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DCT-8 PUMPED LIMITER DESIGN CONSIDERATIONS*

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Abstract

Disruption erosion drives the life of the DCT-8 pumped limiter. This result came from an evaluation of beryllium (Be), beryllium oxide (BeO), and silicon carbide (SiC) as candidate surface tile materials. Beryllium oxide was selected as the reference tile material because it has the longest life: 13 full power hours (2300 burns @ 20 s/burn) or 2.3 years of DCT-8 operation. The fabricability of any of the candidate materials and the ability to survive thermal shock conditions and electromagnetic loads imposed by disruptions are serious concerns. The most desirable materials from an engineering standpoint (graphite and high-Z, e.g., tantalum) were eliminated due to physics considerations.

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Introduction

The DCT-8 (driven current tokamak) is the eighth design in a series of tokamak concepts defined to cover the magnetic confinement development gap between the Tokamak Fusion Test Reactor (TFTR) and the Engineering Test Reactor (ETR). The experimental objective of the device is to achieve ignition, demonstrate long-pulse tokamak operation, and integrate the technologies relevant to reactor-like fusion machines.

Summary

A baseline pumped limiter configuration has been defined for the DCT-8 experimental fusion device. This configuration consists of a toroidal belt located at the bottom of the plasma chamber and features a single leading edge and flat limiter surfaces. The pumping slot is located at the inboard side of the blade surface. The limiter is designed to remove 10% of the particles in the scrape-off layer. Beryllium oxide is employed in the protective surface tiles brazed to the water-cooled copper substrate. The life of this device is expected to be 2.3 calendar years of operation, based on 2×10^5 s of D-T full power operation.

The initial review of candidate protective surface materials was limited to materials in the low-Z regime. Materials such as tantalum and graphite were precluded from consideration in this study because physics inputs dictated that they would have unacceptable effects on the plasma. These materials, however, should obviously remain strong candidates in other studies and in component R&D efforts.

Life-limiting factors in this design were material losses due to disruptions. Due to the large uncertainty in disruption characteristics and in plasma edge definition, completely different conclusions can be derived with regard to which conditions are life-limiting, depending on where the selected design point is in the uncertainty space. For instance, in the Fusion Engineering Device (FED) studies, it was determined that sputtering erosion was the life-limiting condition. Therefore, it is important to quantify both disruption characteristics and plasma edge environments to allow better design definition.

It can be concluded from this and past studies that it is important to quantify environmental conditions for design of limiters in advanced devices. Additionally, materials which are acceptable on limiter surfaces must be identified. Without an understanding of these conditions, "worst case" conditions must be used; and significant R&D must be expended on a variety of materials.

Design Options

Design options for the pumped limiter include the type, location, configuration, pumping slot location, materials, and fabrication techniques. Figure 1 illustrates these options and the sequence of evaluation and selection. For reasons of simplicity, several secondary options have been omitted.

The DCT-8 pumped limiter is a toroidal belt located at the bottom of the plasma. It has a flat surface and a single leading edge, as shown in Fig. 2. This design is similar to that used in FED [1].

Options for the limiter configuration and location in a toroidal device have been extensively evaluated in past studies [1,2]. The advantages of the location shown are that it minimizes space required in the outboard wall for limiter removal and it permits the blade to be located in a region where the magnetic flux surfaces are spread out (relative to the midplane location), resulting in larger e-fold distances for particle and heat fluxes.

A flat limiter surface with a single leading edge was selected for DCT-8 because it allows the fraction of particles pumped to be adjusted by moving the plasma inboard and outboard. Although the limiter surface can be contoured to provide a lower peak heat flux, the flat limiter surface provides the least sensitivity to uncertainties in plasma performance and is easier to fabricate than limiter surfaces that are contoured.

The limiter surface is composed of protective tiles that are brazed to a double-walled copper substrate, as shown in Fig. 3. In addition to beryllium (Be) and beryllium oxide (BeO), conventional high-purity (CVD- β) silicon carbide and a newly developed high thermal conductivity silicon carbide doped with BeO were considered as candidate tile materials. Factors such as tritium permeation and retention are no

Fig. 1. Design options and sequence of selection

Fig. 2. Elevation view of DCT-8 torus

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Fig. 3. Limiter configuration

considered to be a significant issue with any of these materials for DCT-8 operation, although some tritium and helium will be formed by the bombardment of beryllium with neutrons.

Design Conditions

Design equilibrium burn conditions and plasma disruption heating conditions are listed in Tables 1 and 2. Eighty percent of the 77-MW fusion alpha power is deposited on the limiter by charged particles leaving the plasma. This results in a peak heat flux of 7.0 MW/m^2 . Plasma ions strike the limiter with energies ranging from 400 to 2400 eV (depending on the location along the limiter surface). The peak ion flux is $1.7 \times 10^{22} \text{ m}^{-2} \cdot \text{s}^{-1}$. Charge-exchange neutral particles strike the limiter at an energy of 450 eV with a uniform flux of $5.2 \times 10^{21} \text{ m}^{-2} \cdot \text{s}^{-1}$.

The energy flux to the limiter during the 1.0-ms thermal quench portion of a plasma disruption is 6.0 MJ/m^2 . An additional 5.4 MJ/m^2 is deposited on the limiter during the subsequent 10-ms duration current quench. The disruption frequency is 1 disruption per 10 burns during the first year and 3 disruptions per 100 burns after the first year.

Erosion Lifetime

Erosion of the limiter surface by sputtering and plasma-disruption-induced melting and vaporization was found to be a critical feasibility issue in past tokamak device studies [1,2]. Erosion lifetime calculations were performed for DCT-8 to establish the effect of limiter replacement on device operation for a set of conditions that represent a realistic "worst case." These conditions are presented in Tables 1 and 2. Gross sputtering rates were used in determining the erosion lifetime (i.e., redeposition of sputtered material was not considered). Brooks and McGrath [3] have shown that significant redeposition could occur, resulting in increased lifetime. The entire melt layer formed during disruptions is assumed to be lost. The accuracy of this assumption is under investigation [4], but resolution of this issue through an analytical approach is unlikely due to the complex coupling of several highly uncertain loading conditions (e.g., disruption heat loads and interaction of magnetic fields with eddy currents induced in the melt layer).

Table 1. Design equilibrium burn conditions for DCT-8 pumped limiter

Parameters

Charged particle transport power to limiter, MW	60
Neutral particle power to limiter, MW	10
Ion flux to limiter, s^{-1}	2.6×10^{23}
Neutral flux to limiter, s^{-1}	1.3×10^{23}
Scrape-off e-folding distances	
- Temperature at midplane, mm	15
- Density at midplane, mm	large

Resulting Conditions

Peak heat flux to limiter, MW/m^2	7.0
Peak ion flux to limiter, $m^{-2} \cdot s^{-1}$	1.7×10^{22}
Energy of ions striking limiter, eV	400 to 2400
Peak neutral flux to limiter, $m^{-2} \cdot s^{-1}$	5.2×10^{21}
Energy of neutrals striking limiter, eV	450

Device Utilization

Years of operation	10
Average burn time, s	20
D-T burn pulses per year	1000
Cumulative D-T burn time, s	2×10^5

Table 2. DCT-8 plasma disruption heating conditions

Parameters

Thermal Quench

Duration, ms	1
Energy, MJ	66
To limiter	75%
To first wall	25%
Peaking factor	
Limiter	Same as distribution operating power
First wall	1

Current Quench

Duration, ms	10
Thermal energy	17
Magnetic energy	25
Region of deposition	Inboard, top & bottom
Extent of region	20%
Peaking factor	2

Disruption Frequency

First year	0.1
After first year	0.03

Resulting Energy Fluxes to Limiter, MJ/m²

Thermal quench	6.0
Current quench	5.4

Erosion rates for the four materials are shown in Fig. 4. Melting and vaporization caused by plasma disruption heating dominate the erosion rate for all candidate tile materials. The opposite conclusion was reached for the FED studies [1] because (1) disruption conditions were less severe for FED, and (2) graphite, which survives disruptions without melting, was used for FED.

Erosion lifetimes for the four candidate materials are shown in Table 3. Beryllium oxide, which has the longest lifetime, lasts only 13 h of D-T operating time. This corresponds to a lifetime of 2.3 years for the low availability of DCT-8 operating schedule. At the time of this paper, conditions for hydrogen operation in DCT-8 were not defined. Assuming that hydrogen operation is considerably longer than D-T operation with the same conditions, predicted erosion lifetimes would be significantly reduced if hydrogen operation was included in this analysis. This would not affect the choice of material, however.

Substrate Thermal Stresses and Life

Thermal fatigue of the copper substrate subjected to a heat flux of 7.0 MW/m^2 was identified as a potentially critical issue in the DCT-8 limiter design. The thermal stresses in the substrate are caused by the temperature difference from the front plate to the back plate. This temperature difference is a strong function of the convection heat transfer between the coolant and substrate. The temperature difference can, therefore, be reduced by increasing the coolant flow rate; but this has an adverse effect on pressure drop and pumping power. Thermal and structural analyses were performed to evaluate the relationship between fatigue lifetime of the copper substrate and coolant flow performance. The resulting life is shown in Fig. 5. This life includes a scatter factor of 4 (life shown is 25% of that calculated). The results indicate that the limiter should last the device life of 10^4 cycles at relatively low pumping powers ($<1 \text{ MW}$).

Stresses in the direction of the ribs are largest at the surface closest to the plasma. Bending stresses due to coolant pressure were included in addition to thermal stresses in the direction perpendicular to the ribs. Considering the combined stresses, the critical location for purposes of fatigue evaluation is half-way between the ribs on the surface of the substrate panel closest to the plasma. The alternating stress intensity (one-half the peak stress) was compared with copper fatigue data to obtain the predicted fatigue life.

Fig. 4. Disruption-induced erosion is much greater than physical sputtering erosion

Table 3. Erosion lifetimes for all tile candidates are short

Tile material	Upper temperature limit - °C	Maximum tile thickness mm	Thickness available for erosion ⁽³⁾ mm	Physical sputtering erosion rate $\mu\text{m/s}$	Disruption erosion $\mu\text{m/disruption}$	Operating time 10^4 seconds	Calendar time ⁽⁴⁾ years
Be	700 ⁽¹⁾	9.0	6.5	0.009	340	1.3	0.63
BeO	900 ⁽¹⁾	11.5	9.0	0.008	128	4.6	2.3
SiC (conventional)	1440 ⁽²⁾	5.0	2.5	0.010	180	0.9	0.45
SiC (high conductivity)	1440 ⁽²⁾	13.5	11.0	0.010	180	4.0	2.0

(1) Upper temperature limit based on reduced tensile strength.

(2) Upper temperature limit based on excessive vaporization (10 mm/year)

(3) End-of-life thickness assumed to be 2.5 mm.

(4) Assumes 1000 20-second duration burn pulses per year with a disruption frequency of 0.03 (3 disruptions/100 burn pulses).

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Fig. 5. Effect of pumping power on substrate life

Braze Stresses

Stresses developed in limiter tiles and substrate materials during fabrication and operation have been investigated under FED and INTOR studies. Study results indicate that high stresses develop between tile and substrate during cooldown from braze temperature. Analysis was conducted under the FED studies to evaluate graphite brazed to a copper substrate. Braze shear stresses were shown to be sensitive to the properties of both materials. In the case of copper, properties vary significantly with specific alloys.

Evaluation of braze shear stresses indicates the need for relatively small tiles to allow cooldown without failure in the braze. For silicon carbide and beryllium oxide tiles brazed to copper, tile sizes approximately 1.0 cm by 1.0 cm may be required. These requirements complicate the design. Costs of designs and comparisons of material costs were not included in the study. Results depend on braze stress allowables and specific materials considered. Development testing is needed to provide designs for the acceptable limiter surface materials.

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