Fusion Engineering and Design 193 (2023) 113834

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Analysis of implementing a rail-based maintenance system into a HELIAS 5-B device☆

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ARTICLE INFO

Keywords:
Fusion power generation
Fusion reactor maintenance
High payload robotics
Nuclear fusion
Nuclear robotics
Remote handling
Remote maintenance
Tokamaks
Stellarators
HELIAS

ABSTRACT

This paper reports on the analysis of potential rail-based maintenance systems when implemented into a Helical Advanced Stellarator (HELIAS) 5-B device. The main purpose of such a system would be to handle and exchange the internal vessel components, namely the breeding blanket segments, which are expected to be the largest and heaviest components within the vessel. Other rail-based maintenance systems for tokamak devices, particularly the ITER Blanket Remote Handling System (BRHS), were studied, and their suitability when introduced to the differing constraints of a HELIAS device was determined. Rail-based systems envisaged for DEMO and CFETR devices were also studied. An ITER-like handling system was shown to be unsuitable for a HELIAS device of this scale. This is due to significantly higher blanket masses with an in-vessel operating space no larger than that of ITER, but with the additional complication of longer toroidal lengths and non-uniform vessel geometry. Movement of large components on rails like those found in DEMO and CFETR was shown to be more applicable to the HELIAS device. The main obstacle to the implementation of such rails would be the non-uniform geometry which complicates the selection of a rail path that avoids collisions with other in-vessel components, remote handling equipment, or the vessel structure itself.

1. Introduction

HELIAS 5-B is a stellarator based alternative concept fusion power plant as opposed to that of DEMO, the current main tokamak based fusion power plant design being developed by EUROfusion. The name HELIAS stems from the term Helical Advanced Stellarator, the 5-B aspect representing respectively the 5-fold symmetry of the device (Fig. 1) and the second major iteration of the design. The physics design basis for HELIAS is the W7-X (Wendelstein 7-X) reactor that will demonstrate stellarator optimisation. However, as W7-X concentrated on physics issues very little development has occurred for the engineering and technology aspects of HELIAS within the W7-X project, and therefore not many remote maintenance technologies and strategies have been developed [1]. Remote maintenance is a topic that has been more developed in the similar tokamak fusion devices, with some aspects of these systems possibly being applicable to a HELIAS device. A Rail Based Maintenance System (RBMS) has been suggested in previous papers [2] as the main system to perform routine prolonged downtime maintenance for internal components of the HELIAS 5-B Vacuum Vessel (VV). This report will look at the emerging constraints and requirements for such a system within HELIAS 5-B and compare an RBMS and its operating environment against those found in other devices, such as DEMO and ITER.

2. HELIAS geometry and environment comparisons with similar devices

The 5-fold symmetry of HELIAS 5-B generates 5 repeating sections of recurring geometry. These fifths of the vessel are all non-uniform in shape, as are the magnet coils encapsulating them. The VV itself twists to

☆ This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion) and from the EPSRC [grant number EP/T012250/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk*. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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https://doi.org/10.1016/j.fusengdes.2023.113834
Received 26 October 2022; Received in revised form 12 April 2023; Accepted 17 May 2023
Available online 3 June 2023

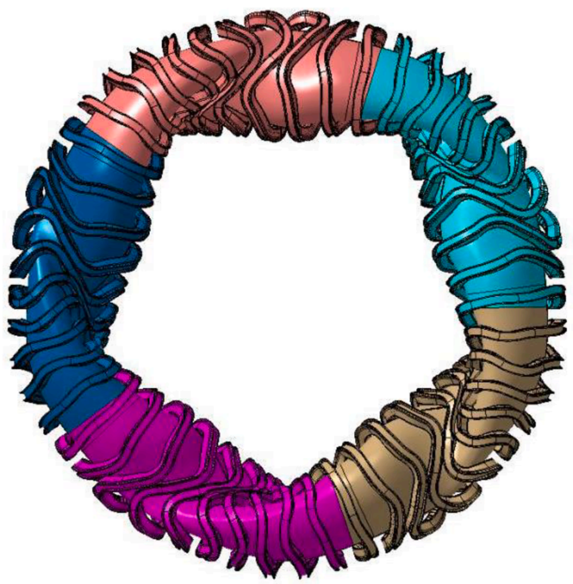

Fig. 1. CAD model displaying the 5-fold symmetry of a possible HELIAS 5-B geometry.

form a helical shape. The major radius of the vessel is 22m while the average minor radius is 1.8m. This major radius would be significantly larger than that of ITER or DEMO devices with ~6m [2] and ~9m [3] major radius respectively, as shown in Fig. 2. A HELIAS 5-B average minor radius would be similar in scale to the ~2m minor radius found in ITER. However, the non-uniform geometry of a HELIAS device means that the minor radius is inconsistent in size and shape throughout the vessel.

The major component of the inner wall of the vacuum vessel consists of breeding blankets, as well as divertors that would be located in islands between breeding blanket segments. The inner wall blanket consists of 80 total rings throughout the vessel, each blanket ring having 5 segments to give a total of 400 blanket segments throughout the vessel. Given the non-uniform geometry of the vessel, the blanket segments will also be non-uniform in shape, with each blanket segment within a single fifth of the vessel likely being unique in shape, size, and weight. Recent design iterations of DEMO have ~80 breeding blanket segments, these being significantly larger than blanket segments proposed for HELIAS 5-B as each blanket ring is generally presented as 2 segments, although the outboard segment may be further segmented depending on limiters and other components around the equatorial port. Due to the early concept stages of HELIAS 5-B, it is unclear what the exact mass of these blanket segments would range due to factors such as final blanket composition and segmentation, as well as if the blankets would be drained of breeding material prior to handling. Density estimations have ranged between 3 tonnes/m^3 and 8.2 tonnes/m^3, meaning that the handled mass of these blanket segments could range between 20 and 80 tonnes, perhaps more depending on final design decisions.

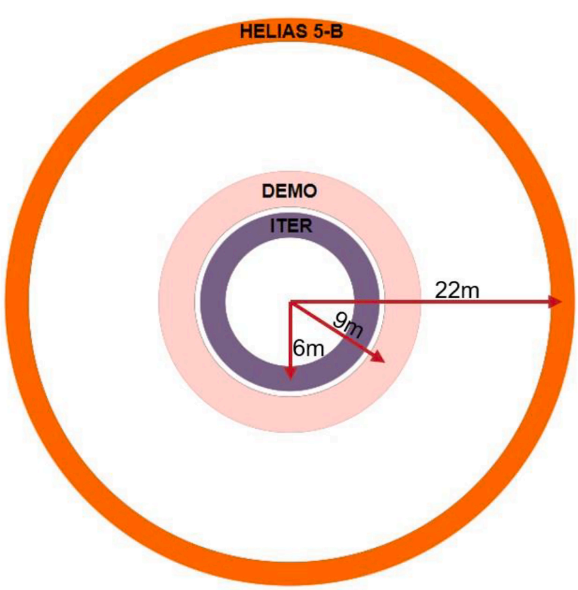

Fig. 2. Major radius and average plasma volume size comparison of Fusion devices.

ITER is to have 18 poloidal rows containing a total 440 blanket modules in the VV to be replaced during the main planned maintenance session. These modules consist of a shield block and a first wall panel [4]. These blankets are not breeding blankets but are instead heat transfer/cooling blankets that are cooled with circulating water under pressure, so will still have service connections. The first wall panels are to be a maximum of 1tonne in weight and are to be approximately 1.5m x 1m in size. The shield blocks are to be a maximum of 4 tonne in weight and are to be approximately 1.5m x 1m in size. The Heating Neutral Beam blanket modules are similar to a first wall panel and shield block combined so may contain a maximum weight of 5 tonne as well as the general frontal area of 1.5m x 1m.

For DEMO, breeding blanket segments are not handled from within the vessel but are instead withdrawn from the vertical port (Fig. 3) using a blanket handling manipulator. The handled weight of these blankets is not yet fully determined as if they are to be handled empty then the weight would be 60-90 tonne, but if they are not emptied then the weight could be as heavy as 180 tonne.

The DEMO breeding blankets are extracted through the vertical ports supported via contact points on top of the blanket ring halves that are only exposed when the vertical port is opened and cleared of service connections. The majority of these connections, plates, and the neutron shield in this instance are proposed to be lifted out via vertical crane.

3. Developed rail-based maintenance concepts for other fusion devices

The RBMS looked at in this section consist of systems that have been developed or those with well developed concepts for maintaining ITER-scale or larger fusion devices. These devices have RBMS for handling large components that form sections of the vessel inner wall.

3.1. ITER BRHS

The ITER Blanket Remote Handling System (BRHS) is the main planned maintenance equipment to be deployed into the ITER vessel that will be used to handle, remove, and replace blanket modules as well as other related major components such as First Wall panels and Shield Blocks. The divertors are to be handled by a different system entirely [6]. It should be noted that the design of this system is still subject to change and access to specific technical detail of the system is limited due to commercial aspects of the system development. The BRHS accesses the VV through 4 horizontal equatorial ports. These ports are not equally spaced apart along the circumference of the vessel but alternate between being 80° and 100° apart. Originally the BRHS was designed to be deployed and structured so that it formed a 360° continuous ring within the full length of the torus, shown in Fig. 8. The current iteration of the BRHS however only can be deployed and supported between 2 ports at a time. It supports configurations both an 80° and 100° toroidal length to fully cover the distance between any two access ports, ensuring that 360° of the vessel is fully accessible for maintenance.

The rail in both configurations consists of two pairs of articulated rails that lock together to follow the path of the centre of the toroidal vessel. The side of the rail facing the inboard wall of the torus contains a

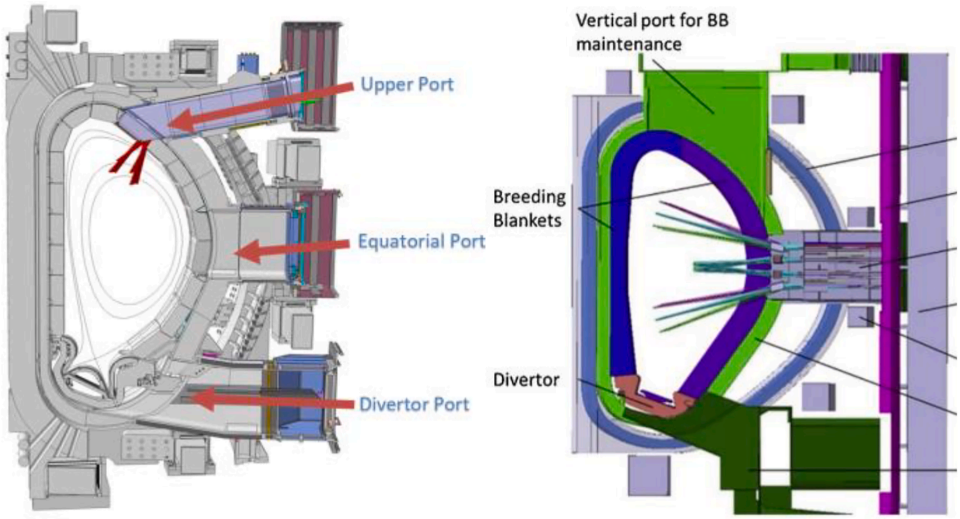

Fig. 3. Cross section of torus showing port orientations of ITER (left [4]) and DEMO (right [5]). Cross section of HELIAS 5-B is displayed in Fig. 9.

rack gear across its length for propelling the Vehicle Manipulator. The side facing the outboard wall contains locking hinges for fixing the joints together in the articulated rail as well as cable guides for supplying power and signal to the Vehicle Manipulator. Rail grasping holes are also indented into specific locations on this side of the rail for rail support arm insertion. The Rail Support Arms and support frame are in turn partially supported with inserting "port keys" into the upper port grooves and pushing ceiling pads to the port ceiling. This adds stability to the system as well as support.

The BRHS system components are expected to be transported between the VV and Hot Cell inside transfer cask containers. A secondary intermediate cask is also to be used to connect between the main cask, which carries the BRHS components, and the vessel port. Main casks containing rail support components are connected to the intermediate casks to connect to and insert the rail components fully into the vessel.

3.2. DEMO lower port divertor exchange

The current proposed maintenance system for exchanging divertors located in the bottom of the DEMO plasma vessel consists of a variety of manipulators that act upon both pre-existing permanent vessel rails and temporary rails introduced during the maintenance process [7]. Access to the lower ports requires the prior removal of many service pipe connections as well as bio-shield doors, plates, vacuum pump modules, and potentially other components and service connections. This strategy, and most other current proposed planned maintenance strategy for DEMO, involves extracting the components through the relevant ports ensuring that no major remote maintenance equipment enters the high-radiation environment of the inner plasma vessel. The divertor exchange maintenance system must act more in the horizontal plane due to the confined space of the lower ports. It must also consider the significant vertical gravitational forces due to the mass of the exchanged components. For this, support rails are used to guide the RME (Remote Maintenance Equipment) and exchanged components out of the port to an external containment cell where a gantry crane is integrated into the maintenance system to handle equipment once outside of the ports, shown in Fig. 4. To access the port, the bioshield door and vacuum closure plate are opened using a variety of ground based remote manipulators, jacks, and boltrunners. The neutron wall also must be removed but the strategy for this has not been fully developed yet. Once these are removed, the port threshold rails can be placed into position at the port entrance by the gantry crane. Autonomous wheels are built into the rail support structure to guide them into place with external robot arms being used to secure the rails in place, shown in Fig. 7. Alignment of the pre-existing rails and introduced rails will likely be an issue that will have to be researched and developed further.

Once the introduced rails are installed and the components are removed from the port, an end-effector platform and toroidal mover, developed by VTT (Technical Research Centre of Finland), is moved in to support the divertor cassettes below their centre of gravity. This minimises moments and deflections occurring in the cassette and handling systems. The divertor cassette positioned in line with the corresponding port is extracted radially from the vessel with minimal manipulation. The adjacent cassettes are moved toroidally around the

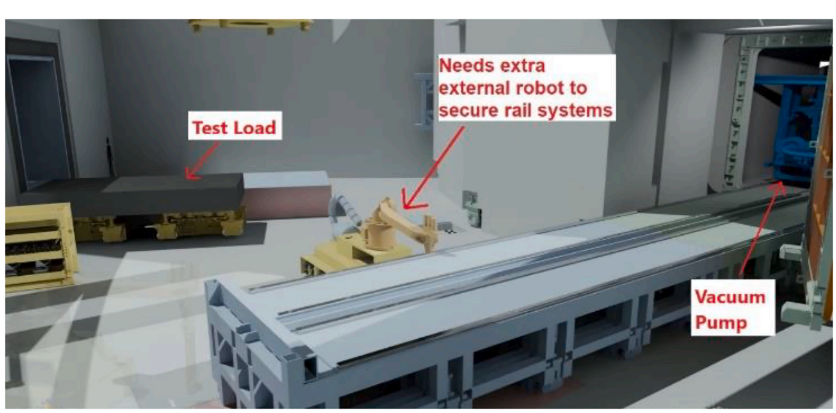

Fig. 4. Port threshold rails in place and being fixed in position by ground manipulator.

vessel (Fig. 5) to the extraction point from where they are also extracted radially from the vessel.

3.3. CFETR breeding blanket exchange

Designs proposed for maintaining the Chinese Fusion Engineering Test Reactor (CFETR) include a maintenance system for exchanging breeding blankets that utilises rails for supporting and transporting the blanket segments, shown in Fig. 6. The reactor is to have large blanket rings that may be split up into 2 segments similar to that of the DEMO design. These rails would be situated between the breeding blanket segments and the vacuum vessel structure and follow the toroidal path of the vessel. During the normal operation the breeding blanket segments would be supported on these rails.

During maintenance periods the blanket segments would be raised using roller jack manipulators that travel along the support rails, as well as a blanket supporter adapter on a divertor mover to support and manipulate the bottom of the blanket segments. These support movers move the blanket segments toroidally within the vessel to the extraction point where manipulators can extract the blanket segments through the vertical ports. This strategy uses a combination of rails that exist within the vessel during standard operation as well as some rails that are introduced only during the maintenance period [9].

4. Rail system comparisons

4.1. Rail-based system categories

For the purposes of comparison, the types of rails that could be used for maintenance purposes have been generalised in this report into three main categories;

- Built-in Rails: a permanent part of the reactor vessel structure. May not be feasible to implement if they impede reactor performance or other necessary reactor structures. Rail performance may also be compromised due to extreme reactor environments.
- Introduced Rails: may be similar to built-in rails but are not a permanent feature as they are typically introduced to and supported directly by the vessel structure as part of maintenance deployment procedures. There can be issues with deployment and alignment of these systems, particularly when utilised with existing rail systems within the reactor.
- Supported Rails: These are rails that are supported externally to the vessel structure at several points typically from a minimum of two ports, but additional points of support could be added from ports or reactor structure to increase performance. These rails may have issues with deployment and maximum payload as well as the possibility of space constraints.

4.2. Implementation constraints

The main issues with both built-in and introduced rails is that they require fixing points on the vessel structure, also often requiring continuous contact with the reactor structure for support. It is likely that fixing points and built-in rails that have been exposed to the extreme environments within vessel may become deformed, potentially causing deployment issues for remote handling equipment. This threat may be reduced through careful material testing and selection, as well as designing systems that allow for high ranges of “as-built” tolerances to account for material swelling and misalignment. Supported rails may only require support and structure contacts from the vessel ports, but the non-uniformity and significantly longer toroidal distances. It is assumed that a ITER BRHS-like system is implemented into a HELIAS 5-B device would have support points from a major port in every vessel fifth (due to the 5-segment design of HELIAS 5-B), but the toroidal distance between supports would be ∼28m compared to ∼10m for the ITER rail supports. This means that a deployed supported rail would likely have considerably larger moments and forces than those found in the ITER BRHS, even before the introduction of the larger mass blanket segments.

4.3. Comparison criteria: MTTR and MTTF

As the Cost of Electricity (CoE) for a fusion power plant is assumed to be highly dependent on the plant availability [11], the time taken for maintenance also directly affects the CoE assuming the plant is not available during maintenance operations. From this, the Mean Time To Repair (MTTR) and the Mean Time To Failure (MTTF) are the main factors to when considering maintenance systems of a Fusion power plant device. Assuming that all of these systems are capable of handling the required breeding blanket segments, the built-in rails would be the most favourable maintenance systems due to the expected significantly reduced deployment time compared to that of the introduced and supported rails. However, due to the harsh environments of the reactor vessel, the MTTF and MTTR of the maintenance systems themselves must be considered. If built-in rails require inspection, maintenance, and *in-situ* correction every time they were required for operations then any benefit gained from the expected reduced deployment time would be reduced or negated. Due to the novel nature of HELIAS 5-B as a power plant demonstration level stellarator device, the anticipated performance and reliability of any rail-based system is uncertain. Supported rails would likely require significant infrastructure support external to the reactor and would likely be very costly to use to maintain the entirety of the reactor in terms of both system cost and lost value from increased deployment time. It is therefore likely that a final rail-based system design would utilise aspects of all three categories proposed so as to reduce MTTR of the reactor to a minimum and increase the MTTF of the maintenance system to a maximum.

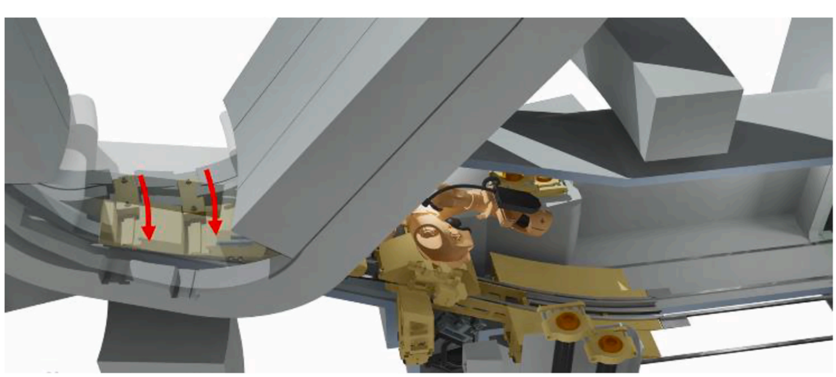

Fig. 5. Toroidal carriers moving divertor cassette toroidally around the vessel to the extraction position, demonstrated in [7].

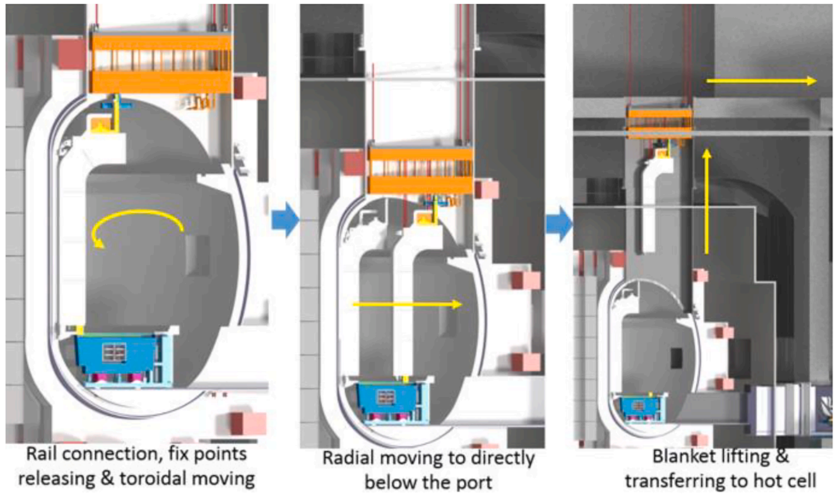

Fig. 6. CFETR blanket maintenance procedure displaying simple manipulations of the blanket segments in-vessel [8].

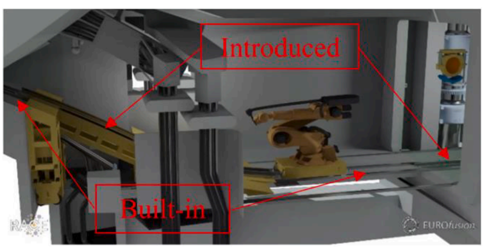

Fig. 7. DEMO Lower Port maintenance concept featuring a support manipulator fixing an introduced rail structure in alignment with built-in rail structures.

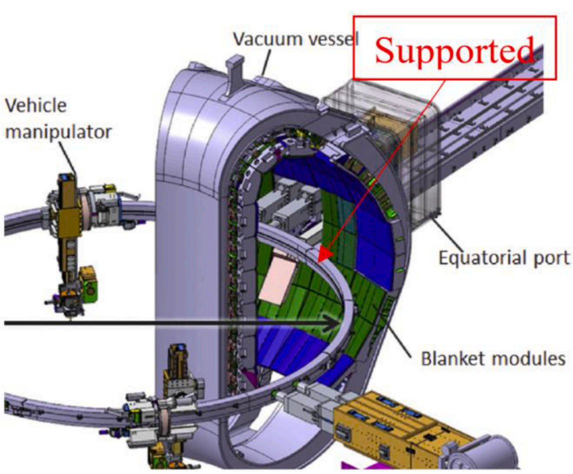

Fig. 8. ITER BRHS featuring articulated rails supported from the maintenance ports [10].

5. Conclusions

HELIAS 5-B has separate distinct issues when compared to similar power output tokamak devices, namely the non-uniform geometry of the reactor, which is inherent to the helical advanced stellarator design. This means that where tokamaks would have simple toroidal movements, HELIAS would have movements and manipulations of varying axes of rotation. This non-uniformity of vessel and blankets creates peak loads and moments at certain orientations of handling. This specific design of HELIAS 5B has many additional issues, where although the expected number of blanket segments and average minor radius is comparable to that of ITER, the non-uniformity of the HELIAS vessel means that it would be incredibly difficult to form a stable supported rail along every section of the vessel. Due to the system not being fully developed or tested, if an existing design of the ITER BRHS would have issues with payload capacity and kinematics for some configurations, a BRHS-like system for this HELIAS 5-B design would not be suitable due to the more complex geometry, longer toroidal lengths, and payloads roughly an order of magnitude greater than ITER. This system structure would fail to meet the requirement of stably handling breeding blanket segments, particularly in the case of extreme load conditions such as seismic events.

Due to the confined non-uniform geometry, significant payloads, and high estimated radiation dose rates of the HELIAS 5-B vacuum vessel, it is much more favourable to not have manipulators for prolonged periods of times within the vessel as rescuability and recoverability would be difficult to assure. There is also considerable difficulty in the deployment of any rails in-vessel due to the complex inner structures within the device, as can be seen in Fig. 9. A more favourable solution would be to manoeuvre the blanket segments to an extractable position adjacent to a port, preferably a vertical port similar to the blanket exchange strategy within CFETR and DEMO. Due to the confined spaces and significant payload of this HELIAS 5-B design, it would be incredibly difficult for an in-vessel manipulator to support and manipulate a blanket segment in-vessel. A solution to this would be to move the blanket segments on rails, either with or without further support from an in-vessel manipulator. Either method would still require roller supports to ensure smooth movement of the blanket segment along the rail. However, the non-uniform geometry of the vessel means that the extraction path and maximum loads incurred of each blanket segment would have to be analysed to ensure collisions would not occur. Another issue with this strategy would be that if only a few significant blankets need replacing then maintenance down-time would be significantly increased due to the required sequential removal of other blankets. Due to the non-uniform geometry of the blanket segments themselves, individual end-effectors/tooling would also likely be required for the proposed 80 different blanket segments within the vessel fifth.

It is unlikely that any of these rail-based systems used in isolation would provide the necessary reliability and reduced reactor MTTR. If a built-in system is to be used, then any aspects that could possibly be subject to damage should be suitably shielded or replaced with introduced rail structure. If this shielding requires significant time to remove ad prepare the built-in rails for operation, then these sections should be considered as introduced rails due to the comparable deployment time. The types of rail that these blankets or a manipulator would move upon

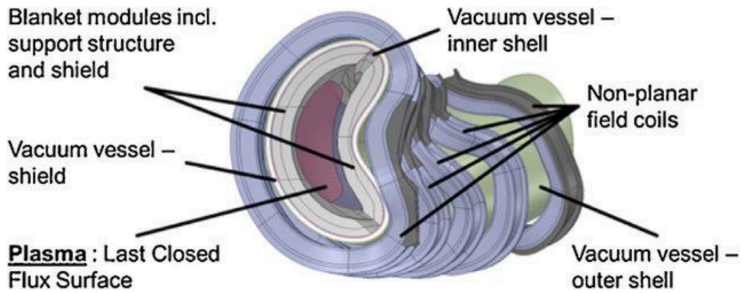

Fig. 9. Cross-section of HELIAS 5-B displaying complex non-uniform geometry [12].

is also significant. Permanent rails would be a preferable option in order to reduce the maintenance downtime of installing rails, although there is the possibility that these could become damaged and deformed due to the extreme conditions of the vessel operations. Similarly, introduced rails could have alignment issues when being installed, particularly if they are to be aligned with existing rails within vessel. Both of these strategy options have the possibility to cause blanket segments and/or rail supported manipulators to become stuck within the vessel with limited options for recovering or rescue.

6. Further work

In order to further remote maintenance concepts, accessibility and deployment of remote maintenance equipment needs to be developed. Due to the non-uniform geometry of both the HELIAS vessel and magnet coils within the current concept, port size and placement is greatly limited within current geometry concepts. This may significantly impact remote maintenance equipment access and general maintenance strategy, also possibly prolonging maintenance downtime for the reactor. In order to minimise downtime and MTTR, the amount and size of ports would need to be maximised while the time taken to access and deploy equipment through these ports minimised. One area of significant interest would be implementing remountable magnet joints to the magnet coils covering areas of the vessel where ideal port positions would be. To achieve a DEMO/CFETR-like extraction of breeding blankets, vertical ports could be utilised to access a blanket "ring" and the two adjacent rings. This would require a significant number of coils, if not all, to have remountable joints for port access. Separation of vessel fifths toroidally may also be an option to consider that may not require magnet joints, but the contamination control may be much more difficult to achieve than port access options, as well as difficulties in realignment and resealing of the vacuum vessel segments. In a long-term scale, it may be beneficial to initially maintain HELIAS 5-B with a low-risk but increased MTTR maintenance system. A testing plan could then be implemented to the HELIAS 5-B device to determine the performance of *in-situ* mock-up fabrications of potential rail-based maintenance aspects that could be de-risked and implemented into subsequent power generating devices.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Data availability

No data was used for the research described in the article.

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