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Energy flow during disruptions in JET

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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 $10\,\mathrm{MW\,m^{-2}}$ in JET. In the thermal quench very high power loads of up to $10\,\mathrm{GWm^{-2}}$ 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 internal transport barrier is discussed.

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1. Introduction

When a JET plasma disrupts the thermal energy ($\leqslant$10 MJ) and magnetic energy ($\leqslant$20 MJ) are lost as heat to the plasma facing components on timescales of 1 ms and 20 ms, 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 $\sim 10\,\mathrm{MW\,m^{-2}}$ which are well handled by the limiters and first wall. Recent results from JET have led to the surprising observation that the main part of the plasma thermal energy is not conducted to the steady state strike points in the thermal quench [1]. In the extreme case sometimes only ~10% of the thermal energy is conducted to the divertor and generally less than 50% of the thermal energy is detected at the divertor [2], depending on the disruption type. 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 20 ms,

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[1] See annex of J. Pamela et al., Fusion Energy 2002, Proc. 19th Int. Conf. Lyon, 2002, IAEA, Vienna.

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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 with 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 [3] 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 [4]. Alternatively the electromagnetic energy flux through a closed surface enclosing the plasma may be measured, using Poynting's theorem to estimate the ohmic heating (W_{ohmic}) as done for DIII-D [5]. Poynting's theorem is given in Eq. (1). The electromagnetic energy (W) is written as $(\boldsymbol{B}_{\text{pol}} + \boldsymbol{B}_{\text{tor}})^2/2\mu_0$ since $B^2 \gg \varepsilon_0\mu_0 E^2$.

$$\frac{\partial W}{\partial t} = -\nabla \cdot \left(\frac{\boldsymbol{E} \times \boldsymbol{B}}{\mu_0}\right) - E \cdot \boldsymbol{j}. \tag{1}$$

Poynting's theorem may decouple in this case into a poloidal magnetic ($\boldsymbol{B}_{\text{pol}}$) and toroidal magnetic ($\boldsymbol{B}_{\text{tor}}$) component. Eq. (2) shows the $\boldsymbol{B}_{\text{pol}}$ component written in terms of the full poloidal magnetic energy balance:

$$\begin{aligned} W_{\text{ohmic}} &= \int_t \int_V j_{\text{p}} E_\phi \, \mathrm{d}V \, \mathrm{d}t \\ &= \frac{1}{\mu_0} \int_t \int_S (E_\phi B_\theta) \, \mathrm{d}S \, \mathrm{d}t - \Delta W_{\text{pol}}, \end{aligned} \tag{2}$$

$$W_{\text{ohmic}} = W_{\text{rad}} + W_{\text{cond}}. \tag{3}$$

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

Eighteen internal discrete coils (IDC) measure $\boldsymbol{B}_{\text{pol}}$. The toroidal electric field ($\boldsymbol{E}_{\text{tor}}$) is deduced from toroidal voltage loops on the top and bottom of the vacuum vessel combined with 14 saddle loops. The other measurement required is the poloidal magnetic energy stored within the vacuum vessel (W_{pol}), both immediately preceding and following the disruption. EFIT [6] was used to obtain the initial W_{pol} by obtaining $\boldsymbol{B}_{\text{pol}}$ 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 is 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.

$\boldsymbol{B}_{\text{pol}}$ measurements are taken on the inside wall of the vacuum vessel. $\boldsymbol{E}_{\text{tor}}$ 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 340 $\mu\Omega$ gives the resistive dissipation of magnetic energy in the vacuum vessel as ~7% of the initial self magnetic energy of the plasma, 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.

The divertor coil resistive heating and energy removed by their power supplies during disruption was found to be negligible (~0.5%).

2.2. Poynting flux of magnetic energy results

The ohmic heating was calculated for 20 disruptions and compared to $W_{\text{self}} = (1/2)LI^2$. The plasma self-inductance (L) was calculated for a toroidal plasma with elliptical cross-section, derived in [7] in addition to the internal inductance (l_{i}). The full plasma self-inductance, which includes the flux outside the vacuum vessel was used as the time constant of the vacuum vessel ($\tau_{\text{vac}} = 4$ ms [8]) is less than the current decay time (~20 ms). l_{i} and other geometric parameters were obtained from EFIT, in the last available time slice before the disruption.

The result of a linear fit showed 72% of W_{self} is used to ohmically heat the plasma in the current quench. The remainder is expected to be dissipated in the conductors outside the vacuum vessel. We also compared the results

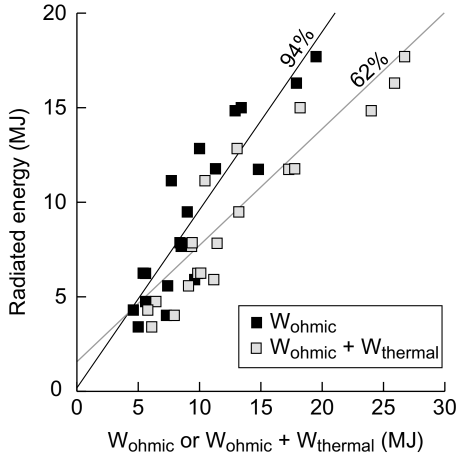

Fig. 1. The radiated energy during the disruption compared to the ohmic heating energy and the total energy (ohmic heating + the initial thermal energy). Also shown are the linear fits. 94% of W_{ohmic} is radiated and as $W_{\text{ohmic}} \to 0$, $W_{\text{rad}} \to 0.15\,\text{MJ}$. 62% of the total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

for two disruptions with the full induction equation method as applied to JET [9]. The ohmic heating energies agreed to 7%.

The radiated energy was measured using the JET bolometer system [10] which gives an estimate of the total radiated energy to 10%. Fig. 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, but in this case the fit is not good as the pulses are not at the same beta and so the linear fit can only show a rough trend. 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 vertical bolometer channel observing the plasma main chamber to a fast acquisition

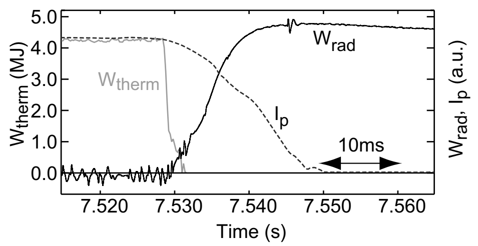

Fig. 2. The time evolution of the radiated energy (W_{rad}) on an arbitrary scale from a single fast bolometer channel. Also shown is the plasma current (I_p) and the thermal energy (W_{therm}).

system the time evolution of the radiation pulse was investigated. The signal from the fast bolometer, with response time 0.54 ms is shown in Fig. 2 and clearly shows most of the radiated energy is detected after the thermal quench. Notice also the energy is radiated on a similar timescale to the plasma current decay.

3. The thermal quench

It is in this phase we expect the highest heat loadings and hence temperatures of the target. The characteristics of the thermal energy losses are very different from disruption to disruption and this is critical for the heat load expected on the targets. Sometimes the thermal energy is dumped extremely rapidly at maximum performance and in other cases the thermal energy is ejected slowly over a long timescale before the final fast quench.

3.1. Evaporative cooling of the target tiles

The worst case in terms of surface temperatures is where the thermal energy is dumped in a very fast timescale. On JET there is poor thermal energy balance in the disruption: in the extreme cases only ~10% and usually <50% of the pre-disruption thermal energy is found as heat in the divertor, as measured by the infrared camera. Thermocouple measurements of the divertor also show a deficit in the thermal energy balance (~30%) [9]. One possible explanation for this may lie in the properties of the divertor target tiles. If the temperature of the carbon fibre composite (CFC) material surface is high enough, the surface will evaporate, cooling the target and possibly reducing further conduction to the target through vapor shielding. This was not included in the previous heat flux calculations [1,2] and is briefly investigated here.

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

$$T_{\text{surface}} = \frac{2\Phi_0}{K}\sqrt{\frac{\kappa t}{\pi}}. \tag{4}$$

For a CFC tile at 500 K, $\kappa = 60\,\text{mm}^2\,\text{s}^{-1}$ and $K = 180\,\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$. Now taking the full plasma thermal energy of 10 MJ to be conducted to the steady state strike points of $1\,\text{m}^2$ gives $\Phi_0 = 10\,\text{GW}\,\text{m}^{-2}$ for 1 ms. This corresponds to a temperature rise of ~30 000 K. Federici et al. [11] showed evaporative cooling is expected to be dominant at ~3500 K, preventing temperatures increasing much above this. The JET disruption case would be expected to easily enter this regime, evaporating the target and possibly inducing vapor shielding [12]. Results from measurements of the JET IR camera system show the temperature of the target is usually ≪3000 K throughout the disruption. From this it is difficult to imagine evaporative cooling and therefore vapor 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, shown in Fig. 3. 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 Fig. 3 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. JET uses an electron cyclotron emission heterodyne radiometer to measure the radial profile of electron temperature (T_e). Fig. 4 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 Fig. 4 the disturbed plasma region grows rapidly, extending from $r = 3.2\,m$ to $r = 3.8\,m$, 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 $\sim$0.3–0.6 km s^{-1}, but for extreme cases can be as high as $\sim$3 km s^{-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 [3] where the mode appeared to be ideal and ballooning-like with growth time $\sim$50 μs. A non-linear model of radially propagating ballooning flux tubes on the low field side [13], describes features very much like those seen in Fig. 4. This model has recently been applied to ELMs [14], but may also apply to disruptions. The experimental radial velocities of ELMs measured on JET are surprisingly similar to this case [15].

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?

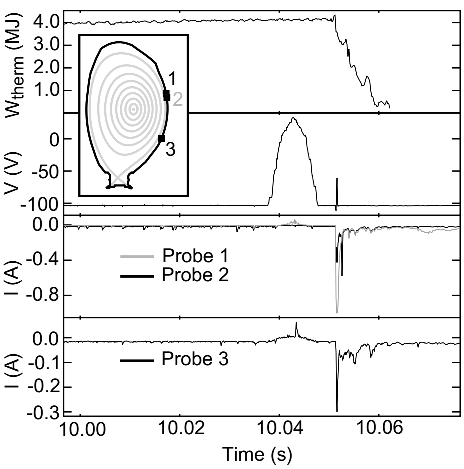

Fig. 3. Limiter Langmuir probe signals at the thermal quench of a disruption due to the collapse of an ITB, pulse 60885. Shown is the plasma thermal energy, the driving potential of the probe, three probe signals and the location of the probes. The current pulse occurs when the probe is at −100 V and is at least an order of magnitude greater than at earlier times in the pulse.

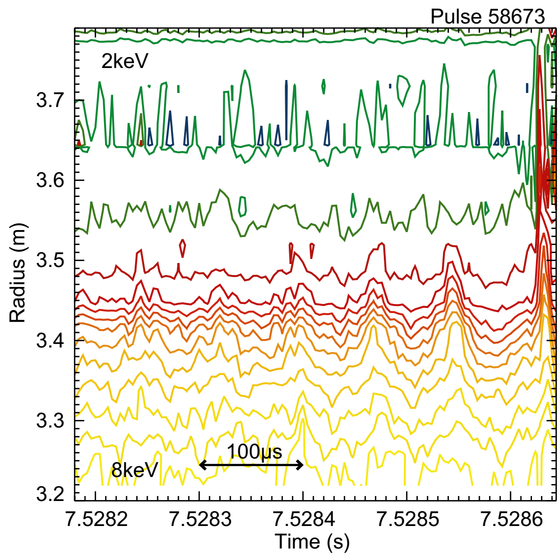

Fig. 4. ECE contour plot of electron temperature in the instant before the thermal quench for an ITB collapse disruption, pulse 58673. Contours are 500 eV apart. Plasma major radius, $R = 2.87\,m$, separatrix at $R = 3.84\,m$.

4. Discussion

During the thermal quench phase of disruptions, nearly the entire thermal energy content of the plasma is expelled (up to 10 MJ in JET). Recent results have shown even though the plasma is in a divertor configuration, usually less than 50% and sometimes only ~10% is conducted to the divertor. We have investigated some of the possible reasons behind this observation.

JET bolometers are nominally too slow to resolve the thermal quench in time so a full energy balance was calculated in order to determine how much of the total energy (thermal + magnetic) is radiated. Poynting's theorem was applied to the system to determine the magnetic energy flow. 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. Results from a temporary fast bolometer channel agree with this.

A possible explanation lies in conduction to the limiters/first wall. Circumstantial evidence from limiter Langmuir probes currently exists to support this hypothesis. A new wide angle IR system planned for 2005 JET operation 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. If these filaments penetrate into the scrape off layer or even to first wall surfaces, they would be an important mechanism in the disruption and a mechanism for conduction to the first wall in this class of disruption. The implications for future devices are severe.

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References

[1] G.F. Matthews et al., Nucl. Fus. 43 (2003) 999.
[2] P. Andrew et al., EPS Control. Fus. Plasma Phys., 2003, P-1.108.
[3] E.D. Fredrickson et al., Phys. Plasmas 3 (1996) 2620.
[4] K. Yamazaki, G.L. Schmidt, Nucl. Fus. 24 (1984) 467.
[5] A.W. Hyatt et al., EPS Control. Fus. Plasma Phys. (1996) 287.
[6] L.L. Lao et al., Nucl. Fus. 25 (1985) 1611.
[7] S.P. Hirshman, G.H. Heilson, Phys. Fluids 29 (1986) 790.
[8] J.A. Wesson et al., Nucl. Fus. 29 (1989) 641.
[9] V. Riccardo et al., Plasma Phys. Control. Fus. 44 (2002) 905.
[10] K.F. Mast et al., Rev. Sci. Instrum. 56 (1985) 969.
[11] G. Federici, A. Loarte, G. Strohmayer, Plasma Phys. Control. Fus. 45 (2003) 1523.
[12] G. Federici, A.R. Raffray, J. Nucl. Mater. 244 (1997) 101.
[13] S.C. Cowley et al., Plasma Phys. Control. Fus. 45 (2003) A31.
[14] A. Kirk et al., Phys. Rev. Lett. 92 (2004) 245002.
[15] W. Fundamenski et al., Plasma Phys. Control. Fus. 46 (2004) 233.