DISRUPTIONS AND HALO CURRENTS IN ALCATOR C-MOD

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ABSTRACT. Disruptions in Alcator C-Mod can generate large eddy currents in the highly conducting vacuum vessel and internal structures, including a significant poloidal component due to halo currents. In order to understand better the stresses arising from the resulting \( J \times B \) forces, Alcator C-Mod has been fitted with a comprehensive set of sensors to measure the spatial distribution and temporal behaviour of the halo currents. It is found that they are toroidally asymmetric, with a typical peaking factor of \( \Delta \gamma = 2 \). The asymmetric pattern usually rotates toroidally at a few kilohertz, thus ruling out first wall non-uniformities as the cause of the asymmetry. Analysis of the information compiled in the C-Mod disruption database indicates that the maximum halo current during a disruption scales roughly as either \( \frac{I_D}{B} \) or \( \frac{I_p}{q_{95}} \), but that there is a large amount of variation that is not yet understood.

1. INTRODUCTION

Disruptions are of great concern in tokamaks, primarily because of the potential for damaging the divertor, first wall and/or other plasma facing components. Disruption damage can be manifested in several different ways, including melting and vaporization of large quantities of surface material due to direct thermal deposition, and structural failures caused by forces due to currents induced in conducting structures by fast transients [1, 2]. Alcator C-Mod, by virtue of its high magnetic field, high plasma current, compact size and shaped plasmas [3] \( (\kappa \leq 1.85) \), is particularly well suited for studying very fast disruption current quenches (instantaneous \( \frac{dI_p}{dt} \) up to 1.4 MA/ms). The vacuum vessel is a thick walled (up to 5 cm) stainless steel structure with no insulating breaks, and therefore its one-turn resistance is only 40 \( \mu \Omega \) in the toroidal direction and \( \sim 10 \mu \Omega \) in the poloidal direction [4]. As a result, very large eddy currents, both toroidal and poloidal, can be induced in the vessel walls during disruptions. The penetration time constants for vertical and horizontal magnetic fields into the vessel are of order 15 ms, and the overall response time for control of the plasma current is of the order of 0.25 s. The vessel wall is protected by 2 cm thick molybdenum tiles.

Induced toroidal currents, and the \( J \times B \) forces they give rise to, can be reasonably well understood and modelled with axisymmetric plasma/circuit models, as used in codes such as TSC [5]. However, induced poloidal currents are neither well understood nor even sufficiently characterized experimentally, despite the fact that they can also give rise to forces on the vessel and internal hardware [6]. In particular, questions about magnitude, scaling, toroidal asymmetry and peaking, radial distribution, temporal behaviour, driving terms and current path need to be addressed before structural forces can be reasonably estimated. The desire to understand better these issues in Alcator C-Mod is the primary motivation for the work described in this paper. Since C-Mod is in some ways prototypical of future reactor designs, it is expected that these results will also be useful for specifying disruption-related engineering constraints.

2. DISRUPTIONS AND VDEs IN ALCATOR C-MOD

Disruption behaviour in Alcator C-Mod is similar to that of other tokamaks running elongated plasmas [7-9]. About a third of all discharges end in a major disruption, although in certain restricted operational scenarios the rate can be less than 5%. Disruptions due to excessive impurity radiation, excessive density (above the Greenwald limit [10]), excessive plasma current \( (q \leq 2) \) and \( n = 1 \) locked modes have all been observed. Whatever the specific mechanism, the result is a sudden increase in energy transport throughout the entire plasma volume, leading to a very rapid loss of plasma temperature and dumping of thermal energy. This phenomenon is commonly called the ‘thermal quench’ and an example as seen with the side-viewing X ray array data is shown in Fig. 1(a).
In Alcator C-Mod, the energy loss time is typically 0.5 ms. Quite often, a series of minor disruptions (i.e. partial thermal losses) leads up to the final thermal quench. Much of this energy is radiated to the walls, but some fraction is conducted in the scrape-off layer to the separatrix strike points, possibly leading to high thermal power loads in the divertor. About a millisecond after the thermal quench there occurs a momentary 10 to 15% increase ('spike') in the plasma current, as shown in Fig. 2, accompanied by a large negative spike in the loop voltage. Both of these classic disruption signatures are the result of a sudden flattening of the current profile [8, 11, 12].

The fast drop in $\beta_p$ and $\ell_1$ at the thermal quench leads to a sudden 3 to 4 cm inward shift (but no sudden downward shift) of the current centroid, as shown by the position traces in Fig. 2. The field decay index, which is typically $-0.7$ at the centre of the vessel, is much more negative at smaller $R$, causing the plasma to become more vertically unstable. It also results in a rapid increase in $\kappa$, as seen in the second frame of Fig. 3, which shows a series of magnetic flux reconstructions at 1 ms intervals. For this case, the plasma axis shifts in to a region where the field decay index is about 0.3 more negative than normal, and $\kappa$ jumps from 1.53 to 1.74. The growth rate of the $n = 0$ (i.e. axisymmetric) mode is about 800 s$^{-1}$, or about an order of magnitude faster than the penetration time for the horizontal magnetic field. Thus the plasma continues to move vertically, eventually terminating in plasma contact with internal hardware at the top or bottom of the vacuum vessel. In Alcator C-Mod disruptions, virtually all (> 99%) non-circular plasmas are lost vertically following the thermal quench. About 80% move towards the X point. The timescale of this vertical drifting phase is characteristically several milliseconds, as seen in the final frames of Fig. 3, and the terminal plasma velocity is typically $\sim 60$ m/s. During this time, the plasma cross-sectional area is shrinking at about 30 to 80 m$^2$/s, and the plasma current is decaying, albeit relatively slowly. Because of contact with the first wall (usually the inner and outer divertor hardware), the plasma equilibrium eventually switches from a diverted...
configuration to a limited one. At this time (typically 4 to 5 ms after the thermal quench) the final stage of the disruption begins. As shown in Fig. 2, this consists of a rapid drop of the remaining plasma current, accompanied by appreciable current flowing poloidally in the vessel structure. These poloidal currents are known as 'halo' currents [13], and will be discussed in detail in the next section. This final phase is commonly called the 'current quench', and in Alcator C-Mod its duration is usually 1 to 2 ms. Much of the stored magnetic field energy of the plasma current is transferred to nearby conducting structures via induced eddy currents, but some can also be converted directly into particle kinetic energy during the current quench, and eventually is deposited on plasma facing components.

The preceding disruption scenario (thermal quench followed by vertical drift followed by current quench) covers many of the disruptions on Alcator C-Mod. However, there is a significant proportion of
disruptions that are actually initiated by a loss of vertical position control, rather than by a thermal quench. This can be due to running excessively elongated plasmas, or to the finite voltage and current limits of the poloidal field (PF) power supplies, or even to intentionally disabling the vertical position control. The end result is that the plasma hits the top or bottom of the vessel and then disrupts, as shown by the side-viewing X-ray array in Fig. 1(b). These types of disruptions are often called vertical displacement events, or VDEs [14]. In Alcator C-Mod, the characteristics of the current quench and halo currents in VDE disruptions are similar to those of non-VDE disruptions, as shown in Fig. 4. The primary difference is that VDEs do not begin with a thermal quench, nor is there a clearly discernible spike in the plasma current. In VDE disruptions, the plasma hits the vessel top or bottom with all of its stored kinetic energy as well as its magnetic energy. The thermal quench and the current quench then occur simultaneously. The results discussed in the remainder of this paper apply to both classes of disruptions.

3. HALO CURRENT DIAGNOSTICS ON ALCATOR C-MOD

It is now known that during disruptions, significant current flows on open field lines in the scrape-off plasma outside of the last closed flux surface [15, 16]. This 'halo' current flows into the vessel wall (or other conducting plasma facing components) where one end of the open field lines contact, and flows out at the other end, thus forming a closed circuit which has a poloidal component. Since there is no appreciable plasma pressure on open field lines, the halo current presumably must flow in a nearly force-free configuration through the plasma exterior, i.e. along helical field lines. However, in the surrounding conducting structures there is no force-free restriction, and purely poloidal current is possible. (The exact current path in the structure depends upon its impedance and the direction of any induced electric fields.) In any case, the halo current has a finite poloidal component, and, coupled with a tokamak's strong toroidal field, large forces can be exerted on conducting structures. Note that this is in addition to forces arising from induced toroidal eddy currents. Furthermore, stresses on the vessel and conducting structures may be exacerbated even further if the halo currents are appreciably non-axisymmetric, i.e. exhibiting a locally peaked distribution toroidally.

In order to address these issues, Alcator C-Mod has been fitted with an extensive set of sensors for measuring the magnitude and spatial variation of poloidal halo currents during disruptions. These consist primarily of full Rogowski coils (which measure

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FIG. 4. Evolution of the plasma current, halo currents, position and cross-sectional area during the VDE disruption shown in Fig. 1(b). The vertical displacement (Z centroid) grows exponentially, in contrast to the linear behaviour exhibited by non-VDE disruptions.
I through the closed coil loop), segmented Rogowski coils (which measure $\int B_d \, dl$ over one tenth of the toroidal circumference) and current shunts (which measure a voltage drop across a known resistance).

Because of the $1/R$ dependence of the toroidal field, the highest $J_{\text{pol}} \times B_d$ forces will be on the inboard wall of the vacuum vessel, so it is important to know the halo current flowing vertically in that region. Two Rogowski coils completely encircle the inner wall, one at the top of the machine, the other at the bottom, as shown in Fig. 5(a). They occupy a small tunnel at the corner of two intersecting plates of protection tiles, and are therefore well protected from exposure to the plasma. Each winding measures the total current flowing vertically in the wall at the top and bottom, respectively. The toroidal field (TF) magnet current (27 MA-turns at 8 T) also passes through these Rogowski coils, and dominates the signal. During the initial operation of these full Rogowski coils, this TF pick-up was quite useful for verifying coil integrity and for in situ calibration. Thereafter, the slowly varying TF contribution was filtered out by simple AC coupling of the signals.

Toroidal variation of halo currents is measured independently by two different sets of sensors at two different locations, namely segmented Rogowski coils and current shunts. As shown in Fig. 5(b), the set of segmented Rogowski coils is conceptually a full Rogowski coil divided up into ten segments, and it...
FIG. 6. Peak halo current at the top and bottom of the vessel versus $I_p$ for downward disruptions, at fixed toroidal field. Note that the halo current reverses direction when the plasma current is reversed. The solid curve is proportional to $I_p^2 \times \text{sign}(I_p)$. (The value of $I_p$ is taken just prior to the disruption.)

is located immediately adjacent to the previously described full Rogowski coil on the bottom of the machine. The choice of 10 segments was dictated by the structure of the vacuum vessel, which has a tenfold symmetry (i.e. 10 sets of ports, 10 divertor modules, etc.). The top of the machine is not yet instrumented with segmented Rogowski coils.

There is also a set of 10 current shunts, one for each of the outboard divertor modules. Were it not for these shunts, the divertor modules would be electrically isolated from the vacuum vessel, but the shunts provide a conducting path through a mechanical attachment to the vessel. Each shunt has a resistance of 0.4 m$\Omega$, and the halo current flowing from the vessel through the divertor module into the plasma boundary is determined by measuring the voltage drop across the shunt. Note that the shunts and the segmented Rogowski coils enable independent measurements of the toroidal distribution of halo currents at two different poloidal locations — bottom inboard and bottom outboard.

Finally, an additional set of four segmented Rogowski coils, each also one tenth of a toroidal turn, has been installed along part of the inboard vessel wall at a single toroidal location, in order to determine the thickness and distribution of the current flowing in the halo layer as it enters the vessel wall. As shown in Fig. 5(c), the sensors are installed at four different vertical positions spaced 10 cm apart, from the inner divertor region up to the midplane.

FIG. 7. Peak halo current at the bottom of the vessel for downward disruptions versus $I_p$, for all $B_0$, indicating an inverse scaling with toroidal field. Scalings of the form $I_p^2/B_0$ or $I_p/q_{95}$ fit the data equally well. (The value of $q_{95}$ is taken just prior to the disruption.)

4. HALO CURRENTS

Extensive measurements of halo current magnitudes, directions, temporal behaviour and spatial distribution have been, and are continuing to be, studied during Alcator C-Mod disruptions using the instrumentation described in the preceding section.

The halo diagnostic signals are digitized at rates of up to 1 MHz for each disruption. A subset of these data, such as peak halo current, peak $dI_p/dt$ and disruption direction, is also compiled in a disruption database, which is useful for discerning general trends in the data. In this section, the behaviour of the total poloidal halo current, as measured by the full Rogowski coils in Fig. 5(a), will be described. The following sections will provide details of the toroidal and poloidal distributions of the halo currents.

Figure 2 shows the temporal behaviour of the total poloidal halo current at the top and bottom of the inboard wall of the vacuum vessel during a typical disruption (i.e. a thermal quench followed by downward motion). A significant amount of halo current flows in the bottom of the machine, while very little is seen at the top. In the ~20% of cases in which the disrupting plasma moves upwards, this behaviour is reversed; significant halo current flows only at the top of the machine. Unlike the magnitude, the direction of the poloidal current flowing in the inboard wall of the vacuum vessel is independent of the direction of plasma vertical motion. For the disruption exhibited in Fig. 2, for which $B_0$ and $I_p$ are in a
clockwise direction when viewing down on the torus from above, the halo currents in the inboard wall flow downward, as indicated by the arrows in Fig. 3. When the toroidal field and plasma current are reversed, the poloidal halo current also reverses direction. (C-Mod is always operated with co-parallel $B_\phi$ and $I_p$.) Thus, in all cases, the total poloidal halo current flows in the direction that generates a $J_{pol} \times B_\phi$ force tending to oppose both the vertical motion of the plasma and the reduction in toroidal flux due to the shrinking cross-section. Of course, the halo current flowing around the plasma exterior must presumably be following helical field lines in order to be force free, and therefore has a large toroidal component (not shown in Fig. 3).

The temporal behaviour of the total halo current closely resembles $dI_p/dt$, which is also shown in Fig. 2. In particular, the halo current peaks at about the same time that the maximum in $dI_p/dt$ occurs — typically several milliseconds after the thermal quench. In fact, for virtually all vertically moving disruptions (both VDEs and non-VDEs), the bulk of the current loss, the bulk of the halo current, and contact with structure at the top or bottom of the machine all occur simultaneously. In marked contrast, the plasma cross-sectional area starts decreasing as soon as the plasma begins moving away from the midplane, as shown in Fig. 2. This suggests that the driving voltage for halo currents may be due to the toroidal electric field generated by $dI_p/dt$ rather than any poloidal electric field generated by reduction of magnetic flux within the plasma cross-section. (Presumably both toroidal and poloidal electric fields could drive halo currents, since they should flow helically around the plasma.)

As mentioned previously, data on halo currents, as well as other disruption phenomena, are compiled into a database, which is useful for determining trends in the data. In Fig. 6, the peak upper and lower halo currents, as measured by the full halo Rogowski coils, are plotted versus $I_p$ for all downward-going disruptions with $|B_\phi| = 5.3$ T. (The plasma current plotted here is the value just prior to the disruption.) Clearly, the bulk of the halo current flows in the vicinity of the vacuum vessel towards which the plasma moves. At this toroidal field (which constitutes the bulk of plasma operation to date), the peak halo current increases roughly quadratically with plasma current, although there is a large amount of scatter in the data. Operations over a large range in toroidal field ($1.5 \leq |B_\phi| \leq 8.2$ T) indicate an inverse scaling with $B_\phi$, leading to either an $I_p^2/B_\phi$ or an $I_p/q_{95}$ scaling, as shown in Fig. 7.

A scaling law for peak halo current may be useful for extrapolating to the higher $I_p$ and $B_\phi$ operational parameters that are planned for Alcator C-Mod. However, there is a considerable amount of scatter in the data, so it is also important to have an estimate of the variation, and of the ‘worst case’ value of peak halo current as well. Figure 8 shows the probability distribution of the ratio of peak halo current to $I_p$ for disruptions with $B_\phi = 5.35$ T and $I_p = 0.8$ MA. For these parameters, the mean ratio is 15%, but the distribution ranges about ±5 percentage points about the mean, or about ±1/3. We currently have no explanation for this variation. In particular, we find no correlation between the scatter in $I_{halo}/I_p$.
and the current quench rate, \( (dI_p/dt)/I_p \). Also shown in Fig. 8 are a handful of cases which have \( I_{\text{halo}}/I_p \) above 30%, with the worst having a peak halo current of 50% of \( I_p \). We know that the most extreme outliers occurred when the horizontal field power supplies saturated while trying to run unusual plasma shapes, so it is possible to avoid these cases.

The disruption database also contains information on the peak current quench rate for each disruption. The peak current quench rate is defined as the maximum instantaneous amplitude of \( dI_p/dt \) during a disruption. The derivative is not smoothed, i.e. it is calculated by the simple two-point difference method. On Alcator C-Mod, the peak quench rate scales roughly linearly with \( I_p \), which indicates that the time-scale for the bulk of the current loss is \( \sim 1-2 \) ms, independent of plasma current, as shown in Fig. 9. This is consistent with the signals shown in Figs 2 and 4. As with the peak halo currents, there is a considerable amount of scatter in the data, particularly for upward-going disruptions. Despite the scatter, it is apparent from Fig. 9 that the fastest current quenches occur in upward or centred disruptions. Note that there is no upper divertor in C-Mod, and thus there is less conducting structure at the top of the vacuum chamber compared with the bottom.

5. TOROIDAL DISTRIBUTION OF HALO CURRENTS

Mechanical stresses arising from \( J_{\text{halo}} \times B_\phi \) in the vacuum vessel, first wall and other conducting structures can be greatly exacerbated if the halo currents are not uniformly distributed toroidally. Measurements of the toroidal distribution of halo current using the array of ten divertor shunts is shown in Fig. 10 for three different times during a disruption. The time slices are separated by about 100 \( \mu \)s. In each time slice, the toroidal distribution is clearly not uniform, with a peak-to-average value of \( \sim 2 \), and a structure that can be roughly described as a combination of an \( n = 0 \) component and an \( n = 1 \) component of comparable magnitudes. (Fourier analysis usually shows a small \( n = 2 \) component as well.) The degree of toroidal asymmetry changes from shot to shot, but
FIG. 12. Comparison of toroidal distribution of halo currents measured with both the divertor shunts and the segmented Rogowski coils. The data are from a disruption that exhibited two complete rotations of the halo current pattern. The two sets of measurements, from two different locations, show the same structure and phase.

In some cases the rotation gradually slows down (even to near zero frequency); in other cases it speeds up; in still other cases the toroidal structure does not rotate at all. So far, we have not discerned any correlation between the toroidal asymmetry and/or rotation of halo currents with global parameters of the disruption (i.e. $dI_p/dt$, $q_0$, type of disruption, etc.).

Comparison of the toroidal distribution of halo currents measured by the segmented Rogowski coils and by the divertor shunts shows identical structure and identical phase with respect to toroidal angle (within a measurement resolution of one tenth of 360°), as shown in Fig. 12. This implies that within the stainless steel wall of the vacuum vessel, the halo current flows poloidally, with little or no toroidal component. This is not necessarily surprising, since the path of least resistance is poloidal, and the current flow does not have to be force free. However, to complete the circuit, the halo current must leave the outer divertor at one end of the open field lines, flow across the top of the plasma in a presumably
force-free, and thus helical, direction and re-enter the wall at the inboard end of the open field lines. The fact that our measurements show that the inboard and outboard halo currents have identical structure and phase implies that the helical flow must make an integral number of toroidal transits in going from the outboard to the inboard contact points. Thus, there may be a resonance in field line helicity involved in the flow of halo currents, and perhaps in the current quench itself. Another possibility is that an \( m = 2/n = 1 \) MHD instability is playing a role in the current quench. This is also plausible, since \( q_a \approx 2 \) at the time of the quench for most of our disruptions. To date, we have not found a magnetic signature of an \( m = 2 \) mode, but this may be because the plasma ends up very far away from most of the \( B_p \) probes. We are currently studying these interesting implications in greater detail.

6. POLOIDAL DISTRIBUTION OF HALO CURRENTS

In addition to the measurements of the toroidal distribution of halo currents, there are also data on the vertical distribution, as measured by the set of segmented Rogowski coils described previously in Section 3 and shown in Fig. 5(c). Figure 13 shows the vertical array data for a typical downward disruption. Only the lowest sensor registers significant halo current. Halo current flows into the inboard wall only in the vicinity of the inboard divertor hardware, which indicates that the thickness of the halo current layer is rather small. The lack of appreciable signal on the next higher sensor places an upper limit on the halo layer thickness that corresponds to \( \sim 3 \) cm when mapped back to the plasma midplane. This example is representative of all downward-going disruptions. Curiously, the halo current seen in the lowest wall sensor always peaks noticeably after the halo current measured at the bottom of the vessel, possibly suggesting that the halo layer spreads upward at the very end of a downward-going disruption.

For the few disruptions that stay near the midplane, the halo diagnostics at the bottom and top of the vessel see no halo currents. However, the midplane sensor on the inboard wall does detect significant halo current, as shown in Figs 14 and 15. The magnitude is comparable to that seen for vertical disruptions with similar plasma current and field. The next lower sensor in the inboard wall detects nothing, which is another indication that the halo current layer is thin. Although the number of vertically stable disruptions is very small, halo current is always seen on the midplane sensor in these cases. Therefore, it is reasonable to conclude that vertical motion by itself does not directly generate halo currents [17]. The axisymmetry of halo currents at the midplane is not measured.

7. SUMMARY

Owing to its compact size, high \( B \) field, high current density and highly conducting vacuum vessel, disruptions in Alcator C-Mod result in substantial eddy currents and \( J \times B \) forces on tokamak structures. Studies using a comprehensive set of diagnostics on C-Mod show that large halo currents are generated only during the current quench portion of disruptions, with a temporal evolution that closely resembles \( dI_p/dt \), suggesting that halo currents are
Disruption sequence, shot 950112008

FIG. 14. Magnetic flux reconstructions at 1 ms intervals for a midplane-centred disruption. The arrows show the poloidal projection of halo current flow, which exists primarily during the last two frames.

FIG. 15. Data from the vertical array of four halo Rogowski segments on the inboard wall for the midplane-centred disruption shown in the previous figure. Halo current is observed on the midplane sensor.

primarily driven by induced toroidal rather than poloidal electric fields. Significant halo currents are observed only in the region of the vessel towards which the disrupting plasma moves. The halo currents have a large toroidal asymmetry, with a typical peak-to-average ratio of 2, and a predominantly \( n = 1 \) structure that usually rotates toroidally. They flow in a relatively thin layer (\( \sim 3 \) cm) outside the last closed flux surface. Halo currents exist even in disruptions that remain positioned on the midplane. Analysis of our disruption database indicates that the maximum halo current during a disruption scales like \( I_p^2/B_\phi \) or \( I_p/g_0 \), but that there is a large amount of variation, which for the most part is not understood. Data from the halo diagnostics are currently being used to refine engineering calculations of the stresses and deformations of the C-Mod vacuum vessel and internal components.

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