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Applicability study of mechanical multi-pipe connections for DEMO breeding blanket maintenance concept

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ABSTRACT

Maintenance of DEMO breeding blanket includes the removal and replacement of plasma facing components, for example the breeding blankets (BB). For access, multiple coolant pipes need to be removed. As an option to reduce downtime and increase maintenance speed, a so-called mechanical multi-pipe connection (MPC) concept is developed to allow removal of multiple pipes at the same time using remotely operated mechanical connections. MPC is one promising candidate to allow fast remotely controlled opening and closing of multiple pipe connections by using flanges and bolts.

Some major challenges for the application of MPC are highly constrained space on top of the BBs, accessibility for appropriate tools and homogenous distribution of sealing forces on the gaskets. Numerous studies on arrangement and force application methods were performed to identify suitable concepts – of which a compact flange design using direct bolted connection is favourable. Finite Element Analyses on the shape and geometry optimization of the MPC led to analytically verified solutions. Furthermore, material selection and behaviour under radiation, vacuum, and thermal cycling at high temperature conditions requires advancement of available material treatment solutions in terms of things such as coated surfaces of threads and contact areas on flanges to avoid diffusion bonding.

1. Introduction

A mechanical multi-pipe connection (MPC) concept is developed to allow removal of multiple pipes at the same time using remotely operated mechanical connections. This concept is designed to facilitate BB-maintenance downtime reduction by having all the pipes connecting a BB segment disconnected remotely and simultaneously. This process is done without removing the pipes and the shielding blocks above the BBs, which presents some advantages. This BB-maintenance concept aims for further reduction of downtime by reducing the number of ports to be opened. That means, that all pipe connections must be disconnected remotely and directly at the top of the BBs, - without removing the pipes and the shielding blocks above the BBs.

2. Design adaptation

2.1. First iteration of MPC

In an earlier study, application of MPC was developed to work in HCPB (Helium Cooled Pebble Bed). The MPC concept was designed in conjunction with cut and weld (C&W) concept, as shown in Fig. 1, where multiple pipes will first be disconnected from the overall system by the means of a mechanical connection. The pipes will then be cut off on the BB side using C&W concept to improve the overall handling when removing the components out of the vacuum vessel. Multiple pipes are connected through a single manifold connection, which was done to reduce maintenance downtime. Therefore, The MPC is designed to operate on the upper port section [1,2].

To fulfil this requirement, MPC is designed with stability and uniform sealing forces as priorites, with a relaxed dimension requirement. A manifold connection is designed to be used with clamps as a force distribution tool, as shown in Fig. 2. The clamp provides a more stable and

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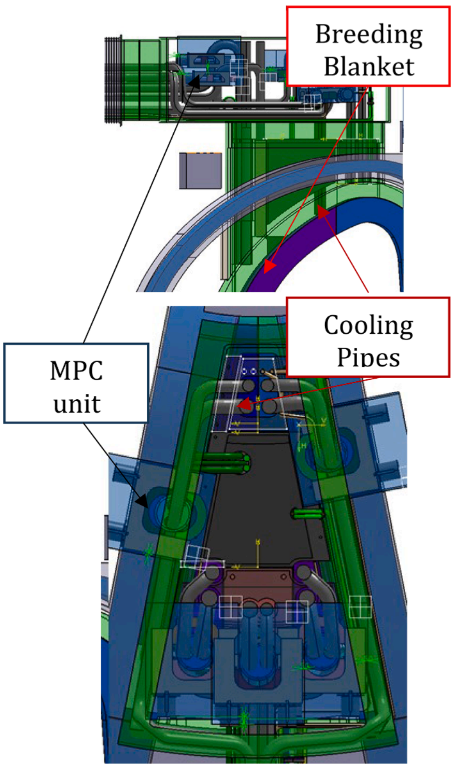

Fig. 1. Application of previous MPC concept in DEMO upper port.

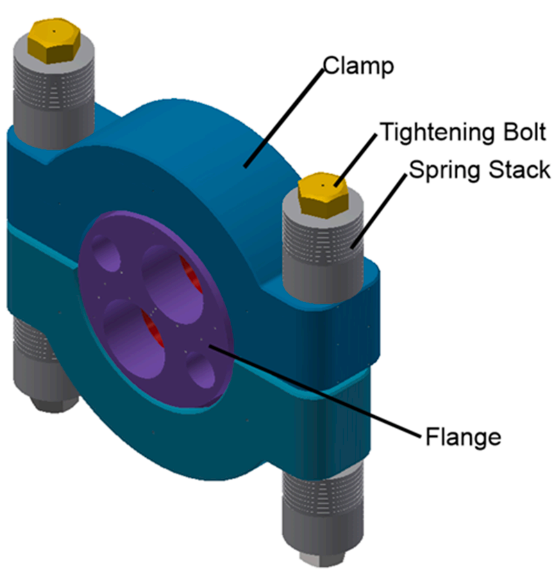

Fig. 2. Previous Iteration of MPC concept using clamp as force distribution tool.

uniform connection, albeit at the price of overall geometry dimension. During FP8 period of DEMO development, a prototype of the MPC design using clamps were designed, built and tested, which showed that the MPC usage with further development is feasible for its intended use in upper port maintenance [3].

On this study, MPC is redesigned to work with the WCLL (Water Cooled Lithium Lead) concept, where the mechanical connection is directly located on the breeding blanket [4]. The main reasoning for this design is to improve the overall maintenance planning, wherein to remove the blanket, only the mechanical connection needs to be removed, thereby improving the overall downtime [5].

2.2. Design adaptation

To adapt the MPC concept for the maintenance concept for WCLL, some fundamental changes need to be carried out.

2.2.1. Clamp removal

The clamp removal was a necessary part as the MPC is located under the shielding block of the access hatch, which has some of the tightest dimension constraints in the whole upper port architecture, while at the same time being compatible with the gripper concept [6].

The Clamp is replaced with a direct bolted connection concept, where the two halves of the pipe connection are secured with a set of tightening bolts. This leads to a significantly more compact design and is therefore better suited for the condition in the upper port. An ongoing study is also being carried out on the feasibility of attaching the MPC directly to the blanket.

2.2.2. MPC material and seals

To fit the strict dimension requirements, the pipe setup and size of MPC has to be adjusted, while maintaining the capability to provide preload tension to the metal seals. With the WCLL concept, the pipes are made from SS316L [7]. To improve the material compatibility and ease of the welding process required to attach the MPC flange to the pipes, the flange is also made from SS 316 L, which are in general weaker than the EUROFER97 used as general use structural steel [8].

However, the tensioning unit can be made from material other than SS316L as they are designed to be replaceable in case of a failure. With this Inconel 718 was chosen as the material for the tensioner unit since it provides high tensile strength even under high temperature conditions. Because Inconel716 is only used in this application, the risk of activation and embrittlement which are quite relevant for nickel-based alloys can be mitigated.

The metal gasket is using Helicoflex® metal seals provided by Technetics, which are rated and certified for use in a nuclear grade installation.

2.2.4. Tensioner unit

One MPC concept uses stacks of springs, as shown in Fig. 3, to work around the diffusion bonding which would happen on two contacting surfaces which are made from the same material and under load.

Due to the dimension restrictions, to achieve the same preload force required to compress the metal seals, as the concept with the spring requires larger space as to maintain the elasticity of the spring, oversized

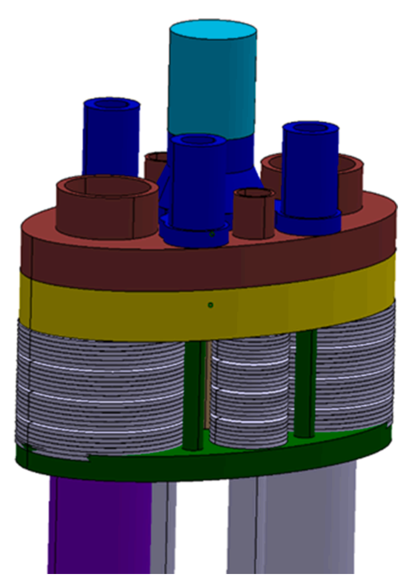

Fig. 3. Initial MPC design with springs stack concept.

springs are required. However, as there are no readily off the shelf available springs which can withstand the high preload and temperature required by the metal seal and the operating temperature, the spring stack concept was scrapped in favour of a coated threaded connection, as shown in Fig. 4.

To overcome the issue of the diffusion bonding which has a high chance of occurring in high temperature and vacuum condition, surface coating using a Diamond-Like-Carbon (DLC) Coating is currently being investigated to use for the threaded connection surface. The fastening unit is developed based on the Superbolt threaded connection developed by Nordlock [9]. To achieve the required high preload forces, the bolts are made from INCONEL718.

2.3. Flange design

With the removal of the clamp as was discussed in Section 2.2.1, a redesign of the flange was necessary to facilitate the clampless design. The previous design with the clamp uses a circular flange, as shown in Fig. 5. The circular flange provides a uniform contact area between the clamps which are shaped as half circles. However, circular shaped flanges are not space efficient as there is a large unused surface on the flanges. Another reason to move away from the circular flange is the dimension requirement, as the upper port will be shared with multiple other components. Using a more tailored shape provides more advantage to the available space, in this case, a more elongated shape fits better in the available space.

To fit on the available space in the upper port, a more elongated flange is used, as shown in Fig. 6, with a pair of through holes on the outside section of the vacuum seal to be used for the threaded connection.

3. Design optimizations

From the initial design considerations and adaptations, further optimizations are being carried out.

3.1. Seal layout and threaded connection optimization

The number of screws used in the threaded connection has a negative correlation with the overall operational time required to engage or disengage the mechanical connection, while having a positive correlation with the uniformity of the sealing force on the metal seals. Therefore, it is imperative to have a mechanical pipe connection design where the total amount of screws is kept to a minimum while keeping the sealing forces uniform.

While having only a single screw to operate the whole MPC unit, as

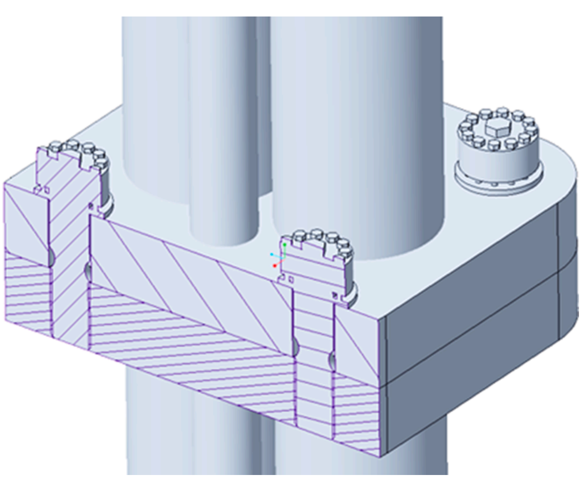

Fig. 4. Initial MPC design with bolted connection.

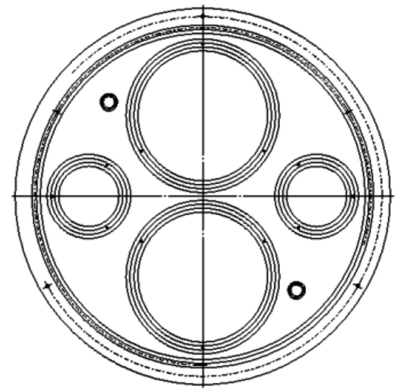

Fig. 5. Cross section of pipe flange for MPC with clamp concept.

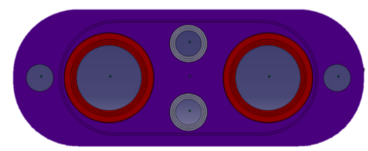

Fig. 6. Cross section of the pipe flange for the initial threaded connection concept.

shown in Fig. 7, would provide the fastest handling time, this idea was eventually scrapped as this would necessitate having two sets of vacuum seals, one for the outer part of the MPC, and another one to seal the threaded connection, as the threaded connection itself is not vacuum compatible.

With the limited available space, the purge and coolant pipes are then arranged in a diamond shaped configuration to limit the length of required metal seal while still fitting in the available space in upper port, as shown in Fig. 8. At the time of writing, four screws are used. However, further development may necessitate the use of extra screws, either to improve seal force uniformity or to reduce the mechanical stress.

3.2. Flange geometry optimizations

The next step is to carry out a topology optimization of the flange using ABAQUS. The aim of this is to reduce the maximum stresses in the flange and at the same time ensure sufficient deformation of the gaskets. The gasket model used for the modelling purposes are HELICOFLEX® metal seals which were also used for ITER and the previous iteration of MPC. The main mechanical property of HELICOFLEX® seal is the gasket deformation. To maintain a vacuum condition on the metal seal, a minimum gasket deformation of 0.7 mm is required to be achieved at all the working conditions [10]. This includes room temperature and high temperature conditions. This must be achieved at room and at operating temperature to ensure that no fluid is leaking out of the pipe connection. This means the flange must be stiff enough to not flex under high tensioning force and stable enough to maintain the sealing force from room temperature up to overtemperature condition.

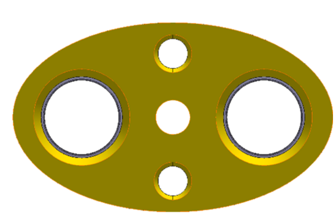

Fig. 7. Cross section of the pipe flange concept with single bolted connection in the middle.

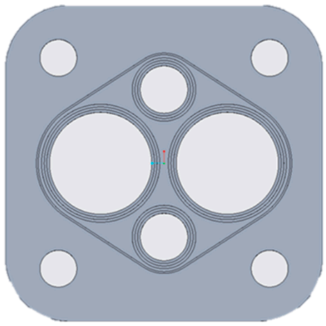

Fig. 8. Flange pipe seal layout with four screws, four sets of pipe seals, and a diamond shaped vacuum seal.

To keep the metal seal length at a minimum while keeping the overall geometry to fit in the available space, an ongoing shape optimization campaign using finite element analysis is being undertaken to ensure homogenous sealing performance on all the metal seals by modifying the overall flange geometry, as shown in Fig. 9.

The minimization of the maximum stresses serves as the target function, whereby a maximum stress as a limit value and a minimum deformation of the gaskets are defined as boundary conditions. In addition, material areas directly adjacent to the gaskets are fixed so that the gaskets are always surrounded by enough material.

As part of the sensitivity-based topology optimization in ABAQUS, the so-called SIMP (solid isotropic material with penalization) [11] approach is used for material interpolation. ABAQUS recommends the value 3 as a penalty factor, as numerical experiments show that good results can be achieved with this value. In addition, the Abaqus sensitivities are used where possible, as this supports all structure types and the von Mises stresses can be considered both as a boundary condition and in the objective function.

The optimization process leads to a flange with a thicker centre and thinner side, shown in Fig. 10. This is designed to maintain the stiffness of the flange. A stiffer flange provides better capability to maintain uniform sealing forces.

The optimisation program is also used to ensure minimum gasket deformation is achieved along with one example shown in Fig. 12, where the numerical model is modelling a quarter of metal seals layout consisting of one diamond shaped vacuum seal and four circular pipe seal, as shown in Fig. 8. Leak tight parameter of the seal is achieved along the seal after the optimization process. However, further improvements are being made to improve the homogeneity of the gasket deformation along the metal seals.

Further improvement on the flange is aimed at maintaining the stiffness of the flange while keeping a similar or even lowering the overall geometric footprint, such as attaching directly to the breeding blanket, as shown in Fig. 11.

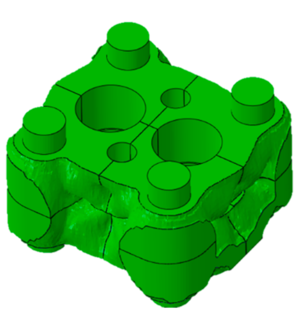

Fig. 9. Early optimization iteration result on the flange geometry using finite element analysis.

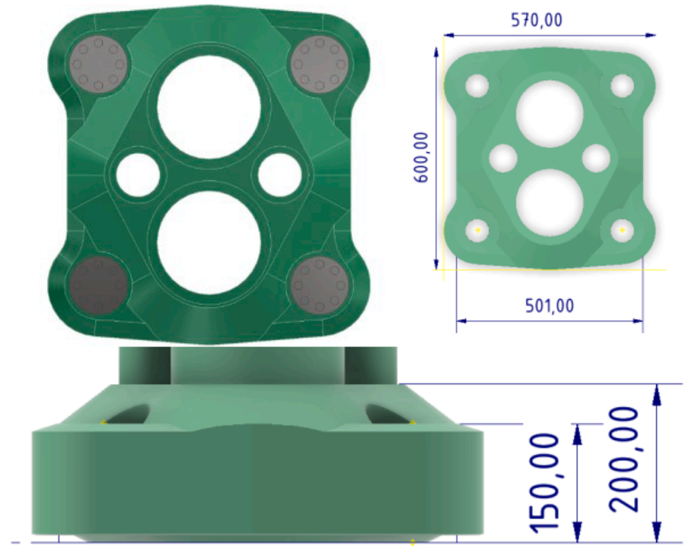

Fig. 10. Current design of MPC.

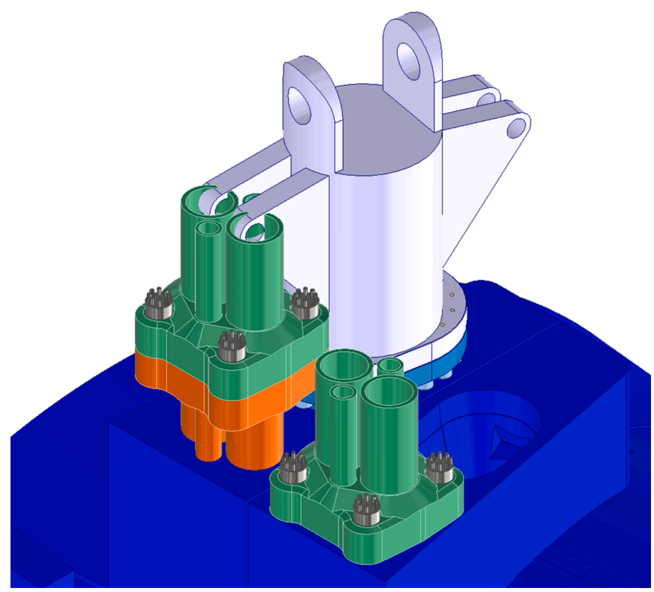

Fig. 11. Possibility of MPC mounting at independent mounting point (left) or directly connected to the Breeding Blanket.

4. Proof-of-Principle and test bench design

To implement the design, several proof-of-principle experiments are designed to verify the applicability of the design. Two components were identified as the critical parts, the metal seals and the thread coating.

4.1. Friction and thermocycling test for

While the DLC-coating is rated to work under high pressure and high temperature conditions, DLC has yet to be implemented on any on any components designed for DEMO. To simulate the working conditions found in DEMO, a series of tests is designed to induce load and stress similar to what the surface coating will be subjected to during its lifetime. The coating will be subjected to two main factors, oscillating temperature and high friction spikes. Oscillating temperature would be analogous to the thermal cycling during the lifetime of the component, an example is shown in Fig. 13. A series of high friction force spikes, created by the opening and closing of the superbolt thread designed to

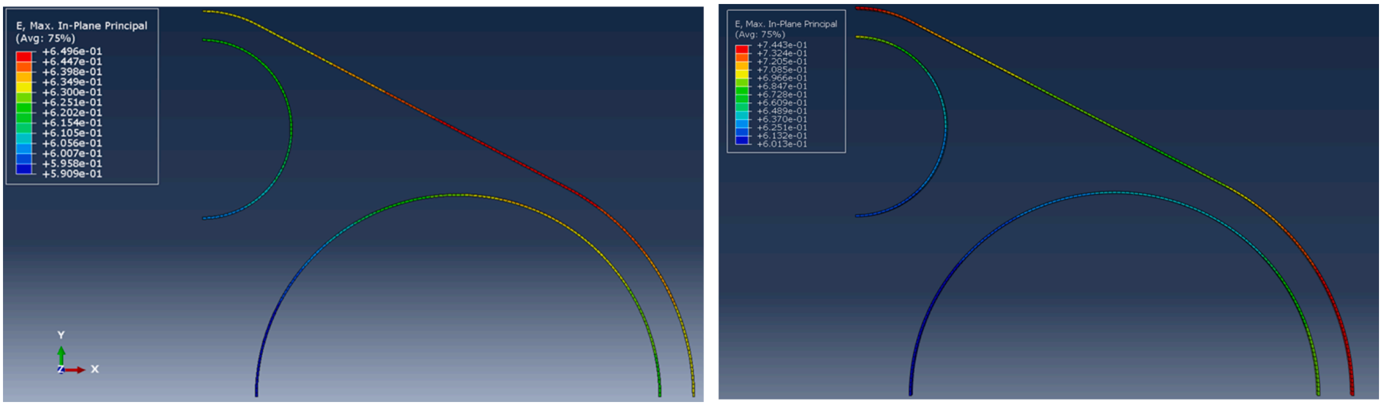

Fig. 12. Optimization of the sealing forces (left: before, right:after).

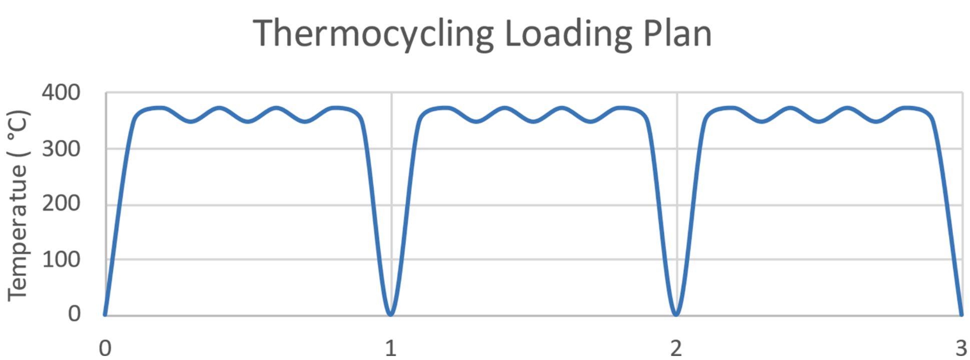

Fig. 13. Example of Thermal cycling procedure to simulate the oscillating temperature on the MPC.

simulate multiple engagement and disengagement procedures done during each maintenance phase.

4.2. Helium leak tightness test

While the overall mechanical pipe connection integrity and leak tightness can be analysed using finite element analysis, an experimental proof-of-principle testing is planned to test the sealing performance.

Using previous proof-of-principle designs as baseline [3], the seals can individually be tested through a specific scheme in pressurization of the pipe chambers or the interspaces, such a scheme is shown in Table 1. The sealing performances are analysed using helium sniffer sensor which can detect an increase of helium concentration on the air.

5. Conclusion

During the development course of DEMO, MPC was developed. for the use in HCPB configuration. With some modifications, MPC can also be applied at the WCLL configuration as well. Further improvement efforts were made with the main objectives of improving stress and sealing force distribution, while keeping the overall footprint as small as possible.

Using FEA, the current design is shown to be able to maintain minimum seal deformation during all the operating conditions, which would translate to maintaining the required helium leak rate of 10e-9 mbar*l/s. However, further shape optimisation is still required to improve overall sealing force distribution and seal deformation uniformity.

The design will be tested in two upcoming PoP testing procedure to compare the real-life results with the numerical analysis. One PoP test bench is designed to test the resilience of the thread coating when subjected to the Friction and Thermocycling Test, and the other PoP test bench is used to test the overall design for leaks.

Table 1
Pressurizing scheme to test seal integrity.

Test number	Pressure (bar)					
	Ambient	Purge Inlet	Purge Outlet	Coolant Inlet	Coolant Outlet	Interspace
1	1	1	1	187	1	1.5
2	1	1	1	1	187	1.5
3	1	1	1	187	187	1.5
4	1	1	1	187	187	187
5	187	1	1	1	1	1
6	1	1	1	1	1	187

CRediT authorship contribution statement

A. Azka: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K.J. Büscher:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **M. Mittwollen:** Writing – original draft, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **C. Bachmann:** Supervision, Project administration, Conceptualization. **G. Janeschitz:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Azman Azka reports financial support was provided by European Consortium for the Development of Fusion Energy. This work has been

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Data availability

Data will be made available on request.

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