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Concept design studies on the ITER HNB Duct Liner

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HIGHLIGHTS

- Engineering design of the ITER Heating Neutral Beam Duct Liner is outlined.
- A vector-calculus method is used for calculations which evaluate directional heat flux on different scraper panel layouts.
- A scraper panel layout with equal panel lengths and common thermal loading was achieved through these calculations.
- The thermo-mechanical performance of a scraper panel satisfies ITER structural design criteria under a normal operation scenario.
- Fast blow-out draining is used for complete emptying of a cooling arrangement.
- Numerical simulations of the blow-out draining were carried out using RELAP5 and found to demonstrate satisfactory draining.

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ABSTRACT

The Duct Liner for the International Thermonuclear Experimental Reactors (ITER) Heating Neutral Beam (HNB) system is a key component in the beam transport system. Power loading on the top and bottom beam scraping panels of the Duct Liner occurs primarily due to direct interception of the HNB and it is highest at the extreme steering angles of the beam. Furthermore, power loading due to direct interception is dependent on the size and orientation of the scraper panels with respect to the neutral beam axis. This paper outlines the design features of the proposed Duct Liner and describes the analysis performed to optimize the compatibility of the top and bottom scraper panels (also known as Duct Liner Modules) with a normal beam operation scenario. Thermo-mechanical analyses have been performed to validate the design of Duct Liner Modules incorporating deep-drilled cooling technology with a peak power density of 1.2 MW/m^2 and incident power of 0.27 MW, and also to verify its conformity with ITER structural design criteria. Furthermore, numerical simulations of the transient draining procedure were performed by using a one-dimensional thermo-hydraulic code to demonstrate complete emptying of the proposed parallel-layout cooling circuit without any reliance on conventional gravity draining.

1. Introduction

The ITER Tokamak is the latest step in the progress toward the realization of fusion energy. To heat the plasma contained by the magnetic fields within the Tokamak, a number of heating systems will be used. One such system is the neutral beam system, which projects neutral hydrogen isotope atoms into plasma at high velocities/energy. It can also be used to provide diagnostic information on the condition of the plasma. The neutral beam system for ITER consists of two heating and current drive neutral beam injectors and a diagnostic neutral beam injector.

Culham Centre for Fusion Energy (CCFE) has a long history of designing, building, upgrading, maintaining and operating world-class neutral beam systems. Presently, CCFE is developing a detailed design for a number of components for the ITER Heating Neutral Beam (HNB) system including the Duct Liner (DL). The focus of present analysis work has been to avoid excessive beam scraping to and thereby contribute toward minimizing thermal–hydraulic overheads of the component. The compatibility of the top and bottom scraper panels with a normal beam operation scenario was optimized by performing conveniently repeatable vector-calculus computations on the data output from a single run of the Beam Transport and Re-ionization code [1] which is normally used to provide information on the neutral beam. Furthermore, finite element thermo-mechanical analyses were performed to validate the design of a Duct Liner Module (DLM) against the resultant thermal loads using ANSYS software. Finally, transient, one-dimensional numerical simulations carried out using the

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Abbreviations: BTR, Beam Transport and Re-ionisation; CCFE, Culham Centre for Fusion Energy; DNB, diagnostic neutral beam; DL, Duct Liner; DLM, Duct Liner Module; EM, electromagnetic; HNB, Heating Neutral Beam; ITER, International Thermonuclear Experimental Reactor; LHS, left hand side; NS, neutron shield; RH, remote handling; RHC, Remote Handling Class; SDC-IC, structural design criteria for in-vessel components; VV, vacuum vessel.

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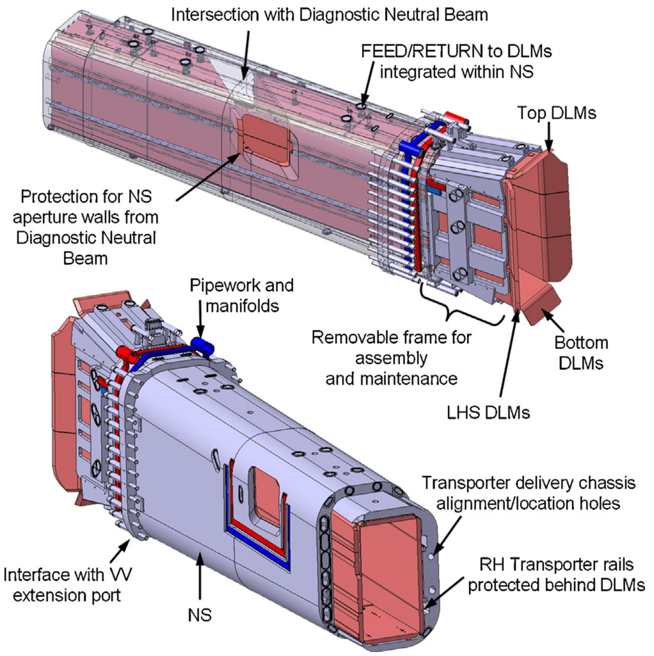

Fig. 1. DL concept design.

RELAP 5 thermal–hydraulic system code [2] are briefly described. These simulations have been used to check the compatibility of the cooling network arrangement with a fast blow-through draining procedure.

2. Duct Liner design description

The DL for the ITER HNB system is a key component in the beam transport system. Initially, a DL will be installed into equatorial ports 4 and 5 of the ITER Tokamak vacuum vessel (VV) to protect the port extension from power deposition due to re-ionization and direct interception of the HNB. Furthermore, it will contribute toward the nuclear shielding of the port extension and superconducting magnetic coils from the plasma nuclear radiation.

On HNB1, the DL shall also incorporate an aperture compatible with the crossing of the intersecting diagnostic neutral beam (DNB). Fig. 1 shows pictures of the DL concept design for HNB1.

The DL incorporates a 316L (N)-IG neutron shield (NS) and actively cooled CuCrZr DLMs which line all four internal walls of the NS. The NS is Remote Handling Class (RHC) 3 whilst the majority of DLMs are RHC 2. These DLMs are mounted on the NS in a manner that does not excessively constrain their thermal expansion. Coolant feed and return to the DLMs is accomplished through welded connections to the internal coolant network of the NS which incorporates deep drillings for cooling the structure itself as well as routing cooling water to the DLMs. They are fed in parallel by three independent loops – top, bottom and sides. The DLMs are thermal shields which protect against the heat deposition from the HNB, but without excessive scraping in order to maximize the power injected into the Tokamak. There are two rails permanently mounted on the left hand side (LHS) of the NS to allow a remote handling transporter tool to traverse along the length of NS for remote maintenance of the DLMs· Whilst the DLMs are designed for full functionality with remote handling (RH) installation, removal and maintenance procedures, their design must provide a thermal fatigue life consistent with the total number of pulses and pulse duration foreseen by ITER operation to contribute toward a high beam reliability and availability.

3. Optimization of top/bottom DLM Layout

The primary function of the top and bottom DLMs is to define the edge of the beamline as it passes through the neutral beam duct by scraping the fringe of the beam illustrated in Fig. 2. This limits the beam dimensions to protect the vacuum vessel (VV) wall from the HNB direct interception. The scraping by these DLMs should not preclude the injection of a 16.7 MW HNB into the ITER Tokamak. The incident heat flux on a top or bottom DLM due to direct interception depends on the intensity of the beam (normal power density measured in power per unit area) and the angle of interception between the DLM and the beam. Whilst the use of a shallow angle of incidence provides an effective way of attenuating high power densities, it could drastically increase the length of the DL· Therefore, the liner profile and positioning within the power absorbing zones need to be optimized to ensure that no excessive power density peaks occur.

The Beam Transport and Re-ionization code (BTR) [1] developed by Eugenia Dlougach at the Kurchatov Institute can provide incident power density on a plane in a grid pattern with user-defined resolution. However, BTR code simulation typically takes several hours to complete and the results give no information on the angle of the beam interception.

In order to optimize panel positions in the DL, it is desirable that the power loading for a panel in any position and orientation can be estimated quickly; this rules out the use of BTR in an optimization loop. Instead a method has been developed to estimate power densities on any arbitrary panel with the output of only one BTR simulation. This method accounts for both the diffuse nature of the beam source and the resulting spread of directions the power arrives from.

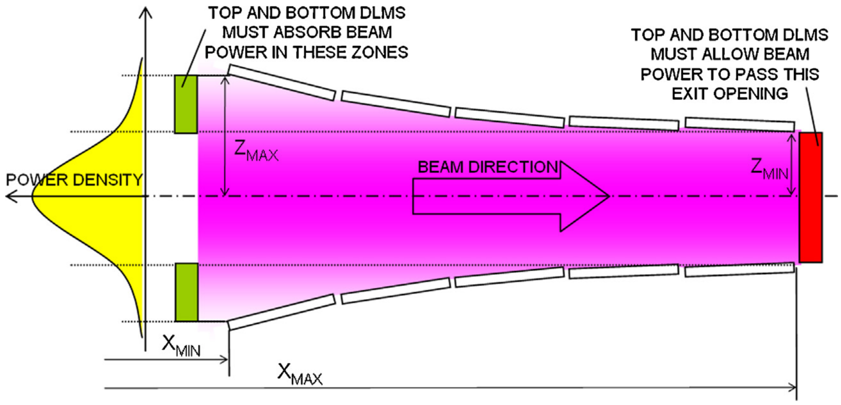

Fig. 2. Cross-section of DL showing scraping at the fringe of the beam.

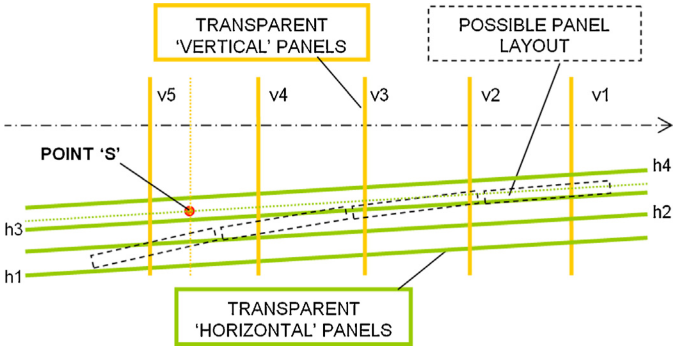

Fig. 3. Illustration of grid or array of transparent orthogonal panels.

Using the data output from a single BTR simulation performed on an array of transparent near-orthogonal panels Fig. 3, and a vector-calculus method to evaluate the directional heat flux in the entire area where the DLMs might be positioned, a calculation tool was designed to establish the power density on a plane for any angle without performing repeated computations using the BTR code.

Using linear interpolation, the power deposition on any vertical and horizontal plane can be estimated from these BTR results. This allows incident power densities to be established at any point in the Duct Liner for a vertical and horizontal plane. Using vector-calculus it is then possible to establish the direction and magnitude of the compound incident power at that point. It is then possible to calculate the power densities for any surface by taking the dot product of the surface normal and the power density vector.

This calculation tool was then used in conjunction with a generic optimizing algorithm to iterate and optimize the size, orientation and number of top/bottom DLMs. The optimization study showed that it was possible to fulfill the DL scraping requirement using only 4 top and bottom DLMs arranged symmetrically about the beam axis. The illustration in Fig. 4 shows an overlay of the outlines of the optimized symmetrical layout to compare it with the concept design layout.

In terms of the wider DL design implications this layout offers the following benefits over the 5-DLM concept design:

- It is possible to eliminate the fifth DLM position entirely which is susceptible to high induced eddy currents during plasma disruptions and the resultant excessive electromagnetic (EM) torques. They present a design challenge for the fixings at that DLM position.
- The narrower cross-section of the resulting opening enables the thickness of the NS to be increased thereby affording greater neutron shielding function and greater design space for engineering the routing of coolant and diagnostic cabling through the NS.
- A DLM layout in which DLM 2, 3 and 4 were of a common length and each was predicted to experience approximately equal thermal loading – both in terms of integral power and peak power density.

4. Thermo-mechanical analysis of a generic DLM

Steady-state finite element analyses were performed to investigate and validate the proposed design for the common length DLMs realized from the work described under Section 3. These analyses were performed against loads prevailing under normal operating condition during injection of a full power Deuterium beam for pulse durations of 1 h under worst case conditions of steering and halo divergence.

4.1. Description of steady-state thermo-mechanical analysis

The normal operating condition loads for such DLM are based on the thermal load applied on the front face and the internal coolant pressure. The heat load consists of the sum of the beam direct interception at a worst case vertical steering angle of 10 mrad, and nuclear radiation. This results in a total integral power on the entire duct panel of 0.27 MW and a peak power density peak of 1.2 MW/m^2. Although disruptions are also regarded as normal operating loads, they mostly affect attachment stresses rather than stresses on the DLM front wall sections, which do represent the most loaded sections. Therefore within this context, they were not critical to the analyses performed.

A steady state thermal analysis of the generic DLM was carried out with the heat flux distribution (obtained through BTR computations performed on the optimized DLM layout), applied over the panel surface and coolant heat transfer coefficients based on satisfying all thermo-hydraulic constraints [3]. This analysis revealed a thermal field with a peak temperature of 160 °C. The obtained thermal field was used as a loading condition for a structural analysis together with a 4 MPa coolant pressure load corresponding to the absolute inlet water pressure. The stress distribution showed the same trend as the heat flux with a peak equivalent stress of 114 MPa (Fig. 5).

4.2. Design criteria checks

The procedure and the criteria used for the analyses rely on the ITER structural design criteria for in-vessel components (SDC-IC) [4] design rules. For the performed elastic analyses, Level A criteria have been assumed.

The CuCrZr negligible thermal creep limit (according to IC 3050 of the SDC-IC [4]) scaled to the maximum number of 1 h operating cycles shows that the thermal creep will be negligible up to 100,000 cycles for a max operating temperature of 200 °C. Thermal creep

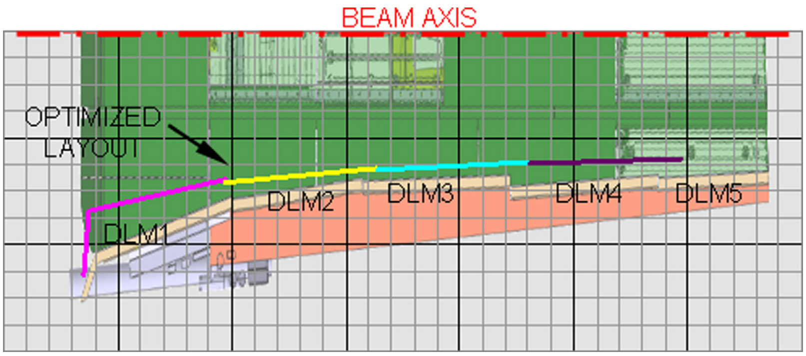

Fig. 4. Comparison of optimized symmetrical layout with the concept design layout.

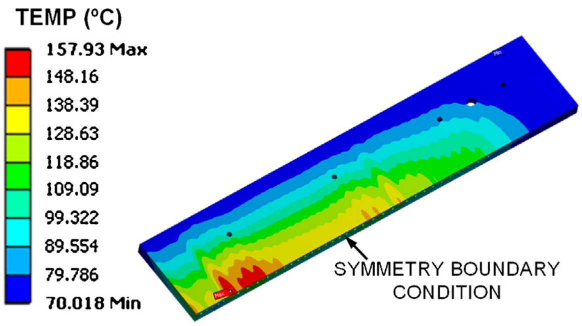

Fig. 5. Temperature field from steady state thermal analysis of DLM.

Table 1
Summary of SDC-IC rule checks.

Rules	Result (MPa)	Reserve factor
Primary membrane and bending stress (IC 3211.1.2) $\bar{P}_m \le S_m(T_m, \phi t_m)$	16	>5
$\overline{P_L + P_b} \le K_{eff} S_m(T_m, \phi t_m)$	71	2.6
Immediate plastic flow localization (IC 3212.1.1) $\overline{P_L + Q_L} \le S_e(T_m, \phi t_m)$	82	>5
Immediate local fracture due to exhaustion of ductility (IC 3213.1) $\overline{P_L + P_b + Q + F} \le S_d(T, \phi t, r_2)$	114	No limit for S_d
Global fast fracture (IC 3214.1.1) $K_I \le \gamma_1 K_C(T_m, \phi t_m)$	7.1	>5
Local fast fracture (IC 3214.1.2) $K_I \le \gamma_2 K_C(T_m, \phi t_m)$	25.2	3.6
Progressive deformation or ratcheting (3Sm rule) (IC 3311.1) $Max\left(\overline{P_L + P_b}\right) + \Delta\left[\bar{P} + \bar{Q}\right]_{\max} \le 3S_m(T_m, \phi t_m)$	114	3.1
Fatigue (thermal cycling) $N > 40{,}000$ ITER HNB pulses	$\Delta\varepsilon = 0.0822\%$ $N \sim$ infinite	

can therefore be neglected and the low temperature rules from the SDC-IC [4] utilized.

The most critical line segments for the stress linearization were considered through the DLM front wall thickness. At the maximum DLM temperature the allowable stress values are shown in Table 1.

For the worst case normal injection scenario, at full beam power, the analyzed generic DLM satisfies all the linearization criteria and is predicted to be able to withstand a number of beam pulses significantly in excess of ITER requirements (40,000 cycles).

4.3. *Summary and future work*

The thermo-mechanical evaluation provides sufficient justification to continue implementation of DLMs with deep-drilled cooling technology. Over the course of the upcoming design phase similar thermo-mechanical analyses will be conducted on side DLMs where BTR simulations have shown that re-ionization can deposit heat loads with a power density peak of 2.5 MW/m^2. Feasible design solutions for critical areas of a DLM such as remotely removable water connection access caps, and fixings will be detailed and their thermo-mechanical performance scrutinized against the SDC-IC [4].

5. Compatibility with draining procedure

For all actively cooled in-vessel components in ITER such as the DL, it will be necessary to evacuate their water content prior to any withdrawal operation from in-vessel to minimize risks associated with tritiated water. The draining and drying procedure for the DL will involve draining by gravity, followed by draining through fast blow-out using nitrogen gas, and finally evaporation and drying through circulation of hot dry nitrogen. However, due to the complexity of the cooling network on the DL, gravity draining will have a limited effect. For this reason, the DL will rely heavily on the fast blow-out procedure to remove residual water from the cooling circuits. In order to minimize intervention times, it was imperative to demonstrate the efficacy and speed of the fast blow-out procedure for the DL.

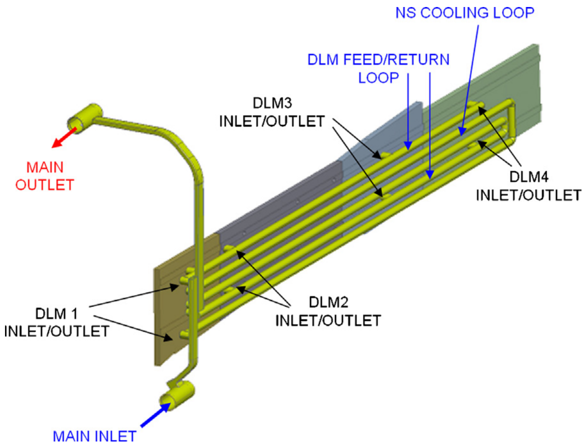

Fig. 6. Modeled part of the Side Duct Liner Modules arrangement.

For this purpose, transient, one-dimensional numerical simulations of two-phase flow inside a representative section of the DL were conducted using the RELAP5 Mod 3.3 code [2]. RELAP5 Mod 3.3 is a thermal–hydraulic system code, which is typically employed in the numerical simulation of light water fission reactor transients. It has already been adopted in other similar research studies for ITER performed by the Department of Nuclear Engineering of the University of Palermo [5,6].

5.1. *Model description and results*

A section of the right hand side DLM cooling network was selected for the modeling analysis. It suitably represents the most challenging geometrical arrangement for draining due to a large number of vertical inverted loops. The modeled part of the Side DLM cooling loop is shown in Fig. 6. It contained the internal coolant network of 4 side DLMs connected in parallel to the corresponding network inside the NS.

A comprehensive flow domain discretization was performed of the network geometrical configurations. The inverting loops and the local resistances due to U-bends were accurately represented. The complete RELAP5 input of the model described can be found in [7].

For the draining simulation analysis, it was assumed that the network system is initially full of water, at atmospheric pressure, with the temperature just below saturation (90 °C). The water in the system is stagnant and no flow is taking place. Such a system was then subjected to increased inlet pressure, which purges the system and replaces the water with nitrogen. The inlet temperature of the gas was set to 40 °C as this is the temperature it is supplied at by the plant. The mass inflow of nitrogen purely depends on the system resistance (i.e. wall and interface friction).

Numerical simulations were conducted for the pressure drops of 0.5, 1.0, 2.0 and 4.0 bar across the system with the exit pipe held at atmospheric pressure. Time variation of water mass fraction in the network is shown in Fig. 7. The slope change of the water mass

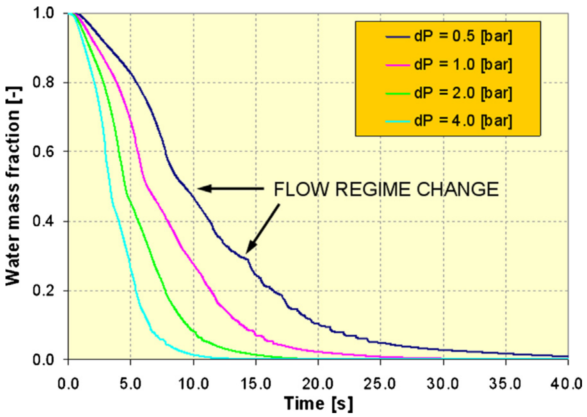

Fig. 7. Time variation of water mass fraction.

fraction distributions indicates a flow regime transition. The system was considered empty when it contained less than 1% of the initial water mass. The analysis of the results showed that for all analyzed cases, the network is successfully drained in less than a minute. During the next phase of the DL design work, CCFE will extend the introduced analysis approach to include a complete representation of the entire DL cooling network and use the transient numerical simulations to report the gas flow resistance characteristics of the cooling system to ITER Organization.

6. Conclusions

The engineering design of the ITER HNB Duct Liner was outlined in the paper. Also, the analysis process performed to avoid excessive beam scraping and to optimize the layout of the top and bottom DLMs was reviewed. The thermo-mechanical performance of a DLM, under a typical loading scenario was assessed and conformity to ITER design criteria verified for monotonic loads. Furthermore, numerical simulations of the transient draining procedure were conducted to demonstrate complete emptying of the parallel cooling arrangement without any reliance on conventional gravity draining.

Acknowledgments

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References

[1] E. Dlougach, Beam Transport Code: User's Manual. Kurchatov Institute.
[2] RELAP5/MOD3 code manuals, NUREG/CR-5535 Rev 1.
[3] HNB Duct Liner flow budget, ITER IDM Reference 7GNEU7 v1.0.
[4] ITER Structural Design Criteria for in-vessel components (SDC-IC), ITER IDM Reference 222RHC v2.0.
[5] P.A. Di Maio, D. Paradiso, G. Dell'Orco, C.S. Pitcher, M. Kalish, On the theoretical–numerical study of the ITER Upper Port Plug structure hydraulic behaviour under steady state and draining and drying transient conditions, Fusion Engineering and Design 86 (12) (2011) 2983–2998.
[6] A. Tincani, M.G. D'Angelo, P.A. Di Maio, L. Laffi, G. Miccichè, S. Nucci, et al., Hydraulic characterization of the full scale divertor cassette prototype, Fusion Engineering and Design 86 (October (9–11)) (2011) 1673–1676.
[7] Feasibility of draining the duct liner side panels by blow-out, ITER IDM Reference 7GUE52 v2.0.