JOINT EUROPEAN TORUS

JET–P(91)10

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* *See Appendix 1*

Preprint of Paper to be submitted for publication in
Nuclear Fusion

IMPURITY INFLUX MODEL OF FAST TOKAMAK DISRUPTIONS

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ABSTRACT

The high plasma resistance observed in tokamak disruptions with a very rapid current decay is here attributed to cooling by a rapid influx of neutral atoms from the wall or limiter. It is suggested that this influx proceeds as a narrow front propagating from the edge to the centre of the plasma. The result of such a cooling, with carbon as the limiting material, is a drop in temperature to ~ 5 eV and an increase in electron density by a factor ~ 5.

1. INTRODUCTION

It is often said that disruptions in tokamaks are due to a loss of energy confinement brought about by the turbulent destruction of magnetic surfaces, [1] and that the increased impedance associated both with the reduced temperature and the turbulence itself then results in a rapid current decay. Such a model describes disruptions in many tokamaks reasonably well [2,3], but an analysis of disruptions with fast current decays on JET shows that this model is not adequate to explain the observed results. We consider a fast disruption to be one for which the current decay time,

$$\tau_D \lesssim 0.02\, a^2\, s \quad ,$$

where a is the plasma minor radius.

In fast disruptions in JET the energy loss occurs in two stages, occurring on different timescales, as shown in Figure 1. The disruption is preceded by the growth of magnetic fluctuations and it seems reasonable to attribute the first stage to enhanced losses through an ergodised magnetic field. However we find that the second stage, which is followed immediately by the current decay, is best explained by a completely different physical process.

We shall here give a description of the cooling and subsequent current decay which is based on a sudden influx of impurity atoms. In this process the temperature is reduced to a few eV as the neutral atoms are ionised. This low temperature implies a very high resistance and is consistent with the rapid current decay. In addition this model predicts an extremely high level of impurity radiation, typically several GW, and this is what is observed in the experiment.

Whilst the proposed model is consistent with the experimental observations it has to face a fundamental problem, that of providing a mechanism whereby the impurities can enter the plasma on the very short timescale of hundreds of microseconds. A carbon atom entering the plasma is rapidly ionised and then trapped on the magnetic field. A typical penetration length is 1 cm. Without a possible mechanism for the flux of impurities across the whole plasma the impurity cooling model would be subject to serious doubt. The proposed answer to this problem is that the plasma is quenched by the collective effect of impurities rather than being infiltrated by individual atoms. It is suggested that the impurities move into the plasma following a narrow cooling front. Ahead of this front is pure high temperature plasma, behind it is cold impure plasma. It is shown that such a front can propagate on the required timescale.

2. TEMPERATURE RESULTING FROM LOSS OF CONFINEMENT

Neglecting the power lost by radiation, the steady state electron temperature can be calculated by solving the 1-d power balance equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rn\chi\frac{\partial T}{\partial r}\right) = -\frac{E^2}{\eta} \quad , \tag{1}$$

where χ is the thermal diffusivity, E the toroidal electric field and η the resistivity. The turbulent magnetic field following the disruption gives rise to an enhanced diffusivity, and to calculate the steady state temperature we use the form

$$\chi = \left(\frac{\tilde{B}}{B}\right)^2 \chi_{\parallel} \quad , \tag{2}$$

where $\chi_{\parallel}$ is the parallel thermal diffusivity, B is the equilibrium magnetic field and $\tilde{B}$ characterises the strength of the radial field perturbations. Equation 2 is valid provided the plasma becomes sufficiently collisional that the electron mean free path along the field lines is much less than the connection length, qR. This condition is satisfied in JET provided the temperature falls below 200 eV.

The expressions used for $\chi_{\parallel}$ and η are those given by Braginski [4] and Spitzer [5]. For a plasma with $Z_{eff} = 3$

$$\chi_{\parallel e} = \frac{6T\tau_e}{m_e}$$

and

$$\eta_{\parallel} = \frac{0.4m_e}{ne^2\tau_e}$$

where the electron collision time is

$$\tau_e = 3(2\pi)^{\frac{3}{2}} \frac{\varepsilon_o^2 m_e^{\frac{1}{2}} T_e^{\frac{3}{2}}}{n_i Z^2 e^4 \ln\Lambda}$$

A good approximation to the solution of equation 1 is obtained by rewriting the equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rT^{\frac{5}{2}}\frac{\partial T}{\partial r}\right) = -\beta\frac{T_o^2}{a^2}\, T^{\frac{3}{2}}$$

where

$$\beta = \frac{a^2\, E^2}{\chi_o\, \eta_o\, nT_o}\left(\frac{B}{\bar{B}}\right)^2 \tag{3}$$

and the subscript zero refers to the axial value of the quantity. Then minimising the expression

$$K = \frac{7a^2 \int T^5\left(\frac{\partial T}{\partial r}\right)^2 rdr}{2T_o^2 \int T^5\, rdr}$$

using the trial function

$$T = T_o\left(1-\frac{r^2}{a^2}\right)^{\gamma} .$$

gives the lowest eigenvalue, β. This yields $\gamma = 0.36$ (a rather flat temperature profile) and $\beta = 1.33$.

Calculating the resistance from the temperature profile, equation 3 can be written as an expression for central electron temperature as a function of stochastic field level,

$$T_o = 15\left(\frac{B_{\theta a} Z_{eff}}{\tilde{B}/B}\right)^{\frac{2}{5}} eV \qquad (4)$$

where $B_{\theta a}$ is the edge value of the poloidal field and we have taken $\ell n\ \Lambda = 13$.

Figure 2 shows the variation of temperature with stochastic field level for a plasma with $Z_{eff} = 3$ and $B_{\theta a} = 0.3$ T. Experimental values of $\tilde{B}/B$ can be as large as 1% in disruptions [3], and equation 4 then predicts an electron temperature of 90 eV. Measurements made after disruptions in TFR [2] gave $Z_{eff} \gtrsim 3$, $B_{\theta a} = 0.3$ T and $\tilde{B}/B \simeq 1\%$. The calculated temperature in this case is 100 eV, in reasonable agreement with the measured value of 130 eV.

In JET up to half of the current is often transferred to runaway electrons during the disruption, reducing the input power by a factor of 4. This only reduces the temperature calculated from equation 4 by 30%.

3. RESISTANCE TEMPERATURE IN FAST DISRUPTIONS

The electron temperature after fast disruptions in JET is too low to be measured by the ECE systems. We shall here calculate the temperature on the assumption that the plasma resistance is determined by Spitzer resistivity. The resistance itself will be determined from the power balance implied by the current decay and the measured voltage.

Figure 3 shows a fast current decay following a 1.8 MA disruption. After the short lived current and voltage spike [6], the ohmic current decays away rapidly, reaching a decay rate of 150 MA s^{-1}, and then leaves the 0.8 MA current carried by relativistic runaway electrons [7] which were generated in the disruption. The current decay rate will now be used to estimate the power input to the plasma using the power balance equation

$$P_{in} = -\frac{d}{dt}\left(\tfrac{1}{2} L I^2\right) + I V_\ell \qquad (5)$$

where L is the inductance of the plasma current in the volume enclosed by the vacuum vessel and V_ℓ is the toroidal voltage measured on the vacuum vessel. Just before disruption the inductance was calculated to be 2.7 μH.

The runaway electrons affect the power balance calculation in two ways. Firstly, since they carry 0.8 MA of current, only the remaining 1.2 MA current contributes to ohmic heating. Secondly, the runaways are continuously accelerated in the induced electric field and so part of the total power input goes into kinetic energy of the runaway electrons. Thus the power balance becomes

$$I_{oh}^2 R_p + P_r = \frac{d}{dt}\left(\tfrac{1}{2} L I^2\right) + I\, V_\ell$$

where R_p is the plasma resistance, I_{oh} the ohmic current, and the power, P_r, going to the runaway electrons is given by

$$P_r = I_r\, V_r = I_r\left(V_\ell - L_1 \frac{dI}{dt}\right) \qquad (6)$$

where I_r is the runaway current, V_r is the toroidal voltage accelerating the runaways and L_1 is the flux inductance between the vacuum vessel and the runaway beam. For a uniform runaway current distribution the flux inductance is twice the energy inductance which is approximately 1 μH for a uniform current in JET. Using the measured voltage $V_l \approx 100$ V and $L_1 = 2$ μH, equations 5 and 6 give $P_{in} = 1.1$ GW and $P_r = 0.4$ GW. The remaining power of 0.7 GW is dissipated as ohmic heating, and equating this to $I_{oh}^2\, R_p$ gives

$$R_p = 500\mu\ \Omega$$

to be compared with ~ 0.4 μΩ before disruption.

Interpreting the resistance change as being due to the drop in electron temperature, the Spitzer resistivity formula gives for the temperature after collapse

$$T_e = 4\ eV$$

where a uniform temperature has been assumed together with $Z_{eff} = 3$ and $\ell n\Lambda = 12$.

The low value of temperature determined here is not consistent with the temperature which would result from losses due to the stochastic magnetic field as given by equation 4. With typical values of stochastic field strength < 10% of the poloidal field, (1% of the total field) the predicted resistance which would result from such losses is a factor of 70 too low. Even if the stochastic field strength approached 100% of the poloidal field, the predicted resistance would still be a factor of 20 lower than the measured value.

4. EFFECT OF RADIATION ON TEMPERATURE AFTER DISRUPTION

The calculation of central electron temperature after disruption based on equation 1 neglected radiation losses. The large discrepancy between the resistance calculated from this temperature and the observed value suggests that this assumption is wrong. Furthermore, very large radiation powers have been observed at the time of the disruption [7].

It is well known that a cold, impure plasma radiates strongly due to partially stripped impurity ions. For instance a JET plasma with deuterium density $3 \times 10^{19}\ m^{-3}$, containing 10% carbon impurity in coronal equilibrium would radiate 1 GW at an electron temperature of 7 eV [8]. This is of the same order as the input power during the current decay, demonstrating that radiation can play an important role in the power balance after disruption. In comparison, the power conducted out of such a plasma with $\tilde{B} / B = 1\%$ would be only 7 kW, and the plasma would reheat very rapidly if conduction were the only power loss. The variation of the input, conducted and radiated powers with temperature is shown in figure 4. Whilst both conduction and radiation losses could be important at temperatures $\gtrsim 60$ eV, the rapid fall off of conduction with temperature means that at low temperatures ($\lesssim 10$ eV) it makes a negligible contribution to the power balance. Both the radiated power and input power exceed the conducted power by 5 orders of magnitude at 7 eV.

Returning now to the energy loss shown in Figure 1, we summarise the two phases of the electron temperature fall as

1) A slow drop from 1 keV to 500 eV, and
2) a fast drop to a low value, inferred from the resistance to be 4 eV.

This two stage process is also observed in the soft x-ray emission [9]. The first stage of the energy loss can be understood in terms of conductive loss in a stochastic field and is correlated with a field fluctuation level measured at the wall ~ 1% of the poloidal field [7]. As we have seen, the second stage cannot be understood merely in terms of loss of confinement and it has been suggested [9] that the rapid drop in temperature is due to an influx of impurity atoms. The energy lost in ionising the incoming atoms would cool the electrons to a low temperature and the line radiation from the resulting partially stripped impurities then holds the temperature low despite the gigawatt input power during the current decay.

An influx of impurity atoms could explain how the plasma becomes cold in the disruption and how it can remain cold during the current decay. A large source of impurity at the plasma edge may arise during the disruption due to sublimation or evaporation of the limiter surface for instance. For this to play an important part in the disruption, the impurity must be able to penetrate the plasmas on a rapid timescale.

The penetration of neutral atoms into the plasma is usually restricted by ionisation. A carbon atom entering a plasma with $n = 10^{19}$ m^{-3} and $T_e = 100$ eV is ionised in 1 μs and a 1 eV carbon atom would only travel 3 mm in that time. The problem of how impurities can reach the plasma core on a timescale of hundreds of microseconds is addressed in the next section.

5. IMPURITY INFLUX MODEL

The impurity influx model envisages three stages,

1) A rapid mhd event flattens the temperature over much of the plasma, increases the heat flux to the edge, raising the temperature of the limiting material above a critical level.

2) Impurities are released from the wall, cooling the edge region of the plasma as atoms are ionised. The central temperature falls by conduction to around 100 eV. This is consistent with the temperature calculated from equation 4 and corresponds to cooling by conduction with $\tilde{B}/B \sim 1\%$.

3) Impurities reach the core plasma on a timescale of a few hundred microseconds, reducing the temperature to a low value (~ 5 eV).

The sudden release of impurities from the limiting surface may occur, for example, when the material is heated to evaporation. Such a sudden release can occur because of the strong dependence of the evaporation rate on temperature.

Figure 5 shows how the rate of release of carbon atoms changes by an order of magnitude with a change of temperature of only 300K. The dashed line represents the evaporation rate required to produce 0.01g of carbon (equal to the total plasma mass) every 10μs, assuming a surface area of $1m^2$. It appears that a surface temperature of around 3000K is necessary to give a substantial impurity release. We can estimate the increase in limiter surface temperature due to the rapid mhd event as

$$\Delta T = \frac{CPt^{\frac{1}{2}}}{A}$$

where a power, P, is incident on an area, A, for a time, t. C is a constant dependent on the limiting material, and for the graphite limiters used until recently in JET, $C \approx 10^{-4}\ KW^{-1}\ m^2\ s^{-1/2}$.

For example, allowing 30% of the plasma energy to fall on the limiter in a time of 1 ms (the observed time of the mhd event) would produce a temperature rise of 3000K if the power were concentrated on an area of 0.3 m^2. This area is smaller than the ~ 10 m^2 of the limiters which normally receives the power load, so we see that the release of impurities from the limiter requires an asymmetry in the heat deposition. In the disruption this may be due to the asymmetry of the plasma in the presence of a large mhd instability, or merely a result of irregularity of the limiter surface.

Given a large source of impurities at the edge, it is clear that the edge temperature will fall rapidly as the incoming atoms are ionised. As we have seen, the central temperature will fall by conduction only as low as ~ 100 eV. To cool the plasma further the impurities must penetrate to the core on a short timescale, although a 1 eV carbon atom was calculated above to travel only ~ 3 mm before being ionised. The incoming carbon atom could alternatively charge exchange with a carbon ion already in the plasma. The resulting 100 eV carbon atom could penetrate ~ 3 cm into the plasma but again this is far from sufficient to reach the plasma centre. In order that the carbon can penetrate further, the plasma conditions must be such that charge exchange dominates over ionisation.

Figure 6 shows approximate rate coefficients for carbon ionisation [10] and carbon-carbon charge exchange [11] as a function of temperature (electron temperature for ionisation, carbon temperature for charge exchange). At temperatures below 10 eV, the ionisation rate falls rapidly with falling temperature, increasing the probability that an incoming atom will undergo charge exchange. At $T_e = 3$ eV for instance the time for ionisation of the carbon atom is increased to 200 μs.

If the plasma electrons become sufficiently cold that the ionisation time of incoming carbon atoms is long, charge exchange of the incoming atoms becomes important and allows a rapid penetration of the impurity influx to the plasma core. The proposed sequence of events when a large flux of carbon atoms falls onto the surface of a deuterium plasma is as follows:

1. The carbon atoms are initially ionised (ionisation time ~ 1 μs), cooling the electrons at the edge until charge exchange becomes dominant (at ~ 5 eV).

2. The deuterium ions at the edge are cooled by collisions with the electrons (the equipartition time is ~ 10 μs at $T_e = 5$ eV), carbon ions at the edge are heated by collisions with the deuterium ions.

3. Carbon atoms which arrive slightly later are not ionised since the electron temperature is too low, but instead undergo charge exchange with carbon ions in the edge plasma.

4. The edge region is then dominated by a mixture of 5 eV carbon ions, cold carbon atoms from the limiter, and 5 eV carbon atoms resulting from charge exchange. The 5 eV carbon atoms then penetrate further into the hot plasma, propagating the cooling effect of the influx.

Given a sufficient influx of carbon, this cooling proceeds as a narrow front propagating towards the plasma core as shown schematically in figure 7. On one side of the front of width δ, the hot deuterium plasma is unaffected. On the other side is the plasma already crossed by the front and is a cold impure plasma dominated by line radiation.

Assuming, for simplicity, that the cooling is poloidally and toroidally symmetric, the equations governing the evolution of such a cold front are

$$\left(\mathrm{v_c} - \mathrm{v_f}\right)\frac{dn_c}{dx} = n_c n_e \langle \sigma \mathrm{v} \rangle \qquad (7)$$

$$\mathrm{v_f}\frac{dT_e}{dx} = n_e \langle \sigma \mathrm{v} \rangle \varepsilon \qquad (8)$$

where a flux $n_c v_c$ of carbon atoms is incident on the front travelling with velocity v_f. The ionisation rate is $n_e <\sigma v>$ with n_e the electron density. ε is the energy required to ionise one carbon atom.

Dividing equation 7 by equation 8 and integrating across the front gives

$$\frac{(v_c - v_f)}{v_f} n_{co} = \frac{n_e T_{eo}}{\varepsilon}$$

where n_{co} is the carbon density behind the front and T_{eo} the electron temperature ahead of the front.

The velocity of the front is then determined,

$$v_f = v_c \left(\frac{1}{1+\alpha} \right)$$

where $$\alpha = \frac{n_e T_{eo}}{n_{co} \varepsilon} \quad .$$

If the front is to continue to propagate, the plasma must give up all its energy to ionise the neutrals, so

$$n_{co} \varepsilon = n_e T_{eo}$$

and $$v_f = \frac{v_c}{2} \quad .$$

Thus the front propagates at half the velocity of the charge exchange neutrals. This is the minimum velocity required for the cold front to penetrate the core, as at lower velocity $\alpha > 1$ and there are insufficient impurity atoms to quench the plasma. The maximum velocity occurs in the limit of large carbon density ($n_{co} \rightarrow \infty$) and then $v_f = v_c$. Thus the velocity of the front is given by

$$\frac{v_c}{2} < v_f < v_c .$$

At 5 eV the velocity of a carbon atom is approximately 10^4 ms^{-1} and the time for the cold front to reach the plasma centre is

$$\tau_f = \frac{a}{v_f}$$

which for JET gives

$$100\mu s < \tau_f < 200\mu s$$

We see that the carbon influx is sufficiently fast to explain the observed behaviour.

The width of the cold front as it propagates across the plasma is given by the penetration distance of the charge exchange neutrals into the hot plasma. For 5 eV neutrals and 100 eV plasma this is ~ 1 cm. The cooling of a local region of plasma is therefore very rapid as the front only remains in a given region for ~ 1 μs.

We have assumed that the cooling described above is a 1 dimensional process where heat can flow very rapidly in a flux surface. In practise, if there is a localised release of impurities from the limiting surface, the cooling will have a 3-d character. This will affect the way the cooling proceeds into the plasma, but not the physics of the cold front.

The impurity influx model inevitably predicts an increase in the carbon and electron density of the plasma. The number of carbon atoms which penetrate the plasma must be sufficient to cool the electrons. If the average ionisation energy per carbon atom is ε, and each carbon ion is ionised only once (since the local cooling is so rapid) then the electron density will change by a factor

$$\frac{\Delta n_e}{n_e} = \frac{T_e}{\varepsilon} \tag{9}$$

which, with the temperature reached by conduction alone of T_e = 100 eV and

ε = 20 eV (making an allowance for radiative losses), gives $\frac{\Delta n_e}{n_e} = 5 \cdot$ The mass of carbon required is 0.3 g compared with the initial plasma mass of 0.01 g.

It is feasible that an influx of impurity atoms can occur on the timescale of the observed cooling in disruptions. The low value of temperature required (~ 5 eV) is consistent with the temperature inferred from the plasma resistance. The electron density is not known during JET disruptions hence the predicted factor of 5 increase in density cannot be checked directly at present. The plasma can only be quenched by an impurity influx if there are sufficient impurity atoms falling on the surface. With fewer impurity atoms the cold front would not penetrate to the core and would leave a hot central current channel.

6. CONCLUSION

It is suggested that an influx of impurity atoms plays an important role in the class of tokamak disruptions for which the current decay is very fast. The main motivation for this investigation was the observed large increase in plasma resistance in fast disruptions in JET. The temperature inferred from the resistance is ~ 5 eV whereas the value expected due to ergodisation of the magnetic field lines is ~ 70 eV, representing a factor of 50 discrepancy in the resistance.

A mechanism for the impurity influx is proposed in which a narrow front (width 1 cm) penetrates rapidly (in 100 μs) from the edge of the plasma to the centre, cooling the plasma to a low temperature. The resulting temperature must be very low (~ 5 eV) since the model requires the incoming impurity atoms to charge exchange with impurity ions already in the plasma, rather than being ionised.

The predictions of the impurity influx model are

1) an electron temperature of around 5 eV, held low by impurity line radiation, and

2) an increase in electron density by a factor ~ 5.

The low value of temperature is in agreement with the value determined from the resistance. The predicted substantial density increase should serve as a critical test of the impurity influx model, but the density after disruption is unknown in JET.

It appears that interaction between the plasma and the surrounding surfaces can play a crucial role in tokamak disruptions, often thought to be largely an mhd phenomenon.

Acknowledgements

The authors would like to thank Drs. H. Summers, D. Campbell and R. Gill for helpful advice.

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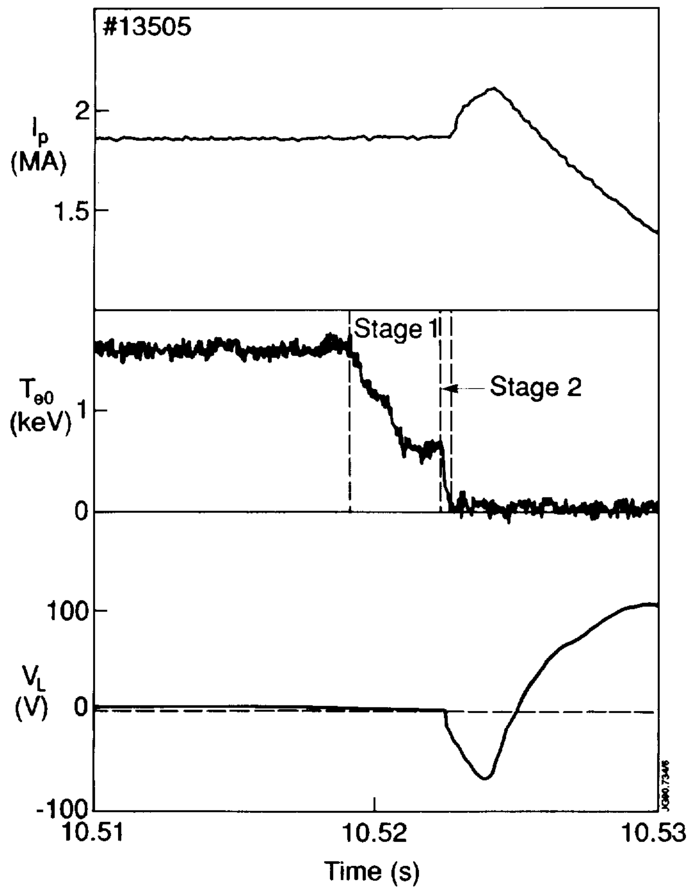

Figure 1 The disruptive energy loss occurs in two stages. The negative voltage spike and the current decay occur after the second, fast stage.

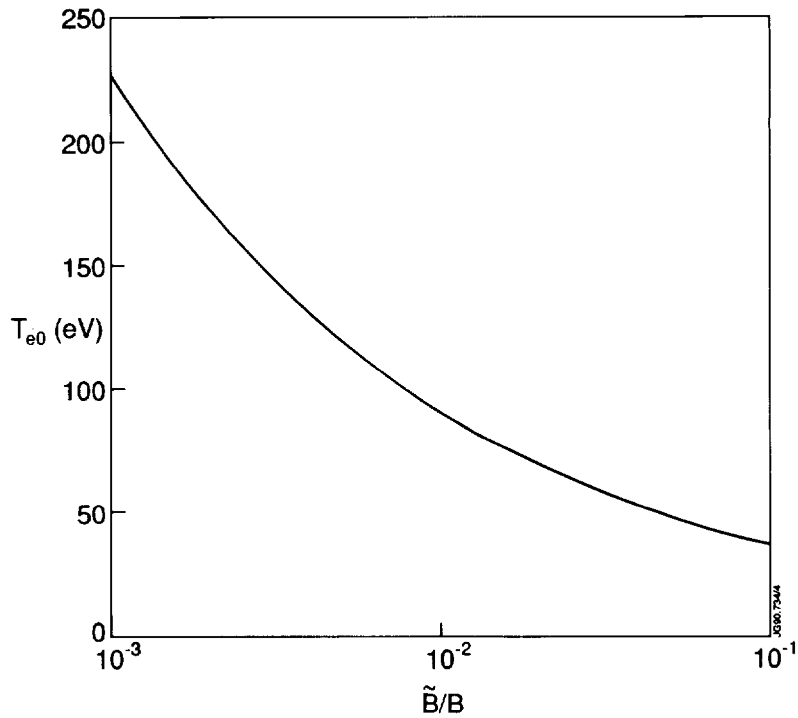

Figure 2 The calculated value of axial temperature is shown as a function of stochastic field level. The ohmic input power is balanced against conduction losses.

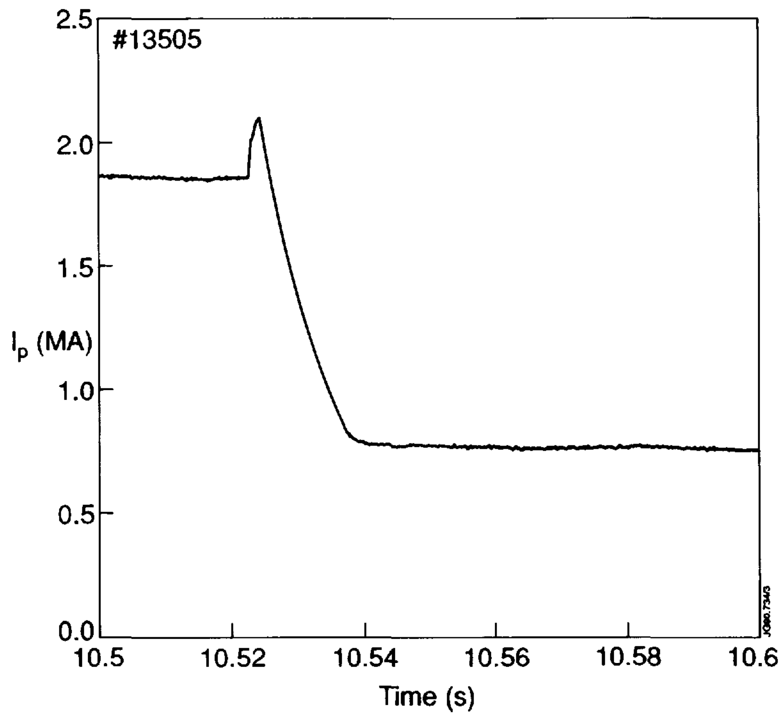

Figure 3 An example of a fast current decay following a disruption in JET. After the voltage/current spike the current decays with a characteristic time of 10ms until a plateau is reached where the current is carried by runaway electrons.

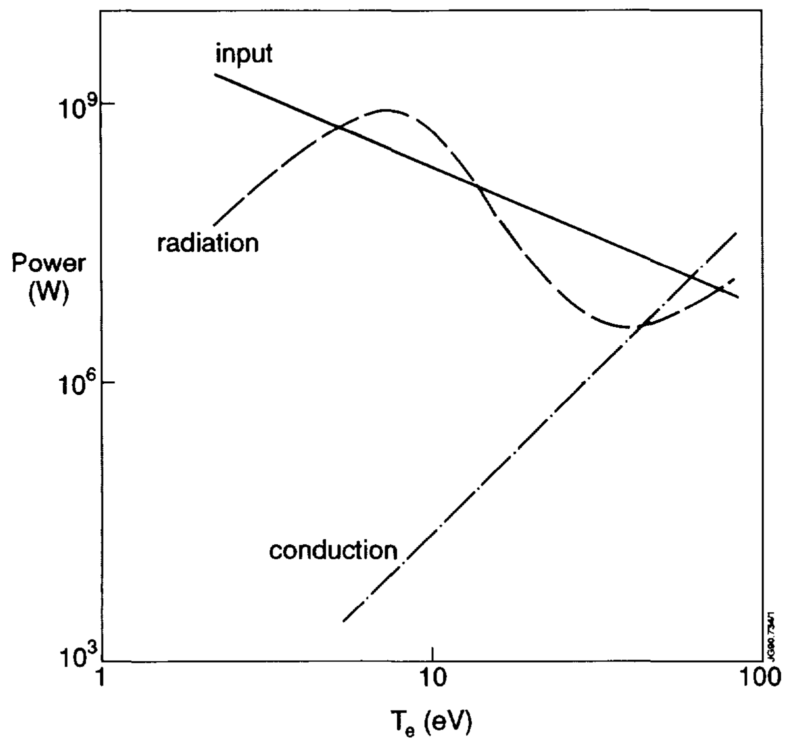

Figure 4 The variation with electron temperature of the input, radiated and conducted powers under the conditions given in the text. Thermal conduction is inefficient at low temperatures because of the short electron mean free path.

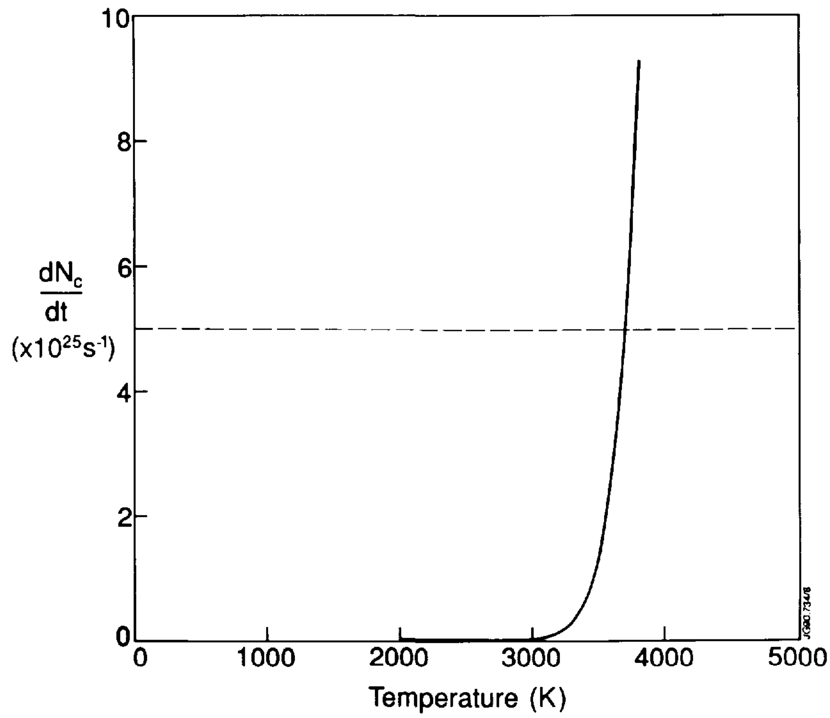

Figure 5 The number of carbon atoms released per second from $1m^2$ of limiter surface is shown as a function of temperature. The dashed line shows the release rate which results in a doubling of the total mass of plasma every 10 μs.

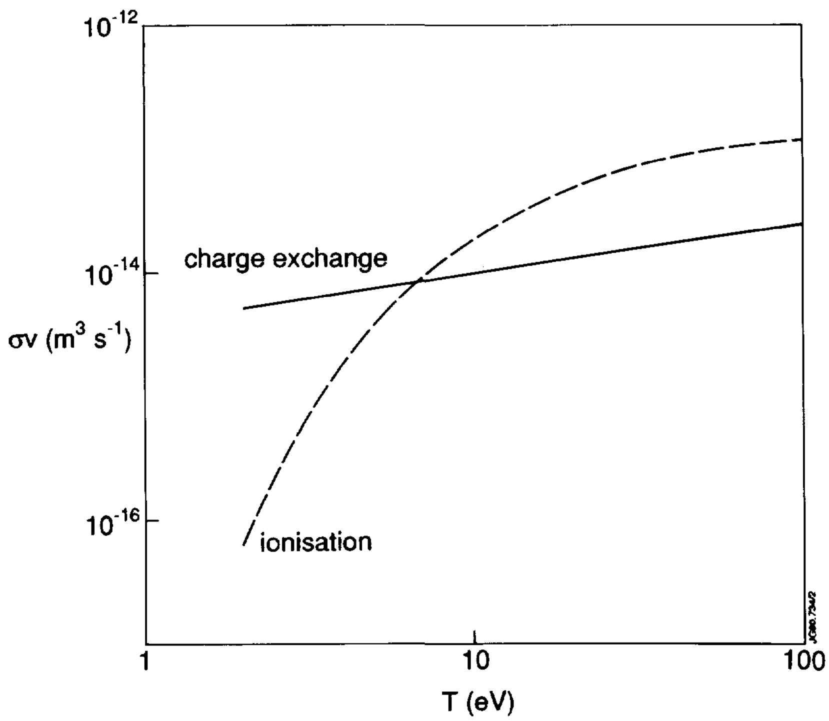

Figure 6 Rate coefficients for ionisation of the incoming carbon atoms through collisions with electrons and for charge exchange with carbon ions already in the plasma. For ionisation the electron temperature is important whilst for charge exchange the carbon temperature is important.

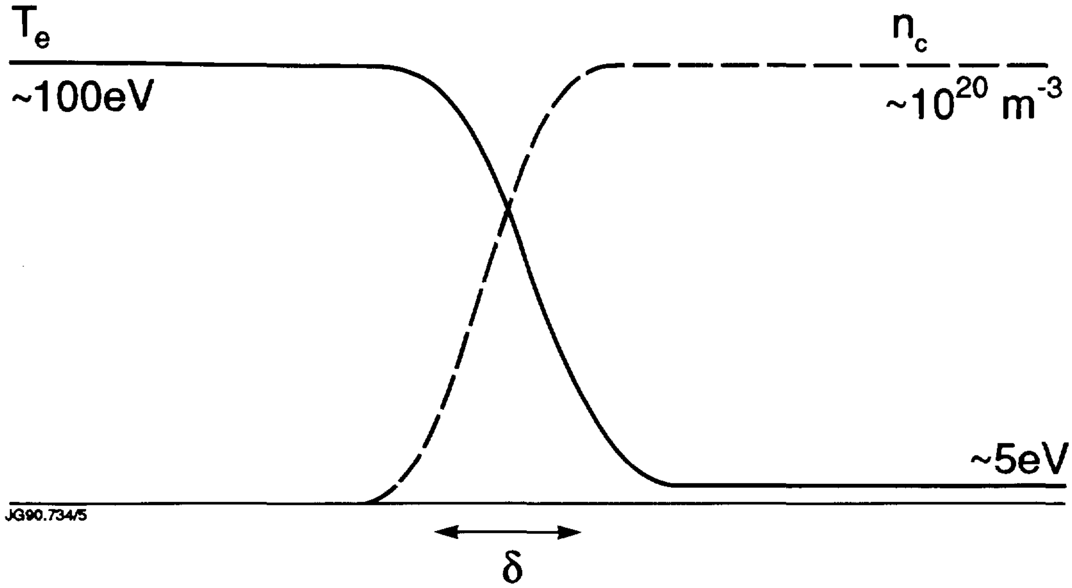

Figure 7 Schematic showing the cooling front of width δ, with the hot deuterium plasma ahead of it, and the cold, impure plasma behind.

APPENDIX 1.

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CR 88.49.1A