DESIGN AND FABRICATION OF A BERYLLIUM LIMITER FOR ISX-B[1]

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ABSTRACT

A movable, temperature-controlled, beryllium rail limiter has been used in the Impurity Study Experiment (ISX-B) tokamak at the Oak Ridge National Laboratory (ORNL). The purpose of the experiment was to evaluate the suitability of the material for installation on the Joint European Torus (JET) experiment. The limiter was designed for a surface temperature rise of 600°C for each tokamak shot. This rise corresponds to a heat flux to the limiter surface of approximately 2.1 to 2.4 kW/cm^2 for 0.3 s. The experimental test was expected to require a lifetime of approximately 3000 neutral beam-heated plasma discharges to meet the planned surface fluence of 10^{22} hydrogen ions per cm^2. A temperature control system was used to maintain the base-plate temperature of the limiter at about 200°C. Normal plasma radius was 24 cm. The experimental results indicate that the beryllium limiter functions normally unless brought to melting point, when evaporated beryllium covers the liner walls, gettering the discharge. Under these conditions beryllium was the dominant impurity.

I. INTRODUCTION

Beryllium is a metal with a low atomic number, a relatively high melting temperature, and a high thermal conductivity. For these reasons it has the potential to make an excellent plasma limiter for a tokamak experiment and is being considered for use in the JET tokamak [1]. A significant drawback to its use is the toxicity of beryllium dust. An extensive description of the properties of beryllium relevant to plasma physics is given [2]. A pioneering experiment using a beryllium limiter has been conducted on the Unitor tokamak [3]. To make an experimental evaluation of the suitability of beryllium for the JET application, a beryllium limiter has been designed and fabricated and installed in the ISX-B experiment and an extensive experimental program completed. The experiment was jointly carried out by the JET undertaking and the ORNL ISX-B group. Material tests [4] and the fabrication of the limiter were done by the Fusion Technology Division at Sandia National Laboratory, Albuquerque, New Mexico.

The ISX-B experiment is a medium-size tokamak [5] with neutral beam heating. The main ISX-B experimental program has been carried out with titanium carbide (TiC) limiters and a plasma radius of 26 to 27 cm. Some experiments to test pump limiter systems have been performed with a plasma radius of 22 cm [6].

In addition to the beryllium limiter, a number of other diagnostics were installed on the tokamak to measure the plasma material interaction and edge plasma properties. Figure 1 is an installation drawing of the experiment showing these additional diagnostics and also the location of the primary plasma diagnostics. For the experiment described here, the beryllium limiter was set for a plasma vertical radius of 24 cm. Since the elongation was 1.2, the horizontal radius was 22 cm. The limiters were withdrawn to at least 6 cm behind the beryllium limiter, which was also located

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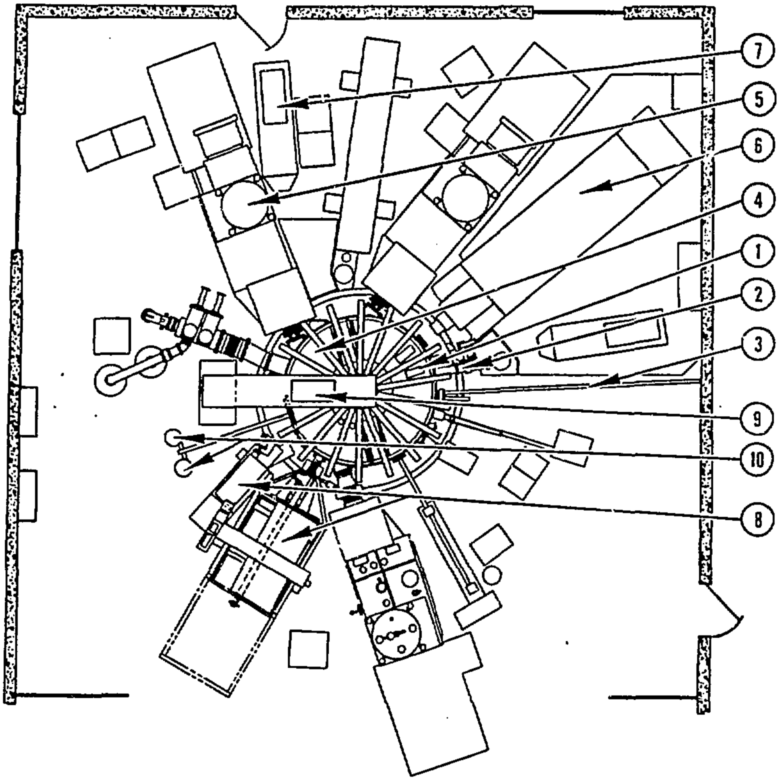

1–BERYLLIUM LIMITER
2–LIMITER SPECTROSCOPY
3–SURFACE ANALYSIS TRANSFER STATION
4–LANGMUIR PROBES
5–BEAM LINE USED DURING EXPERIMENT
6–THOMSON SCATTERING APPARATUS
7–VISIBLE
8–V.U.V. SPECTROMETERS
9–TiC LIMITERS
10–LINER VENTILATION APPARATUS

Fig. 1. Installation drawing of ISX-B beryllium limiter experiment.

180° away from the TiC limiters. Only one beam line was used for the experiment. Injected power for the main fluence test was approximately 750 kW. Plasma current and toroidal field directions were both counterclockwise, except for the counterinjection experiment.

2. LIMITER DESIGN

The limiter design consisted of a top rail limiter similar to the TiC rail limiters which had been installed on ISX-B in early 1982. This design was modified to meet the special requirements of the beryllium limiter experiment. The limiter was constructed from S-65-B beryllium. Figure 2 shows a cutaway view of the limiter assembly installed on the main vacuum vessel, showing the plasma cross section. In addition, the toroidal projection of the TiC limiters is shown.

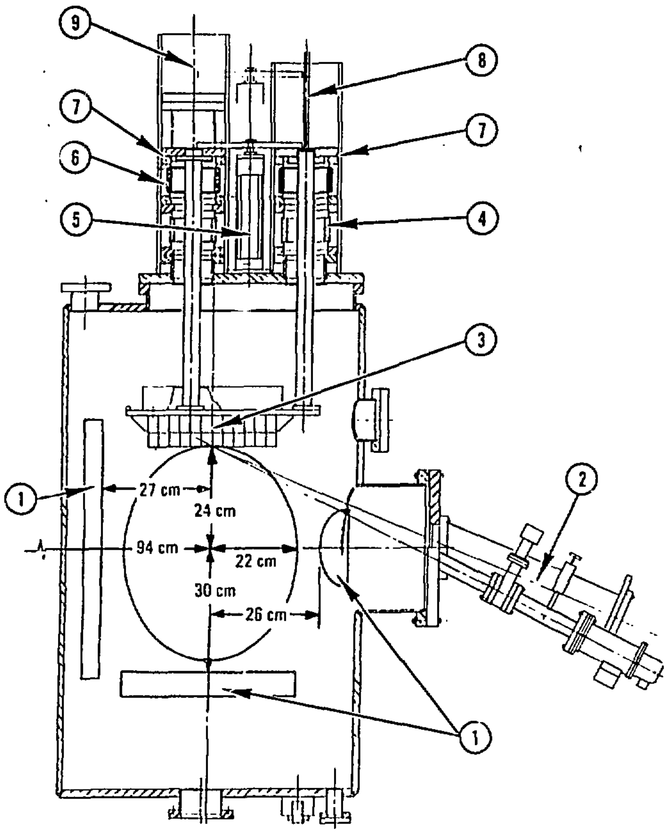

Fig. 2. Cross section of ISX-B experiment, including cutaway of limiter assembly.

2.1 Limiter blade design

The limiter blade was made from 12 tiles, rather than from 1 single piece, primarily to reduce thermal stress during operation. With a single large tile, all the stresses would be contained within the material; however, with multiple tiles, each tile can relieve the loads through the mounting bolts. Other reasons were that better thermal contact could be made to the base plate and, as there was little heat flow between adjacent tiles, the radial thermal profiles could be measured; that on completion of the experiment it would be simple to distribute tiles to different locations for analysis; that a weight measurement could be used to evaluate material loss and migration; that the beryllium material could be efficiently utilized; and that spares could be economically made to protect against loss or damage during manufacture, shipment, and installation.

The limiter profile was calculated for a characteristic scrape-off length of 2 cm and for a surface temperature rise of 600°C, corresponding to a maximum incident heat flux of 2.1 to 2.4 kW/cm^2. Details of the plasma model used to generate the surface profile are given in [7]. An additional restriction was the overall width of the limiter, which had to fit through an existing rectangular port. The original TiC rail limiters were partially assembled inside the vacuum vessel, thus avoiding this constraint.

Because of the extremely brittle nature of beryllium, there was concern that the surface might experience thermal overstressing and premature failure. One method of reducing this thermal stress is to machine slots in the surface of the limiter. (This is a familiar technique in electronic tube anode design [8].) To test this concept, alternate limiter tiles were slotted to produce 13- by 10-mm tessellations. To avoid possible surface corner damage from thermal shock, the edges of the tile surface were relieved 0.5 mm.

2.2 Limiter attachment

Special care was taken in the design of the tile attachment to avoid overstressing the beryllium. The attachment bolts were screwed into threaded cylindrical stainless steel inserts in the beryllium tile to avoid cutting threads in the beryllium. A stack of Belleville washers was placed between the bolt heads and the mounting plate and preloaded to a clamping force of about 400 N per bolt to maintain a more nearly constant contact pressure during thermal and load cycling. Thermocouple wells were drilled into the body of each tile to monitor the tile temperature. Isolated sheathed Chromel-Alumel thermocouples were used. Particular attention was paid to the routing of the thermocouples to ensure proper insertion and low stress at the insertion point. The thermocouples were brought out with a continuous sheath to maintain a continuous stainless steel surface and to avoid degassing. Possible problems with this technique are that the vacuum braze has to be carefully designed and that any sheathing failure will cause a hard-to-detect leak through the insulation. Figure 3 shows the details of a tessellated tile, including the clamping mechanism. The smooth tiles were identical to the tessellated ones except for the absence of any tessellation.

After final machining of the limiter tiles, the surface was electro-etched 0.1 mm to remove machining damage, since such damage is known to cause twinning and susceptibility to surface crack propagation.

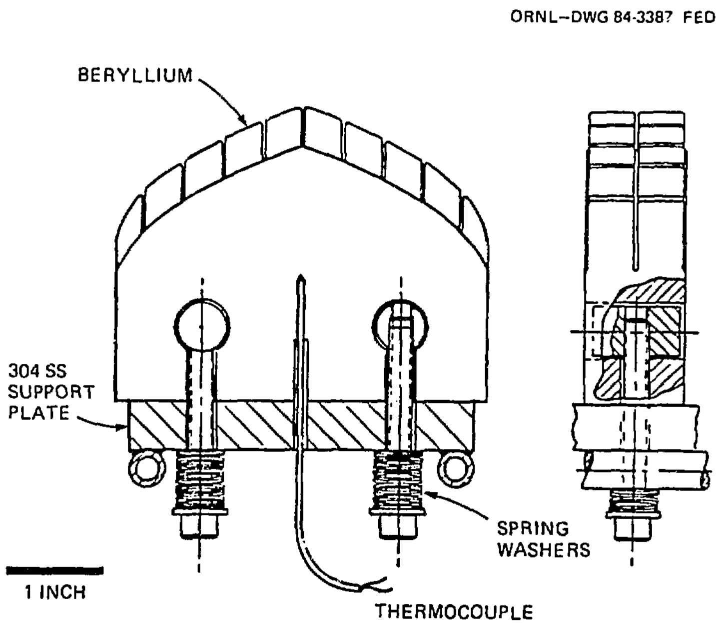

Fig. 3. Detail showing limiter tile with mounting technique.

2.3 Limiter support assembly

During the entire experiment, the limiter blades were maintained at 200°C. This was done for two reasons: (1) the ductility of beryllium increases rapidly with temperature [4], and so operation at elevated temperatures reduces the likelihood of thermal and mechanical failure; and (2) operation at temperatures above that of any other part of the machine reduces the surface contamination from water and other condensables. Temperature control was maintained using a heat-transfer fluid (Dowtherm-LF [9]) circulated at 200°C through the "cooling" lines indicated in fig. 2. The fluid temperature was maintained using a modified commercial apparatus [10] with 9 kW of electric heat, an air-cooled heat exchanger, and a positive-displacement high-temperature pump.

The limiter mounting structure consisted of two massive steel tubes attached at one end to the base plate and at the other end to bellows-supported flanges. The bellows were used to allow moving the limiter. A pneumatic cylinder was installed to drive the motion, but this feature was not used. A ceramic break was located between the bottom of the bellows and the tokamak mounting flange to prevent voltage gradients developing in the bellows during plasma transients. These gradients could have damaged the welded metal bellows. The limiter tubes were supported by two structural cylinders slotted for the positioning arms. Finger stock [11] was installed between the top sliding flange and the inside of the support cylinder as a return path for any limiter currents. A Kaptan insulating sleeve was used to prevent breakdown from the top ceramic-break flange. A slit aluminum flange was attached to the underside of the mounting flange as a bottom bearing surface. Aluminum was used to prevent possible galling and arc-welding. All bolt heads on the assembly were drilled and wired to prevent rotation after installation. The screw threads were treated with a gold flash to prevent galling.

The structure was designed to withstand 30% of the plasma current flowing up either shaft or across the limiter at the planned operating toroidal field (20-kN force on a 15-cm lever arm). These criteria reflect estimates of damage observed elsewhere on ISX-B during its operating history; it is also about the most force that can be accommodated in a reasonable design.

The cooling lines and thermocouples were brought up inside the two support tubes. The vacuum seals were made by brazing. The entire limiter assembly was designed to run at liner electrical ground.

3. BERYLLIUM TOXICOLOGY

A unique feature of this experiment was the health hazard associated with the limiter material. Respirable-size particles containing beryllium are extremely toxic and can produce berylliosis, a chronic disease similar to asbestosis. The threshold limit value (TLV) is 2 $\mu g/m^3$, and strict precautions were taken to prevent the accidental release of any beryllium. Details of the toxicology of beryllium and of the precautions and procedures implemented for this experiment are given in [12] and [13]. A consequence of the hazard associated with beryllium is that following the installation of the beryllium limiter and initial machine operation, it was necessary to assume that any components removed from the machine were contaminated with beryllium dust, and so time-consuming control and testing procedures were necessary during any vacuum opening. Two major interventions were required during the operating cycle of this experiment. One was to replace a substandard calcium fluoride infrared window early on in the experiment and the other to remove a calorimeter probe which developed an air leak. In both cases a glove-bag handling system was used to prevent any accidental spill. A redundant liner-ventilation system designed to maintain the liner interior at a depressed atmospheric pressure in the event of a vacuum accident was also installed on the experiment. No unanticipated problems occurred during the operating or decommissioning phases of the experiment.

4. EXPERIMENTAL PROGRAM

The experimental program consisted of the following six phases.

4.1 TiC limiter characterization

Before the installation of the beryllium limiter, a series of experiments was carried out with the top TiC rail limiter set at 24 cm. The purpose of this period of operation was to establish the operating parameters for the beryllium limiter phase of the experiment and to characterize this set of plasma conditions.

4.2 Beryllium limiter characterization

Following the installation of the beryllium limiter and the initial period diagnostic shakedown and machine cleanup, a detailed survey was made of the operating envelope and plasma parameters produced with the beryllium limiter for both ohmically heated and neutral-beam-injection heated plasmas. These experiments were run at sufficiently low plasma current and neutral beam power that the limiter surface temperature was maintained at below melting point, except during transients.

4.3 High-power limiter test

Plasma disruptions and position displacements are an inevitable consequence of tokamak operation, and an important question to be asked of any limiter is whether or not it will survive these transient and nonuniform thermal and mechanical loads. The purpose of the high-power test was to explore the limiter survivability against high thermal loads. The beam power and plasma current were increased to a level where significant melting occurred on each plasma shot, and the operating envelope and plasma parameters were measured. Under these conditions beryllium was deposited on the inside of the vacuum vessel and acted as a getter, producing results characteristic of a gettered discharge [14].

4.4 Fluence test

After the characterization studies had been completed, the tokamak was run for several months to investigate the effect of extended operation on the limiter. The specific objectives were to simulate a thermal and hydrogen fluence experience similar to that planned for the JET limiter. The target for this fluence test was more than 3000 beam-heated shots with a total estimated fluence more than 1.0×10^{22} ions per cm^2. By the end of the experiment, both these objectives had been achieved.

4.5 Post-fluence characterization

Toward the end of the fluence test, the plasma parameters were again surveyed to assess the changes that had occurred during the fluence phase.

4.6 Additional physics program

In addition to the experiments required for the proper definition of the interaction between the beryllium limiter and the plasma, a number of other physics experiments were carried out. The main criteria for these was that they should not compromise the objectives of the limiter experiment. These experiments included measurements of the plasma potential using the heavy ion beam probe, edge impurity measurements using laser-induced fluorescence, and electron temperature measurements to study the interior plasma details during sawtoothing discharges.

5. SUMMARY OF EXPERIMENTAL RESULTS

The basic properties of the plasma were not affected by whether the limiter was TiC or beryllium. The only significant difference was that the characteristic length of the scrape-off layer for beryllium was measured to be about one-half that with TiC. This difference may have been caused by differences in the measurement geometry for the two cases.

For operation with the limiter surface temperature close to or above the melting temperature, beryllium is plated onto the liner walls and very efficiently getter-pumps the plasma impurities. Under these conditions the dominant impurity is beryllium. The plasma characteristics closely follow the traditional ISX-B results for gettered discharges [15]. The beryllium does not appear to retain a high pumping speed for hydrogen; the characteristics are more similar to chromium gettering [16] than to titanium gettering.

In any experiment using beryllium as a limiter material, it will be necessary to minimize the amount of power deposited on the limiter. One technique that has been proposed is to inject low-Z impurities into the plasma edge; this increases the radiated power and, hence, reduces the power to the limiter. An experiment using neon puffed into a gettered discharge successfully showed this effect with a significant reduction in limiter power observed for small (0.5%) quantities of injected neon. A tantalizing observation was that with the limiter power high enough to produce melting on each shot, the confinement time without impurity injection appeared to have a positive density dependence, suggestive of the ISX-B "Z-mode" experiments [17].

The beryllium limiter is vulnerable to surface damage during transient overloads. The limiter was installed as a top rail and the melt surface was very unstable. Figure 4 shows the limiter surface at the completion of the experiment. The photo was taken shortly after the last neutral-beam-heated shot and before the machine was let up to atmosphere. This effect might be considerably reduced for a limiter located in the lower half of the machine. In spite of this superficial damage, the limiter easily survived the experiment.

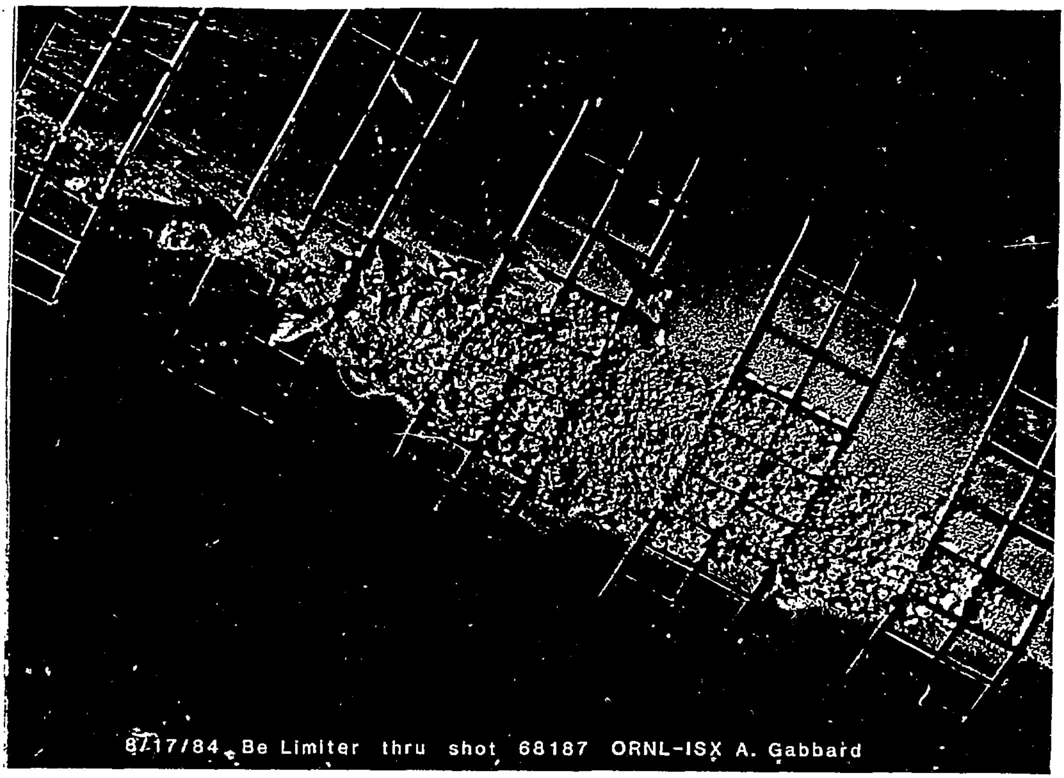

Fig. 4. Photograph of limiter surface at end of experiment. Upper left corresponds to inner end of limiter.

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