy loss. The surprising observation on JET is that the negative voltage spike occurs after the fall in plasma temperature. This is illustrated in Fig.1 which shows the fall in central electron temperature followed by an increase in the plasma current and the associated negative voltage spike. This behaviour is explained here in terms of a model which introduces two new elements to the usual description. The first explains the absence of a prompt voltage response to the instability, and the second explains the later appearance of the voltage spike at the time of the final temperature fall.

It is assumed that the first phase of the observed temperature fall, in which the central temperature drops to 500 eV in a few milliseconds, represents the energy loss caused by the observed mhd instabilities. The temperature profile is observed to become flat across three quarters of the minor radius in this phase. It is then suggested that the associated current rearrangement does not extend to the plasma edge and that the resulting negative voltage is shielded by the electrically conducting outer region of the plasma. This traps the poloidal flux inside the plasma and prevents any voltage change outside the plasma.

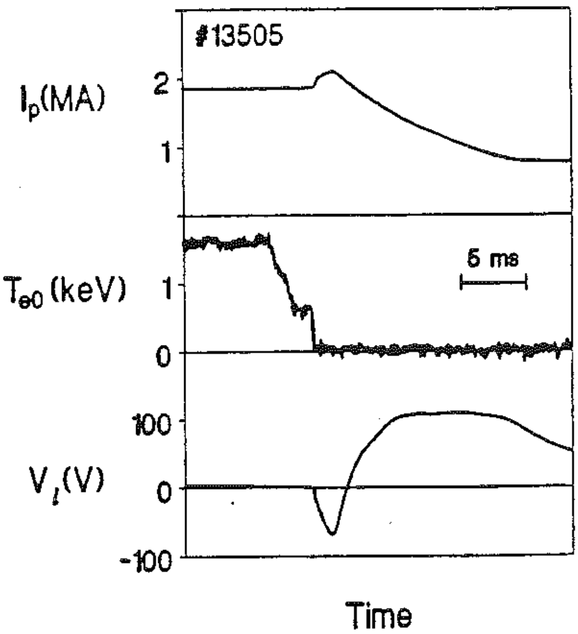

Fig. 1: The temperature drop in the disruption occurs in two phases. The positive current and negative voltage spikes appear only after the second phase.

In the second stage this trapped flux is released by the sudden collapse of the electron temperature to a very low value. This temperature collapse is consistent with earlier studies on JET which attribute the sudden increase of the plasma resistance at the disruption to intense cooling by impurity radiation [1].

The assumption that the current rearrangement occurs in the first phase derives from the conception that it is related to tearing modes. In the conditions existing in the plasma, the characteristic growth time of such instabilities is a few ms. There is no direct evidence against the possibility that the current flattening occurs in the very rapid second phase ($\sim$ 200μs) but the rapidity of the process would then be difficult to explain and a separate reason for the temperature flattening of the first phase would be required.

<u>The Conventional Analysis</u>

Since there is often confusion about the electromagnetic behaviour underlying the conventional model it might be useful first to outline the basic theory for this case.

In JET the voltage is measured at the vacuum vessel and, in the simplest approximation, its transient behaviour is described by the equation

$$V = - L_v \frac{d}{dt} (I_p + I_v)$$

where L_v is the effective inductance of the vacuum vessel, and I_p and I_v are the plasma and vacuum vessel currents. The vacuum vessel current is equal to V/R, where R is the vacuum vessel resistance, and so the voltage is related to the plasma current through the equation

$$V = - L_v \left(\frac{dI_p}{dt} + \frac{1}{R}\frac{dV}{dt}\right)$$

and is therefore given by

$$V = - R\, e^{-(R/L_v)t} \int_o^t e^{(R/L_v)t'} \frac{dI_p}{dt}\, dt' \qquad (1)$$

where t is the time from the onset of the plasma current change.

It is clear from Eq.(1) that the observed negative voltage requires an increasing plasma current and this, of course, is consistent with the observations as seen from Fig.1.

The current behaviour itself is best understood in terms of the internal magnetic energy of the plasma. Tearing instabilities flatten the current profile but, unlike a purely diffusive flattening, the energy released is not entirely dissipated in ohmic heating. Part of the energy released is taken up in the observed increase in plasma current. On a short timescale the magnetic field outside the vacuum vessel is unchanged and the increase in plasma current is given by the energy equation

$$\frac{1}{2} L_p \frac{dI_p^2}{dt} = - f \frac{1}{2} I_p^2 \frac{dL_p}{dt} \qquad (2)$$

where L_p is the effective plasma inductance and f is the fraction of the released energy which is not dissipated resistively. Thus we see how the flattening of the current profile leads to a current increase and hence to a negative voltage outside the plasma.

The Flux Trapping

We now return to the experimentally observed behaviour to see how the appearance of the negative voltage might be delayed. This delay can be understood if the instability driving the current re-arrangement is restricted to an inner region of the plasma. In fact such behaviour is seen in simulations [2,3]. In this case the outer region of the plasma will act as an electromagnetic shield, the highly conducting plasma allowing no immediate change in the poloidal magnetic field.

What happens is that the current profile in the inner region is flattened and the energy so released leads to an increase, δI, in the total current flowing in this region. This internal process is analogous to that represented by Eq.(2) and takes place on a timescale of the order of a millisecond. The behaviour in the region <u>outside</u> this re-arrangement is resistive and is governed by the diffusion equation

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial}{\partial r}\left(\frac{\eta}{\mu_o}\frac{1}{r}\frac{\partial}{\partial r}(r\,B_\theta)\right) \qquad (3)$$

where B_θ is the poloidal magnetic field and η is the plasma resistivity. The inner boundary condition for B_θ is essentially $\delta B_\theta = \mu_o \delta I/2\pi r_s$ where r_s is the radius at the separation of the two regions. The temperature of the plasma before the final collapse is typically 500eV and taking $Z_{eff} = 3$, the resistive scale- length, $(\tau/\mu_o\sigma)^{1/2}$, for a time of 1 millisecond is only $\sim$ 1cm. Thus the solution of Eq.(3) for the change in B_θ implies a strong shielding effect with a rapid radial decay of δB_θ. This in turn implies a negative current layer of magnitude δI at the boundary between the two regions. The change in the current distribution is illustrated in Fig.2.

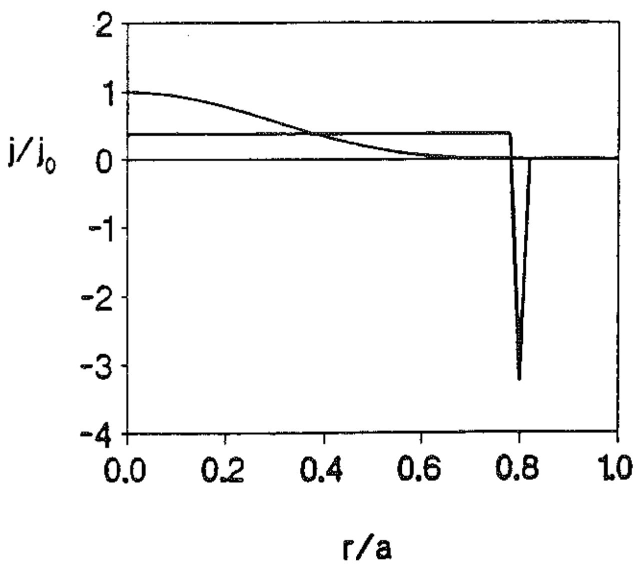

Fig. 2: Flattening the current density profile over the inner region results in an increase in the total current in this region and induces a negative current layer outside.

Thus we see that the flux expelled from the inner region is trapped within the plasma and will not immediately appear at the plasma surface. Since $E = \eta j$, the negative current sheet carries a negative voltage. We can make a rough estimate of the time for this negative voltage to escape from the plasma. If we take the distance of the negative current layer from the plasma surface to be (say) d = 20cm, then the diffusion time, $\mu_o \sigma d^2$, in a 500 eV plasma is more than a second and this is a thousand times longer than the duration ($\sim$ ms) of the disruption process. The negative voltage is therefore effectively frozen inside the plasma.

Release of the Negative Voltage

The delayed but abrupt appearance of the negative voltage spike at the surface of the plasma (Fig. 1) can be explained if the temperature of the plasma is suddenly reduced to a low value, causing a large increase in its resistance. This suggestion is made quite plausible by the evidence from fast disruptions on JET [1]. Although the ECE temperature measurement shown in Fig.1 is not reliable at very low temperatures, a number of experimental results are consistent with a rapid cooling of the plasma brought about by a sudden influx of impurities. An analysis of these events [4] indicates that the electron temperature falls by two orders of magnitude (to $\sim$ 5eV say) in $\sim$ 300μs. Since the resistive diffusion timescale is proportional to $T_e^{3/2}$, the previously estimated timescale of around a second (for 500eV) is now reduced by a factor of a thousand to around a millisecond.

This is seen to agree with the behaviour shown in Fig.1 where the negative voltage spike starts immediately after the observed drop in temperature. The timescale for the observed spike is affected to some extent by the vacuum vessel (resistive time $\sim$ 5ms) but the observed width of $\sim$ 2ms is clearly consistent with the proposed sequence of events.

A more quantitative description of the behaviour has been obtained using a one-dimensional simulation as described below.

Simulation

We take the initial current profile to be $j = j_o(1-r^2/a^2)^6$ corresponding to a safety factor ratio $q_a/q_o = 7$. It is then assumed that instabilities flatten this current profile over the inner 80% of the plasma radius. Taking the poloidal magnetic field energy to be unchanged (f=1 in equation 2) leads to an increase in current in the inner region of approximately 50%. Because of flux trapping by the unaffected outer region this increase in positive current generates an equal negative skin current at the edge of the inner region as shown in Fig.2.

We now follow the evolution of the voltage ($2\pi RE$) inside the plasma using Maxwell's equations combined with Ohm's law in the diffusion equation

$$\frac{\partial V}{\partial t} = \frac{\eta}{\mu_o} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r}\right).$$

The resistivity immediately following the current flattening is $10^{-7}\Omega m$. After 3 ms the resistivity is increased to $10^{-4}\Omega m$ to model a sudden fall in electron temperature to 5 eV. The vacuum vessel is modelled by a thin shell with an effective resistance of 0.3 mΩ and inductance of 1.4 μH.

Figure 3 shows the assumed temperature behaviour and the resulting time development of the simulated plasma current and the loop voltage at the vacuum vessel. It is seen that the anticipated behaviour is reproduced. The negative skin current diffuses out of the plasma on a millisecond timescale and the loss of this negative current leads to a corresponding increase in the total plasma current together with its associated negative voltage spike.

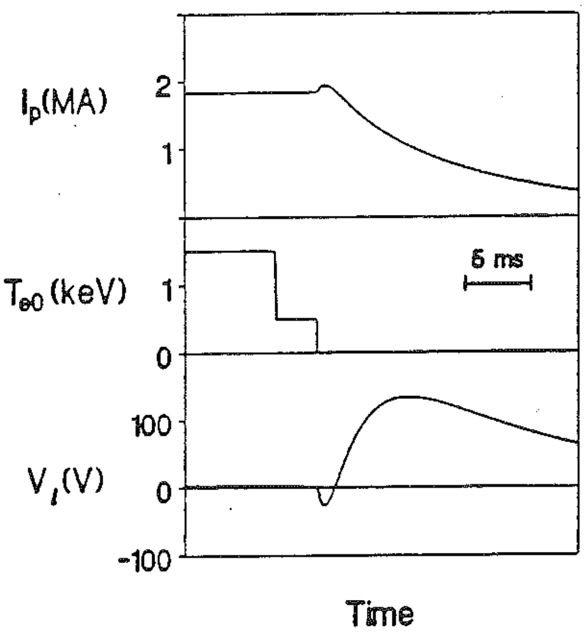

Fig. 3: Simulation of the plasma current and vessel loop voltage shows the same features observed in the experiment.

These results can be compared with the experimental behaviour of the 1.8 MA (q_a = 4.5) disruption shown in Fig. 1. It is seen that the basic features are reproduced in the simulation, but that the simulated voltage and current spikes are too small by a factor of two.

We have identified two processes which have been neglected and it seems likely that a correct treatment of these would remove the discrepancy. Firstly the current flattening is taken to be a single discontinous event whereas in reality it will be a continuing process, and secondly the substantial runaway electron current appearing at the disruption will have a significant effect on the current diffusion. These processes have not been included in the simulation presented here because of the uncertainty as to their precise form and resulting arbitrariness of any model used to represent them.

Conclusion

We have proposed an explanation of the experimental observation that in JET disruptions the negative voltage spike appears after the energy loss. This result was surprising because the negative voltage spike was expected to be coincident with the instabilities which give rise to the energy loss, and therefore to appear at an earlier time than observed.

It is suggested that a negative voltage does indeed arise at an earlier time but that, together with its associated negative current, it is trapped inside the highly conducting plasma. A subsequent catastrophic cooling reduces the temperature to a few eV. The associated very large increase in resistivity leads to rapid diffusion of the negative voltage and allows it to appear at the surface of the plasma immediately following the temperature collapse.

Acknowledgements

The authors are indebted to Drs. D.J. Campbell and J. Snipes for helpful discussions and careful examination of the experimental results and to Dr. M. Keilhacker for suggesting improvements to the paper.

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