Design of the TPX Outboard Toroidal Limiters*

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ABSTRACT

The Tokamak Physics Experiment outboard limiter system incorporates the passive stabilizer plates, the ripple armor, the toroidal break and the support structures. These components are designed to withstand substantial steady state heat loads and high mechanical forces caused by plasma disruptions. The design of these components has been developed to deal with the challenging thermal, structural and remote handling requirements.

INTRODUCTION

The Tokamak Physics Experiment (TPX) plasma facing components (PFCs) are being designed for steady-state operation with a maximum power input of 45 MW. Fig. 1 shows a cross section of the TPX PFCs and vacuum chamber.

The TPX outboard limiter system performs several functions: 1) it protects the vacuum vessel by limiting the plasma boundary with a low atomic number material to limit radiation losses from the plasma due to sputtered atoms, 2) it provides passive vertical stabilization of the plasma by providing an inductive saddle coil circuit, and 3) it acts as a "kink cage" providing kink mode stabilization by locating conductive material close to the plasma boundary [1].

The PFCs generally consist of actively water cooled subassemblies which are mounted to the interior of the vacuum vessel with titanium structural elements. All of the PFCs are designed for remote maintenance since expected activation levels would preclude personnel vessel entry after two years of operation. Low-activation materials are used where possible to allow personnel entry for the initial two years. The primary materials used are carbon-carbon composite for the first wall, copper for heat sinks, and titanium for the vacuum vessel and support structures. The vessel and PFCs are bakeable to 350°C for wall conditioning. Therefore, the supports are designed to accommodate the large mismatch in thermal expansion coefficients between the copper passive stabilizer rings and the titanium vacuum vessel.

DESIGN

A. General

The outboard limiter structure consists of two toroidal copper rings which are electrically continuous except at one toroidal location where a high resistance electrical break limits toroidal current through the passive plates during plasma start-up (Fig. 2). Vertical copper conductors connect the top and bottom rings together on either side of the electrical break forming a saddle coil configuration to passively stabilize vertical movements of the plasma. The two toroidal rings are each formed by 16 water cooled copper "passive plates" which are clad with bolted carbon-carbon (C-C) composite tiles. Local areas of the passive plates employ brazed C-C macroblocks to accept higher ripple particle heat loads (~2.3 MW/m^2). There are three equatorial "floating plates" which add copper structure near the plasma and provide additional kink mode stabilization. The floating plates are mounted to the vessel by titanium supports but there is

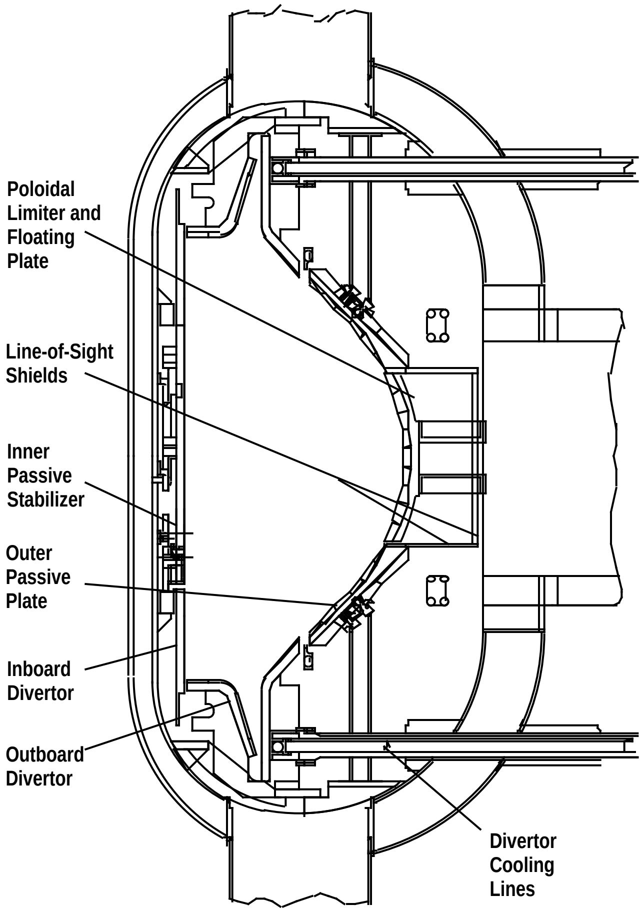

Fig. 1. TPX cross section showing the plasma facing components.

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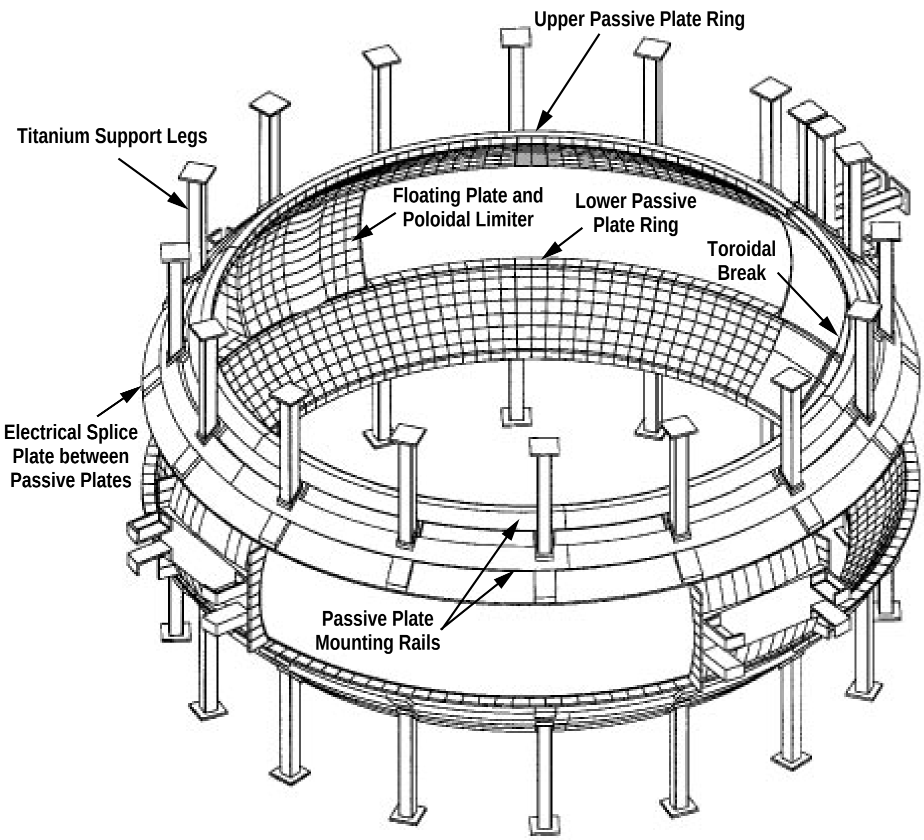

Fig. 2. Outboard toroidal limiter arrangement.

no low resistance electrical connection to the main limiter rings. Poloidal limiters are incorporated into the floating plates to protect the ICRH antennae Faraday shields from plasma impingement.

The outboard limiters are subjected to steady-state plasma thermal radiation heat loads of 0.4 MW/m^2 and plasma startup loads. In addition, portions of the limiters will receive ripple heat loads of 2.3 MW/m^2 and neutral beam shine through heat loads as high 3.0 MW/m^2.

B. Passive Plate

The outboard passive plate (OPP) assemblies consist of 33 mm thick copper heat sink plates covered by protective C-C tiles (Fig. 3). Two candidate copper alloys have been selected for the plates; 1) Cu-Cr-Zr alloy C18150, and 2) Cu-Cr-Zr-Mg alloy C18100. Both of these alloys exhibit good strength and weldability [2]. Furnace brazing of these alloys is prohibited since it results in annealing accompanied by severe reductions in strength. The passive plates are cooled by water which flows through gun-drilled coolant passages with an inlet temperature of 50˚C and an inlet pressure of 2 MPa [3]. The ends of the gun drilled cooling passages are sealed with e-beam welded copper plugs. The water inlet and outlet supply lines are made of 25 mm diameter titanium alloy tubing which is joined to the copper plate by either inertia welding the tube directly to the copper plate or by explosively bonding the titanium tube to a copper transition piece which is then e-beam welded to the passive plate.

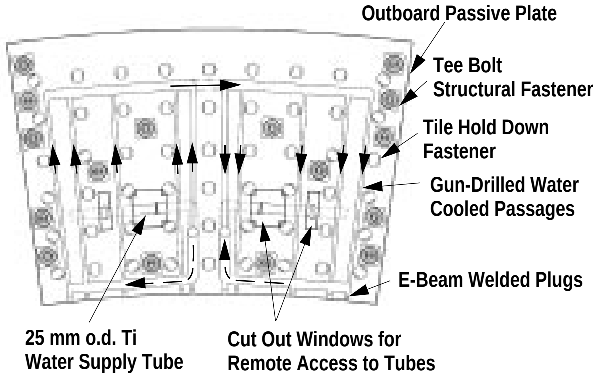

Fig. 3. Outboard passive plate flat pattern showing cooling channel routing and fastener locations.

The OPPs are remotely maintainable. Remote removal of the passive plates is accomplished by first removing bolted tiles to expose the cooling tube connection access windows and structural plate fasteners. The 25 mm o.d. titanium water supply lines are then cut using a remote cutter tool. The tubes are situated behind the passive plate and are accessed through a 100 mm square cutout in the copper plate. Removal of the plate is completed by attaching the in-vessel vehicle and end effector combination which includes grapple points and fastener drive tools. Re-installation takes place in the reverse order. Re-joining of the cooling tubes is accomplished using a tool which positions the tubes and performs an o.d. orbital weld operation [4].

C. Passive Mounting Structure

The upper and lower passive plate rings are made of copper while the vacuum vessel is made of titanium alloy. The vacuum vessel and PFCs are baked to 350°C periodically which leads to a radial differential thermal expansion between the OPP ring and the vacuum vessel of 6 mm ($C_{Ti} = 9.5 \times 10^{-6}$ °C^{-1}, $C_{Cu} = 17 \times 10^{-6}$ °C^{-1}, radius = 2.5 m). In addition to accommodating this large thermal expansion mismatch, the passive plate supports must resist the high electromagnetic disruptions forces (Table I). These conflicting requirements make the support design challenging.

Table I
Electromagnetic forces in outboard toroidal limiter components 0.190 s after initiation of a vertical displacement event (VDE). The magnetic fields prior to disruption are B_r=0.264 T, B_z=0.441 T, and $B_{toroidal}$=3.67 T.

Component	Current (kA)	Radial Force (kN/m)	Vertical Force (kN/m)
Upper limiter ring	295	130	–78
Lower limiter ring	278	–120	–3.5
Vertical plates at toroidal break	286	1,000	0

A design has been developed to provide radial flexibility and sufficient strength during disruptions. The OPPs are attached to a copper support rail system consisting of two toroidal copper rails and an splice plate at every joint between passive plates to achieve toroidal electrical continuity. The rail system provides a well defined mounting interface for remote removal and installation of the passive plates. A series of vertical titanium vacuum vessel supports locates the mounting rail with respect to the vacuum vessel. The vertical titanium support legs are designed flex during bakeout allowing the excess thermal expansion of the copper plates to take place with respect to the vacuum vessel. During disruptions a hoop force of 360 kN is developed in the OPP ring. This force is transferred from plate to plate through the mounting rails. Specially designed remotely handleable “tee bolts” fasten each passive plate to the mounting rails. Finite element modeling has shown that the shear forces in these fasteners will be as high as 90 kN suggesting the need for shear keys between the passive plates and the mounting rails and splice plates.

D. Toroidal Break

The toroidal break is perhaps the most challenging design area of the outboard limiters. Large currents flowing in the vertical current jumpers perpendicular to the toroidal magnetic field produce large radial forces (Table I). A 360 kN hoop force developed in the passive plate rings must be carried across the toroidal gap via the support structure. In addition, the toroidal resistance across the break is specified to be 300 μΩ or greater to allow plasma breakdown during start up. Project design requirements prohibit the use of solid electrical insulators to achieve the high resistance due to arcing problems which have been observed on other tokamaks [5,6]. Therefore, it would be desirable to achieve the high resistance by designing the support structure with and appropriate combination of small cross section and long support members [7].

The present design of the toroidal break is shown in Fig. 4. This design achieves the 300 μΩ resistance requirement without using solid insulators The high radial forces on the vertical current jumpers are reacted to the vessel wall through the titanium support legs which are also designed for high electrical resistance. The toroidal gap has a tendency to open or close due to the 360 kN hoop force carried by the mounting rails. Structural analysis of the design shown in Fig. 4 reveals unacceptable stress and deflection levels in the electrical splice plates and vertical current jumpers. The analyses were also performed with titanium struts placed in other locations but no design could be found to simultaneously satisfy stress, deflection and resistance requirements without the use of insulators. A similar prob-lem exists to an even greater degree on the inboard toroidal limiter design [8]. This indicates that the use of solid insula-tors in the design may be unavoidable given the large loads on these components. Such a design has been built and operated on ASDEX-Upgrade, but not without significant insulator problems [9].

E. Tiles

About half of the tiles covering the OPPs can be mechanically attached (and therefore remotely replaceable) based on the criteria that a maximum heat flux of 0.40 MW/m^2 can be handled by a C-C bolted tile. This is important because water connections, structural fasteners, and other features which must be accessible for passive plate removal can be protected behind removable tiles. Several tile attachment concepts were developed and R&D is scheduled to evaluate their merit. All of these concepts are based on a single fastener with a stack of titanium Belleville washers to maintain a constant pressure of 200 kPa in the tile-Grafoil passive plate interface. Fig. 5 shows one of these concepts in which the tile is retained by a single bolt and a series of Belleville washers which are captive to the OPP.

F. Ripple Armor

Localized ripple heat loads of 2.3 MW/m^2 will strike the OPPs. Ripple armor is an integral part of the OPP consisting of macroblocks which are attached to the passive plates using non-remotely handled fasteners. Reference [10] provides a description of the macroblock concept. The macroblock cooling connections are jumpered into the passive plate cooling channels thereby allowing the ripple armor to be

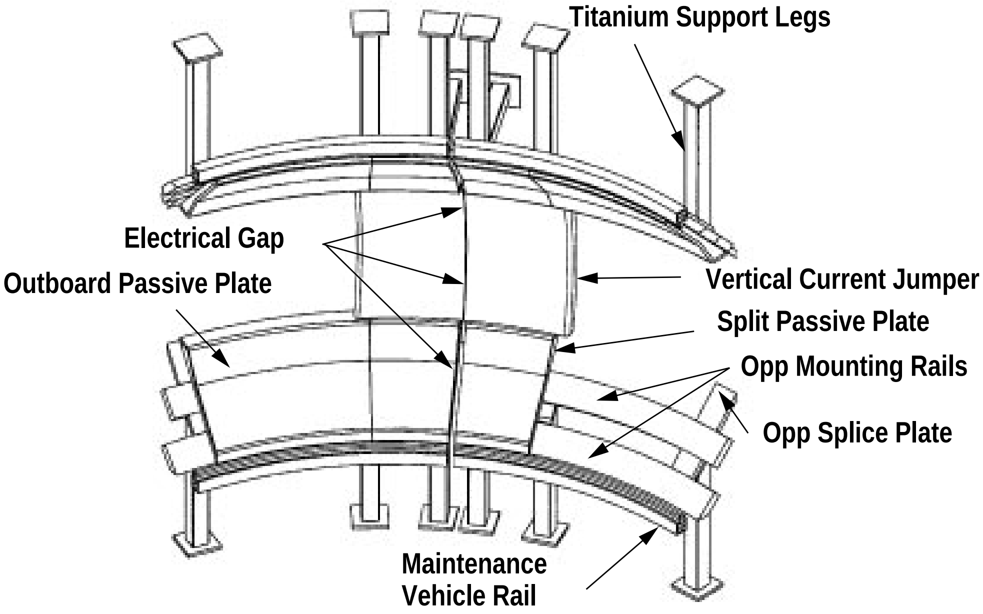

Fig. 4. Outboard limiter toroidal break area. The lower right passive plate is removed to reveal the underlying rail structure. During a vertical displacement event (VDE) the current flows toroidally in the upper and lower passive plates in opposite directions. Current also flows vertically in opposite directions in the two vertical current jumpers.

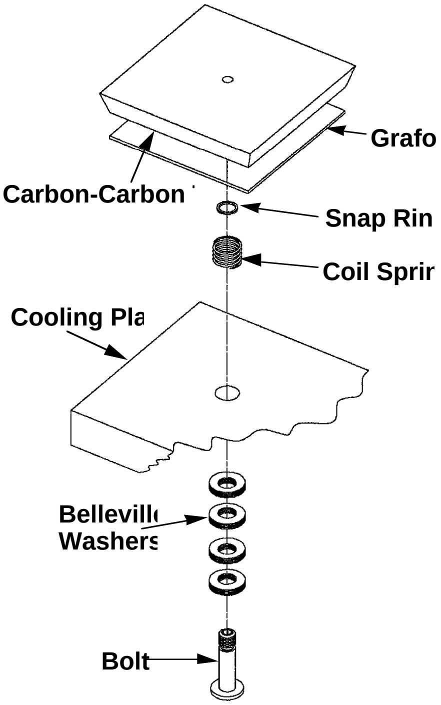

Fig. 5. Exploded view of bolted tile concept. The C-C tile is 100 mm ^{2} x 20 mm thick. The fastener employs Belleville washers to maintain a 200 kPa contact pressure at the interface between the tile and passive plate.

SUMMARY

The TPX outboard toroidal limiters are capable of steady state operations at heat loads of 0.40 MW/m^2. The limiter design utilizes bolted tiles in about 50% of the area with the other 50% requiring more costly brazed or macroblock style tiles to protect against the higher heat loads due to ripple and neutral beam shine through. More design work is needed to achieve a workable design for the toroidal break area. The project requirements of 300 $\mu\Omega$ toroidal resistance without the use of solid electrical insulators appears to be unachievable.

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