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Progress in EU-DEMO In-Vessel Components integration

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In DEMO due to the large number of complex systems assembled into the tokamak vessel for integration it is of vital importance to address the in-vessel integration at an early stage in the design process. In the EU DEMO design, after a first phase in which the different systems have been developed independently based on the defined baseline DEMO configuration, an effort has been made here to define the interface requirements and to propose the integration strategies for the auxiliary heating and fueling systems into the vacuum vessel and the breeding blanket. This work presents the options studied, the engineering solutions proposed, and the issues highlighted for the in-vessel integration of the DEMO fueling lines, auxiliaries heating systems, and diagnostics.

Keywords: in-vessel components (IVC); breeding blanket (BB); vacuum vessel (VV); heating systems; fuelling.

1. Introduction

In the framework of the EUROfusion DEMO Programme, the Programme Management Unit (PMU) is assuming the role of the plant and tokamak design integration. It is recognized, in part thanks to the ITER experience, that due to the large number of complex systems assembled into the tokamak vessel for integration it is of vital importance to address the in-vessel integration at an early stage in the design process. Furthermore in DEMO the auxiliary heating and fueling systems integrated in the tokamak will have to interface with and be integrated into a breeding blanket (BB) and will face a harsh nuclear environment during operation. The in-vessel components (IVC) as a whole will have to satisfy the top level requirements of remote maintainability and high reliability; however for the engineering integration of single systems inside the vacuum vessel (VV) and BB, a deep understanding of the requirements of the interfacing systems is mandatory and has to be developed at an early stage in the design process.

This work presents the options studied, the engineering solutions proposed, and the issues highlighted for the in-vessel integration of the DEMO fueling lines, auxiliaries heating systems, and diagnostics. In section 2 the IVC integration strategy and schedule of activities is presented, in section 3 the design work carried out in 2016 for fuelling lines, electron cyclotron launchers and neutral beam injectors is described, with a brief overview of the on-going activities on the other systems.

2. In-vessel components integration strategy

In the EU DEMO design, after a first phase in which the different systems have been developed independently based on the baseline DEMO configuration defined by the PMU, an effort has been made here: i) to define the interface requirements among systems to be integrated in-vessel and the BB; ii) to propose the integration strategies for the auxiliary heating and fueling systems into the VV and the BB and for the BB and divertor supporting structures; iii) to define a schedule for the design and analyses and to identify the 3D supporting tools.

Considering the level of maturity of the design of the individual systems as of beginning of 2016 the following strategy has been adopted. For the fuelling lines, the Electron Cyclotron (EC) launchers and the Neutral Beam Injector (NBI) a precise design solution has been considered as input for being integrated in 2016 into the BB. For the divertor, 5 different cassette fixation schemes are studied in 2016 and the corresponding definition of the interface among the fixations, the VV and the BB pipes routed thorough the lower port has started. For the BB fixations a reference design

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developed by CCFE and fully compatible with remote maintenance (RM) requirements is being integrated and analyzed this year into the BB. For the diagnostic, where a range of different systems with different requirements needs to penetrate the BB, the priority has been given for this year to the definition of the integration approach and the establishment of the interface requirements documents. For the Ion Cyclotron (IC) heating, for which a toroidally continuous antenna is planned for integration in the future, the priority is given for this year to the definition of interfacing requirements with the BB.

A set of common activities carried out for all systems to be integrated has been established and started. At first, the definition and the progressive completion of interface requirements documents (space, material requirements, heat loads on the BB etc.): a common template has been defined and draft versions of the documents describing the interface of a system with the BB have been prepared in 2016. Secondly, neutronic analyses are performed to assess the impact of the penetrations into the BB on: i) the nuclear loads and irradiation damage on the VV; ii) the BB Tritium Breeding Ratio (TBR) performance and the power distribution in the BB; iii) the nuclear loads on the integrated auxiliary systems. Finally, the support of a 3D virtual reality lab (hosted by CREATE in Napoli's University) for the IVC integration activities has been established for: centralizing and handling the integration of the auxiliary systems CAD models into the detailed CAD models of the BB, the VV and the divertor; supporting the progressive integration of multiple systems, at first studied independently, into the BB; identifying space reservation for systems and clashes among systems in a 3D environment; exploring integrated design solutions for interfacing with RM and its requirements; hosting the design reviews. A schedule for the IVC integration activities to be carried out until end of 2018 has been prepared and is presented in figure 1.

3. 2016 In-vessel components integration activities

4 different BB concepts are presently developed in EU [1]: Helium Cooled Pebble Bed (HCPB), Water Cooled Lithium Lead (WCLL), Helium Cooled Lithium Lead (HCLL) and Dual Coolant Lithium Lead (DCLL).

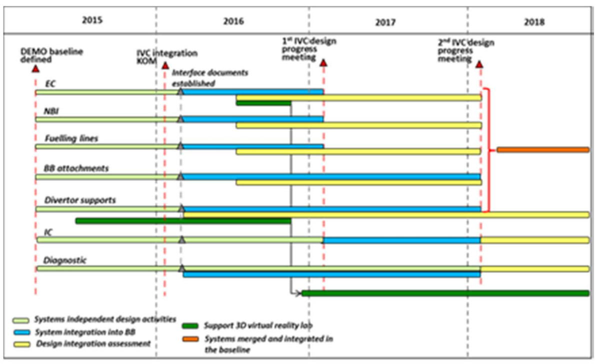

Fig. 1. Schedule of IVC integration activities.

For optimizing the work load distribution the 3 auxiliary systems considered for integration in 2016 have been shared among 3 different BBs, namely: fueling lines into the HCPB, EC launchers into the WCLL and NBI into the DCLL. The HCLL being dedicated to the integration of the diagnostics.

3.1 Fuelling lines

The reference injection configuration for the DEMO fuelling line is vertical, from the high field side and S-shapes are to be avoided into the complete line. The fuel pellet guiding tube is presently considered as rectangular with a cross section of 10x20mm^2. The injection line geometry has been optimized vs. its 3 reference design criteria of having: a minimum bending radius $R > 6$ m; a maximum distance to mid plane $z < 1.5$ m; an angle at the intersection pellet path – separatrix $\alpha = 90°$ [2].

Two options are studied for the line integration into the HCPB BB [3]: i) the guiding tube ends at the BB back supporting structure (BSS); ii) the guiding tube penetrates the BB. In case i) the mechanical interface is simpler and a conical opening is required into the BB for guaranteeing the straight free flight of the pellet, while in ii) the mechanical interface is more complex as the guiding tube would cross VV and BB and have to handle heat loads (the higher the closer to the BB First Wall - FW-). In case i) the opening into the BB and the deviation of the pellet from its ideal path are larger with a negative impact on the fuelling efficiency, while in ii) the pellet remains closer to its ideal path ensuring a better fuelling efficiency.

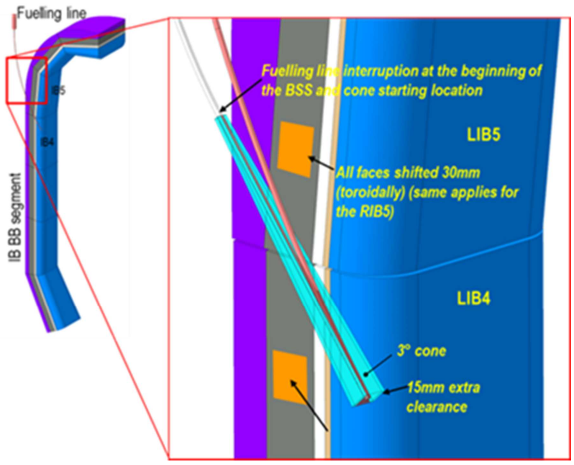

Fig. 2. Fuelling line as integrated in the HCPB BB, with the guiding tube sopped at the BSS.

In case i) to simplify the mechanical integration of the line in between two BB segments, the lateral faces of the 2 impacted BB in-board modules (IB4 and IB5) have been shifted toroidally (see figure 2). The impact of such a larger opening in between IB BBs has been assessed by neutronic analyses [4]. The analyses have been done screening 3 different geometrical integration options: i) gap between modules of 94 mm at IB4 and 80 mm at IB5, with an opening of 3°; ii) gap of 74 mm at IB4 and 60 mm at IB5, with 2° opening; iii) gap of 60mm at IB4 and 46 mm at IB5, with 2° opening and guiding tube inserted 200mm into the BB. The analyses consider 18 fuelling lines integrated in between each BB segment (i.e. each TF coil). Considering the need of redundancy, the possible required core fuelling performances and additional functions, like ELM pacing, a more recent assessment indicate that 9 to 12 lines could be sufficient. The computed impact on TBR is marginal: even in the worst configuration the maximal TBR variation is -0.0029. A moderate increase of the nuclear heating in the VV is observed, and in the worst configuration the nuclear heating on the TF coil remains below the limit of $5x10^{-5}$ W/cm^3. Due to the straight opening neutrons streaming cause an increased dpa level in the VV steeel: the cumulate damage on the VV is close to the limit of 0.45dpa/FPY in the worst configuration (see figure 3).

If the fuelling line stops at the BSS the pellet will follow a straight fly line through the BB and will not comply any longer with the criteria fullfilled by the ideal line computed (and curved) up to the FW. A torough comparison of a re-optimized injection line stopped at the BSS and a line guided thorough the BB is on-going: at first the optimum 2D trajectories will be computed and compared vs. the reference design criteria, then the engineering integration of the two lines will be assessed for balanicing pro and cons.

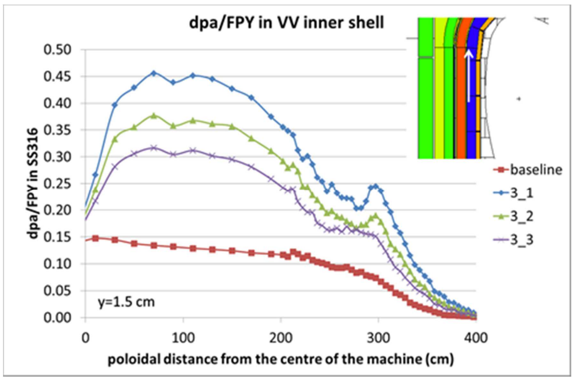

Fig. 3. Computed dpa/FPY in VV steel: maximum damage over DEMO lifetime is <2.75 dpa.

3.2 Electron Cyclotron launchers

The EC Launchers concepts considered for BB and port integration in 2016 are port based on Remote Steering Antennas (RSA). The other concept that is being studied is the truncated waveguide and Step-Tunable gyrotrons. Until the design review in 2017 the BB integration will focus on the RSA: the port plug and radio frequency (RF) lines stop at the BB BSS and an opening through the BB modules is provided for launching the wave. In the present configuration 8 antennas per launching point are planned. Similarly to one of the approaches used for integrating the fuelling lines, the port plug interrupted behind the BB BSS allows for a simpler mechanical integration, as BB and port plug with associated systems remain structurally independent.

2 different RSA configurations have been considered for integration in 2016: i) 2 horizontal rows with 4 RSA each; ii) 1 vertically stacked array of 8 RSA. Case i) implies a large conical opening though the central segment with partial impact also on the lateral segment. Case ii) has been designed to limit the BB impacted to the lateral segment only, with an opening possibly less appealing for the neutron streaming. The stack of 8 antennas as integrated into the WCLL BB [5] is shown in figure 4.

For the EC and also for the NBI penetrations the same design approach has been followed: to maintain the poloidal continuity of the BB BSS and manifolds. The BB BSS are presently designed as a unique continuous poloidal structure providing structural support and ensuring the coolant and breeder (in case of liquid BB) distribution, with a front-end segmentation in individual BB modules (hosting the breeding zone). This design strategy drives the design of the BB thermal-hydraulic, the piping layout and the interfaces with the Balance of Plant as well as with RM, which plans to remove and handle vertically full BB segments via the upper port. The need to cut in 2 halves the BB segments, thus breaking their poloidal continuity, could have a major impact on several key systems and interfaces.

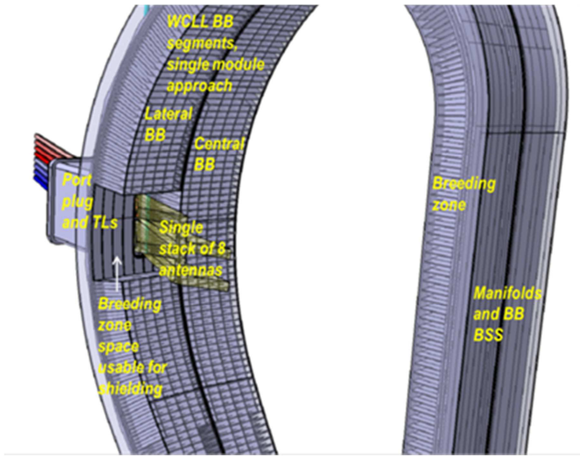

Fig. 4. Stack of 8 antennas in WCLL BB

Therefore in figure 4 the stack of 8 antennas is integrated working out a solution in which the BSS poloidal continuity is kept, while the large volume taken out by the EC opening into the breeding zone can be occupied by shielding material (using complex geometries for breeding purpose is avoided at this stage). The 2 RSA configurations will be compared also considering the results of the neutronic analyses at the 2017 design review, where the further design work will be agreed also considering the maturity of the truncated waveguide port plug concept.

3.3 Neutral Beam Injectors

The present NBI configuration for BB and port integration foresees an injection angle of 30° and an opening size at the BB of 0.7mx0.7m. A larger injection angle (i.e. 34.5°) would ensure the beam tangency at the center of the plasma and less neutrons to the beam but with smaller clearance to the coils. With 30° despite having more neutrons to NBI and no tangency the mechanical integration is much favored, with a larger clearance to coils and VV. As for the opeing at the BB FW, one option would be to focus the beam at the plasma tangential point, with highest concentration of energy to the plasma, but larger aperture in the BB (i.e. 0.7mx1m). Focusing the beam at the middle of the BB FW one ensures a minization of the beam aperture, but a larger beam section at the center of plasma. The mechancial integration aspects have been privileged and the option with 30° injection angle and opening size at the BB FW of 0.7mx0.7m has been integrated in 2016.

As for the EC, the NBI integration into the DCLL [6] has been driven by the necessity to keep the DCCL BSS poloidal continuity: the relative small opening requested by such NBI configuration into the BB allows this approach. Figure 5 shows a DCLL radial-toroidal cut with the integrated NBI. The design will be further assessed also with neutronic analyses up to the design review planned in 2017. Studies are on-going to define the NBI heat loads onto the lateral walls of the BB modules: the integration of the cooling circuit into the BB lateral walls has to be customized depending on those heat loads. The present space allocation and provided clearances to the beam shall be assessed with respect to the heat loads management and the RM requirements.

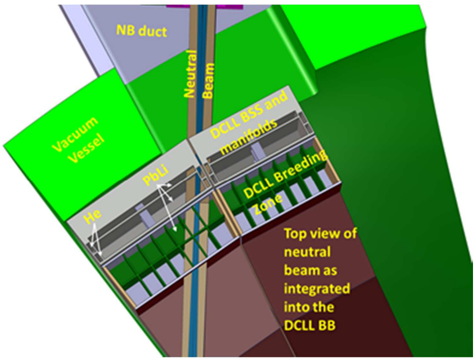

Fig. 5. Top view of a DCLL radial-toroidal cut with the integrated NBI.

3.4 Other systems

BB fixations. BB fixations shall be designed to support the BB segments under the large Electro-magnetic (EM) loads generated by unmitigated disruptions. A BB attachment designed by CCFE [7] and fully compatible with RM requirements is integrated and analyzed this year into a BB. This design encompasses i) pins to fix the BB segments at the bottom (location where the segments engage passively into the VV); ii) RM compatible keys in inboard and outboard segments; iii) a large shield plug with a two stage spring to clamp the BB at the top (an initial pre-load provides stability while the spring hard stop clamps the BB segment). EM analyses will provide the loads to be used for the fixations structural assessment. The fixations will be customized in 2017 to each of the 4 BB concepts.

Divertor supports. 5 different cassette fixation schemes are under design and assessment. The interface between divertor cassette, divertor fixations and BB pipes routed via the lower port has started. In parallel the gaps and opening between divertor and BB segment are assessed by neutronic analyses and with respect the RM requirements.

Diagnostic. 3 approaches are followed for the integration of diagnostic sightlines into the BB (~400 estimated): i) a dedicated full diagnostic port plug to be integrated into an equatorial or upper port; ii) slim diagnostic cassettes (~20cm wide in toroidal direction) to be integrated in between two BB segments; iii) customized individual penetrations through the BB (cylindrical standardized penetrations, ~10cm in diameter). In 2016 the integration of microwave diagnostics using poloidally continuous slim cassettes has started.

4. Conclusions

In the EU DEMO conceptual design activities the different systems have developed independently their own design based on the baseline DEMO configuration defined by the PMU: here an effort is made to define a workplan and start the activities for the IVC integration. In particular the work has focused on: i) defining a schedule for the IVC integration design and analyses and identifying the 3D supporting tools; ii) defining the interface requirements among systems to be integrated in-vessel and the BB; iii) proposing the integration strategies for the auxiliary heating and fueling systems into the BB and for the BB and divertor supporting structures. A first IVC integration design review meeting is planned to be hosted in the 3D CREATE laboratory beginning of 2017 for assessing the design solutions explored in 2016 and define in detail the future work.

Acknowledgments

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