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ENGINEERING ASPECTS OF DISRUPTION CURRENT DECAY

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ABSTRACT

Engineering features associated with the configuration of a tokamak can affect the amount of energy that produces melting and damage to the limiters or internal wall surfaces as the result of a major disruption. During the current decay period of a major thermal disruption, the energy that can damage a wall or limiter comes from the external magnetic field. By providing a good conducting torus near the plasma and increasing the plasma circuit resistance, this magnetic energy (transferred by way of the plasma circuit) can be minimized. This report addresses engineering design features to reduce the energy deposited on the inner torus surface that produces melting of the structures.

1. INTRODUCTION

Disruption has been a major problem in experimental efforts associated with tokamak plasma physics. Present machines have not been designed to withstand major disruptions. Therefore, the primary effort has been to learn how to avoid them in order to prevent a large influx of impurities and the damage that results in a machine shutdown. The second most important effort has been to gain an understanding of how disruptions start and how to prevent them. This paper considers only the engineering features associated with the current decay phase of the disruption. The main emphasis will be on how to minimize the damage for the worst-case condition on future large fusion devices.

There is an assumed understanding that increasing disruption time is a desirable goal. This is partially true for the current decay phase, but not true for the thermal decay phase. If a major thermal disruption occurs, the thermal energy in the core of the plasma is transferred to the outer surface of the plasma. The predominant portion of the energy will be deposited on the limiter or on whatever is in contact with the plasma. The plasma radial position does not change greatly during this phase of the disruption, and there is not a large change in plasma current magnitude. If the thermal decay occurs very fast, the material in contact with the plasma edge will ablate and there will be a loss of surface material. If, however, the thermal decay time is long (milliseconds instead of microseconds), the surface material will melt and the electromagnetic forces can displace the liquid metal. This will result in a much larger loss of surface material.¹

The advantage of a long disruption time is in the current decay phase. This is intuitively understood, but the specifics have not always been determined. The decay of the external magnetic field should be long, although not necessarily the decay time of the plasma current. After the thermal disruption time has elapsed (less than $125 \mu s$ in Doublet III)², the energy remaining is primarily in the magnetic field external to the plasma. If this energy can be deposited

in the bulk of a vessel as I^2Rt energy, damage resulting from the current decay need not occur. How fast the plasma current decays under these conditions is not important.

2. ENGINEERING FEATURES

The vessel electromagnetic design features should be

- (1) a low impedance vessel, close to the plasma and
- (2) enhanced toroidal current paths and poor radial current paths in the vessel structure.

The low impedance current path allows vessel currents to support the external field in the event of a disruption and to dissipate the energy in ohmic heating of the vessel. Radial currents are not desired because they interact with the intense toroidal fields and produce high forces. The toroidal currents are at right angles to the lower intensity poloidal fields; hence, the resultant forces are an order of magnitude lower than for radial currents. The low impedance path near the plasma eliminates the possibility of inducing high voltages in the poloidal field coils and insulation breakdown due to disruption, it eliminates the possibility of arc voltages developing and the resultant arc erosion, and it reduces the eddy current heating in the superconducting coil structure and the possibility of driving the superconductors normal during a disruption. Finally, a good conducting shell near the plasma provides self-position control stabilization. This results in a minimum-size active position control system.

To further understand the advantage of or need for a good conducting wall or sets of toroidal conductors as close to the plasma as possible, the two cases in Fig. 1. can be analyzed. In case A, there is no conducting vessel near the plasma, only two internal limiters. If the magnetically stored energy is 100 MJ, the approximate value for future tokamaks, then a current disruption in case A will result in essentially 100 MJ being deposited on the surface of the limiters. The energy per unit area will be large, and excessive melting and loss of material can occur. Note that the bulk of the magnetic energy is deposited as thermal energy on the limiters. As the plasma

CASE A

CASE B

Fig. 1. Disruption configuration cases.

loses its equilibrium due to the thermal disruption effects, it can move into the limiter. Once this inward motion starts, it further reduces the current and equilibrium and speeds the plasma current decay. There is an avalanche effect. The process is one in which the plasma movement inward is limited by the inner radius of the limiter. As the external field decays, its energy goes into ohmically heating the remaining plasma, which in turn deposits the energy thermally on the limiter by conduction. *The current decay time is basically how fast the plasma transfers the thermal energy to the limiter.*

In case B, which has a good electrical conductor at the wall behind the scrape-off region, the plasma can move into the wall or limiter, but the external field can be maintained by the vessel eddy currents. In this case, the external stored energy is deposited primarily as I^2R heating in the vessel. The melting of the limiters or the vessel walls due to the magnetically stored energy can essentially be eliminated. Note that it isn't really the time decay of the plasma current that is significant in determining the damage to the structures for the case of a major thermal disruption. A fast decay of plasma current is not necessarily damaging. The important factors are actually the time decay of the magnetic field and where the energy is deposited. To be effective in absorbing the external magnetic energy, the torus resistance must be low in comparison to the plasma resistance after the thermal decay has occurred.

Two conditions of thermal disruption are presented to show how the current decay phase of disruption should be considered from an electromagnetic design viewpoint. The first will be a minor thermal disruption, and the second will be a major thermal disruption. In condition 1, the plasma will be hot compared to 100 eV following the thermal quench. In this case, the good conducting shell will allow a small powered active position control system to maintain the current in the center of the vessel. The tokamak could then be shut down normally or the plasma reheated. In condition 2, the temperature following the thermal quench would be low (100 eV or less). In this case, the thermal energy has essentially been dissipated in the limiter and only the magnetic energy remains to inflict additional damage. To maintain the plasma in the

center of the vessel and to maintain the plasma current, it would require a large power system for heating and to maintain equilibrium. The large influx of impurities would also add to the power required. A better process for handling the major thermal disruption is to absorb the external field energy in the conducting shell near the plasma and prevent the energy from being absorbed as ohmic heating of the plasma. The system can be shut down with no ohmic heating or heating power and the PF coil currents lowered as quickly as possible to further aid in removal of the external magnetic field energy.

The resistance of the conducting shell near the plasma should be comparable to the resistance of the plasma at a temperature of approximately 100 eV. In the Fusion Engineering Device (FED) Baseline or DCT-8/TFCD, this value should be $4.5 \times 10^{-6} \Omega$. Its time constant would be approximately 1 s.

In FED studies, as in ref. 3, a vessel time constant of a half second resulted in a plasma current decay of 30 ms. The important point is that 98% of the magnetic energy went into the electrical heating of the wall or the external power system. Only 2% was directly deposited as thermal energy on the wall surface. The self-stabilization of the conducting wall prevented the plasma from moving quickly into the wall.

With a good conducting wall near the plasma, the current decay phase for a minor disruption can be avoided by a feedback control system, which maintains the plasma in equilibrium at the center of the vacuum vessel. With a good conducting passive circuit near the plasma, this can be accomplished with a relatively low power control system. For the FED design, an active control system of 32-MW peak (8-MW rms) was adequate to maintain equilibrium in time scales of a few milliseconds.⁴

3. CONCLUSIONS

To minimize the ablation and melting of the limiters or walls of a tokamak during disruption, the following steps should be considered:

- (1) For a major thermal disruption, the thermal energy in a hot plasma will essentially be dissipated in the limiter or by radiation.
- (2) For a major thermal disruption, the external magnetic energy,

which is approximately equal to the ignited thermal energy, can be dissipated in a good conducting shell without adding to the plasma thermal heat load on the limiter or first wall surfaces. (Any damage can be limited to that produced by the thermal decay phase of disruption.)

- (3) The damage due to a minor thermal disruption can be minimized by providing a passive circuit near the plasma. With a shell having a few hundred millisecond time constant, an active feedback control system rated for a few megawatts will be sufficient.³ (The active control should provide variations in the equilibrium field and not ohmic heating power.)
- (4) With a low impedance shell, high voltages will not be produced on coils and structures during a disruption. A low impedance shell will result in less heat on superconducting structures and will reduce arc damage.
- (5) The disadvantages of a long time constant structure near the plasma are the possible large energy for startup and the need to provide electrical connections between removable shield segments. Startup should be achievable by utilizing rf with an ohmic heating coil voltage of less than 10 V per turn. (This should not be a limitation on the design.)

In the case of a major disruption, maintaining the plasma current from decaying quickly is not the important factor. Keeping the thermal energy from melting the surfaces and the electromagnetic forces from becoming excessive is important.

Appendix A. DESIGN OPTIONS FOR REDUCING DISRUPTION DAMAGE

A-1. The primary objective in preventing disruption damage is to provide a good conductor adjacent to the plasma that will absorb the external magnetic stored energy. To provide this, a low voltage startup development is most advantageous. The aim should be to start up with less than 1 V per turn provided by the ohmic heating system. Use of rf [electron cyclotron resonance heating (ECRH) and lower hybrid resonance heating (LHRH)] for initially heating the plasma and for current drive should be pursued. Startup with electron-beam-assisting LHRH current drive should also be pursued.

A-2. The plasma circuit should have high resistances during the current decay phase of disruption. There are a number of methods which could provide the advantageous condition:

- (a) Pulsing cold gas into the plasma, especially near the inner walls and limiter.
- (b) Injecting excessive fuel pellets to cool the plasma.
- (c) Inserting or allowing the plasma to move toward getter material, which would aid in improving the vacuum for the subsequent operations.
- (d) Injecting impurities, which would provide large radiation power and thus reduce the energy deposited on the limiter surface.

A-3. The operations could possibly utilize the following:

- (a) Driving the plasma toward areas where the thermal energy could be safely dissipated.
- (b) Using material such as graphite, which withstands transient excessive short period temperatures, for areas such as (a) above. (These need not be in contact with the

plasma in normal operations.)

- (c) Designing the limiter to allow halo or scrape-off regions around the plasma to carry currents during the disruption to control where the heating occurs. [Putting holes and slots in the limiter could result in disruption energy being deposited in the larger areas of the limiter not normally in contact with the plasma in normal operation (see Fig. A.1).]
- (d) Subdividing the limiter in the toroidal direction to provide larger impedance paths through the limiters⁵ (with less current and heat produced in limiters).

A-4. On existing machines such as the Tokamak Fusion Test Reactor (TFTR), disruption damage may be reduced by the following:

- (a) Shorting out as many bellows or insulating breaks as possible with straps of tungsten, which have lower resistance than the bellows.
- (b) Providing good toroidal conductors, which are open circuited during startup but are closed after startup.
- (c) Installing toroidal bus bars external to the vacuum vessel. Switches required to complete the circuit after startup may be mechanical or solid-state semiconductors.

The position of these conductors in (c) above could assist in controlling the position of the plasma during the current decay phase, which could result in depositing of the magnetic energy at a desirable location.

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LIMITER WITH CAVITIES

Fig. A.1. Toroidal limiter configuration.

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