Fusion Engineering and Design 96–97 (2015) 433–437

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Key enabling design features of the ITER HNB Duct Liner

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HIGHLIGHTS

- Key engineering design details of the ITER HND Duct Liner are presented.
- A standardised CuCrZr water cooled panel that can be remotely handled is detailed.
- Bolts are protected from beam power by means of a tungsten cap to radiate heat away.
- Water connections placed coaxially are protected from beam power by a tungsten ring.
- Explosion-bonded CuCrZr-316L panels result in a tenfold disruption torque reduction.

ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form 11 March 2015
Accepted 16 March 2015
Available online 15 April 2015

Keywords:
ITER
Neutral Beam
Duct Liner
High Heat Flux
CuCrZr
Tungsten

ABSTRACT

The Duct Liner (DL) for the ITER Heating Neutral Beam (HNB) is a key component in the beam transport system. Duct Liners installed into equatorial ports 4 and 5 of the Vacuum Vessel (VV) will protect the port extension from power deposition due to re-ionisation and direct interception of the HNB. Furthermore, the DL contributes towards the shielding of the VV and superconducting coils from plasma photons and neutrons.

The DL incorporates a 316L(N)-IG, deep-drilled and water cooled Neutron Shield (NS) whose internal walls are lined with actively cooled CuCrZr Duct Liner Modules (DLMs). These Remote Handling Class 2 and 3 panels provide protection from neutral beam power. This paper provides an overview of the preliminary design for the ITER HNB DL and focusses on critical features that ensure compatibility with: high heat flux requirements, remote maintenance procedures, and transient magnetic fields arising from major plasma disruptions.

The power deposited on a single DLM can reach 300 kW with a peak power density of 2.4 MW/m^2. Feeding coolant to the DLMs is accomplished via welded connections to the internal coolant network of the NS. These are placed coaxially to allow for thermal expansion of the DLMs without the use of deformable connections. Critically, the remote maintenance of individual DLMs necessitates access to water connections and bolts from the beam facing surface, thus subjecting them to high heat flux loads. This design challenge will become more prevalent as fusion devices become more powerful and remote handling becomes a necessity. The novel solutions implemented to overcome this are detailed and their performance scrutinised.

The designs presented include tungsten caps that protect bolted and remotely welded connections by radiating heat away, and explosion bonded CuCrZr/Stainless Steel panels designed to reduce by a factor of 10 the eddy current torques caused by plasma disruptions.

1. Introduction

The HNB system for ITER consists of two heating and current drive neutral ion beam injectors. Each beamline can inject up to 16.7 MW of beam power for 1 h, with a current of 40 A and beam energy of 1 MeV. The proposed physical plant layout allows a possible third HNB injector to be installed later, taking the total injected power up to 50 MW.

Each HNB injector incorporates a Duct Liner assembly which protects the Tokamak Vacuum Vessel port and port extension from power deposition due to re-ionisation and direct interception of the beam. Furthermore, the DL also contributes towards the nuclear shielding of the VV and ITER Coils from nuclear radiation from the

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http://dx.doi.org/10.1016/j.fusengdes.2015.03.036
0920-3796/

plasma. Of the many requirements fulfilled by the DL, two of them are key design-drivers, the solutions to which are presented here.

Firstly, the DL must be able to withstand localised heat flux power densities of up to 2.4 MW/m^2 originating from re-ionised and direct beam interception. The total power removed by the DL can reach 1.24 MW for the worst case beam scenario.

Secondly, the components that are subject to the highest heating loads must be remotely handled (RH). The Remote Handling Class for these items is Class 2, meaning that scheduled remote maintenance is not required but unscheduled maintenance is likely. The remote handling operations required for maintenance of RH Class 2 panels include manoeuvring, cutting, welding, bolting and helium-puffing.

When combined, these requirements have proved very challenging for the design. In particular, protecting the bolts and RH water connections from the beam heat flux led to the employment of solutions that are novel when compared to existing neutral beamline designs.

2. Design overview

The Duct Liner is split into two main parts that fulfil different functions. The first is the Neutron Shield, a thick stainless steel conduit that lines the inside of the VV port and is connected to the VV port extension flange. The second is a set of 35 copper alloy panels called Duct Liner Modules that are attached to the NS. Both parts are based on concept designs previously assessed and presented at the 27th Symposium On Fusion Technology [1].

2.1. Neutron Shield

The primary function of the Neutron Shield is to provide nuclear radiation shielding for the VV and ITER coils. The secondary function is to provide structural support, water and thermocouple connections for the DLMs that are attached to it.

The neutron shield is manufactured from 316L(N)-IG stainless steel plates that are welded together to form a tapered rectangular tube of length 4.8 m, width 0.9 m and height 1.6 m (Fig. 1). The plates are deep-drilled to allow water to cool the structure and to deliver coolant to the DLMs.

2.2. Duct Liner Modules

The Duct Liner Modules provide a heat sink to remove unwanted heat from re-ionised or intercepted beam particles. The DLMs are all water-cooled and made from deep-drilled, CuCrZr-IG alloy plates.

All four sides of the NS are lined with five panels in the lengthwise direction (Fig. 2). The LHS of the duct has three rows of smaller panels, which are separated by two grooves in which a pair of rails

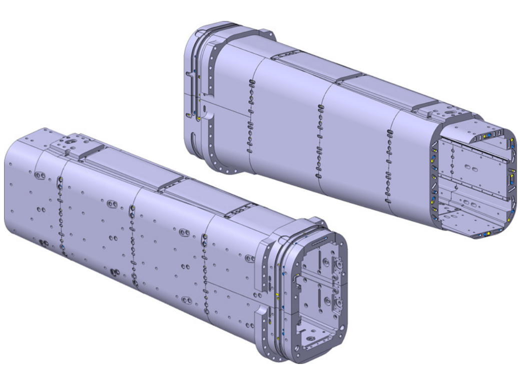

Fig. 1. Duct Liner Neutron Shield.

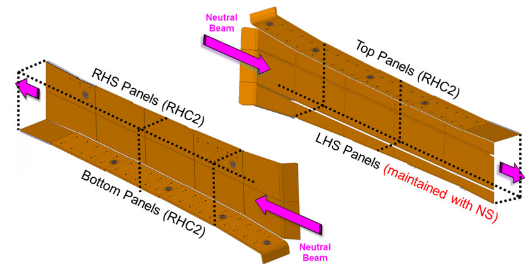

Fig. 2. Duct Liner Modules arranged in the duct.

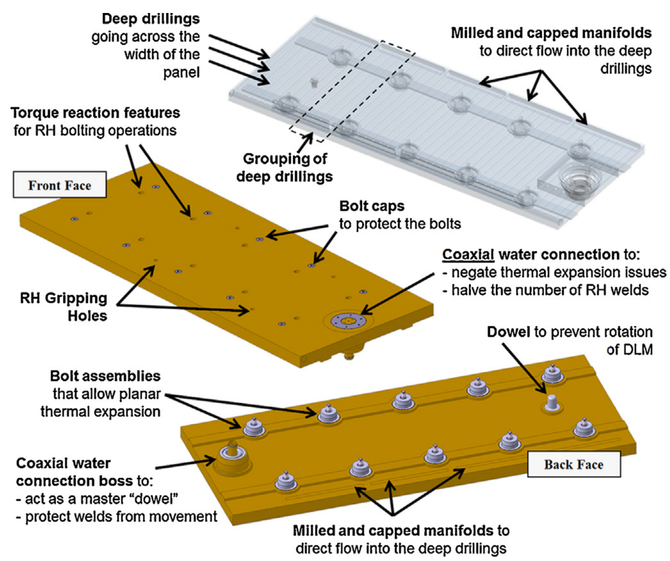

Fig. 3. Duct Liner Module detail.

is located, to enable remote handling equipment to travel inside the duct.

The panels vary in size but the majority of them are 1.3 m by 0.5 m, and 40 mm in thickness. The water channels are deep-drilled along the shortest direction, to maximise the drilling accuracy (Fig. 3). They are grouped into four parallel drillings that traverse the panel back and forth five times. Pockets are machined from the panel edges to provide coolant distribution manifolds and flow return paths, before being capped and welded.

Two of the key features of the DLMs are the bolted connections and the coolant connections. Both are exposed to the HNB power and both need to be remotely maintained. In both cases a tungsten "cap" is secured into the panels to protect the connections. One particular feature of the water connections is that the feed and return circuits are coaxial, whereby the return flows through an annular pipe section.

All DLMs use 10 bolts arranged at a standard pitch and separation, with torque-reaction features for remote handling operations. A further 4 threaded holes are present on the front face to allow the RH equipment to grip the panel and to provide a datum for the RH tooling.

2.3. Tungsten bolt cap protection assembly

The bolt cap is a small cylindrical part inserted in all the DLM bolt recesses and locked using a "bayonet-mount" spring-loaded system (Fig. 4). The cap is 30 mm tall with a maximum diameter of 22 mm, and it has "feet" that slide into the DLM and provide the locking upon rotation of the cap.

The cap works by reaching temperatures high enough to radiate all of the beam power landing on it to the neighbouring cooled

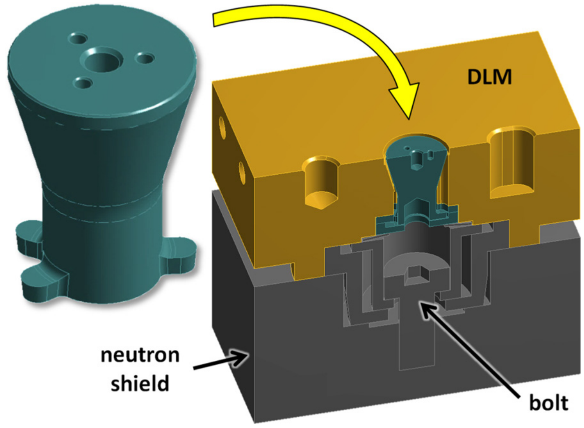

Fig. 4. Tungsten bolt cap protection.

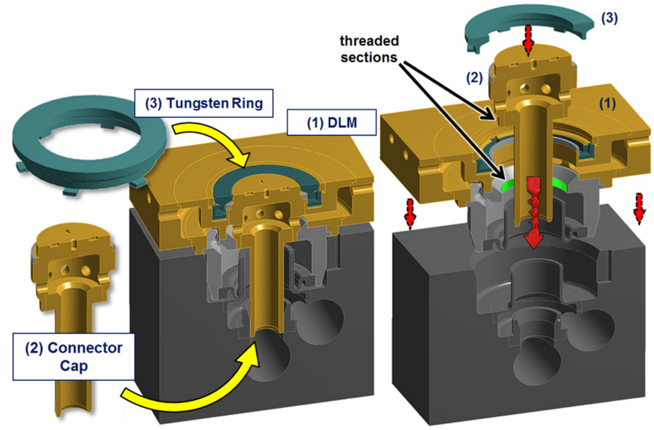

Fig. 6. Coaxial water connection assembly.

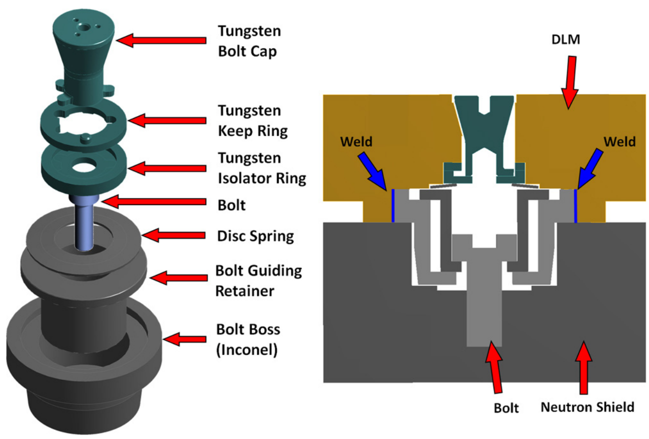

Fig. 5. DLM bolting assembly.

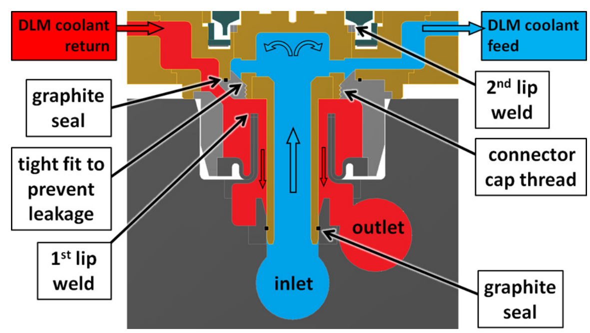

Fig. 7. Coaxial assembly cross section.

CuCrZr surfaces, and also outwards to the other DLMs. In order to withstand the high temperatures involved, above 2000 °C, tungsten is used due to its very high melting point.

The contact points of the component are kept further away in the cooler regions at the foot of the cap. Parts in contact are also made from tungsten to withstand the high temperatures and provide a thermal break between the cap and the CuCrZr DLM, thus removing the risk of melting the copper alloy. A more detailed breakdown of the assembly can be found in Fig. 5.

The remainder of the bolt assembly is designed such that the bolt is captive and kept straight via the Bolt Guiding Retainer. Furthermore, the assembly allows up to ±3 mm of lateral sliding for the DLM to expand thermally without placing the bolts in shear or bending.

2.4. Coaxial flow assembly and tungsten ring

The coaxial flow assembly relies on a single coaxial connection to feed and return water to the DLM. A tungsten ring is also used to protect the RH lip-weld which would otherwise be exposed to the beam power. The ring works in the same manner as the bolt cap.

There are two reasons for using a coaxial configuration. Firstly, it provides a single datum from which thermal expansion takes place, so no loads are placed on the coolant connections and welds during thermal expansion of the DLM. Secondly, the design halves the number of lip welds required, thus reducing the probability of leaks accordingly.

A cross-section of the assembly can be seen in Fig. 6. The complete system, once pre-assembled, is comprised of three parts that fit onto the Neutron Shield. These are the DLM body (1), which requires several parts to be assembled and welded together, the Connector Cap (2) which is made of three parts welded together, and the Tungsten Ring (3).

Upon assembly the DLM is brought into place, after which an inner lip-weld is sealed (Fig. 7). Then the Connector Cap is screwed into position, and a second upper inconel lip weld seals up the entire flow circuit. Finally, the Tungsten Ring is inserted and rotated, where the spring loaded system keeps it locked in place.

Fig. 7 shows a cross section of the assembly with the flow regions identified. To prevent internal leakage between the inlet and outlet coolant circuits, two crushable graphite seals are used. The seals are integral to the DLM so new ones are always used in the event of a DLM replacement. A third potential leakage path through the threaded section is sealed by the screwing action of the connector cap, which provides a large force pressing two flat surfaces together in a tight fit, located above the threads.

The DLM assembly is comprised of a CuCrZr Keep Ring which is electron beam welded to the Flow Manifold, trapping the Tungsten Keep Ring, Tungsten Isolator Ring and annular Disc Spring in place (Fig. 8). One half of the Inconel lip weld is also welded to the Flow Manifold, the latter of which splits the flow into two directions for the DLM flow feed and return.

A further Inconel Boss is welded on the bottom of the Flow Manifold to which half of the Inner Lip Weld is connected. The boss also directs the water flow appropriately.

2.5. Eddy current suppressing panels

In the regions closest to the ITER plasma, rapid changes in the magnetic fields from the plasma during disruption events, of the order of 15 T/s, lead to large eddy currents being generated in all

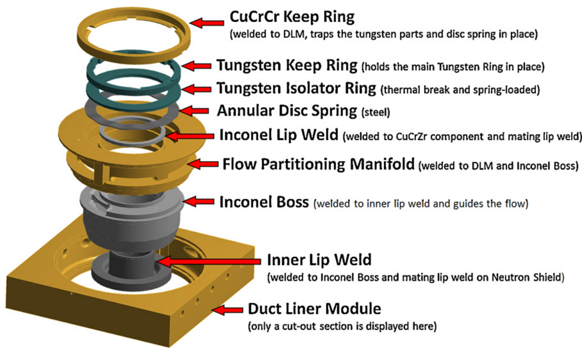

Fig. 8. Coaxial assembly detail in the DLM.

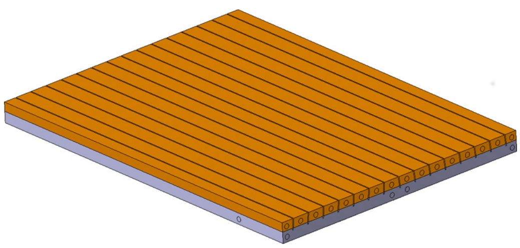

Fig. 9. Eddy current suppressing DLM.

metallic parts. These then react with the steady magnetic fields from the ITER coils, causing large torques to be generated.

The DLMs most affected are those at the top and bottom of the Duct Liner, in the plane normal to the direction of the strongest magnetic field change. A standard solid CuCrZr panel in these regions would be subject to huge disruption torques reaching 170 kNm, giving rise to bolt loads of up to 250 kN. These loads would be far too high for any panel to survive so eddy current mitigation solutions are required to reduce them. The design used on the Duct Liner makes use of two methods to achieve this.

The first is the use of a "sandwich" construction whereby a plate of CuCrZr alloy is explosion bonded to one made from 316L(N) stainless steel (Fig. 9). As steel is a poor conductor when compared to copper alloy, the eddy current build-up is diminished as a result.

The second design feature is a set of machined grooves in the CuCrZr, reaching into the steel layer, thereby separating the CuCrZr layer into several long sections. The result is that it becomes more difficult for eddy currents to circulate in the copper alloy and hence the loads on the panel are diminished further.

3. Duct Liner performance

All analyses were performed using the maximum coolant temperature permitted, 126 °C, along with the Dittus–Boelter equation for forced convection in a pipe. A temperature dependant emissivity was used for all tungsten parts, ranging almost linearly from 0.04 at 200 °C to 0.32 at 2500 °C, while constant values of 0.3 and 0.8 were used for CuCrZr and stainless steel, respectively. The value of 0.8 is the upper bound observed in the literature, to provide conservative estimates of the temperatures of the spring washer and bolt head, to be protected. An ambient temperature of 200 °C was specified for thermal radiation away from the DLM, which is representative of the average temperatures in the remainder of the DLMs.

No progressive degradation of emissivity values or material properties was modelled. However it should be noted that the very high temperatures reached by the tungsten components are likely prevent copper deposition and subsequent emissivity reductions from taking place, an effect which is typically observed within neutral beam systems using copper electrostatic acceleration grids.

All thermal conductance values for parts in non-bonded contact were dependant on the local contact pressures and material properties, and were estimated using the Fletcher and Gyorog correlations [2]. The disc spring force used in both the cap designs is 100 N, giving rise to thermal contact conductance values in the range of 637–1717 W/m^2 K for the bolt assembly, and in the range of 6–35 W/m^2 K for the coaxial assembly.

3.1. Tungsten bolt cap analysis

Under the worst case beam loading scenarios, the bolt cap will be subject to a thermal flux of 2.4 MW/m^2. In this case it will reach a maximum temperature of 2283 °C, which is 2/3rd of the melting point of tungsten, 3422 °C. These high temperatures mean that the tungsten will re-crystallize (above 1350 °C) however the associated significant loss in mechanical properties is accounted for in its structural assessment, which finds the design integrity to be suitable (Fig. 10).

The temperature of the Duct Liner Module is unaffected by the presence of the cap, reaching a maximum temperature of 295 °C in a region away from the cap.

3.2. Tungsten coaxial assembly ring analysis

Again, under the worst case beam loading scenarios a thermal flux of 2.4 MW/m^2 is envisaged. In this case the tungsten ring would reach a temperature of 2110 °C (Fig. 11).

The DLM temperature in this case is only slightly affected by the coaxial assembly, reaching a maximum temperature of 319 °C in the vicinity of the tungsten ring.

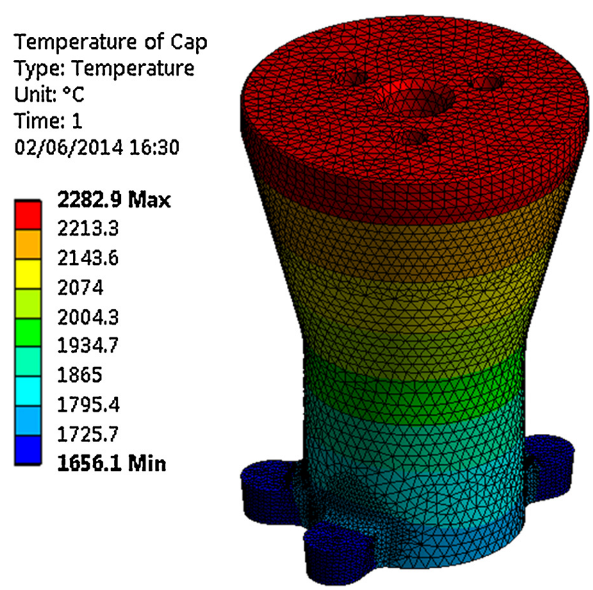

Fig. 10. Tungsten bolt cap temperature.

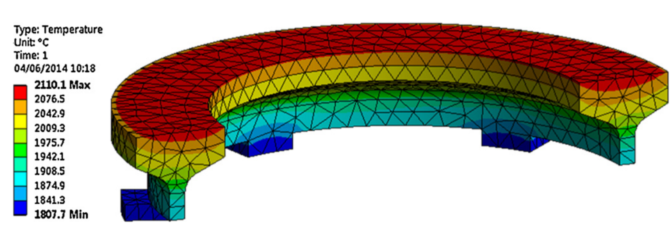

Fig. 11. Tungsten ring temperature.

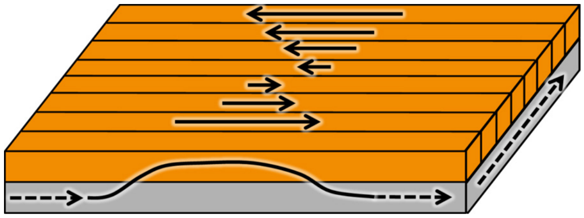

Fig. 12. Current flow behaviour in the eddy current suppressing DLM.

3.3. Eddy current suppressing DLM

The general behaviour of the eddy currents brought about by the design intent is that they only flow in one direction in the CuCrZr sections, and must penetrate the stainless steel structure beneath in order to complete a current loop (Fig. 12).

The design results in a reduction in eddy current driven torques and bolt loads by a factor of 10. The total disruption torque calculated for the modified panels is now only 15 kNm, and the highest bolt load is 25 kN.

4. Summary

The requirements placed on the ITER HNB Duct Liner have led to the use of novel design solutions to achieve its purpose.

The main body of the Duct Liner is composed of a stainless steel Neutron Shield, onto which CuCrZr alloy Duct Liner Modules are bolted. Both are deep drilled and water cooled, and most of the Duct Liner Modules are Remote Handling Class 2, presenting certain challenges.

Two of the key design features used are as follows. Firstly the RH bolts and water connection welds are protected by tungsten caps that radiate heat away without the need for coolant, by reaching temperatures above 2000 °C. Secondly, explosion bonded CuCrZr-316L(N) panels with grooves cut in the copper alloy layer are used to reduce eddy currents, and hence magnetic disruption loads, by a factor of 10.

Acknowledgments

This work was funded by the RCUK Energy programme and F4E, under Grant F4E-2009-GRT-022.

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