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Replacement strategy of the EU-DEMO and CFETR breeding blanket pipes

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Both EU-DEMO and CFETR need a workable replacement scheme for their tritium breeding blanket (BB). The radioactive environment dictates that all associated operations must be carried out through remotely controlled tools. Accessing and extracting the large BB segments requires their feeding pipes to be removed first from the upper vessel port and later re-installed. In the current design, each of the 80 BB segments is connected with four feeding pipes, two for cooling and two for tritium extraction. Thus, in the process of BB maintenance operation, 320 pipes must be cut, removed and rewelded. The developed concept for this task is presented here. It aims at reducing the associated plant downtime, thereby increasing the overall plant availability. Features underpinning this integrated BB pipe service concept are: (i) parallel pipe service operations, (ii) pipes in each upper port are grouped in a pipe forest and handled as a single component, (iii) the configuration of the individual pipes is standardized such that cutting and joining locations are aligned and with good accessibility from the top, (iv) the number of pipe sizes is limited to two, reducing the number of required tool sets, and (v) the same pipe configuration is adopted in each of the 16 upper ports. The paper will present design solutions and the progress on the manufacturing of prototypes developed for the challenging cutting and welding tasks from both within and outside, as well as the leak detection methodology and pipe stub handling. Prototypes will be used to perform design validation and verification on dedicated test benches currently being implemented in close collaboration between European laboratories and the Comprehensive Research fAcility for Fusion Technology (CRAFT) at ASIPP in China.

1. Introduction

The European DEMOnstration power plant (EU-DEMO) and China Fusion Engineering Test Reactor (CFTER) are fusion devices aiming the production of MWs of electricity to the grid. In this context, the plant availability of both power plants is one of the key aspects to be considered already in the conceptual phase. Considering that their maintenance has a huge impact on the overall plant availability, already in the conceptual phase a proper remote handling (RH) strategy must be developed. These components, due to high irradiation and stress levels induced by the thermal, electromagnetic and mechanical loads, need to be replaced during the life of the fusion devices. Both DEMO and CFETR are equipped with a tritium breeding blanket (BB) covering the inner surface of the machine installed in the vacuum vessel (VV). The BB is subjected to high neutron irradiation, high thermal, electromagnetic and mechanical loads causing high degradation [1] of the component. Due to this, its regular replacement is needed during the machine life. The complete replacement of the BB and also a regular removal of single segments for in-service inspection [2] are needed during the machine operation. Past studies, carried out already in the 1980s years [3,4] addressed these issues proposing the BB should be divided into vertical segments that can be removed by crane-type tools through large ports placed on the upper part of the VV. Studies of the last years pointed out the BB segments are huge components with a potential mass up to 125 tons [5,6] to be lifted and tilted in a very narrow space with a lifting point off centered, all that causes huge loads and moments on the lifting devices. Bachmann et al. in their studies [2,7] proposed a preliminary concept coupled with an integrated strategy for the removal, storage and

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replacement of these huge BB segments. Moreover, the BB is assumed to be a radioactive hazard due to (i) the radioactivity caused by neutron irradiation, (ii) the presence of radioactive dust on its surfaces and (iii) the outgassing of the tritium [2]. These aspects the remote handling tools to be operated in a double sealed environment to prevent the spread of contamination into the building. A maintenance strategy allowing for a double confined space for remote handling tools has been developed for ITER [8–10]. The strategy proposed for BB replacement [2,7,11] assumes all components inside the upper port (feeding pipes, port plug, upper limiter, BB support features, et al. [12]) would be removed prior the BB removal. In the current configuration, DEMO is conceived as divided into 16 sectors [13] with five BB segments each. Depending from the BB design concept, Water Cooled Lithium Lead (WCLL) or Helium Cooled Pebble Bed (HCPB), the number of the feeding pipes in the upper port are respectively 25 for WCLL and 20 in case of HCPB concept for each sector. Their dimensions vary from DN80 up to DN350 with pipe walls in the range 5÷16 mm as stated in [14]. Hence prior the BB replacement, about 400 (WCLL concept) and 316 (HCPB concept) pipes shall be disconnected and removed and then re-joined after the installation of the new BB segments. These numbers mean that the removal and re-installation of the pipes in the upper port are the bottleneck of the overall remote handling procedure for the BB replacement in terms of duration [11]. The pipe servicing concept developed for DEMO varies significantly from the ITER approach due mainly two reasons: (i) dimensions and thicknesses of the pipes are larger than the ITER ones requiring filler material during the welding process, (ii) the structure of the upper part of EU-DEMO and CFTER machines are different from the ITER since its upper port is almost horizontal while in DEMO and in CFTER it is vertical,. Similarly to the BB replacement strategy adopted in [2,7] the maintenance of the feeding pipes shall be operated in a double sealed environment to prevent the spillover of the radioactive dust once the upper port is opened, to prevent the outgassing of the tritium and to reduce the radiation propagation in the tokamak building. This work proposes a strategy, consistent with the one proposed in [2,7] for BB segments, for the removal and reinstallation of the BB feeding pipes in the upper port. Starting from the aforementioned requirements, assumptions about the maximum number and dimensions of the pipes arranged in the upper port and a sequence for removal and installation of the pipes have been suggested.

Chapter 2 identifies the boundary conditions and main requirements for the pipe replacement in the upper port of EU DEMO, chapter 3 describes the sequence of the operations required for the pipe replacement, chapter 4 describes the arrangement of the pipes in the upper port, chapter 5 describes the different pipe service tools, and chapters 6 and 7 describe the transporters used inside the cask to operate the tools.

2. Main assumptions as base of the strategy

HCPB and WCLL are the two promising concepts could be adopted for fusion power plant even if at the moment these two options are still under evaluation and development [15]. The development of a feasible strategy for removal and re-installation of the feeding pipes shall be conducted in parallel with the development of the BB design. In this respect, our work is based on the following assumptions, which could serve as drivers and suggestions for the development of the BB design concepts. A reference configuration for the feeding pipes in upper port has been assumed as starting point. Ten pipes DN200 16 mm in thickness, and ten pipes DN80 with 6 mm of thickness have been chosen as reference for the development of the remote handling strategy. The thicknesses have been chosen compatible with the values of the operating pressure assumed in the current configuration of the reference design of WCLL and HCPB [5,6]. The material assumed for the pipes is AISI 316 L. The feeding pipes, as described in [14], are routed from the chimney of the BB segments through the upper port, the upper port ring channel and the upper port annex up to the penetration plate that is the vacuum boundary, see Fig. 1. Each pipe consists of a horizontal and a vertical leg; on top of the vertical ones pipe stubs with removable caps are installed for the insertion of the remote handling tools. The vertical legs are grouped in a pipe forest to be manipulated and transferred to and from the active maintenance facility as a single component [2,7]. It is assumed that the removed pipe forests are re-installed after the replacement of the BB. Hence, the re-weldability after n-irradiation of the AISI 316 L must be verified. The horizontal legs are permanent, they remain in situ during remote handling of the BB segment. A proper supporting system connects these legs to the upper port ring channel and upper port annex structures. A double confinement approach is adopted for the remote handling of the pipe forest, in particular, an upper port cask is used for the transfer of pipe forest between the VV and the active maintenance facility. It is a sealed container that prevents contamination to spread from the VV or from hot components inside the cask into the building. The transfer cask docks to the docking flange of the upper port before both the VV and the cask are opened (Fig. 1 and Fig. 2). Before leaving the docking flange a double-lidded contamination control door is split into the port door that seals the VV and the cask door that seals the cask. The cask has a confinement function and therefore is a safety-important class component [7]. The pipe forest is assumed to be disconnected and rejoined, both from the blanket segment and permanent pipes, respectively at level of the BB chimney and on the horizontal permanent legs (Fig. 1).

Pipe forest removal is carried out considering the port plug in situ, for this reason in-bore tools are assumed to be used for cutting and joining at the level of the BB chimney due to space constraints (pipes and port dimension, port plug presence). Ex-bore orbital tools are adopted for cutting and joining of the pipes at the level of the horizontal legs.

As a first attempt, parallelization of the cutting and joining tasks is assumed: all pipes in the upper port are cut and re-joined in parallel, the activities are parallelized as much as possible to increase the overall machine availability.

Dry parting and beveling are assumed as reference technology for pipes cutting (motivation in [16]).

Parting and beveling in one single shot are assumed (motivation in [16]).

Tungsten Inert Gas (TIG) welding is assumed as reference technology

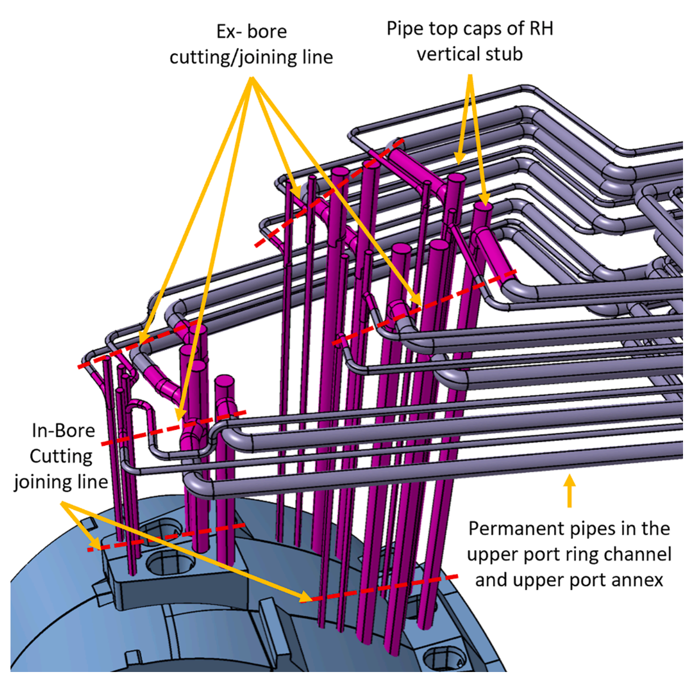

Fig. 1. Cutting and Joining lines for pipes forest replacement – upper port, upper port ring channel and upper port annex not shown.

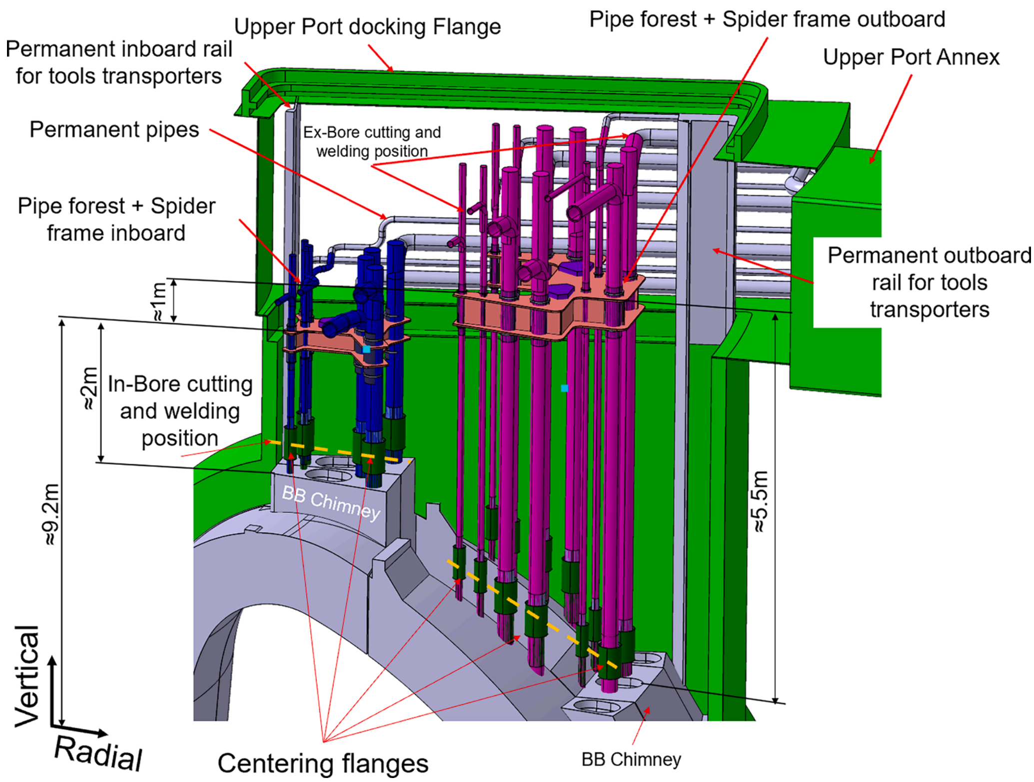

Fig. 2. Pipes arrangement in upper port – port plug not shown – dimension are in meters.

for pipes joining (motivation in [16]) since past studies already proved the feasibility of this technologies for small diameters and thicknesses [17,18].

Same as in the case of BB segment replacement, it is currently assumed the pipes remote handling (RH) is carried out simultaneously in 4 ports, the remote handling ports, it means that a design of toroidal in-vessel transporter for the BB segments is needed [19]. The pipes forest in the not RH ports will be only disconnected from the BB segments only at the level of the BB chimney, remaining in situ. This assumption could guarantee a strong reduction of the maintenance times since the pipe forests in the not RH ports will remain in situ during the remote handling activities.

Proper devices for In-bore cutting (parting and beveling) and welding need to be developed and tested, the conceptual design of this tools is described in [16] for pipes DN200 with thickness of about 16 mm in AISI 316 L. These devices will be installed on dedicated transporters that will have the function to deploy in position the devices operating from inside the transfer cask as for the BB segments. Already available technologies will be adopted for the Ex-bore devices, both parting/beveling and welding [20–22]. These technologies will be adapted to our context taking into account the aspects related to the pipe dimensions and pipes alignment features.

As for the case of the In-bore tools, the Ex-bore ones will be installed on a dedicated transporters that will serve the pipes forest for its disconnection (parting and beveling) and joining (TIG welding), alignment and manipulation in the transfer cask. The Ex-bore tools transporter will deploy in position the ex-bore devices, manipulate, remove and install the pipe forest in the RH ports operating from inside the transfer cask. All automatic connection and interfaces of the devices and transporters shall be standardized in order to reduce the complexity of the systems. More details about the conceptual design of the transporters are reported in the following chapters.

3. Removal and re-installation sequence for upper port pipes forest

In order to develop an integrated RH strategy for upper port pipes forest a preliminary sequence has been defined according to the current configuration of EU-DEMO [13,23], assuming that the power plant, the tokamak building, the contamination protection structure and active maintenance facility [2,7]are ready to start the RH of the BB.

The pipes forest replacement sequence could consist of the following phases:

1. Removal of vacuum vessel closure plate
2. Pipe top caps removal (Fig. 1)
3. In- Bore cutting (parting and beveling in one shot) of the pipes at level of BB chimney plus edge joint preparation for the subsequent welding
4. Ex-bore parting - beveling of the pipes at level of horizontal leg plus edge joint preparation
5. Pipe forest removal and transportation to the active maintenance facility by mean of a transfer cask
6. Port Plug removal (not in the scope of this work)
7. BB replacement (not in the scope of this work)
8. Port Plug installation (not in the scope of the work)
9. Pipe forest deployment, vertical leg of the pipes engaged in the pipe stubs on the BB chimney by mean of a proper centering system (Fig. 2).
10. Ex-bore welding at the level of the horizontal leg
11. In-bore welding at the level of the Breeding Blanket chimney plus pipes leak checking
12. Pipes top caps installation plus pipes leak checking

4. Pipes arrangement in upper port

The layout of the pipes in the upper port has been arranged considering: the space needed for the footprint of the BB gripper interlock [24,25]; a minimum distance between the pipes allowing for the placement of the pipes aligning flanges at level of BB; the space needed for the engagement of the orbital tools for the ex-bore operation (i.e. parting/beveling and welding devices); the space needed for the permanent rails of the vertical transporters (i.e. BB transporter, BB pipes transporters Fig. 2). The interlock that engages with the BB segment consists of a massive housing that is inserted about 450 mm deep into a countersunk hole in the chimney of the BB segment. To enable guided engagement, it has a somewhat conical shape with reduced cross-section in the lower part [24,25]. The footprint dimensions of the gripper interlock are about 630 × 430 mm. In the current configuration of the tokamak, the overall height of the vertical legs at the outboard and inboard is about 7.5 m and 3.5 m, respectively. According to reference code for pipe dimensions [26–28] the overall dead weight of the pipes forest is about 6tons. This number gives an idea of the potential amount of radioactive waste in case the pipes forest will not be re-used after the BB replacement and the impact that potentially this choice could have on the associated costs. The pipes forest is equipped with vertical stubs and caps to allow for insertion of the in-bore tools during the BB segment remote maintenance (Fig. 1 and Fig. 2). The pipes are kept together by permanent spider frames that remain in situ during operation (Fig. 2, Fig. 3) equipped with quick change grippers, properly dimensioned for the masses to be considered (provisionally *off-the-shelf* components have been chosen). The spider frames shall:

- Ø keep together the vertical legs of the pipes forest
- Ø avoid the relative rotation of each pipe around its own axis
- Ø allow for different thermal expansion of each vertical leg, reducing as much as possible potential thermal stresses
- Ø lift and manipulate the overall pipes forest
- Ø deflect horizontally on the left and on the right side the pipes forest during the ex-bore orbital welding (i.e. junction between the top part of the pipes and the permanent pipe in the upper port)
- Ø push down, if needed, the pipes forest during the in-bore welding to guarantee the edges alignment and coupling

A couple of steel rings connected by vertical square bars are assumed to be welded on each pipe. These components assure that the pipes can slide vertically about +/−50 mm (the number shall be confirmed by a test campaign) with respect to the spider frame and avoid the rotation of the single pipe about its own vertical axis. Proper slots are realized on the spider frame structure to insert the pipes. Each pipe can expand vertically during operation, thus avoiding thermal stresses in the spider frame (Fig. 3).

Each vertical leg at the level of the BB chimney is equipped with a couple of flanges (one on the pipes forest and the other on the BB pipes stub side Fig. 2) to algin and position the pipe forest during the installation and replacement (Fig. 4). Moreover, once the pipes forest is positioned, the two flanges create a chamber outside the pipes for the temporary storing of the shielding gas for the in-bore welding (Fig. 4). The flanges will be equipped with proper orifices to allow for shielding gas removal once the installation process is concluded. The aspect related to the presence of the shielding gas outside (for back protection on the underside of the weld) the pipes during the in-bore welding shall be addressed with a proper test campaign. The centering flanges, in the current configuration, could tolerate an axis misalignment during the positioning of the pipes forest of +/−35 mm (Fig. 4) for each pipe. The vertical height of the flange on the BB stub and on the pipes forest side will be adapted according to the number of pipe forest reinstallations (i. e. number of cuts and re-welds).

The pipes forest shall be also aligned at the level of the ex-bore cut during their replacement (Fig. 2). A proper alignment system has to be developed to assure this function. The permanent legs of BB feeding pipes (i.e. the horizontal ones) are assumed as welded at the level of the penetration plate and properly supported in the upper port annex and upper port ring channel. The layout of the supports of the permanent pipes has been studied considering seismic, mechanical and thermal loads both during operation and installation of the pipe forest. The pipes forest needs to be properly supported to keep the natural frequencies of the pipes as high as possible in case of an earthquake. In [29] a potential layout of the permanent pipes supporting structure has been proposed. More specifically, the recommended support structures deliver the lowest frequencies of about 14 and 11 Hz for the inboard and outboard pipes, respectively, with the maximum Mises stress during normal operation of about 270 MPa, thus respecting the structural requirements. The highest values of the Von Mises Stress occurs in the bent radius of the horizontal legs, more details of the results of the assessment are reported in [29]. However, the inboard pipes suffer from rather high reaction forces, moments and Mises stresses during alignment operation due to the fix displacement in toroidal direction of one of its supports.

5. Pipe service tools

A preliminary list of the transporters and devices needed for the RH of the pipes forest has been prepared. In Table 1, the tools that need to be developed are reported according to the assumed removal and re-installation sequence and considering the assumptions listed in the previous chapter. The number of tools to be developed is also a

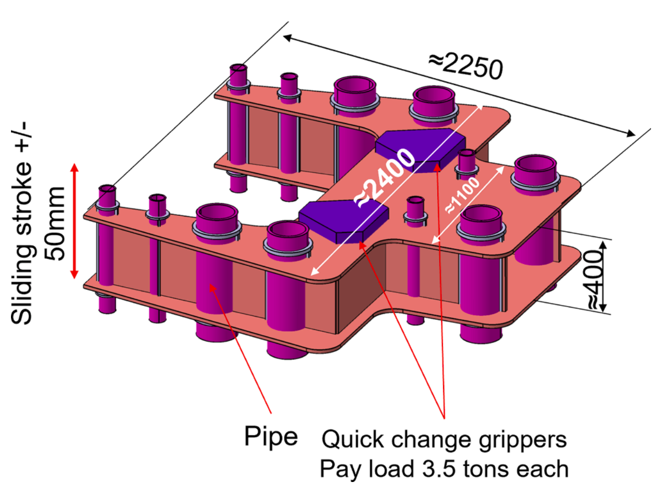

Fig. 3. Frame structure for pipe forest manipulation - only a short stub of the pipes is shown – dimensions are in mm.

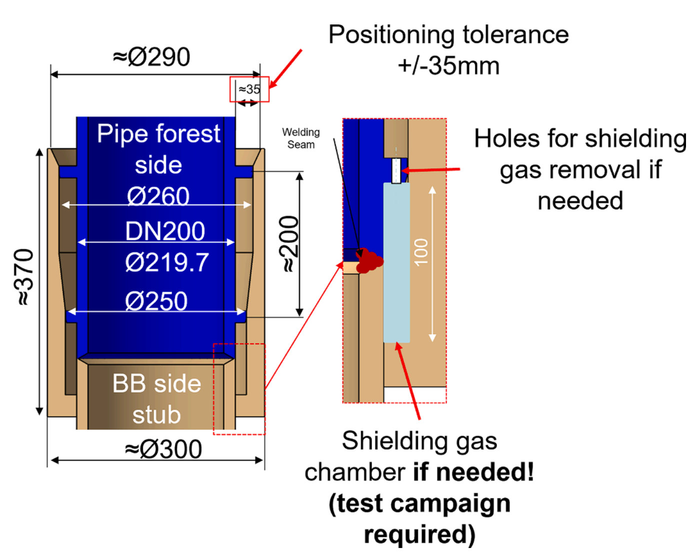

Fig. 4. Detail of the centering flanges at level of the BB Chimney – Pipe DN200 16 mm in thickness.

Table 1
Preliminary tools list for pipes replacement.

ID	Task	Tool
Small devices for singles operations (welding, cutting, leak checking)		
1	In-Bore Cutting	In-bore cutting devices for pipes DN200 and DN80
2	In-Bore Welding	In-bore welding devices for pipes DN200 and DN80
3	In-Bore pipes caps cutting	Caps In-bore cutting and removal devices for pipes DN200 and DN80
4	In-Bore pipes caps Welding	Caps In-bore welding and installation devices for pipes DN200 and DN80
5	Ex-bore Cutting	Ex-bore cutting devices for pipes DN200 and DN80
6	Ex-bore Welding	Ex-bore welding devices for pipes DN200 and DN80
7	Leak detection	Leak detection devices for pipes DN200 and DN80
Transporters for deployment of the small devices in the working position and manipulation of the pipes forest		
1	Pipe caps removal	Pipe caps removal transporter equipped with 20 caps cutting devices (10 for pipes DN200 and 10 DN80) plus features for caps manipulation
2	Pipes caps installation	Pipe caps installation transporter equipped with 20 caps welding devices (10 for pipes DN200 and 10 DN80) plus features for caps manipulation
3	In-bore cutting	In-Bore Cutting transporter equipped with 20 In-Bore cutting devices (10 for pipes DN200 and 10 DN80)
4	Ex-bore cutting	Ex bore cutting tool transporter equipped with 20 ex-bore cutting devices (10 for pipes DN200 and 10 DN80) plus features for pipes deflection and positioning
5	In-Bore welding	In-Bore welding transporter equipped with 20 In-Bore welding devices (10 for pipes DN200 and 10 for pipes DN80) plus features for pipes positioning
6	Ex-bore Welding	Ex-bore welding transporter equipped with 20 orbital welding devices (10 for pipes DN200 and 10 for pipes DN80) plus features for pipes deflection and positioning
7	Leak detection	Leak detection transporter equipped with the leak detection devices (10 for pipes DN200 and 10 for pipes DN80) possibility to equip the welding tool with ND test should be investigated

parameter to show the complexity of the remote operations that are needed.

The Table 1 shows clearly how the number and type of tools are strictly related to the pipes dimension and their arrangement in the upper port. The list presented could not be exhaustive and it could be potentially improved during the future development of the pipes RH strategy, but it is a first step in definition of the tools set needed for the remote maintenance of the pipes. The design of the tools reported in Table 1 shall be developed in the next design phase, some of these are currently under development and presented in [16]. The development phase shall include also the development of proper test facilities to improve and validate the designs proposed for each transporter and small device.

6. Ex-Bore transporter

The EX-Bore transporter is assumed to work inside the transfer cask. It will deployed in position by means of its three rigid chains and skids [27]. It is assumed that the same transfer cask could serve all the type of transporters using standard interfaces (i.e. same skids and rigid chains, standard automatic connectors). Its main functions consist in: (i) transportation and deployment of Ex-Bore Cutting and Welding devices in the working position (i.e. at the level of the junction with pipe forest and the permanent pipes in the upper port ring channel); (ii) transport, manipulation and positioning of the pipes forest inside the transfer cask; (iii) insertion of the vertical pipes in the centering flange of the BB side; (iv) deflection of the pipes in toroidal direction allowing for the alignment of their horizontal stubs with the corresponding permanent pipes. The transporter is composed by a main support frame joined to the three skids that slide inside the vertical rails of the transfer cask, they are served by the three rigid chains [2]. Two ex-bore devices support frame (one on the left and other on the right side of the main frame) are joined to the main frame by mean of two linear bearings rollers each and actuated by a couple of electric actuators. Ten devices (i.e. cutting or welding devices, as first attempt) are joined to each frame through spring systems. Each frame can slide vertically independently of about +/500 mm allowing for the engagement and disengagement of the ex-bore devices on the pipes to be processes (i.e. cut or welded). The spring systems accommodate potential misalignment between the horizontal stubs of the pipes forest and the corresponding on the permanent pipes (Fig. 5). The pipe forest manipulation platform is placed under the main frame and it is joined to it through four vertical beams equipped with spherical joints on the ends. The vertical beam shall support the dead weight of the pipes forest and allow for small movements in the horizontal plane (i.e. in radial and toroidal directions). The platform is equipped, in the lower part, with three quick change grippers that plug the corresponding components on the pipe forest spider frame (Fig. 5). The grippers have pneumatic actuation and are dimensioned for the required design loads. In the current configuration *off-the-shelf* components have been integrated in the design. The platform is actuated by three electrical actuators: one is placed on the inboard side oriented in toroidal direction, one the outboard oriented in toroidal direction, while the third is placed on the center of the platform oriented in radial direction. The actuators guarantee the movement and the deflection of the pipes forest in toroidal and radial directions. The cutting and welding of the pipes is carried out in two different steps: in the first one, the pipes placed on the right side of the upper port are processed (i.e. cut or weld), then the ones placed on the opposite side. In case of the welding for example, in the first step the pipes on the right side of the upper port are welded then the others, in this frame time the welded pipes are deflected in toroidal direction to align the stub of the pipes on the other side. The pipe forest platform and the electric actuators have been dimensioned taking into account the forces needed to deflect horizontally the ten pipes placed on one side. As first attempt, the platform should consent radial and toroidal movement in the range +/−50 mm (Fig. 5). This numbers shall be confirmed through a proper test campaign. The frames structures of the ex-bore transporter have been provisionally dimensioned with analytical models. The ex-bore tools both for cutting and welding will be designed starting from the cutting edge technologies already available on the market. The design activities of these tools will focus mainly on the alignment systems to be equipped on the ex-bore tools, in detail this system will allow for the alignment of the stubs of the horizontal legs to be joined.

Upon the pipes forest is disconnected from the BB segments and the permanent pipes, the VV and the cask are closed by a double-lidded contamination control door while the cask transports the pipes forest to the active maintenance facility (Fig. 6).

7. In-Bore tools transporter

The In-bore devices transporter is simpler than the ex-bore since in terms of its main functions, that consist on: (i) transportation and deployment of In-Bore Cutting/Welding Tools in position at the level of the BB chimneys; (ii) vertical pushing of the pipe forest to guarantee the alignment of the pipes at the level of the centering flanges. As in the case of the Ex-bore transporter, it is served by the cask transfer and it is plugged to its three skids. It is composed by a steel frame, joined to the skids, that supports 20 conduit tubes. These tubes are the vertical guides for the in-bore devices. In detail, they have the same dimensions of the pipes to be served (10 conduit pipes DN200 and 10 DN80), each one engages in the corresponding vertical leg of the pipes forest by mean of a proper spring system for pipes misalignment compensation (Fig. 7). The spring system is installed to the lower ends of the conduit tubes. The in-bore devices during the transporter deployment are inside the conduit tubes, just above the spring system. Once the conduit tubes are engaged, the device slide inside the conduit tubes and the vertical legs of the pipe forest up to the working position (welding or cutting line) at the level of the BB chimney (Fig. 7).

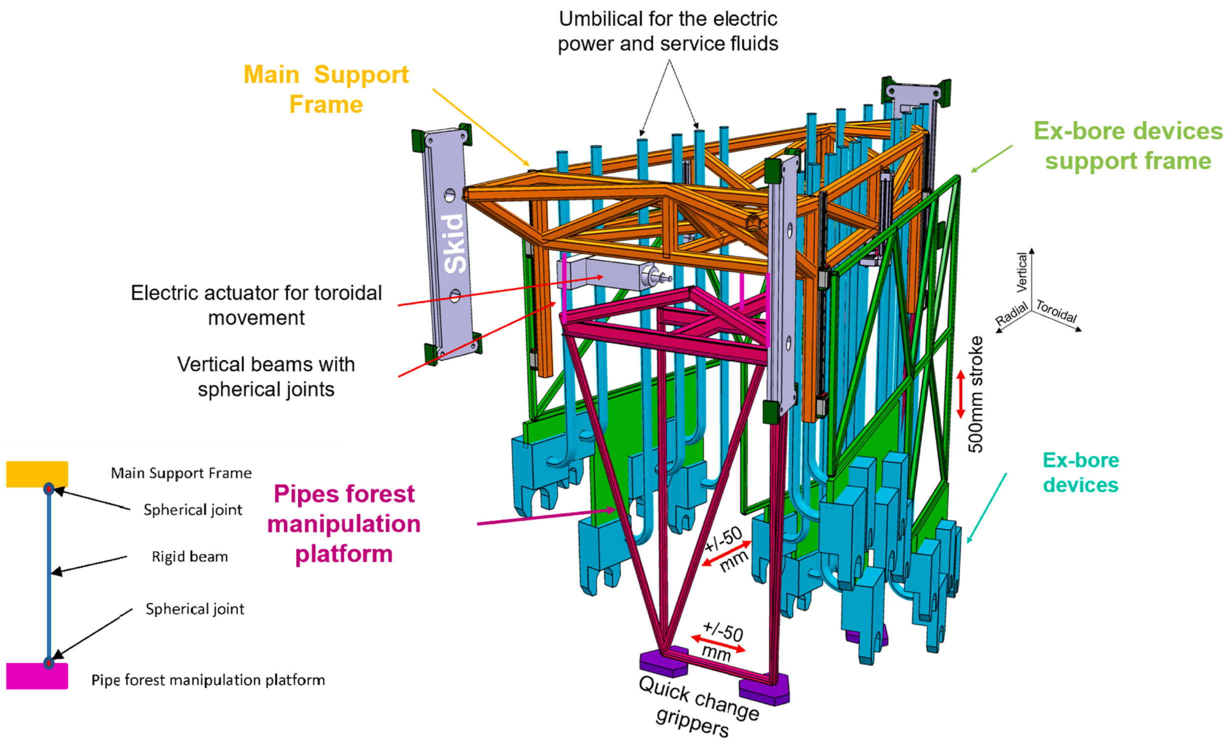

Fig. 5. Conceptual design of the Ex-bore Transporter.

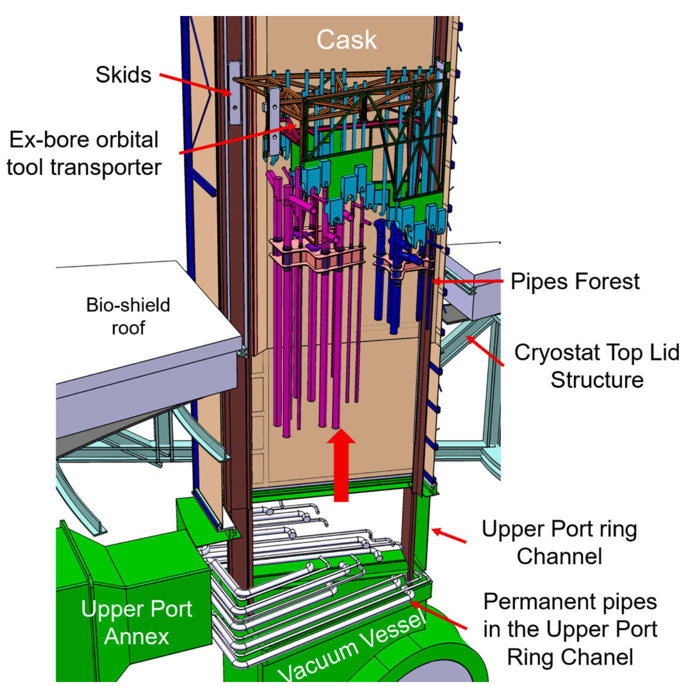

Fig. 6. Pipes forest lifted in the cask transporter.

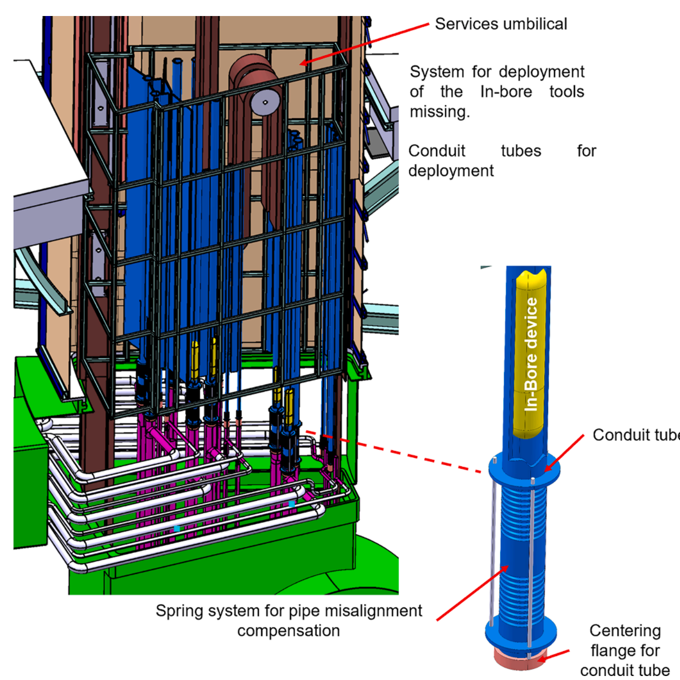

Fig. 7. Pipe forest being installed in the Upper Port.

8. Conclusion

The work proposed summarized the results of the activities that the European and Chinese teams are developing under the framework of EU-China collaboration. The assumptions on which the development of the integrated maintenance strategy for the feeding pipes of the BB segments in upper port is based, have been defined taking into account the engineering aspects related to the whole RH process. The list of the tools needed could be improved in the next development phase to guarantee the remote removal and installation of the BB feeding pipes. The reference configuration of the pipes in the upper port has been defined taking into account: the pipes dimensions, the space needed for the BB gripper interlock and the port plug. It is strongly suggested to reduce as much as possible the number of different dimensions of the feeding pipes (in the current configuration two different diameter and thicknesses have been considered) since this aspect has a huge impact on the RH strategy and the number of different tools to be provided. A preliminary sequence for removal and installation of the feeding pipes has been also proposed, since the number, type and complexity of the RH tools strictly depend form the fundamental assumptions and the RH tasks sequence.

The proposed approach is consistent with the one in [2,7,19] for the BB segments removal and installation. Our work is only a first step in development of the overall RH tools for pipes removal and installation in upper port configuration and gives an idea of the challenges that the RH teams shall overcome in the next future to achieve an integrated and consistent design of the RH tools for the fusion reactors. The approach and the design of the RH tools here proposed, need to be validated and improved through dedicated test facilities, where, proper test campaigns will confirm the assumptions that are the base of the approach, taking into account also the work carried out in the 90 s years [17,18]. A lot of aspects are still missing and need to be investigated in the next years:

- the conceptual design of the tools listed in Table 1 shall be developed for both pipes DN200 and DN80
- all auxiliary systems have to be integrated in the design of the transporters based on the requirements coming from the design of the small devices (rack for electric power, inert gas, filler wire, air compressed system, feedback and control system)
- the automatic connection system for the feeding of the transporter and cask transfer (electric power, inert gas for welding, filler wire, air compressed system, feedback and control system, other potential fluids) have to be integrated in the design
- test campaign development for design validation of the proposed concept

CRediT authorship contribution statement

Rocco Mozzillo: Conceptualization, Methodology, Writing – review & editing. **Christian Bachmann:** Supervision. **Günter Janeschitz:** Supervision. **Vincenzo Claps:** Resources. **Oriol Costa Garrido:** Formal analysis. **Hongtao Pan:** Resources. **Fei Li:** Resources. **Donato Sorgente:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] G. Federici, C. Bachmann, L. Barucca, C. Baylard, W. Biel, L.V. Boccaccini, J. H. You, Overview of the DEMO staged design approach in Europe, Nucl. Fusion 59 (6) (2019) 066013.
[2] C. Bachmann, C. Gliss, G. Janeschitz, T. Steinbacher, R. Mozzillo, Conceptual study of the remote maintenance of the DEMO breeding blanket, Fusion Eng. Des. 177 (2022) 113077.
[3] F. Farfaletti-Casali, Configurational aspects and structural problems of systems integration, maintenance, containment and shielding for next-generation tokamaks (INTOR and NET), Nuclear Eng. Design Fusion 3 (4) (1986) 385–397.
[4] M. Chazalon, et al., Next European torus assembly and maintenance, Fusion Technol. 1 (1988) 156–164, 14.
[5] P. Arena, G. Bongiovì, I. Catanzaro, C. Ciurluini, A. Collaku, A. Del Nevo, M. Utili, Design and Integration of the EU-DEMO Water-Cooled Lead Lithium Breeding Blanket, Energies 16 (4) (2023) 2069.
[6] F.A. Hernández, P. Pereslavtsev, G. Zhou, Q. Kang, S. D'Amico, H. Neuberger, F. Cismondi, Consolidated design of the HCPB Breeding Blanket for the pre-Conceptual Design Phase of the EU DEMO and harmonization with the ITER HCPB TBM program, Fusion Eng. Des. 157 (2020) 111614.
[7] C. Bachmann, G. Janeschitz, P. Fanelli, C. Gliss, P. Mollicone, M. Muscat, R. Mozzillo, Progress in the development of the in-vessel transporter and the upper port cask for the remote replacement of the DEMO breeding blanket, Fusion Eng. Des. 194 (2023) 113715.
[8] I. Ribeiro, et al., The remote handling systems for ITER, Fusion Eng. Des. 86 (2011) 471–477.
[9] S. Beloglazov, et al., Configuration and operation of detritiation systems for ITER Tokamak complex, Fusion Eng. Des. 85 (7–9) (2010) 1670–1674.
[10] C. Damiani, J. Palmer, N. Takeda, C. Annino, S. Balagué, P. Bates, M. Saito, Overview of the ITER remote maintenance design and of the development activities in Europe, Fusion Eng. Des. 136 (2018) 1117–1124.
[11] O. Crofts, A. Loving, M. Torrance, S. Budden, B. Drumm, T. Tremethick, A. Vale, EU DEMO remote maintenance system development during the pre-concept design phase, Fusion Eng. Des. 179 (2022) 113121.
[12] C. Vorpahl, R. Mozzillo, C. Bachmann, G. Di Gironimo, Initial configuration studies of the upper vertical port of the European DEMO, Fusion Eng. Des. 146 (2019) 2469–2473.
[13] C. Bachmann, L. Ciupinski, C. Gliss, T. Franke, T. Härtl, P. Marek, C. Vorpahl, Containment structures and port configurations, Fusion Eng. Design 174 (2022) 112966.
[14] R. Mozzillo, C. Vorpahl, C. Bachmann, F.A. Hernández, A Del Nevo, European demo fusion reactor: design and integration of the breeding blanket feeding pipes, Energies 16 (13) (2023) 5058.
[15] F.A. Hernández, P. Arena, L.V. Boccaccini, I. Cristescu, A. Del Nevo, P. Sardain, G. Zhou, Advancements in Designing the DEMO Driver Blanket System at the EU DEMO Pre-Conceptual Design Phase: overview, Challenges and Opportunities, J. Nuclear Eng. 4 (3) (2023) 565–601.
[16] Sorgente, D., Salvato, R., Bachmann, C., Gliss, C., Janeschitz, G., Pan, H., Zhoue, X., Wang, H., Mozzillo, R.. Overview of in-bore pipe cutting and welding tools for the maintenance of CFETR and EU-DEMO. (This conference).
[17] F. Andritsos, C. Damiani, F. Farfaletti-Casali, D. Maisonnier, G. Mercurio, E. Ruiz-Morales, Simulation and experimental validation of first wall/blanket assembly and maintenance for the next step fusion reactor, Fusion Eng. Des. 42 (1–4) (1998) 473–484.
[18] D. Maisonnier, F. Amelotti, A. Chiasera, P. Gaggini, C. Damiani, L. Degli Esposti, E. Ruiz, Remote handling of the blanket segments: testing of 1/3 scale mock-ups at the Robertino facility, Fusion Eng. Des. 29 (1995) 298–308.
[19] Claps, V., Bachmann, C., Janeschitz, G., Steinbacher, T., Mozzillo, R.. Conceptual design of DEMO Breeding Blanket In-Vessel Toroidal Transporter (This Conference).
[20] Mills, S., et al., Orbital Cutting Tool Description. ITER IDM: ITR-321-TNT-006-A (PRIVATE COMMUNICATION).
[21] Polysoude. Orbital pipe welding. https://www.polysoude.com/orbital-pipe-welding/.
[22] Mills, S.F., McCarron, E., Sargent, M., Sky, J., Froud, T., Yapp, D.. ITER Divertor Water Pipe Joint and Tooling Development. ITER IDM: ITR-321-REP-003-A. (PRIVATE COMMUNICATION).
[23] Bachmnan, C.. EU-DEMO Plant description document. EUROFUsion IDM 2KVWQZ. (PRIVATE COMMUNICATION).
[24] T. Steinbacher, C. Bachmann, C. Gliss, G. Janeschitz, R. Mozzillo, Design of the gripper interlock that engages with the DEMO breeding blanket during remote maintenance, Fusion Eng. Des. 193 (2023) 113641.
[25] R. Mozzillo, C. Bachmann, P. Fanelli, G. Janeschitz, T. Steinbacher, Structural assessment of the gripper interlock of the DEMO breeding blanket transporter, Heliyon 9 (8) (2023).
[26] ASME B36.10M-2004. Welded and seamless Wrought Steel Pipe.
[27] EN-10220:2016. Seamless and welded steel tubes – Dimensions and masses per unit length.
[28] EN-ISO4200. Plain end steel tubes, welded and seamless – General tables of dimensions and masses per unit length.
[29] O. Costa. Structural analysis of the upper port pipe forest. Idm_EFDA_D_2MSV2T (Private Communication).