

PFC/JA-96-41

**Disruptions, Halo Currents, and
Killer Pellets in Alcator C-Mod**

R.S. Granetz, I.H. Hutchinson, J. Sorci, D. Garnier, J. Irby,
B. LaBombard, E. Marmor and the Alcator Group

October 1996

To be published in the Proceedings of the 16th IAEA Fusion Energy Conference.

This work was supported by the U. S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

DISRUPTIONS, HALO CURRENTS, AND KILLER PELLETS IN ALCATOR C-MOD

1. ABSTRACT

During the current quench phase of disruptions in Alcator C-Mod, large poloidal 'halo' currents flow in the conducting vacuum vessel and internal structures. In order to better understand these halo currents and the stresses arising from the resulting $J \times B$ forces, Alcator C-Mod has been fitted with a comprehensive set of sensors to measure their magnitude, temporal evolution, and spatial distribution. It is found that these halo currents are toroidally asymmetric, with peaking factors (i.e. peak/average) typically about 2, although extreme cases can go well above 3. The asymmetric pattern usually rotates toroidally at a few kHz, thus ruling out first-wall non-uniformities as the cause of the asymmetry. Analysis of information compiled in the C-Mod disruption database indicates that the maximum halo current during a disruption scales roughly as either I_p^2/B_ϕ or I_p/q_{95} , but that there is a large amount of variation which is not yet understood. Attempts have also been made to reduce the magnitude of halo currents flowing in the divertor region of the vacuum vessel by injecting high-Z doped pellets to greatly speed up the current quench.

2. INTRODUCTION

Disruptions are of great concern for tokamaks, primarily because of the potential for damaging the divertor, first wall, and/or other plasma facing components. Disruption damage can be caused by localised thermal deposition on the first wall, as well as structural failure due to $J \times B$ forces arising from induced currents. Alcator C-Mod, by virtue of its high magnetic field, high plasma current, compact size, and shaped plasmas is particularly well-suited for studying fast disruption current quenches (instantaneous dI_p/dt up to 1.4 MA/ms). Due to its highly conducting first wall, very large eddy currents, with a significant poloidal component due to halo currents^[1-4], can be induced in the structure.

Disruption sequence, shot 950112013



Figure 1— Magnetic flux reconstructions at 1 ms intervals of a typical disruption. The arrows show the poloidal projection of halo current flow. The current path in the plasma scrape-off must actually be helical, in order to be force-free.

Disruption research on Alcator C-Mod has concentrated on measuring the temporal behavior and spatial distribution of these halo currents, characterising the scaling of their magnitude with plasma current, dI_p/dt , κ , etc., and identifying ways of reducing their magnitude, including injection of killer pellets.

Most of the results presented in this paper have been obtained using an extensive set of Rogowski current sensors specifically designed for measuring halo currents. Two Rogowski coils completely encircle the inboard cylindrical wall of the vacuum vessel at the top and at the bottom, and measure the *total* halo current flowing in the vessel wall. The lower coil is situated close to the inboard half of the divertor structure. An additional coilset is also located at the position of the lower full Rogowski, but its length is segmented into 10 ‘partial’ sensors. (Alcator C-Mod has a ten-fold toroidal symmetry, i.e. 10 sets of ports, 10 divertor modules, etc.) This array provides information on the toroidal structure of halo currents in the vicinity of the inboard divertor. The outboard half of the C-Mod divertor is functionally toroidally continuous, but is actually comprised of 10 discrete modules. Each module is mechanically and electrically attached to gussets welded to the vacuum vessel. An array of 10 ‘gusset’ Rogowski sensors measure the currents through the contact points, providing information on the toroidal structure of halo currents in the vicinity of the outboard divertors. Additional sensors for determining the vertical distribution of halo current in the inboard wall, as well as instrumentation to directly measure mechanical strains, have also been installed.

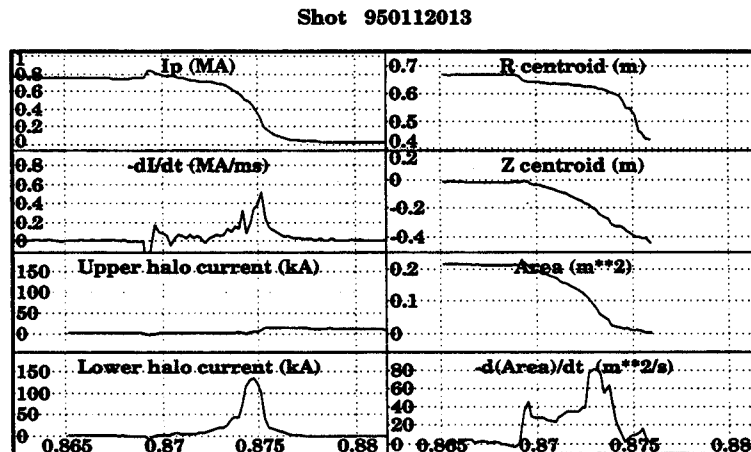


Figure 2— Evolution of plasma current, upper and lower halo currents, etc. for the disruption shown in Fig. 1. Note that for a downward disruption, appreciable halo current only flows in the lower portion of the vacuum vessel.

3. HALO CURRENT CHARACTERISTICS

In Alcator C-Mod virtually all disruptions are either caused by, or result in fast vertical displacement of the plasma ($\sim 80\%$ move towards the x-point), eventually terminating in contact with internal hardware at the top or bottom of the vacuum vessel. For downward-going disruptions, large halo currents flow in the bottom of the machine, while very little is seen at the top, as shown in Figs. 1 and 2. For upward-going disruptions this behavior is reversed. 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 normal configuration (B_ϕ and I_p in the clockwise direction when viewing down on the torus from above), the halo currents in the inboard wall flow downward. When

the toroidal field and plasma current are reversed, the poloidal halo current reverses direction as well. Thus, in all cases the total poloidal halo current in the plasma SOL flows in the direction which generates a $J_{\text{pol}} \times B_{\phi}$ force tending to oppose the vertical motion of the plasma. Measurements of the halo current magnitude over a wide range of operating parameters ($0.2 \leq |I_p| \leq 1.2$ MA, $1.5 \leq |B_{\phi}| \leq 8.0$ T) indicate that the peak current scales as either I_p^2/B_{ϕ} or I_p/q_{95} , as seen in Fig. 3, with a large degree of scatter, not all of which is understood. No independent variation with elongation is observed.

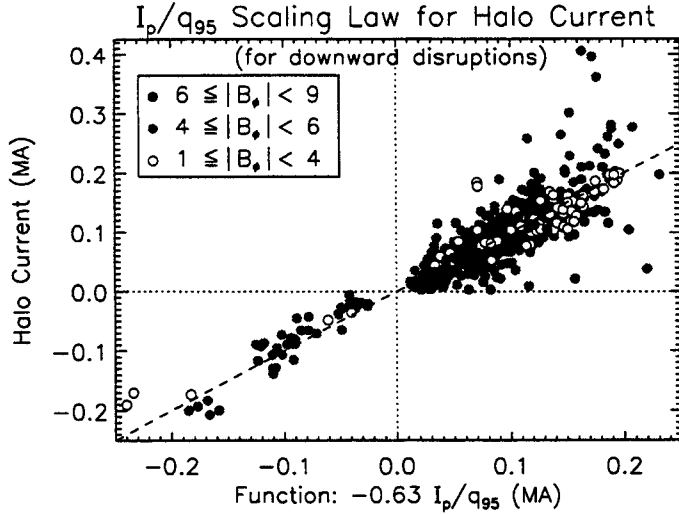


Figure 3— Peak halo current at the bottom of the vessel for downward-going disruptions. Scalings of the form I_p^2/B_{ϕ} or I_p/q_{95} fit the data equally well. (The values of I_p and q_{95} are taken just prior to the disruption.)

4. TOROIDAL STRUCTURE OF HALO CURRENTS

Spatially resolved measurements of halo currents reveal significant toroidal asymmetry, which is usually well characterised as an $n = 1$ component superimposed on an $n = 0$ background (although a few examples having $n = 2$ structure have also been seen). The amplitudes of the two harmonics are comparable, resulting in toroidal peaking factors (i.e. peak/average) of order 1.5–2. Furthermore, this asymmetric pattern usually rotates toroidally at a few kHz, as shown in Fig. 4, thus ruling out first-wall non-uniformities as the cause of the asymmetry. When I_p and B_{ϕ} are reversed, the halo rotation also reverses. The $J \times B$ force due to halo current is locally exacerbated by the toroidal peaking. However, for the few disruptions with unusually high halo current fractions, the peaking factors have all been relatively low.

Comparison of the halo currents flowing through the outboard divertor (measured with the array of ‘gusset’ Rogowskis) and through the inboard divertor (measured with the array of ‘partial’ Rogowski segments) reveals nearly identical toroidal structure *and* toroidal phase, as shown in Fig. 5. This implies that the halo current path through the bottom portion of the vessel wall is purely poloidal. Since the halo current must form a closed circuit between first wall contact points by flowing around the plasma periphery, and since this flow must be helical in order to satisfy force-free constraints, a resonance condition on the field-line helicity may be involved in the development of halo currents and perhaps in the current quench as well. Axisymmetric reconstructions of the plasma equilibrium suggest that this is true, however, full 3-D MHD recon-

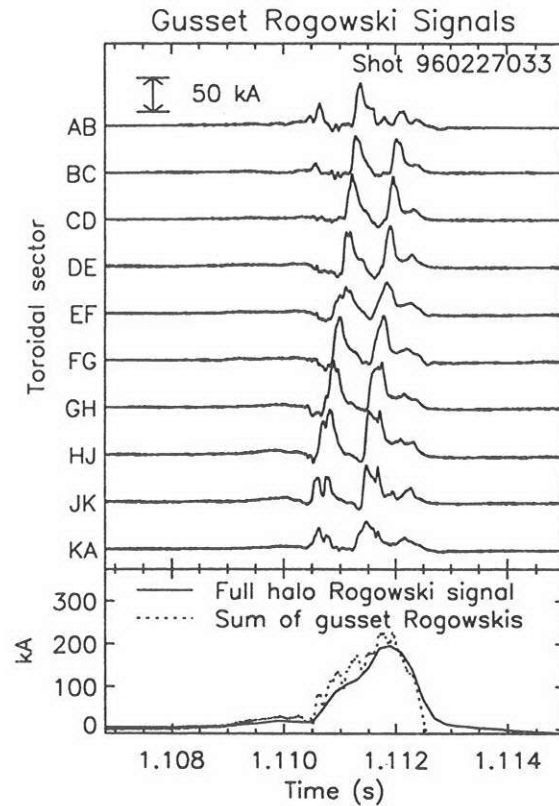


Figure 4— Halo currents flowing through the outboard divertor modules, as measured by the toroidal array of ‘gusset’ Rogowski coils, during a disruption. A rotating $n = 1$ structure is clearly seen.

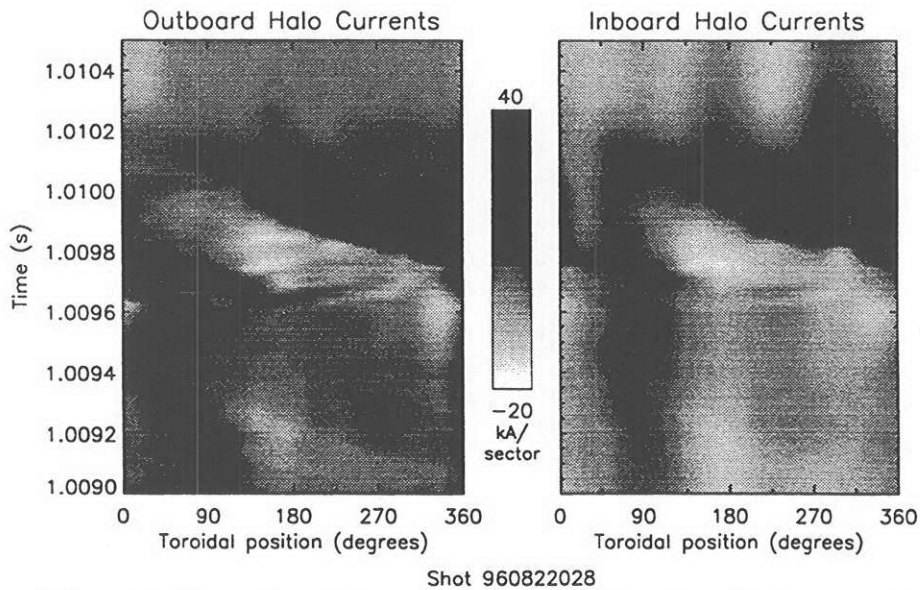


Figure 5— Comparison of the toroidal structure and rotation of halo currents flowing through the outboard divertor (measured with the ‘gusset’ Rogowskis) and the inboard divertor (measured with the ‘partial’ Rogowski segments). The two sets of measurements, from two different poloidal locations, show nearly identical toroidal structure and phase.

structions may be necessary to properly describe the plasma configuration when significant halo currents have developed.

5. KILLER PELLET RESULTS

Experiments aimed at reducing the deleterious effects of disruptions on the divertor have been carried out using “killer” pellets, as proposed by ITER^[5]. The goal is to eliminate both the stored thermal and magnetic energy by enhanced radiation before the plasma has time to move a significant distance downwards. In Alcator C-Mod, this requires the dissipation of about 1 MJ in 500 μ s. In principle this can be accomplished with a few milligrams of any high- Z metal. An additional requirement is that the electron temperature must be reduced to ≤ 10 eV in order to increase the plasma resistance enough to give a sufficiently fast L/R time for the current quench. The best results to date have been obtained by injecting plastic pellets impregnated with 2.5 mg of silver powder. The disruption quench time has been reduced from ~ 5 ms to 1 ms, resulting in a two-fold reduction of halo current in the divertor region, as shown in Fig. 6. These accelerated quench disruptions also exhibit a short burst of hard x-rays at the time of pellet ablation, indicating probable generation of runaway electrons.

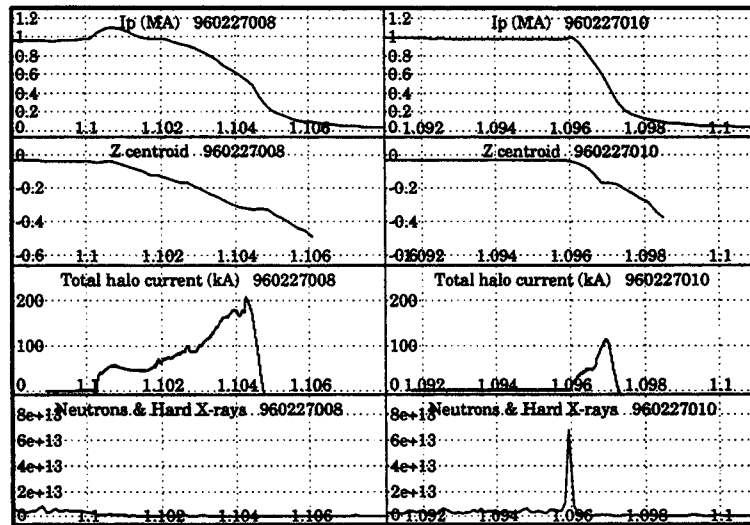


Figure 6— Comparison between typical current quench (on left) and killer pellet accelerated quench (on right). Due to the shorter quench time, the vertical displacement is reduced, resulting in less halo current in the lower part of the vessel.

REFERENCES

- [1] JENSEN, T.H., CHU, M.S., Phys. Fluids B 1 (1989) 1545.
- [2] PICK, M.A., NOLL, P., BARABASCHI, P., MARCUS, F.B., ROSSI, L., “Evidence of Halo Currents in JET”, in Proceedings of the 14th Symposium on Fusion Engineering, San Diego (1991) 87.
- [3] GRUBER, O., LACKNER, K., PAUTASSO, G., SEIDEL, U., STREIBL, B., Plasma Phys. Control. Fusion 35 (1993) B191.
- [4] R.S. GRANETZ, I.H. HUTCHINSON, J. SORCI, J.H. IRBY, B. LaBOMBARD, D. GWINN, Nucl. Fusion 36 (1996) 545.
- [5] G. JANESCHITZ, for ITER-JCT and Home Teams, Plasma Physics and Controlled Fusion 37 Suppl 11A (1995) p. A19.