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Plasma Facing Components for the European DEMO: Advances in Engineering Designs

Thomas R. Barrett[a], G. Ellwood[a], M. Kovari[a], B. Chuilon[a], G. Pérez[ab], M. Fursdon[a], F. Domptail[a], L. V. Boccaccini[c] and J. H. You[d]

[a]CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom
[b]working at ITER Organization, Route de Vinon-sur-Verdon - CS 90 046 - 13067 St Paul Lez Durance Cedex – France
[c]KIT, INR, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[d]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

The European DEMO is a high fusion power and long-pulsed device, and hence amongst the most critical and high-risk technologies are the plasma-facing components (PFCs). The divertor PFCs remain a critical challenge, while a preliminary assessment of the wall surface loads has led to the anticipated requirement for high heat flux PFCs in certain regions of the main chamber first wall (FW). In this paper, we present engineering concepts of divertor and FW PFCs which, compared to baseline designs, are intended to improve power handling. An update is given on the Thermal Break divertor PFC development, a discrete limiter is outlined, and progress is reported on the de-coupled FW finger PFC design.

Keywords: DEMO, plasma facing components, PFC design, high heat flux, divertor, first wall

1. DEMO PFCs and the heat flux specification challenge

The European DEMO is currently being designed under the framework of EUROfusion. This 2 GW_{th} power reactor must possess plasma facing components (PFCs) which can function in the extreme environment of the fusion core over multiple full-power years of operation. The PFCs are primarily in the divertor, which acts as the main power exhaust for charged particles, and the main plasma chamber first wall (FW).

Perhaps the most design-driving load on these PFCs is the surface heat flux (power density, MW/m^2). The heat flux magnitude and distribution are, however, subject to large uncertainties and a specification is currently under development using a suite of modeling tools and methodologies [1]. What is known is that the heat flux arises from a number of sources, dominated by charged particle heating and thermal radiation in normal operation, but with additional transient events such as the wall-limited plasma and loss of divertor detachment. For the 2015 DEMO baseline, if one divides the total charged particle heating power of roughly 450 MW by the wall area of 1500 m^2, the average surface heat flux is 0.3 MW/m^2. Of course, there will be both localised load effects and myriad engineering imperfections that will lead to substantial increases above this level of heat flux.

One of most significant sources of such heat flux peaking is the modularisation of the plasma-facing wall and the effect of module gaps. Modularisation of the main chamber FW in DEMO is required for manufacturing feasibility and to alleviate thermal stresses, but inevitable consequences are 1) gaps between modules and 2) module misalignment. Both present the risk of edge exposure, which causes considerable surface heat flux, as elaborated in a companion paper [2]. It is well established that the geometric shaping needed to protect these module edges can lead to an order of magnitude increase in the peak heat flux compared to a continuous wall with no gaps or misalignments [3]. Consequently, it is essential to design the wall PFCs in 3-D, carefully shaping the surface with consideration of field line trajectories and realistic wall panel misalignments. This is a critical and escalating activity in the design of the European DEMO.

With such uncertainty over the design heat flux, it is necessary to design PFCs with the aim of maximising the engineering heat flux limit (that is, the heat flux at which first failure is predicted), while also attempting to fulfil other requirements such as manufacturability and reduced material activation. In what follows the progress in developing a number of PFC concepts is presented, for first the divertor and second the FW.

2. The divertor PFCs

2.1 Design approach

In the DEMO reactor, as in ITER, it is the divertor inner and outer vertical target surfaces that receive the highest heat flux. The baseline PFC here is the ITER-like design featuring tungsten monoblocks on a CuCrZr alloy structural pipe. However, a range of advanced concepts are under investigation which aim to either improve the structural material high temperature strength, or aim to alleviate the stress in the structure [4]; both of which would raise the heat flux limit of the divertor. For each PFC concept studied, it undergoes two successive phases of: 1) numerical analysis and design optimisation, followed by 2) mock-up fabrication, NDT/qualification and high heat flux (HHF) testing. Presently the project is undertaking the first phase mock-up testing, and typically six mock-ups of each concept are under test.

2.2 *Thermal break* concept

One such alternative divertor concept is the Thermal Break [5,6], first developed by design optimisation using

author's email: tom.barrett@ukaea.uk

a parameterisation of the interlayer thermal conductivity and elastic modulus [5]. The practical embodiment of this is a pure Cu interlayer, between the tungsten monoblocks and CuCrZr pipe, which features machined grooves on the plasma facing side (running in the direction of the pipe axis) as shown in Figure 1. The resulting reduced thermal conductance between armour surface and pipe redirects the heat flow, reducing heat flux peaking, and the compliance of the narrow Cu 'spokes' brings structural decoupling and hence reduced stress. The design also features a split in the monoblock on the plasma-facing side (width 0.25mm), which was found as part of the design study to reduce the stress in the monoblock and pipe. By numerical analysis (the "MEAP" method described in [6]) we find that this design has a lower Von Mises stress range (moving from standby to full plasma HF) in the pipe by a factor of 0.6, compared to a design with a solid Cu interlayer.

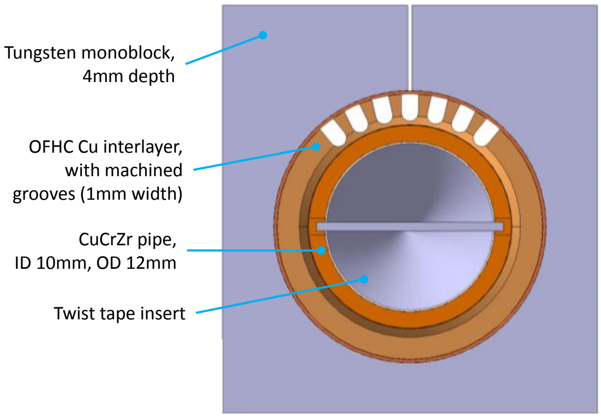

Fig.1. Geometry of the Thermal Break mock-up.

The 'design by analysis' approach involves a number of idealistic assumptions, and must be heavily complemented by 'design by test'. It is also essential to demonstrate the manufacturing feasibility of the concepts under study. Accordingly, mock-ups of the Thermal Break design shown in Figure 1 have been fabricated (Figure 2). Vacuum brazing is used to join the three parts: 1) CuCrZr pipe, 2) OFHC Cu 'sleeve', and 3) monoblock with cast OFHC Cu lining. Ten monoblocks are used per mock-up assembly giving a 'target' section length of 42.7 mm. Six mock-ups of this type have so far been manufactured and are ready for the first phase HHF testing. The testing aims to verify fabrication procedures as well as reveal potential performance improvement compared to the baseline PFC.

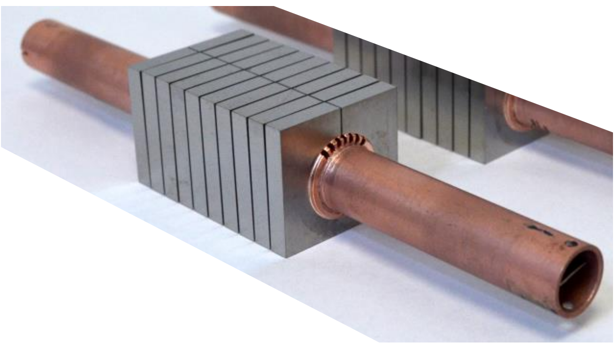

Fig.2. A completed Thermal Break divertor PFC mock-up.

3. The main chamber first wall (FW) PFCs

The FW of DEMO is expected to be manufactured using reduced activation materials, and, as it removes a significant fraction of the plasma (heating) power, it should exhaust this power at a temperature useful for the balance of plant. However, while the divertor PFCs have received considerable research focus in recent years, the FW PFCs remain relatively undefined, largely because of the difficulty specifying the heat flux. There is concern that this heat flux will in certain areas of the FW exceed engineering limits. Table 1 compares selected requirements and design bases of the divertor and FW. It can be concluded that the engineering of the FW is at least as challenging as the divertor, and perhaps more so.

Table 1. Comparison of Divertor and FW design requirements.

	Divertor	**First Wall (FW)**
n irradiation damage	'Low', 2-5 dpa/fpy in Cu [7]	'High', >13 dpa/fpy in Cu [7,8] @ OMP
Coolant temperature	'Low', 150°C [4]	'High', ~300°C (for power cycle, but could be as divertor in specific HHF components)
Materials	W, Cu alloys	W, Eurofer, … → reduced activation desired
Effect on reactor TBR	None (the divertor is non-tritium breeding)	Substantial, FW must be 'thin'
ITER technology applicable?	**YES**, although must be developed to suit DEMO requirements and loads	**NO**, e.g. Cu alloy not feasible or must be very limited
ITER max. design heat flux	20 MW/m^2 [9]	4.7 MW/m^2 [9]
Supposed DEMO max. design heat flux	15 – 20 MW/m^2 [10]	0.5 – tens MW/m^2 depending on wall design / shaping
Calculated Heat flux limit of current PFC designs	10-20 MW/m^2 Based on thermo-structural assessments	So far < 2 MW/m^2 Based on thermo-structural assessment

3.1 Baseline FW

The conceptual baseline FW is the *integrated* type, composed of the front face of the breeding blanket module with integral cooling channels and a thin clad tungsten armour layer facing the plasma. Since the blanket box and therefore FW structure are Eurofer, this technology has heat flux limits (as calculated by thermo-structural numerical analysis and assessment to design code) of about 0.7 MW/m^2 for He coolant and 1.5 MW/m^2 for pressurised water coolant [6]. Depending on the FW heat flux, these limits may not be sufficient in order to develop a feasible DEMO design.

3.2 Limiters

All tokamaks operate with limited as well as diverted plasmas in which, respectively, the last closed magnetic flux surface is defined by the main chamber wall (i.e., a limiter) or by the divertor surfaces. The main instances of a limited plasma are during the start-up and ramp-down phases of a discharge. Crucially therefore, all tokamaks including DEMO require limiter PFCs which directly intercept the near scrape-off layer (SOL) and are subject to a high heat load. There can be two types of limiter: a *discrete limiter* or a *wall-limiter*, where the latter has gaps between wall panels which are smaller than the panels [3]. The ITER design uses a wall-limiter with a high coverage of HHF components, however in DEMO this wall-limiter approach may not be feasible due to the negative impact on reactor TBR, and because of the difficulty (and cost) of applying tight manufacturing tolerances over a very large area. The use of discretely placed limiter HHF components would have a smaller impact on TBR and it could be much more feasible to tightly control the position and dimensional accuracy of PFCs and gaps between them (key to controlling charged particle heat flux). Note that it is thought that such limiters would not be retractable. Crucially, it remains to be demonstrated whether a DEMO limiter concept with relatively small plasma wetted area can lead to tolerable heat fluxes at the PFCs, especially as it may not be feasible to use copper alloys as a FW structural material in the near-term DEMO.

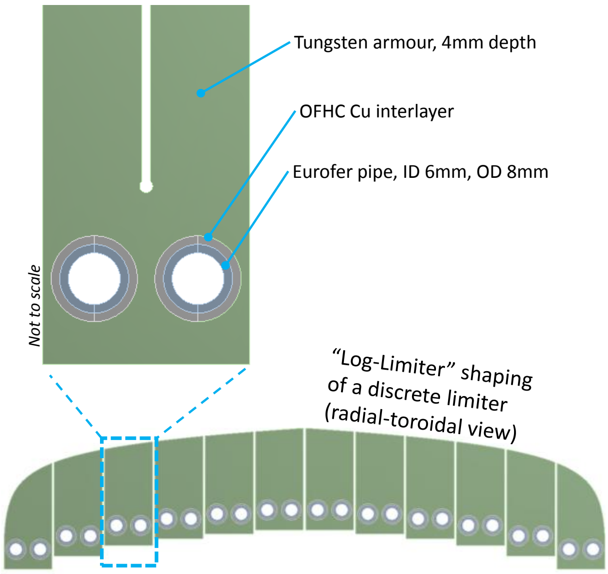

Fig.3. A discrete limiter PFC concept, with thick W armour.

A design study of a discrete limiter has been started. The limiter is envisaged as poloidally elongated, and in the radial-toroidal plane would likely have a log-limiter shape to give uniformity of heat flux over the plasma-facing surface (Figure 3). The PFC has a thin-walled Eurofer structural pipe bonded (via Cu interlayer) to radially thick slices of W armour. The rationale for this large amour thickness is to exploit the high thermal inertia of W to improve the heat flux handling capability for short pulse durations. By thermal-structural analyses and assessment to the RCC-MR elastic design criteria, the design is limited (by the 3Sm rule) to 1.5 MW/m^2 steady state heat flux and 7.5 MW/m^2 for pulses of up to 10 s. The concept is early in development but may help to sustain the high power loads expected during the start-up and ramp-down phases.

3.3 Protection Panels

The discrete limiter, if adopted in DEMO, will by definition sustain a high thermal charged particle flux. However, even in the diverted phase, there is expected to be a substantial particle load on the FW (from filaments and fast alpha particles and in particular from transient events such as a large plasma displacement). Since the baseline FW heat flux limit is ~1 MW/m^2, there may be need for discrete FW *protection panels*. A protection panel is a HHF component, considered to be poloidally elongated and discrete (covering only certain parts of the FW), but it is quite distinct from a discrete limiter and must (at this stage) be treated as a different component. At least, due to the much larger SOL power decay length the protection panel has very different shaping requirements compared to a discrete limiter.

The rationale of protection panels is to protect the remainder of the FW from charged particle loads/events and in doing so improve the feasibility of using the integrated FW technology (with aforementioned modest heat flux limits) over the remainder of the FW. In covering only part of the main chamber, protection panels have a 'small' effect on the reactor TBR and allow the specification of tighter manufacturing tolerances. It is possible (and desirable) for the protection panels to be exchanged more frequently than the breeding blanket segments, although a remote handling strategy is still under development.

As with discrete limiters, protection panels have a 'small' plasma wetted area and it is currently not known whether the resulting surface heat flux will be tolerable with any near-term technology or materials. Modelling to develop a specification for the charged particle heat flux is underway, following the approach outlined in [2].

A PFC concept is under development which may be suitable for use in a protection panel. The design is based on splitting the FW panel into individual *fingers* (in this way similar to the ITER wall panels [9]), toroidally oriented and wrapping around the front face of the breeding blanket box (see Figure 4). The rationale of FW fingers is to alleviate thermal stress in the structure and to give more freedom for surface shaping which may be infeasible or too costly for the formed blanket box but which will be essential to manage the charged particle heat flux. Also, *de-coupling* the FW from the breeding blanket means that this HHF component does not need to be designed for the (safety critical) in-box LOCA event and the consequences of a FW failure are less severe [6].

In the de-coupled FW finger design in Figure 4, each finger contains four water (or He) cooling channels with supply and return provided via a manifold side box which passes radially along one side of the blanket module. The coolant makes a 180° turn at the opposite end. The structural material is Eurofer with 2mm thickness W armour tiles bonded to the surface. More detail on the basis, analysis and features of this design are to be reported in a future publication by the authors.

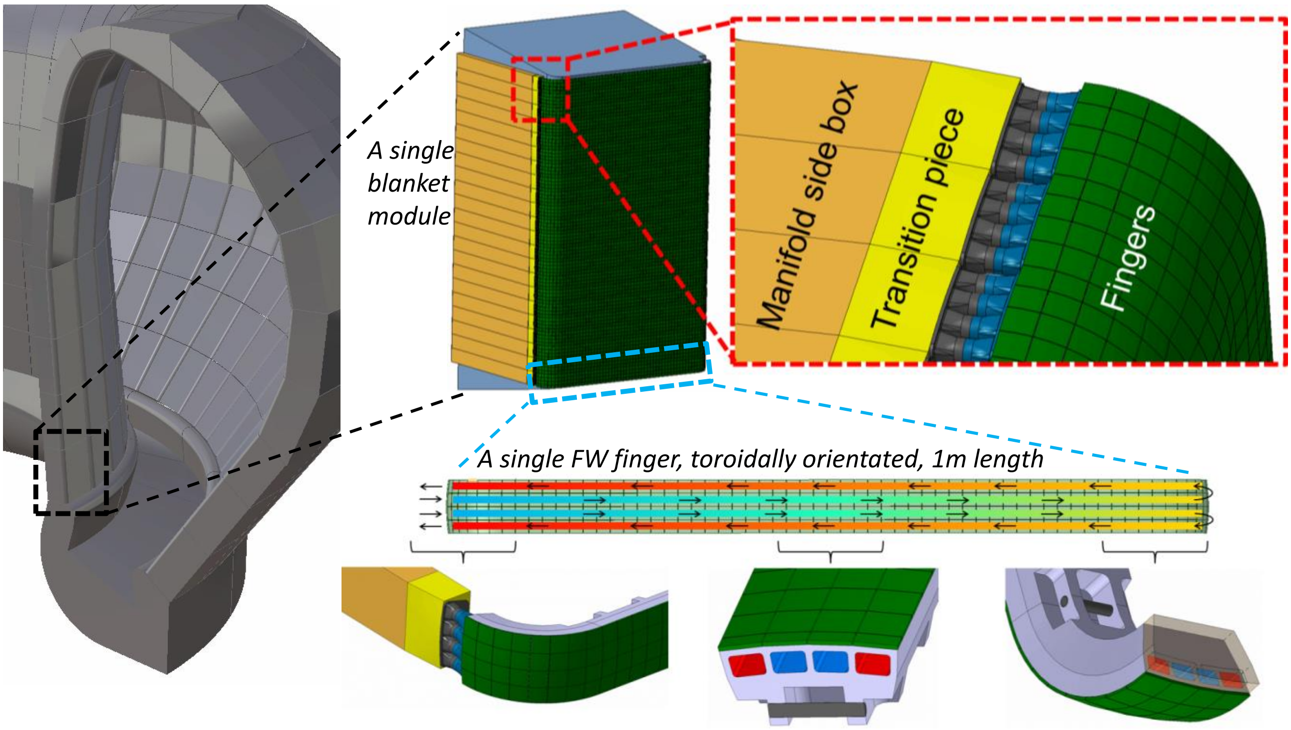

Fig. 4. The de-coupled FW finger concept, which may be a feasible option for a protection panel PFC.

4. Conclusions

This paper has presented progress with design concepts of the divertor and first wall PFCs for the EU DEMO. The design requirements are highly challenging, and a specification for the surface heat flux is under development which will elaborate them further. This surface heat flux is a strong function of the wall design and topology of modularisation, not least because FW shaping to protect module edges can lead to an order of magnitude increase in the peak FW heat flux, compared to a continuous wall with no gaps or misalignments.

For the divertor PFCs, a range of concepts evolved from the ITER-like design are under development in a process of design by numerical analysis and high heat flux mock-up testing. The *Thermal Break* mock-up design is currently under the first phase of testing.

Based on the need to sustain high heat flux, high neutron flux, and the need to minimise impact on reactor TBR and use low activation materials, the engineering of the main chamber FW PFCs is just as challenging as the divertor PFCs, and perhaps more so.

Discrete limiters will be needed in DEMO if a wall-limiter is not feasible for the limited plasma phase. A design concept has been presented with high thermal inertia which could improve power handling for short durations e.g., start-up and ramp-down phases.

For the diverted plasma phase, discrete *protection panels* may be needed to protect the remainder of the FW against charged particles arising from filament transport and from certain transient events. A design based on de-coupled FW fingers has been reported which may be a feasible option for these protection panels and will be developed as part of ongoing work.

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