DEVELOPMENT STATUS OF A SiC-FOAM BASED FLOW CHANNEL INSERT FOR A U.S.-ITER DCLL TBM

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The U.S.-ITER DCLL (Dual Coolant Liquid Lead) TBM (Test Blanket Module) uses a Flow Channel Insert (FCI), to test the feasibility of high temperature DCLL concepts for future power reactors. The FCI serves a dual function of electrical insulation, to mitigate MHD effects, and thermal insulation to keep steel-PbLi interface temperatures below allowable limits. As a non-structural component, the key performance requirements of the FCI structure are compatibility with PbLi, long-term radiation damage resistance, maintaining insulating properties over the lifetime, adequate insulation even in case of localized failures, and manufacturability. The main loads on the FCI are thermally induced due to through the thickness temperature gradients and due to non-uniform PbLi temperatures along the flow channel (~1.6 m). A number of SiC-based materials are being developed for FCI applications, including SiC/SiC composites and porous SiC bonded between CVD SiC face sheets. Here, we report on an FCI design based on open-cell SiC-foam material. Thermo-mechanical analysis of this FCI concept indicate that a SiC-foam FCI structure is capable of withstanding anticipated primary and secondary stresses during operation in an ITER TBM environment. A complete 30 cm long prototypical segment of the FCI structure was designed and is being fabricated, demonstrating the SiC-foam based FCI structure to be very low-cost and viability candidate for an ITER TBM FCI structure.

I. INTRODUCTION

The U.S. ITER Double Coolant Lead Lithium (DCLL) Test Blanket Module (TBM) program aims to validate a future power reactor (DEMO) design concept, which is based on circulating liquid breeder (PbLi) at elevated temperatures of more than 700 ^{o}C and at low velocities of ~10 cm/s (Ref. 1) through the blanket. The candidate ITER TBM and DEMO structural materials are based on reduced activation ferritic/martensitic steel alloys, which have maximum allowable PbLi interface temperatures of less than ~470 ^{o}C. Higher PbLi operating temperatures require that the ferritic/martensitic based structures be thermally insulated from the breeder material. Furthermore, to mitigate the pressure drop due to magneto-hydrodynamic effects in liquid breeders, the metallic walls need to provide electrical insulation from the flowing PbLi. Ceramic coatings could provide both, electrical and thermal insulation, if micro-crack densities are kept below stringent levels and coating materials are compatible with the structural as well as liquid breeder materials. Due to these limitations, the concept of a Flow-Channel-Insert (FCI) was proposed for the EU advanced lead–lithium blanket concept (Ref. 2) and for the US ARIES-ST blanket design (Ref. 3). The FCI is a standalone ceramic structure located inside the blanket flow channels. The FCI shields the metallic structure from high temperature breeder materials as well as insulates the bulk of liquid breeder material electrically from the wall. The FCI does not serve a structural purpose, which reduces the design requirements to merely surviving radiation, thermal, and mechanical loads imposed by the liquid breeder and the nuclear heating environments.

Previously, SiC/SiC composites with degraded thermal and electrical conductivities have been proposed as FCI structural material (Ref. 2, 5, 6). However, the low conductivity requirements of the FCI structure, necessitates further R&D of SiC/SiC composite materials, such as using 2-D woven fiber architectures and doping of the SiC matrix to reduce conductivities across the thickness of the SiC/SiC structures.[2] Alternatively, an FCI structure based on sandwiching porous SiC between dense CVD SiC face sheets was proposed, because of low cost, ease of fabrication and limited verification R&D needs of CVI- and CVD SiC materials.

Chemical vapor infiltrated (CVI) open-cell SiC-foam was proposed as a candidate porous SiC material with dense CVD SiC closeout face sheets. Production of SiC-foam materials is a relatively mature technology, which started in the early 1990's (Ref. 7) and SiC foam structures with a variety of geometric configurations are now commercially available.[8] The primary advantage of using this technology is that all SiC materials are CVD/CVI based, which have been shown to have excellent radiation damage resistance, thermal stability, and chemical compatibility with PbLi.

In this paper, we outline performance and material requirements of a SiC-based FCI structure, followed by the design of a prototypical FCI structure. Next, results of static thermo-mechanical analyses of a SiC-foam based FCI under ITER operating conditions are presented. Development and testing of SiC-foam based FIC material samples are discussed, and fabrication of 30 cm long prototypical FCI components are reported. We conclude with the results of first thermal exposure tests and planned liquid metal exposure tests of the complete FCI segments.

II. FCI KEY PERFORMANCE REQUIREMENTS

A number of performance requirements have to be met by the FCI structure, which include compatibility with high temperature PbLi, low through the thickness thermal conductivity, and low through the thickness electrical conductivity. However, specific required material properties depend on the reactor design (ITER, DEMO), the FCI design itself, as well as the blanket configuration and location within the reactor. Furthermore, future DEMO blanket designs will be based on optimization and sensitivity studies that will ultimately determine necessary performance parameters of the FCI for each, inboard and outboard blankets.

The requirements for thermal- and electrical conductivity of an FCI structure were recently analyzed using 3-D magnetohydrodynamic models for a 5 mm to 15 mm thick SiC FCI structures for a typical DEMO reactor design.[5] It was shown that the MHD pressure drop in a 2-m long poloidal duct dropped by a factor of 190 to 5 depending on the electrical conductivity value of between 5 and 500 S/m, respectively. Furthermore, using a thermal conductivity value of 2 W/m-K the analysis showed that the interface temperature between the structure and PbLi decreased from 538 to 504 ^{o}C with increasing FCI electrical conductivity from 5 to 500 S/m.

Hence, at present time required thermal- and electrical conductivity values of FCI structures can at best be expressed as a desired range: the through thickness electrical conductivity fall somewhere between 1 and 100 S/m and the thermal conductivity is assumed to be less than 2 W/m-K for future DEMO Inboard and Outboard blanket designs (Ref. 1, 5).

Chemical compatibility between the FCI structure and the liquid breeder PbLi is particularly critical for future DEMO reactors, where PbLi temperatures as high as 700 ^{o}C are required. Experiments with PbLi have shown that high-purity, chemical vapor deposited (CVD) SiC exposed to PbLi for up to 5000 h at 800 ^{o}C showed no sign of dissolved Si (Ref. 4). Hence, CVD SiC is considered chemically compatible with PbLi for ITER and DEMO operation. It is therefore more or less critical that FCI structures based on SiC materials would all have a high-density CVD face sheet in contact with the liquid PbLi.

The FCI has to have adequate structural integrity capable of withstanding thermal and fluid loads without resulting in significant loss of insulating properties. Structural integrity depends on choice of materials, material architecture (for SiC/SiC composites), and FCI geometry, which are addressed in the next sections. Damage or cracks have to remain localized and ingress of liquid metal has to remain limited to the extent of the damage. Ingress of liquid PbLi into cracks that form during operation should not result in "soaking" of the FCI interior structure, which could result in increasing local thermal and electrical conductivity of the FCI.

Liquid Metal Leak Tightness is critical for the FCI structure to prevent changes in thermal and electrical conductivity during operation. In case of localized damage, such as surface cracking, PbLi penetration should remain localized and be limited to the extent of the crack or damage and not diffuse or "soak" deep into the FCI structure.

The mechanical integrity of the FCI structure must be adequate enough to withstand all primary and secondary stresses without failure and it must be capable of withstanding cracking stresses induced by through the thickness temperature drops of up to $\Delta T \sim 100$ K for US DCLL TBM and $\Delta T \sim 200$ K for DEMO reactors. Dynamic Loads due to flow perturbations as well as off normal large temperature gradients along the duct must also be withstood by the FCI structure. Disruption events, such as Vertical Displacement Events (VDEs) in ITER or full disruptions in DEMO reactors may result in additional dynamic loads on the FCI structure resulting from rapid displacement or movements of the liquid PbLi within the duct.The impact of neutron irradiation induced damage on the FCI structure and material properties must be considered for the D-T Phase of ITER and full operation of DEMO. All of the aforementioned requirements of the FCI structure and material properties must remain fulfilled during neutron irradiation. Key FCI requirements are summarized in Table 1.

III. FCI-STRUCTURE DESIGN

A schematic of the U.S. ITER DCLL TBM is shown in Fig. 1. Details of the U.S. ITER DCLL TBM design are given in reference.[1] Liquid PbLi enters through a plenum near the bottom of the TBM module, flows up in the channels behind the plasma facing first wall (FW), and then at the top of the TBM turns around and flows downward to exit the TBM near the bottom. All internal PbLi breeder flow channels need to be protected by FCI structures, which includes the upper and lower turning sections. Here we present the design of the straight FCI section located in the upward channel behind the FW. Figure 2 is a close-up view of the schematic FCI structure relative to the ferritic/martensitic structure. There is a 2-mm gap between the FCI and the structure, which is filled with PbLi. The PbLi flow in the gap and inside the FCI is driven by the same pressure head. If necessary, pressure equalization between these two PbLi volumes can be achieved by openings. In this work, it is assumed that no significant pressure difference exists between the two PbLi volumes. The bulk of the PbLi travels with a mean velocity of about 0.06 m/s.

TABLE I: Key Requirements of the FCI Structure

PROPERTY	KEY REQUIREMENT
Thermal Insulation, RT - 700°C (k_{th})	2 to 5 W/m-K
Electrical Insulation, RT-700°C (σ_{el})	<1 to 100 S/m
Chemical Compatibility with Pb-Li	≤ 470 °C (ITER) ≤ 750 °C (DEMO)
Temperature Drop across FCI (ΔT)	< 100 K (ITER) < 200 K (DEMO)
Liquid Metal Leak Tightness	Limited to the extent of the crack/damage
Mechanical Integrity	Withstand primary & secondary stress
Dynamic Load	Withstand flow perturbations with off normal ΔT
Disruption Events	Withstand expected number (ITER: VDEs; DEMO: Full Disruptions)
Neutron Irradiation	Satisfy above requirements during D-T Phase (ITER); full operation (DEMO)

The total height of the DCLL TBM is 1.6 m, which includes the top and bottom cover plates (~ 0.05 m each). The straight section of the FCI will be attached to a curved section at the top (~0.1 m) and one at the bottom (~0.1 m). Thus, the total length of the straight section of the FCI structure is about 1.3 m. Figure 3 shows a candidate FCI geometry, which is analyzed in this work. The FCI is divided into five 0.25 m tall sections for ease of fabrication and assembly and to mitigate deformations associated with large structures. The temperature gradient through the thickness of the FCI is not uniform along its length (Ref. 5), thus by sectioning the FCI structure hot spots can be isolated from other parts of the FCI structure.

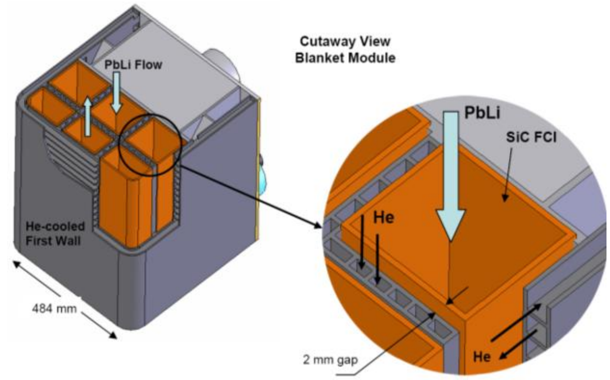

Fig. 1: Schematic CAD Model of the DCLL ITER-TBM design, showing the PbLi flow path through the FCI structures (TBM height is 1.66 m).

The solid model of one complete 1.298 m tall FCI sector was constructed of 5 segments, each with a height of about 0.255 m, and a width and depth of ~0.125 m (Fig. 3). The segments are stacked using 2-mm thick CVD-SiC brackets with a height of about 0.023 m. The brackets have grooves into which the FCI box fits. The brackets are not joined to the FCI box. They serve several functions: (1) as a guiding rail for mounting adjacent panels, (2) to stabilize the FCI position inside the TBM by providing a standoff between the FCI and the structure, (3) to provide mechanical support along the tall (1.3 m) FCI structure, and (4) to accommodate stresses and deformations by breaking up the FCI structure into sections. Design of the bracket has not been optimized, and may change significantly in future designs.

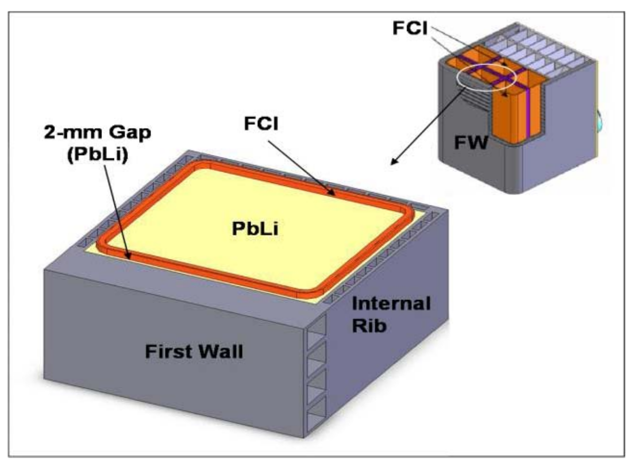

Fig.2: Details of the FCI in the front channel of DCLL.

To minimize loads on the FCI panels, openings might become necessary to equalize the pressure on both sides of the FCI. They can take the form of either pressure equalization holes or slots. However, these features have not yet been designed and are currently not included in the analysis.

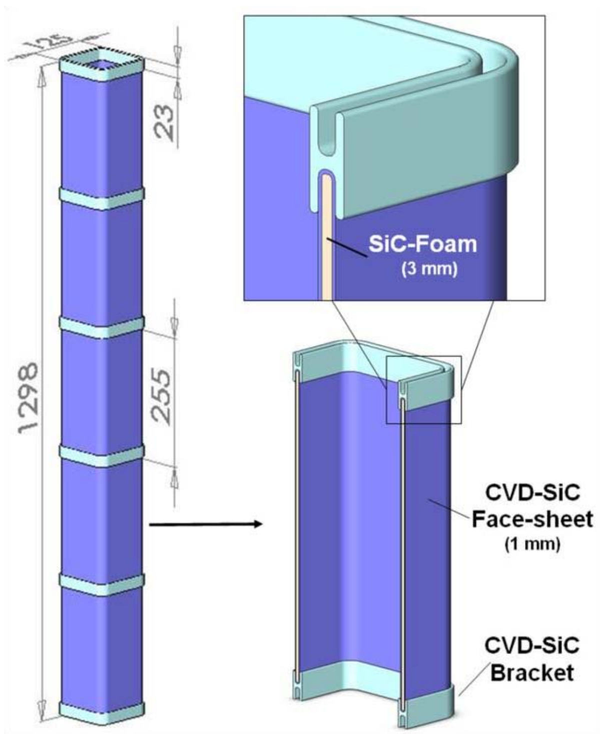

Fig. 3: Schematic of the segmented FCI structure; also a cross sectional view of a single sector and a close-up view of the bracket are shown (dimensions are in mm).

III.A. SiC Foam-based FCI Material

SiC/SiC composites have been suggested as structural materials of FCIs. However, these advanced SiC/SiC composites have thermal and electrical conductivities, which are above the desired limits. Figure 4 shows typical un-irradiated SiC/SiC composite materials properties. Depending on irradiation temperature, dose, and architecture, SiC/SiC can experience a wide range in thermal conductivity degradation of K_{irr}/K_o ratios between 0.1 and 0.6 between 400 ^oC and 1000 ^oC (Ref. 10). An effort is currently underway to develop new SiC/SiC composites with 2-D fiber architecture to satisfy the key requirements of electrical- and thermal conductivity limits outlined earlier.

Here we report on the use off-the-shelf CVD-based SiC materials for the FCI, consisting of open-cell SiC foam sandwiched between CVD SiC face sheets. SiC-foams are routinely manufactured at low cost compared with SiC/SiC composites, which fulfill FCI conductivity requirements. No significant R&D development, especially neutron irradiation data is necessary, as all of the proposed SiC materials are produced by a CVD process. A potential advantage of using the combination of SiC-foam with CVD face sheets is that CVD SiC materials have been established to have good resistance to neutron irradiation damage. However, the radiation performance of SiC foam materials has yet to be validated.

Figure 5 shows a micrograph of the proposed FCI structure, which consists of SiC foam between two CVD SiC face sheets. The parts with 12% SiC foam exhibited flexure strength of 50.3 ± 1.4 MPa, while the parts with 22% SiC foam had a strength of 115.4 ± 7.4 MPa (Ref. 11). The SiC foam is integrally attached (mechanically and chemically-bonded) to the CVD SiC faceplate. For a 100 pores per linear inch SiC-foam, there are 10,000 support points per square inch for the SiC face sheet. The foam is integrally fused to the CVD-SiC face sheet, because of the nominally 1 to 2 pore depth penetration of the face sheet into the foam. The reticulated ligamental structure of SiC foams provides favorable thermo-mechanical properties, such as high thermal shock resistance and the ability to withstand steep temperature gradients, by reacting stress through small movements of individual ligaments. Fully dense SiC structures are not capable of reducing stress through this micro-distortion behavior, and can result in microcracks.

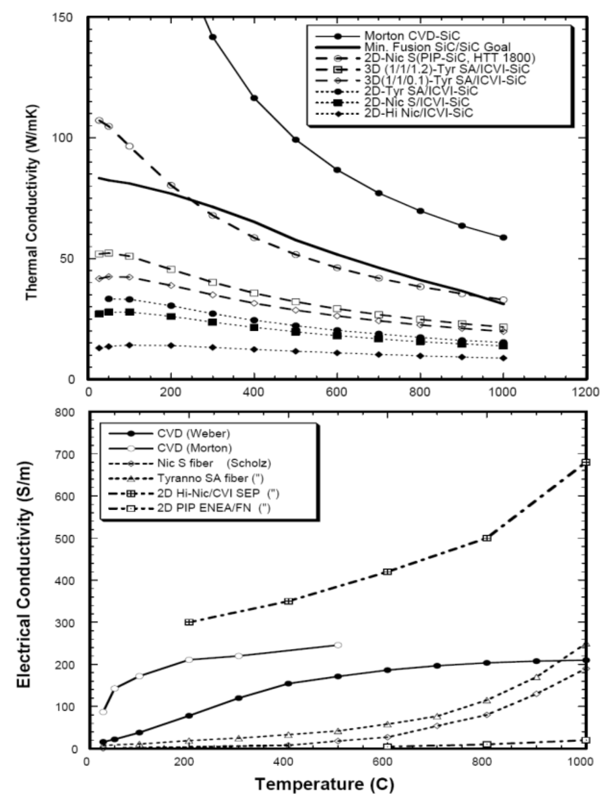

Fig. 4: Transverse thermal (top) and electrical (bottom) conductivities of un-irradiated SiC/SiC composites.[9]

Figure 6 shows the thermal and electrical conductivities of SiC foam as a function of temperature for 65 and 100 pores per linear inch (ppi) foam at 10% and 20% density. The average thermal conductivity of 10% dense, 100 ppi SiC foam is close to 1.0 W/m-K at 700^{o}C, which is less than the required 2 W/m-K for the FCI structure. The effective electrical conductivity of FCI development structure with 8 mm thick, 20% dense, 65 ppi foam and 0.08 mm thick face sheets was measured and found to be less than 0.2 S/m at a current of 1 A (Ref. 11). Prior to testing, the residual carbon at the core of the SiC foam ligaments was removed by oxidation. The low electrical conductivity of the FCI development piece indicates that design requirements of less than ~1 S/m are readily met using SiC foam sandwiched between two CVD SiC face sheets.

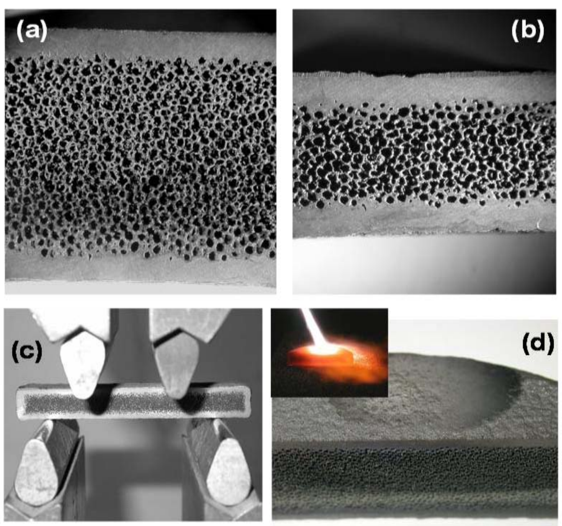

Fig. 5: (a) Cross-sectional photograph of 10-mm thick 12% dense CVD SiC foam with 1.8 mm thick CVD SiC face sheets; (b) 5-mm thick 22% dense CVD SiC foam with 1.8 mm thick CVD SiC face sheets; (both 5X); (c) FCI development specimen in 4-point bend fixture; (d) post-test photo of torch-tested SiC faceplate surface (1200 ^{o}C) (2X).[11]

Limited room temperature mechanical property measurements of SiC foam have been made. Figure 7 shows the strength and modulus of SiC foam as functions of bulk density.[11] Under compression, 10% dense SiC foam (0.32 g/cc) had a modulus of about 6 GPa, which rises to about 15 GPa at a 20% density. In tension, the modulus of 10% and 20% dense SiC foams are about 3 GPa and 8 GPa, respectively. Tensile/compressive strengths of 10% and 20% SiC foams are about 3.5/10.5 MPa and 7.6/27.2 MPa, respectively.

IV. THERMO-MECHANICAL ANALYSIS

The FCI model used for thermo-mechanical analysis is shown in Fig. 3, which shows a cross sectional view of one of five FCI segment. The FCI panel consists of a 3-mm thick foam sandwiched between two 1-mm thick CVD SiC face sheets. For finite element analysis a three layered material model was used to represent the CVD-Foam-CVD structure of the FCI wall. Here, we assume that each layer consists of a homogeneous material. For the 1-mm thick face sheets, CVD-SiC material properties were used and for the homogeneous "SiC-foam" material measured SiC-foam properties were assigned. (Table II). This analysis is, thus by its nature not exact in that the local response of individual SiC-foam ligaments are not analyzed. Therefore, the uncertainty associated with this FEM analysis must be taken into account in ascertaining the performance of this structure.

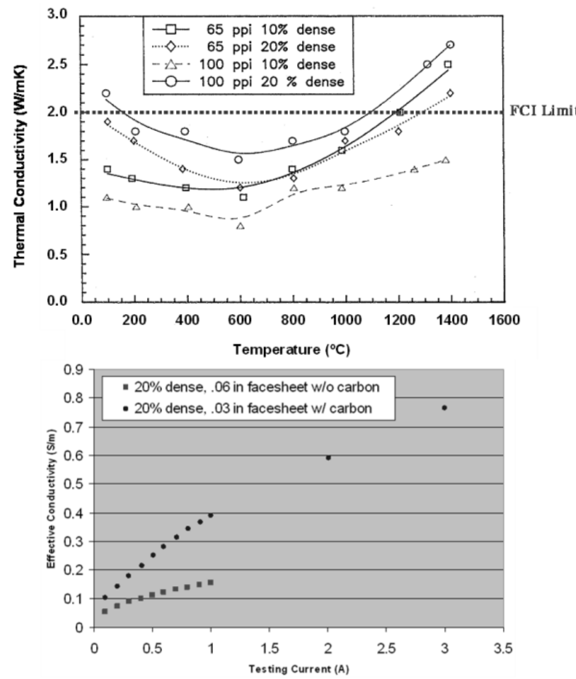

Fig. 6: Thermal conductivity versus temperature of 65 and 100 ppi SiC foam at 10% and 20% dense and electrical conductivity for 20% dense SiC foam with 1.8-mm CVD face-sheets (w/o carbon core).[11]

Two thermo-mechanical analyses were conducted, one on a single segment with a constant heat flux from the inside of the FCI and the other on the entire structure using detailed temperature maps, generated in conjunction with magnetohydrodynamic models.[5] The thermal loading conditions for the single FCI segment were chosen such that a mean temperature difference of about 40 ^{o}C (Ref. 1) would exist between the inside and the outside of the FCI. A heat flux of 0.2 MW/m^2 was applied to all inner areas of the FCI and the outside surfaces were cooled assuming a PbLi temperature of 450 ^{o}C with a heat transfer coefficient of 10 000 W/m^2-K. The brackets are not bonded to the FCI SiC-foam panels, rather they are simply slid into each other. Hence, there is a thermal resistance across the contact area between the bracket and the face sheet. The heat transfer coefficient of ceramic-to-ceramic joints ranges between 500 W/m^2-K to 3000

W/m^2-K, depending on the interface smoothness and contact pressure. For unpolished CVD SiC surfaces a heat transfer coefficient of 1500 W/m^2-K is assumed, which translates into a thermal resistance of 6.67×10^{-4} K-m^2/W. The location of thermal resistance interfaces are indicated in Fig. 9. The FCI material properties used for the analyses are summarized in Table II. The CVD-SiC brackets, shown in Fig. 3 serve to secure adjacent FCI segments to each other and to provide a stand-off distance from the TBM wall structure. However, following thermo-mechanical analysis of the brackets it was decided to change the "H" shape SiC brackets into "T" shaped brackets. Figure 8 shows the latest design of the bracket along with characteristic dimensions.

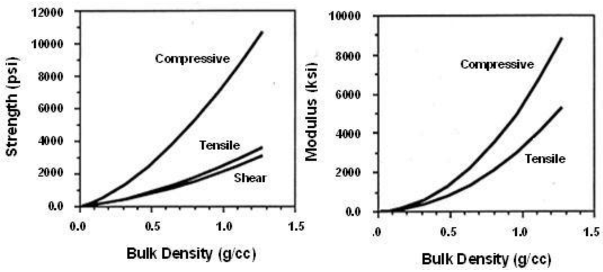

Fig. 7: Strength and modulus of SiC foam as a function of bulk density.[11]

TABLE II: FCI material properties at room temperature*

PROPERTY	CVD-SiC[12] (100% dense)	SiC-Foam[11] (20% dense)
Thermal conductivity (W/m-K)	48	2
Thermal expansion (10^{-6}/K)	4.55	4.20
Specific heat (J/kg-K)	1096	1096
Density (kg/m^3)	3210	630
Young's modulus (GPa)	430	11
Poisson's ratio	0.21	0.22
Tensile strength (MPa)	150	7.6

*un-irradiated properties

IV.A. FCI Segment Thermo-Mechanical Response

To model typical ITER conditions, the response of the FCI segment with a uniform through the thickness gradient of 40 ^{o}C was analyzed. Results of this thermal analysis are shown in Fig. 9. The high thermal resistance between the bracket and the FCI panels results in the maximum temperatures inside the top and bottom of the FCI panels near the brackets of about 550 ^{o}C, while the outside of the bracket is maintained at about 450 ^{o}C. The majority areas of the FCI outside panels are between 470 and 480 ^{o}C, while the inside panels are closer to 510 ^{o}C.

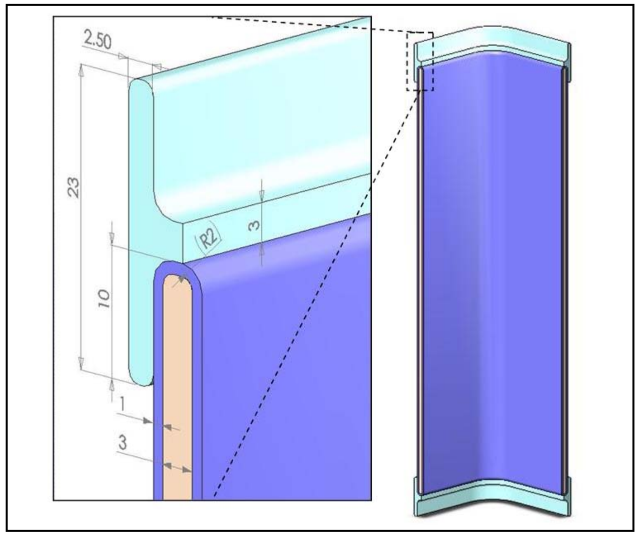

Fig. 8: Solid model of 1/4th of a single FCI segment showing bracket details (dim. in mm); this model was used for thermo-mechanical analysis with top half of the bracket removed for symmetry BCs.

Thus, the largest temperature difference between the inside and outside of the FCI exists near the brackets due to the thermal resistance between bracket and FCI panels. The corresponding von Mises stress contours are shown in Fig. 10. Average stress levels along the surface of the CVD-SiC brackets are of the order of 100 MPa, while those on the foam/CVD face sheets are below 80 MPa.

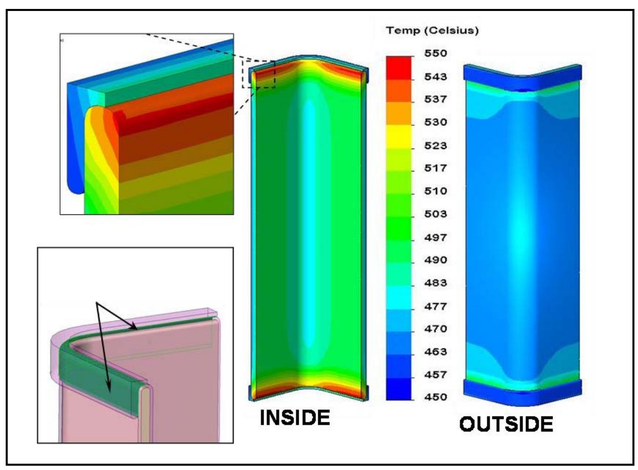

Fig. 9: Temperature contours of the SiC Foam-based FCI segment; insert shows thermal resistance surfaces between bracket and FCI panels (inner FCI wall: q"=0.2 MW/m^2; outer FCI wall: cooled with PbLi at 450 ^{o}C and h=10,000 W/m^2-K).

The stresses are highest along the outside of the SiC brackets, for two reasons: (1) the bracket is assumed to be

100% dense CVD SiC with a high modulus of 412 GPa (high stiffness), and (2) the FCI foam panels exert stresses due to their thermal expansion which concentrates along the upper and lower edges of the foam panels. The high thermal resistance between the bracket and the foam panel causes the highest temperature gradients to occur near the FCI foam panel edges. This exacerbates the stresses in the brackets. This analysis indicates that improved thermal heat transfer coefficient between the bracket and the FCI foam panels are desirable to reduce temperature gradients near the support brackets.

Figure 10 also plots the detailed localized stress levels along the inside edge between bracket and FCI foam panel. Stress levels in the FCI foam/CVD structure are above the tensile stress limit (~120 MPa) for un-irradiated CVD SiC materials, with stresses in the bracket material being about 10 MPa to 20 MPa higher. These results indicate that the bracket design has to be modified in order to reduce stresses. Potential reduction in stress levels may be achieved, by rounding of all edges and changes and by changing bracket geometry.

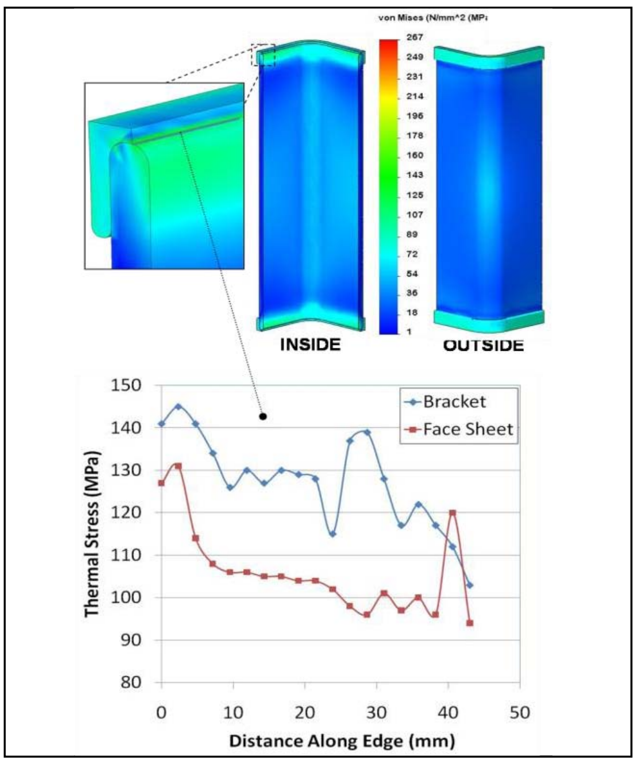

Fig. 10: Thermal stress contours of the SiC-Foam Based FCI segment; also shown are the stresses along the edge between the SiC bracket and CVD SiC face sheet.

IV.B. Full-length FCI Thermo-Mechanical Response

Based on 3-D magnetohydrodynamic calculations, detailed temperature distributions along the inside and outside faces of the entire 1.3 m long FCI structure were developed for typical ITER operations, which are shown in Figure 11 (Ref. 5). The maximum temperatures along the FCI structure occurs toward the top (exit) of the FCI, in addition, the temperature distributions are not symmetrical nor are the uniform.

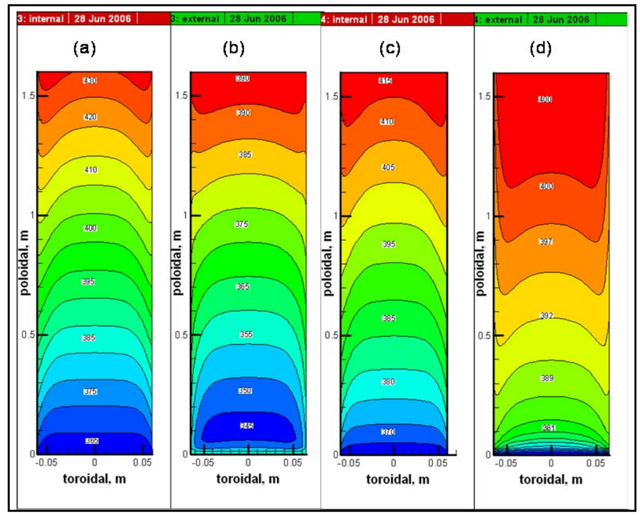

Fig. 11: Temperature contour maps of FCI surfaces: (a) behind FW (inside the FCI); (b) behind FW (outer); (c) back of the FCI (inner); (d) back of the FCI (outer).

This results in non-uniform thermal gradients across the FCI structure, which differ significantly from the simple uniform temperature conditions used to investigate a single segment (Fig. 8 – Fig. 10). Figure 12 shows the results of the thermal analysis of the full length FCI structure. Temperatures along the FCI range from a low of 343 ^{o}C at the inlet to 427 ^{o}C at the outlet. The temperature gradient across the FCI structure at the exit is between 30 ^{o}C and 40 ^{o}C, while at the bottom the gradient is less than 15 ^{o}C.

In calculating the stress distributions, we considered as a primary load the pressure head of PbLi along the 1.3 m height of the FCI. The maximum pressure load is of the order of 0.1 MPa exerted at the bottom and from the inside of the FCI. We did not include any pressure difference between the inside and outside of the FCI structure, because these estimates were not available. The von Mises stress contours of the combined thermal plus pressure loads are shown in Fig. 13. The maximum stresses of about 66 MPa occur above the mid-plane of the FCI on the FCI panel and behind the bracket. The stresses do not vary greatly as a function of FCI height, in fact most of the FCI structure experiences relatively uniform stress levels, ranging between 20 MPa and 50 MPa, with the lowest stresses occurring at the brackets.

The combined von Mises stresses in the FCI structure made of SiC-foam sandwiched between CVD SiC face sheets and supported by CVD SiC brackets are below the allowable stress levels of for CVD SiC (~120 MPa).

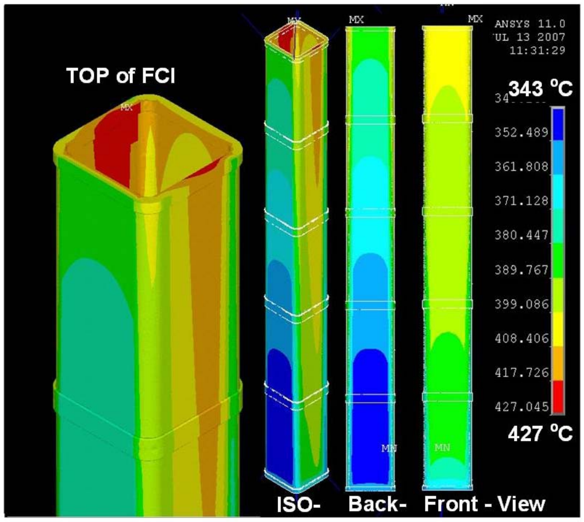

Fig. 12: Temperature contours along the FCI structure.

However, more detailed analysis is required to ascertain the impact of PbLi pressure differences between the inside and outside of the FCI. Furthermore, in these analyses we did not consider the actual mechanical contact between the FCI structure and the TBM walls. These contacts have to be designed to allow the FCI to expand without creating clamping loads on the FCI. Lastly, no dynamic loading on the FCI structure was analyzed.

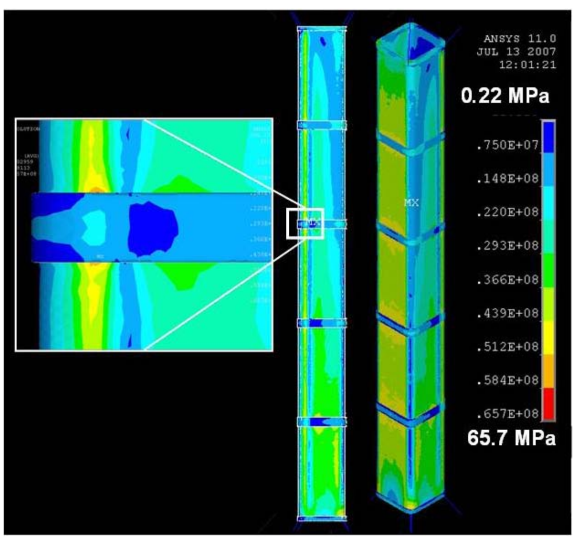

Fig. 13: Von Mises stress contours of the FCI structure; σ_{maz}~65.7 MPa occurs behind the bracket (on midplane).

V. FCI PROTOTYPE FABRICATION

Ultramet Inc. is developing a prototype of the FCI made of a 5-mm SiC-foam core with 1.8-mm thick CVD SiC face sheets.[8] The FCI segment under construction is 116 cm × 116 cm × 300 cm tall. Standard SiC foam processing involves conversion of polyurethane foam to 99% porous carbon foam billet, which is then cut into 130 × 130 × 300 mm long pieces. The FCI ID is established by press fitting a mandrel of desired size into the foam and the OD is formed with a fly-cutter (carbon foam is easily machinable). Next, the carbon foam is infiltrated with CVD SiC to the desired volume density. Finally, the SiC face sheets are CVD deposited on the outside of the SiC foam. Figure 14 shows a prototypical SiC-foam core prior to the application of the face sheet.

VI. SUMMARY AND CONCLUSIONS

The key requirements and performance parameters of a FCI structure for DCLL blankets were discussed. Primary requirements are low electrical and thermal conductivity. Electrical conductivity ranging between <1 and 100 S/m and thermal conductivity of less than about 2 W/m-K are desired, depending on blanket design.

SiC/SiC composite based FCI materials are currently under development consisting of 2-D woven SiC architecture with CVD SiC finished surfaces. Conductivity properties of SiC/SiC based FCI materials are underway and will be reported in the near future. Another candidate FCI structure consists of using porous SiC between dense CVD SiC face sheets. A FCI design based on open-cell SiC-foam sandwiched between two CVD SiC face sheets is being developed.

Fig. 14: Prototypical FCI foam core after SiC infiltration to 10 vol.% (nominal size is 0.116 × 0.116 × 0.300 m^3 and 7×10^{-3} m thick); next step deposition of CVD SiC face sheets.

We presented here the design, the thermo-mechanical analysis, and the prototype fabrication status of a SiC-foam based FCI structure.

The flow channels for PbLi in the ITER DCLL TBM design are about 1.6 m high. Allowing for supply and return space at the bottom and the top of the channel a straight FCI structure of 1.3 m is required. The 1.3 m tall FCI structure was divided into five 0.25 m tall segments, which are assembled using CVD-SiC brackets. Two analyses were performed, one with uniform through the thickness temperature gradients of 40 ^{o}C and one with established ITER relevant non-uniform temperature gradients.

The porous FCI design is based on a 3-mm thick SiC-foam core between two 1-mm thick CVD SiC face sheets. The current design uses brackets to assemble five 25-cm tall FCI segments. Thermo-structural analysis of a single section with a uniform temperature gradient shows that the thermal resistance between the brackets and the FCI panels would have to be minimized in order to reduce thermal stresses in the FCI panels to acceptable levels.

A thermo-mechanical analysis of the full-length FCI structure, 1.3 m long including the hydrostatic pressure head of PbLi was also performed. Detailed FCI-breeder interface temperature distributions based on 3-D magnetohydrodynamic calculations representative of ITER operations were using and mapped as thermal boundary conditions onto the full-length FCI walls. Maximum temperatures (~430 ^{o}C) and temperature gradients (~40 ^{o}C) were found to be highly localized in the top region (exit) of the FCI structure. Calculated von Mises stresses were shown to be relatively evenly distributed over the entire FCI structure, ranging between 20 and 50 MPa. Maximum stresses (~66 MPa) were shown to occur on the FCI panel underneath a bracket near the mid plane of the FCI structure. The preliminary analysis of a SiC-foam based FCI indicates that this concept satisfies key design requirements for ITER operation.

Ultramet Inc. is fabricating a prototype of the SiC-foam based FCI consisting of a 5-mm SiC-foam core with 1.8-mm thick CVD SiC face sheets. The FCI segment under construction is 116 cm×116 cm×300 **c**m tall.[8]

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