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Doublet III is a large non-circular tokamak (R = 1.4 m, a = 0.45 m, plasma elongation 3:1) that is now operating at General Atomic Company in San Diego. It has a toroidal magnetic field of 2.6 T, an ohmic heating flux swing of 5 V-sec and has delivered plasma currents in excess of 2 MA with a flat top of ∿ 300 msec. The machine can be upgraded to $B_T \simeq 4$ T, $\Delta\phi \simeq 10$ V-sec, $I_p \simeq 5$ MA with a multi-second flat top as physics experiments deem necessary.

An 80 keV neutral beam injector system has been designed[1] and is now in the final construction phase. The first two beamlines, which will be capable of delivery ∿ 7 MW of energetic hydrogen neutrals to the plasma, will be coupled to the torus in 1980. Additional pairs of beamlines will be procured as quickly as possible to increase the injected power to ∿ 20 MW. This should enable us to attain simultaed reactor conditions ($n\tau \sim 10^{14}$ cm^{-3} sec, T ∿ 5-10 keV) in a hydrogen plasma.

We expect that at the time that the neutral beam system comes on line, Doublet III will routinely operate with plasma densities of about 1×10^{14} cm^{-3}. Beam penetration studies show that an 80 keV injection system with ion sources conservatively rated to deliver a species mix of 60% H_1^+, 30% H_2^+ and 10% H_3^+ can provide significant heating of the central plasma region when injection at 14° to the perpendicular is used as shown in Fig. 1. Initially we expect to limit the beam heating pulse length to 0.5 seconds. However, as the machine upgrade proceeds we anticipate that this heating pulse will be stretched significantly and acceleration of other ions (for example, deuterons) will be employed.

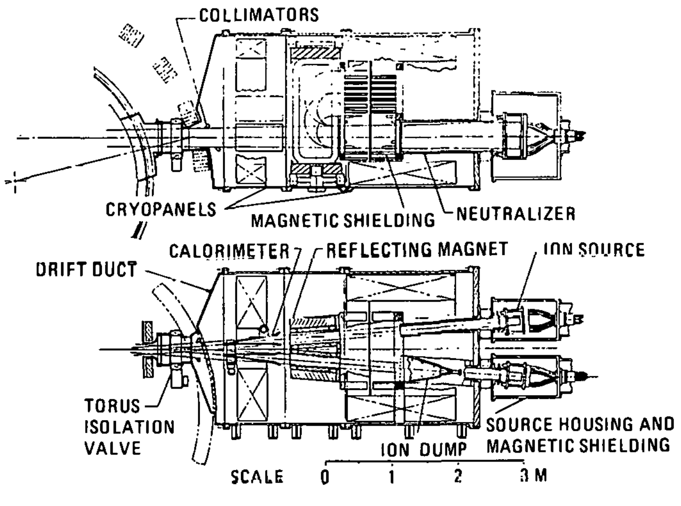

Fig. 1. Plan and elevation views of the Doublet III Neutral Injection Beamlines

One consequence of the use of near-perpendicular injection, as shown in Fig. 1, is that significant "shine through" of the neutral beam to the inner wall of the torus can occur at low plasma densities. Because the vacuum vessel wall itself cannot withstand any substantial power flux ≤ 100 watt/cm^2), we propose to place armor plates on the wall in the region bombarded by the beams. Similar protective plates are to be used at Princeton for the PDX and TFTR experiments.

Physics Design Parameters

Each beamline utilizes two LBL-type rectangular ion sources and the divergence of the beams produced is approximately ±1.5° × ±0.5° (1/e points). For hydrogen operation, the nominal neutral power delivered by one ion source to the plasma is expected to be 1.8 MW for 0.5 sec every 300 seconds. In the absence of a plasma, when no attenuation of the injected beam takes place, we therefore calculate that the power density at the inner wall of Doublet III, when measured normal to the beam through the hottest spot, will be as shown in Fig. 2. The peak power density is seen to be ∿ 5 kW/cm^2 normal to the beam. If deuterium acceleration is used instead, the extracted beam current drops by ∿ $\sqrt{2}$ but this is offset by the increased neutralization efficiency (80 keV D^+ ions have the same velocity as 40 keV H^+ ions). In this case, the corresponding peak power density is ∿ 5.8 kW/cm^2. These peak power densities (when corrected for angle of incidence on the wall) would have to be sustained by the proposed armor plate during a plasma disruption. A fast interlock chain will be incorporated into the beam system controls to shut down the ion sources within 10 msec if such a loss of plasma occurs. It is also desirable to be able to use the armor plate as a torus calorimeter so that a measurement of the beam power transmitted through the beamline drift tube into the plasma can be made. Beam loss in this region with the injectors on PLT was found to be a non-negligible effect, and studies of the Doublet III and other beam systems have paid particular attention to this point.[2] To make such a measurement requires that the armor plate system be able to withstand the full power density for some significant fraction of the pulse length and be suitably instrumented.

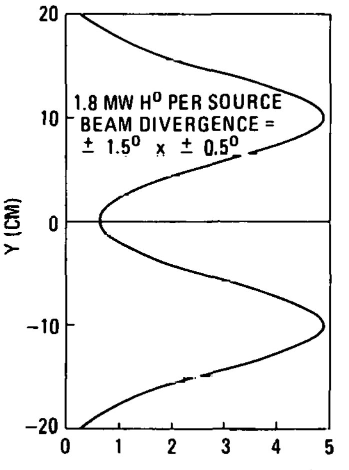

Fig. 2. Vertical power density profile (normal to the beam) for one beamline (two ion sources) at the location where the central trajectory intersects the vacuum vessel inner wall.

The peak heat load on the armor plate when corrected for angle of incidence is shown as a function of central hydrogen plasma densities in Fig. 3. With no plasma present in the vacuum vessel, the power densities are seen to be ∿ 3.5 kW/cm^2 and ∿ 4.1 kW/cm^2 for hydrogen and deuterium beams respectively. For a hydrogen plasma of nominal central density n(o) = 1×10^{14} cm^{-3} the peak heat loads have dropped to 490 watt/cm^2 and 160 watt/cm^2 for the two isotopes. For design specification purposes we are allowing a ∿ 35% increase in the peak power densities to account for any near-term improvement in the performance of the ion sources. Our requirements are summarized in Table 1 and represent the worst cases of combining hydrogen and deuterium operation. A plan view of a 1.8 MW hydrogen beam from one of the two ion sources in each beamline impinging on the armor plate is shown in Fig. 4. The variation in power density across the plate is clearly seen in this example in which no plasma attenuation is assumed. A small fraction of the beam is not intercepted on the inner wall of the torus but traverses the vacuum vessel and strikes the far wall some 8 meters from its point of origin at the ion source. The power density at this far wall is very low even with an 80 keV hydrogen beam in the absence of a plasma, being approximately 76 W/cm^2 normal to the beam. The heat flux on the actual Inconel wall is further reduced to ∿ 54 w/cm^2 because of the ∿ 45° angle of incidence. The primary reason for this low flux is that only about one-third of the source can illuminate this region of the torus.

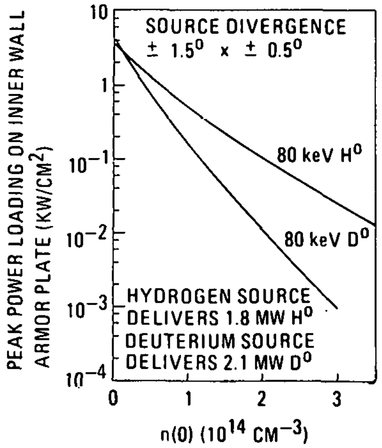

Fig. 3. Peak heat load on the armor plate as a function of central hydrogen plasma density

Table 1
Specifications for the Armor Plate Power Densities for a Doublet III Repetition Period of 300 Seconds

Operating Mode	Max Power Density Normal to Wall (kW/cm^2)	Max Pulse Length (sec)	Required Number of Pulses Before Failure
Routine Plasma Operation	0.8	1.0	20,000
Plasma Disruptions	5.5	0.01	1,000

Conceptual Design

The proposed design for the armor plate to be attached to the inner wall of the torus is described in detail elsewhere in these proceedings.[3] Briefly, a region about 115 cm long by 60 cm high of the inner wall opposite each beamline must be covered with protective plate. Vertical slats of Inconel about 60 cm tall, 8 cm wide and 0.6 cm thick, with water cooling pipes on their rear surfaces will be attached to the torus wall with welded studs (Fig. 5). The front surface of these slats will be covered by ∿ 8 × ∿ 8 cm carbon tiles about 1 cm thick held in place with spring clips. The graphite blocks (Poco AXF 5Q) will be coated with titanium carbide to minimize hydrocarbon production. Preliminary data[4] indicates that these surfaces can withstand heat pulses of ∿ 4.5 kW/cm^2 for greater than 0.5 second without being damaged. Sixteen thermocouples will be embedded into the critical areas of each armor plate to detect abnormal temperature rises, and the flow and temperature rise of the water coolant in the Inconel backing plates will be monitored for calorimetry purposes.

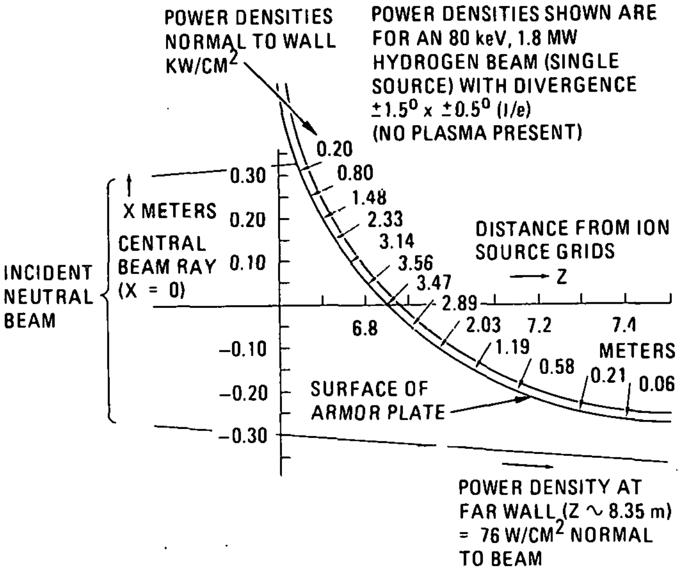

Fig. 4. Plan view of the power densities (normal to the wall) to be expected at various locations across the armor plate due to an incident 1.8 MW H^0 beam with divergence ±1.5° × ±0.5°. No plasma is present to attenuate the beam.

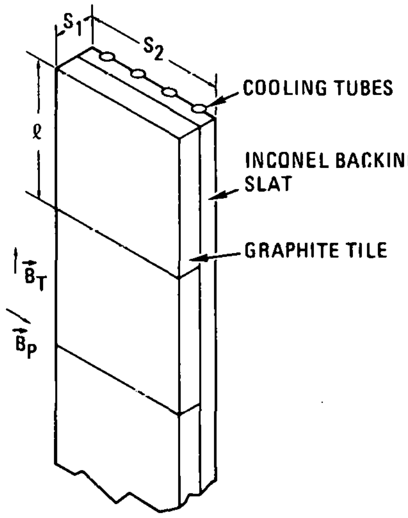

Fig. 5. Isometric view of a segment of the proposed armor plate

Plasma Contamination

A graphite front surface was chosen in order to minimize contamination of the plasma by high Z impurities. A bare graphite surface appears to have the undesirable property that, upon heating to ∿ 600°C by hydrogen beams in the presence of background hydrogen gas, methane production occurs. Further, acetylene production becomes important when the temperature rises to ∿ 1500°C. With only radiative cooling to the torus walls, the maximum temperature of the graphite tiles would ratchet up to ∿ 1450°C under the influence of 10% beam shine through with a pulse of 1 second duration every 300 seconds. Because of our desire to suppress hydrocarbon evolution we have therefore decided to use active water cooling and to coat the tiles with a titanium carbide layer. This latter feature has been found to very significantly depress the hydrocarbon formation processes.[4]

Physical sputtering of the graphite plates may still give rise to plasma contamination but, as we shall see, this is not a disastrous situation. In traversing a nominal density Z = 1.0 plasma of n(o) $\sim 1 \times 10^{14}$ cm^{-3}, an 80 keV hydrogen beam is attenuated to ∿ 10% of its initial value. For our two-beamline (four-source) system, the input power of hydrogen neutrals would be ∿ 7 MW. The particle flux surviving to bombard the far wall during a 0.5 sec duration heating pulse would therefore be $\sim 3 \times 10^{19}$ H°/pulse. The sputtering rate[5] for hydrogen ions at this energy incident on graphite could be as high as 10^{-2} atoms/ion. If these sputtered atoms are uniformly distributed throughout the Doublet III plasma of volume 17 m^3, the carbon impurity concentration will be:

$$\left\langle n_{imp} \right\rangle = \frac{3 \times 10^{19}}{1.7 \times 10^{7}} \cdot 10^{-2} \simeq 1.8 \times 10^{10} \text{ atom cm}^{-3}\text{/pulse}$$

The corresponding Z_{eff} of the plasma would be ∿ 1.01 which would be quite acceptable.

Forces on the Plates during a Plasma Disruption

During a plasma disruption forces will be exerted upon the armor plate segments (slats) due to 1) induction current flow from the disruption, and 2) current flow due to the electrons impacting the tiles faster than the plasma ions. It is important in designing the mechanical supports for the armor that they be capable of withstanding these forces and of conducting the resultant currents to the body of the Doublet III machine without melting.

To evaluate the first class of forces due to the induction currents, we assume that the slats are isolated from the vacuum vessel wall (electrical connections at the top and bottom do not alter this calculation). The forces and torques on a magnetic dipole in an external field $\vec{B}_{ext}$ are given by

$$\vec{F} = \vec{m} \cdot \nabla\vec{B}_{ext}$$

$$\vec{\tau} = \vec{m} \times \vec{B}_{ext}$$

The current I flowing in the slats of cross sectional area a (= S_1S_2 in *Fig.* 5)

$$L_p I = B_p a$$

where the slat inductance

$$L_p \simeq \frac{\mu_o a}{\ell}$$

and the poloidal magnetic field at the wall (r = 0.45 m) is

$$B_p = \frac{\mu_o I_p}{2 \pi r}$$

ℓ is the effective length of the graphite tile in the direction of B_p (∿ 8 cm). Hence

$$I = B_p \ell/\mu_o$$

and

$$\vec{m} = \vec{B}_p V/\mu_o$$

in the direction of B_p, where V is the volume of one tile.

The force acting to pull a single tile off the wall during a disruption of duration t_d is

$$\vec{F} = \vec{m} \cdot \nabla\vec{B}_p \, (1 - \delta) = - \frac{\delta \, (1-\delta) \, \mu_o I_p^2 \, V}{4 \pi^2 r^3}$$

The maximum force occurs at 0.5 t_d (∿ 5 msec) when $\delta = 0.5$. For a plasma current I_p = 2 MA and tile plus backing plate volume (8 cm × 8 cm × ∿ 2.4 cm) $V \simeq 1.5 \times 10^{-5}$ m^3, the magnitude of this force is

$$F_{max} = \frac{\mu_o I_p^2}{16 \pi^2 r^3} \cdot V \simeq 54 \text{ Newton}$$

which is modest.

The torque on a single tile due to the toroidal field is easily seen to be of magnitude

$$\tau = B_T B_p V/\mu_o \simeq 270 \text{ Newton-meter}$$

for B_T = 2.5 T.

The force due to the interaction of currents flowing in adjacent plates is also very modest and is calculated to be ∿ 47 newtons.

Because of the two-component nature of the armor plate, graphite tiles on top of an Inconel slat, the trapped magnetic flux during a disruption acts to cause the plates to delaminate. The self energy of the plate is $W = LI^2/2$ and the resulting force on a single tile is

$$F_d = \frac{1}{2} I^2 \frac{\partial L}{\partial S_1} = \frac{1}{2} I^2 \frac{L}{S_1} = \frac{B_p^2 V}{2\mu_o S_1}$$

$$\sim 1200 \text{ Newtons}$$

The springs holding the graphite on to the Inconel must therefore withstand this force. The forces discussed above all appear to be entirely tractable with the armor plate design proposed.

The second type of force mentioned above arises because of a displacement current flow due to the electron velocity being much greater than the ion velocity in the plasma. For a disruption time t_d this displacement current is

$$i_d = Ne/t_d$$

For a plasma of average density $\bar{n} \sim 5 \times 10^{19}$ m^{-3} with a total volume of 17 m^3, N = 8.5×10^{20} electrons and we may assume that half of these are in each lobe of the Doublet III plasma. For a disruption time of 10 msec we therefore have i_d ∿ 7 kA. The assumption in the above is that the electron temperature profile is quite peaked so that, as the plasma strikes the wall, the sheath formed by the preceding flux surface is negligible compared to the electron temperature on the succeeding flux surface. The force and torque on a single armor plate slat is computed from

$$\vec{F} = \int \vec{J} \times \vec{B} \, dv$$

and

$$\vec{\tau} = \int \vec{r} \times (\vec{J} \times \vec{B}) \, dv$$

For a current flowing into the plate and dividing equally to flow to the top and bottom wall studs there will be no net force. However, a torque will exist to push the top of the slat into the wall and pull the bottom out. This torque has an approximate magnitude of

$$\tau = 0.5 \, i_d \, B_T \, h^2/2$$

where h ∿ 0.6 m is the distance apart of the studs supporting an Inconel slat, and $B_T \sim 2.6$ T. Hence $\tau \simeq 2730$ N-m. If one end of the slat is electrically connected to the torus wall better than the other end (for example, to allow for thermal expansion), then all the current scraped off on the armor slat flows one way. The force resulting from this would be of magnitude

$$F = i_d \, B_T \, h \simeq 10900 \text{ N}$$

which is significant. If a uniformly distributed current scrape-off were assumed, this force would be reduced by a factor of 2.

Protective Interlocks

For normal plasma operations, in which hydrogen beam pulses of duration 0.5 seconds are fired every 300 seconds, the surface temperature of the graphite plates should reach ∿ 670°C at the peak power density point during the shot. If a disruption were to occur, however, the temperature of this hot spot would rise rapidly. We propose to use a fast infra-red optical pyrometer to view each of the two hot spots (due to the upper and lower ion source) on each of the armor plate assemblies. These detectors are active in the range around 1 micron and appear to be relatively insensitive to plasma light. They will be set to trigger a power system abort to the beamlines in the event that the hot spot temperature is seen to exceed a predetermined limit. The response time for this abort is expected to be less than ∿ 10 msec. Thermocouples will be used to monitor critical points on the armor immediately after a plasma shot (electrical isolation problems and the relatively long reaction time of the thermocouples precludes their use as real-time monitors) to determine if any abnormal temperature distribution is developing. The most difficult task lies in ensuring that the graphite tiles maintain their integrity. It is possible that, because of mechanical stresses, a tile could fracture and fall off, thereby exposing the underlying Inconel backing plate. The following beam pulse would result in a rapid elevation of the exposed metal surface temperature resulting in melting of the surface and, ultimately, in failure of the plate. We are presently exploring the possibility of using a scanning infra red camera to view each armor plate assembly after a shot. Anomalies in the thermogram obtained would signal the need for closer inspection of the tile surface.

Conclusions

The design of vacuum vessel armor plate for neutral beam systems presents a number of challenges to the engineer. Heat fluxes of several hundred watts/cm^2 must be handled on a routine basis during normal plasma operations, and a factor of ten increase in these fluxes can occur during plasma disruptions. At the present time, a graphite tile system appears to be the best candidate for such a situation. Heat fluxes in excess of 4 kW/cm^2 can be routinely sustained and the material sputtered or evaporated from the surface has a low atomic number. The system proposed for Doublet III will provide valuable data for the designers of future fusion reactors and will also provide proof-of-principle demonstrations for such machines as TFTR and JET. Instrumentation to monitor the condition and integrity of the armor in real time does not presently exist and will require development. This, however, should be extremely useful for studying first wall conditions in future machines.

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