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* See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",
Fusion Energy 2002 (Proc. 19th IAEAFusion Energy Conference, Lyon (2002).

ABSTRACT

Disruptions place severe limitations on the materials selected for plasma facing components in fusion devices. In a disruption, the plasma stored thermal and magnetic energy is dissipated leading to predicted power loadings in the current quench of up to 10MWm^{-2} in JET. In the thermal quench very high power loads of up to 10GWm^{-2} would be expected if all the power flowed to the steady state strike points, however this is not observed. In this paper the energy balance associated with both events is investigated. The magnetic energy is found to balance well with radiated energy. Circumstantial evidence for limiter interaction during the thermal quench of plasmas in divertor configuration is presented and a possible mechanism for limiter interaction in disruptions resulting from the collapse of an ITB is discussed.

1. INTRODUCTION

When a JET plasma disrupts the thermal energy (≤10MJ) and magnetic energy (≤20MJ) are lost as heat to the plasma facing components on timescales of 1ms and 20ms respectively. Initially the thermal energy is dissipated in the thermal quench followed by the magnetic energy dissipation in the current quench. During the current quench the energy stored in the poloidal magnetic field is radiated uniformly over the entire first wall surfaces generating heat loads of ~10MWm^{-2} which are well handled by the limiters and first wall. Recent results from JET have led to the surprising observation that the thermal energy is not conducted to the steady state strike points in the thermal quench, sometimes only ~3% of the total energy is conducted to the divertor [1]. In this paper we investigate the possible thermal energy sinks, including radiation and conduction to the limiters. The radiated energy on JET is currently measured by bolometers with time resolution 20ms, insufficient to distinguish between the thermal and current quenches. By investigating the overall energy balance of the magnetic energy, it may be possible to deduce how much of the thermal energy might be radiated.

In the disruption of plasmas having an Internal Transport Barrier (ITB) an oscillating, strongly peaked disturbance is visible from electron cyclotron emission temperature profiles originating on the ITB in the instant before the disruption. The disturbance is similar to the ballooning instability precursors seen during high beta disruptions in TFTR [2] and is thought to be a possible mechanism for conduction to the limiters during the quench.

2. THE MAGNETIC ENERGY BEHAVIOUR IN DISRUPTIONS.

During the plasma current decay the energy stored in the poloidal magnetic field is dissipated, mostly by radiation due to Ohmic heating of the cold resistive plasma. As the plasma current is inductively coupled to the vacuum vessel and poloidal field coils, magnetic energy may also be coupled to these. In order to estimate the amount of energy coupled out of the system, the self and mutual inductances of all the conductors could be computed together with the full magnetic induction equation to determine the coupling [3]. Alternatively the electromagnetic energy flux through a

closed surface enclosing the plasma can be measured, using Poynting's theorem to estimate the Ohmic heating (W_{ohmic}) as done by Hyatt [4] for DIII-D. Poynting's theorem is given in equation . The electromagnetic energy (W) is written as $(\mathbf{B}_{pol}+\mathbf{B}_{tor})^2/2\mu_0$ since $B^2 \gg \varepsilon_0\mu_0E^2$.

$$\frac{\partial W}{\partial t} = -\nabla \cdot \frac{\mathbf{E}\times\mathbf{B}}{\mu_0} - E\cdot j \tag{1}$$

Poynting's theorem may decouple in this case into a poloidal magnetic ($\mathbf{B}_{pol}$) and toroidal magnetic ($\mathbf{B}_{tor}$) component. Equation shows the $\mathbf{B}_{pol}$ component written in terms of the full poloidal magnetic energy balance.

$$
\begin{aligned}
W_{ohmic} &= \int_t \int_V j_p\, E_\phi\, dVdy \\
&= -\frac{1}{\mu_0} \int_t \int_S (E_\phi B_\theta)dSdt - \Delta W_{poloidal\,()} \\
&= W_{rad} + W_{cond}
\end{aligned}
\tag{2}
$$

The surface S is defined by the vacuum vessel, V is the volume within the vacuum vessel, ΔW_{pol} is the change in the poloidal magnetic energy contained within the vacuum vessel, W_{rad} is the radiated energy and W_{cond} is the conducted energy. The required quantity is the Ohmic heating†– we would like to know how much of the energy stored in the poloidal magnetic field is dissipated in the plasma by Ohmic heating.

2.1. FIELD MEASUREMENTS

18 Internal Discrete Coils (IDC) measure $\mathbf{B}_{pol}$. The toroidal electric field ($\mathbf{E}_{tor}$) is deduced from toroidal voltage loops on the top and bottom of the vacuum vessel combined with 14 saddle loops. The saddle loops are attached to the vacuum vessel surface such that together they cover the full poloidal circumference. The voltage measured through each saddle loop may be thought of as the potential difference between the toroidal voltage at the top and bottom of the loop. Combining the saddle loop voltages with the loop voltage measured at the top of the machine will give the toroidal loop voltage at each of the saddle loops. As the IDC coils are not poloidally aligned with the saddle loops, a weighted difference between neighbouring IDC coils is used to estimate $\mathbf{B}_{pol}$ at the loop. The other measurement required is the poloidal magnetic energy stored within the vacuum vessel (W_{pol}), both immediately preceding and following the disruption. EFIT [5] was used to obtain the initial W_{pol} by obtaining $\mathbf{B}_{pol}$ at every point over a computational grid encompassing the whole vacuum vessel and integrating over the volume. Careful attention must be made to the existence of the divertor field coils within the integrating surface and are discussed later. To calculate W_{pol} after the disruption, where EFIT reconstructions are unavailable, the Poynting flux was simply measured as all the divertor and poloidal field coil currents decay to zero and by calculating the resistive heating in the divertor coils as those currents decay to zero.

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$\mathbf{B}_{pol}$ measurements are taken on the inner wall of the vacuum vessel. $\mathbf{E}_{tor}$ is measured on the outer surface. The effect this discrepancy has on the calculation warrants further investigation. By measuring the resistive dissipation of current in the vacuum vessel itself, an estimation of the inaccuracy introduced by this procedure may be gained. We know the toroidal loop voltage at the vacuum vessel surface. The vacuum vessel resistance of 340mW gives the resistive dissipation of magnetic energy in the vacuum vessel as ~5% of W_{self}. Of course this only calculates the energy dissipated in the vacuum vessel whereas we would like the effect the vacuum vessel has on the magnitude of the electric and magnetic fields. This was not investigated.

From the toroidal magnetic energy component of Poynting's theorem, we have good toroidal magnetic energy balance over an entire pulse to ~5%. The divertor coil resistive heating and energy removed by their power supplies during disruption was found to be ~0.5% and is therefore negligible.

2.2. POYNTING FLUX OF MAGNETIC ENERGY RESULTS

The Ohmic heating was calculated for 20 disruptions and compared to the initial self-magnetic energy of the plasma, $W_{self} = {}^{1}/_{2} LI^{2}$. The plasma self-inductance (L) depends on the internal inductance (l_i) which is a measure of the current profile [3]. We used the last available EFIT result for l_i before the disruption. The result of a linear fit showed 61% of W_{self} is used to ohmically heat the plasma in the current quench. We also compared the results for two disruptions with the full induction equation method as applied to JET [6]. The Ohmic heating energies agreed to 7%.

The radiated energy was measured using the JET bolometer system [7] which gives an estimate of the total radiated energy to 10%. Figure 1 compares the radiated energy to the Ohmic heating of the plasma for 20 disruptions and we find ~94% is radiated. The accuracy of this figure is indicated by the tendency of the radiated energy to zero as we interpolate to zero Ohmic heating. If the thermal energy is included ~62% is radiated. The radiated energy can be completely accounted by the amount of magnetic energy coupled into the plasma. Radiation, therefore, appears an unlikely channel for the thermal energy dissipation.

By connecting a single bolometer channel to a fast acquisition system the time evolution of the radiation pulse was investigated. The signal from the fast bolometer is shown in Figure 2 and clearly shows most of the radiated energy is detected after the thermal quench.

3. THE THERMAL QUENCH

Figure 3 shows the thermal energy can be lost in different timescales dependant upon the disruption type. For example in a disruption due to the collapse of an ITB, the thermal energy is usually lost extremely quickly < 1ms. In beta limit disruptions, MHD modes in the plasma grow over a longer timescale and cause the thermal energy to be much reduced before the final fast quench.

The worst case in terms of surface temperatures is probably where the thermal energy is dumped in a very fast timescale. On JET we do not find most of this energy conducted to the divertor as measured by the infrared camera [8] and the thermocouples [6]. One possible explanation for this

may lie in the properties of the divertor target tiles. If the temperature of the CFC material surface is high enough, the surface will evaporate, cooling the target and possibly reducing further conduction to the target through vapour shielding. In the next section this is briefly investigated further.

3.1. EVAPORATIVE COOLING OF THE TARGET TILES

The analytical solution of the heat diffusion equation for the surface temperature of a tile with constant applied heat flux of Φ_0 is:

$$T_{surface} = \frac{2\Phi_0}{K} \sqrt{\frac{\kappa t}{\pi}} \tag{3}$$

For a carbon CFC tile at 500K, $\kappa = 60 \text{mm}^2\text{s}^{-1}$ and $K = 180 \text{ Wm}^{-1}\text{K}^{-1}$. Now taking the full plasma thermal energy of 10MJ to be conducted to the steady state strike points of 1m^2 gives $\Phi_0 = 10\text{GWm}^{-2}$ for 1ms. This corresponds to a temperature rise of ~30000K. Federici et al [9] showed evaporative cooling is expected to be dominant at ~3500K, preventing temperatures increasing much above this. The JET disruption case would be expected to easily enter this regime, evaporating the target and possibly inducing vapour shielding [10]. Results from measurements of the JET IR camera system show the temperature of the target is usually <<3000K throughout the disruption. From this it is difficult to imagine evaporative cooling and therefore vapour shielding of the divertor tiles being an important mechanism in the thermal quench.

3.2. LIMITER INTERACTION DURING THE THERMAL QUENCH.

There are indications that plasma thermal energy conducted to the limiters may play an important role in the thermal quench. The temperature of the main wall in JET is poorly diagnosed, especially not on a fast timescale. There are a small number of limiter Langmuir probes on the low field side limiter at one toroidal location, separated about the midplane as seen in Figure 4. During disruptions, an extremely large current is often observed in all the probes, orders of magnitude above the plasma steady state phases. Shown also in Figure 4 are the probe currents during the disruption of pulse 60885, a disruption due to the collapse of an internal transport barrier (ITB). All the probes are found to carry a very large current during the thermal quench, at least an order of magnitude above steady state values. In general, a large current pulse may be observed on these probes during most disruptions. The large signal even exists in plasmas run with a large plasma-limiter gap. This suggests there is significant plasma interaction with the limiter during the quench and work is underway to quantify this data.

3.3. DISRUPTIONS RESULTING FROM THE COLLAPSE OF AN INTERNAL TRANSPORT BARRIER (ITB)

Disruptions resulting from the collapse of an ITB have a particularly fast thermal quench that usually occurs at maximum thermal energy, see Figure 3. JET uses an electron cyclotron emission

heterodyne radiometer to measure the radial profile of electron temperature (T_e). Figure 5 shows an ECE contour plot of the electron temperature in the last few hundred microseconds before the thermal collapse of a disruption due to the collapse of an ITB. The profile shows a growing oscillation in the T_e contours in the vicinity of the ITB. In Figure 5 the disturbed plasma region grows rapidly, extending from r = 3.2m to r = 3.8m, at the plasma edge by the final oscillation. The radial velocity of the disturbance, estimated from the radial growth of the T_e contours is usually ~0.3 - 0.6kms^{-1}, but for extreme cases can be as high as ~ 3kms^{-1}. Generally a disruption resulting from the collapse of an ITB will show this precursor, but it may also proceed by a slow decay of the barrier followed by a slow quench in which case this precursor is not visible.

This disturbance is similar to observations of high beta disruptions using ECE emission on TFTR [2] where the mode appeared to be ideal and ballooning-like with growth time ~ 50µs. S. C. Cowley et al [11] have developed a non-linear model of ballooning flux tubes on the low field side if the pressure gradient is high enough, which would look very much like those seen in Figure 5. This model has recently been applied to ELMs [12], but may also apply to disruptions. The experimental radial velocities of ELMs measured on JET are surprisingly similar to this case [13]. There remain many unanswered questions. What is the full radial extent of the growth? Does it extend through to the SOL or perhaps to the first wall?

DISCUSSION

We have investigated the possible reasons behind the JET observation that the thermal energy is not conducted to the steady state strike points during the thermal quench of disruptions. Radiation as a mechanism seems to be discounted as there is good overall energy balance of the magnetic energy over the disruption, ~94% of this is detected as radiation. There is not sufficient remaining to account for the radiation of the thermal energy.

A possible explanation lies in conduction to the limiters/first wall. Circumstantial evidence currently exists to support this hypothesis. JET-EP plans for a wide angle IR system should resolve this.
In disruptions resulting from the collapse of an ITB, a clearly oscillating, rapidly growing perturbation in the electron temperature is observed on the ITB. This could be a plasma filament ballooning radially, driven by the large pressure gradients associated with the ITB. The radial velocities of the filament are ~ 0.2 - 0.6 kms^{-1} and are similar to radial velocities of ELMs observed in JET.

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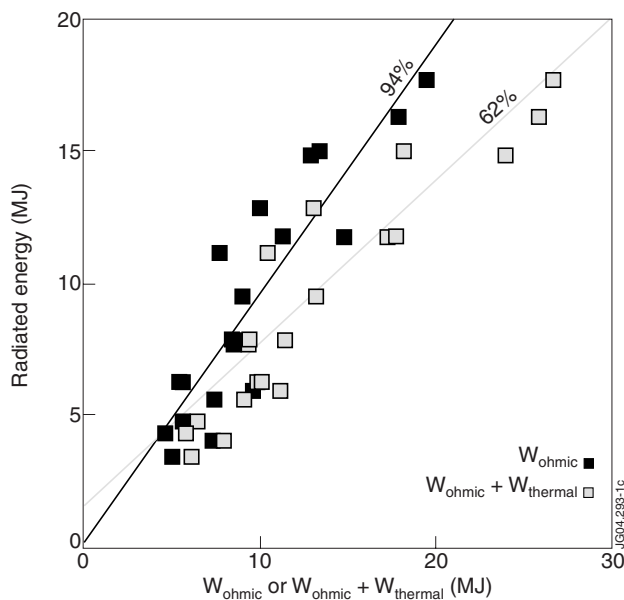[13]. W. Fundamenski, Plasma Phys. Control. Fusion 46 (2004) 233

Figure 1: The radiated energy compared to the Ohmic heating energy and the total energy (Ohmic heating + the initial thermal energy). Also shown are the linear fits. 94% of W_{ohmic} is radiated and as $W_{ohmic} \rightarrow 0$, W_{rad} 0.15MJ. 62% of the total energy, $W_{ohmic} + W_{thermal}$ is radiated, with offset 1.5MJ.
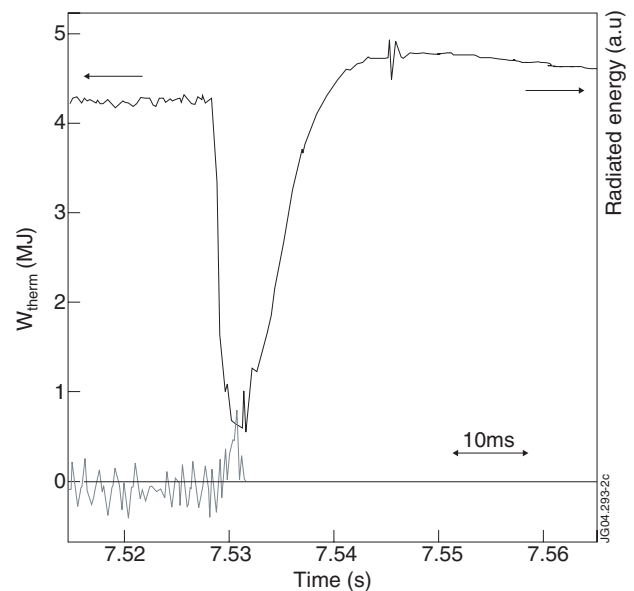

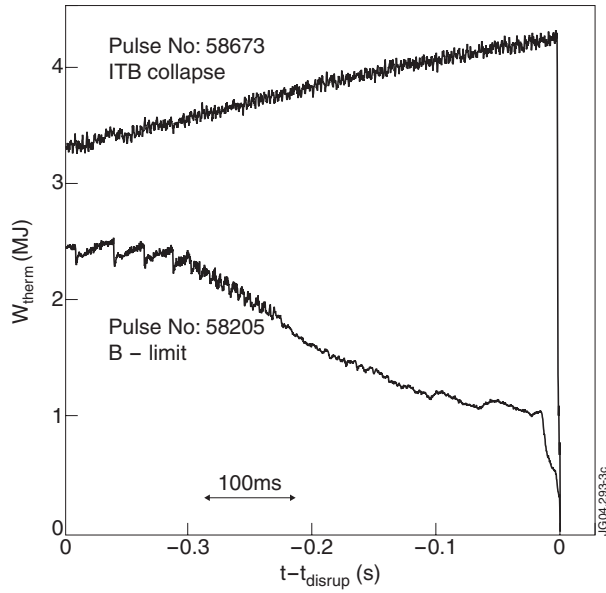*Figure 2: Radiated energy on an arbitrary scale from a single fast bolometer channel.*

Figure 3: Time evolution of the thermal energy on approach to the thermal quench for two disruptions.
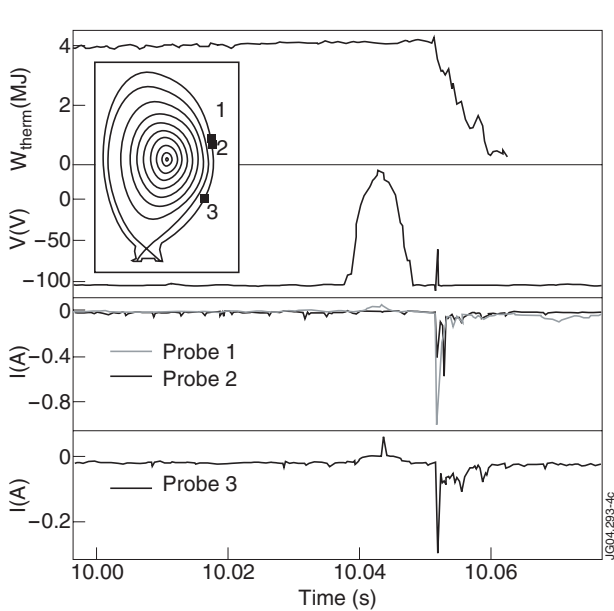

Figure 4: Limiter Langmuir probe signals at the thermal quench of a disruption due to the collapse of an ITB, pulse 60885. Shown is the plasma thermal energy, the driving potential of the probe, three probe signals and the location of the probes. The current pulse occurs when the probe is at -100V and is at least an order of magnitude greater than at earlier times in the pulse.
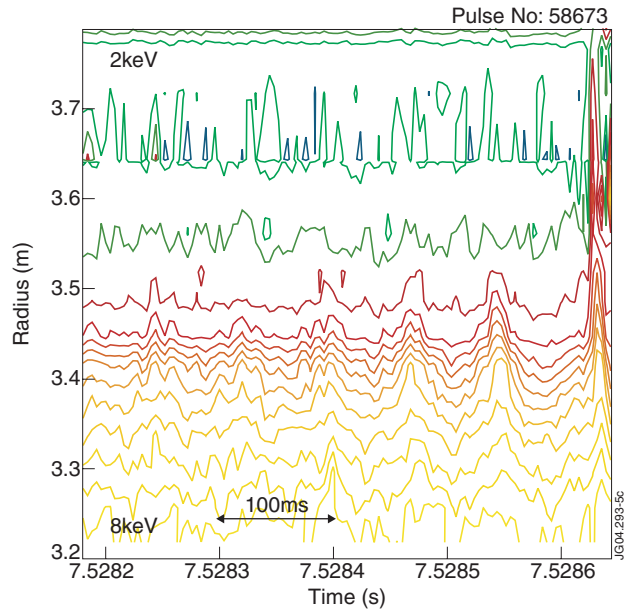

Figure 5: ECE contour plot of electron temperature in the instant before the thermal quench for an ITB collapse disruption, pulse 58673. Contours are 500eV apart.