Fusion Engineering and Design 124 (2017) 562–566

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Progress in EU-DEMO in-vessel components integration

F. Cismondi[a,*], P. Agostinetti[b], G. Aiello[c], J. Aubert[c], C. Bachmann[a], W. Biel[d], L.V. Boccaccini[e], A. Bruschi[f], Chr. Day[e], A. Del Nevo[g], G. Di Gironimo[h], I. Fernandez[i], T. Franke[a,k], G. Grossetti[e], F. Hernandez[e], D. Iglesias[j], J. Keep[j], P. Lang[k], A. Loving[j], P. Norajitra[e], G. Mazzone[g], D. Marzullo[h], B. Ploeckl[k], R. Mozzillo[h], D. Rapisarda[i], P. Sonato[b], M.Q. Tran[l], A. Vaccaro[e], R. Villari[g], J.H. You[k], C. Zeile[e]

[a] *EUROfusion Consortium, PPPT Power Plant Physics and Technology, Garching, Germany*
[b] *Consorzio RFX, Padova, Italy*
[c] *CEA Saclay, France*
[d] *Forschungszentrum Juelich GmbH, Juelich, Germany*
[e] *KIT, Karlsruhe Institute of Technology, Karlsruhe, Germany*
[f] *IFP, Istituto Fisica del Plasma – CNR, Milano, Italy*
[g] *ENEA, Fusion and Technology for Nuclear Safety and Security Department, Italy*
[h] *CREATE, University of Naples Federico II – DII, Napoli, Italy*
[i] *CIEMAT, Fusion Technology Division, Madrid, Spain*
[j] *UKAEA CCFE/RACE, Culham Science Centre, Abingdon, UK*
[k] *IPP, Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[l] *Swiss Plasma Center – EPFL, Lausanne, Switzerland*

HIGHLIGHTS

In the frame of the conceptual design phase of the EU DEMO an effort is made here:

- To define the interface requirements among systems to be integrated in the VV and the BB.
- To propose the integration strategies for the auxiliary heating, diagnostic and fuelling systems into the VV and the BB and for the BB and divertor supporting structures.
- To define a schedule for the in-vessel components integration design analyses.
- To identify the 3D supporting tools.

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form 22 March 2017
Accepted 24 March 2017
Available online 4 April 2017

Keywords:
In-vessel components
Breeding Blanket
Vacuum Vessel
Heating systems
Fuelling systems

ABSTRACT

In the EU DEMO design (Romanelli, 2012; Federici et al., 2014), due to the large number of complex systems inside the tokamak vessel 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 to define the interface requirements and to propose the strategies for the mechanical integration of the auxiliary heating and fuelling 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 mechanical in-vessel integration of the DEMO fuelling lines, auxiliaries heating systems, and diagnostics.

1. Introduction

In the EU DEMO design development programme it is recognized, partially also thanks to the ITER experience [3], that due to the large number of complex systems assembled into the tokamak vessel it is of vital importance to address the mechanical in-vessel

---

[*] Corresponding author.
E-mail address: fabio.cismondi@euro-fusion.org (F. Cismondi).

http://dx.doi.org/10.1016/j.fusengdes.2017.03.147

integration at an early stage in the design process. Furthermore in DEMO the auxiliary heating and fuelling 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 fuelling lines, auxiliaries heating systems, and diagnostics. Nuclear design aspects of the in-vessel integration related to the tritium cycle are not treated in the paper which focuses on the in-vessel mechanical integration. 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 an overview of the on-going activities on the other systems.

2. In-vessel components integration strategy

In the EU DEMO design [1,2], after a first phase in which the different systems have been developed independently based on the EU DEMO baseline defined in 2015 an effort has been made: i) to define the interface requirements among systems to be integrated in the VV and the BB; ii) to propose the integration strategies for the auxiliary heating, diagnostic and fuelling systems into the VV and the BB and for BB and divertor fixations; iii) to define a schedule for the design studies and identify the 3D supporting tools.

The strategy presented here considers the level of maturity of the design of the individual systems as of beginning of 2016. For the fuelling systems, the Electron Cyclotron (EC) launchers and the Neutral Beam Injector (NBI) a specific design solution has been considered as input for being integrated 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 through the lower port has started. For the BB fixations a reference design fully compatible with remote maintenance (RM) requirements is being integrated and analyzed in 2016. For the diagnostic, where a range of different systems with different requirements needs to penetrate the BB, the priority has been given 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 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 through the BB on: i) the nuclear loads and irradiation damage on the VV; ii) the BB Tritium Breeding Ratio (TBR) performance and the BB power distribution; iii) the nuclear loads on the integrated auxiliary systems. Finally, the support of a 3D virtual reality lab [4] (hosted by CREATE in University of Napoli) 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 (see Fig. 1).

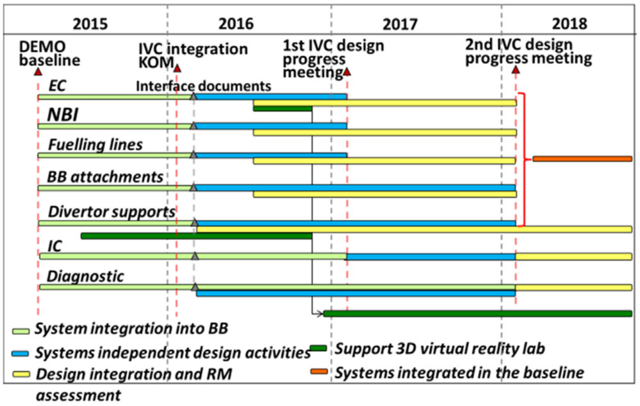

Fig. 1. Schedule of IVC integration activities.

3. Progress in EU-DEMO in-vessel components design integration

Four different BB concepts are presently developed in EU [5]: Helium Cooled Pebble Bed (HCPB), Water Cooled Lithium Lead (WCLL), Helium Cooled Lithium Lead (HCLL) and Dual Coolant Lithium Lead (DCLL). For optimizing the work load distribution the 3 auxiliary systems considered for integration in 2016 have been shared among 3 different BBs, namely: fuelling lines into the HCPB, EC launchers into the WCLL and NBI into the DCLL. The HCLL is dedicated to the integration of diagnostics.

3.1. Fuelling systems

The reference injection configuration for the DEMO fuelling systems (developed at IPP Garching) is vertical, from the high field side (in-board) and S-like bendings are to be avoided into the complete line. The fuel pellet guiding tube is presently considered as rectangular with a cross section of $10 \times 20\,\mathrm{mm}^2$. The injection line geometry has been optimized vs. its 3 reference design criteria of having: a minimum bending radius R of at least 6 m; a maximum distance to mid plane z of 1.5 m; an angle at the intersection pellet path – separatrix $\alpha = 90^\circ$ [6].

Two options are studied for the line integration into the HCPB BB (developed at KIT) [7]: i) the guiding tube ends at the BB back supporting structure (BSS); ii) the guiding tube penetrates the BB up to the First Wall (FW). In case i) the mechanical interface is simpler and limited to the VV, as a conical opening is required between two adjacent BB modules (realized shifting toroidally the lateral faces of in-board (IB) modules 4 and 5, see Fig. 2) for guaranteeing the straight free flight of the pellet, while in ii) the mechanical interface is more complex as the guiding tube would mechanically interface both, VV and BB, and have to handle higher heat loads (the higher the closer to the FW). In case i) the required toroidal shift and the deviation of the pellet from its ideal path are larger with a negative impact on the fuelling efficiency, while in case ii) the pellet is guided along its ideal path up to the FW ensuring a better fuelling efficiency.

The impact of the opening in between BB modules in case i) has been assessed by neutronic analyses (by ENEA) [8]. The analyses have screened 3 different geometrical integration options: i) gap of 94 mm between IB4 modules and of 80 mm between IB5, with an

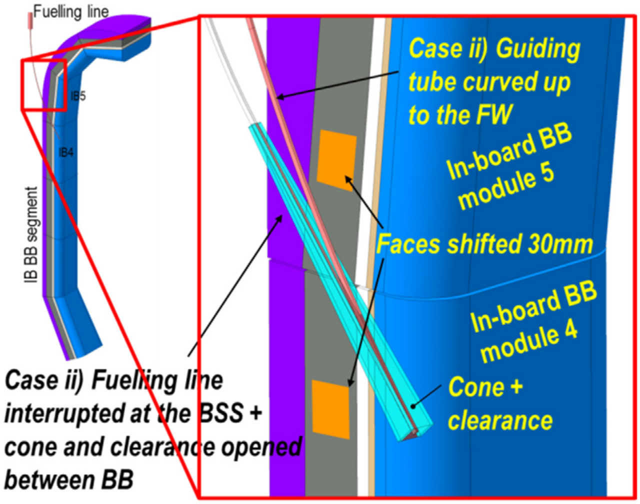

Fig. 2. Fuelling line as integrated in the HCPB BB, with the guiding tube stopped at the BSS.

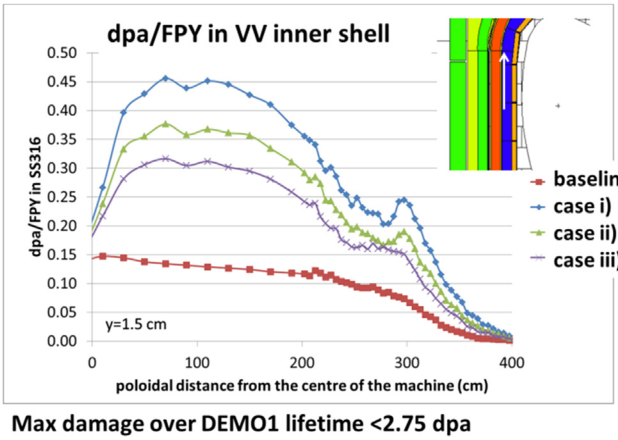

Fig. 3. Computed dpa/FPY in VV steel: maximum damage over DEMO lifetime (6 FPY) is <2.75 dpa.

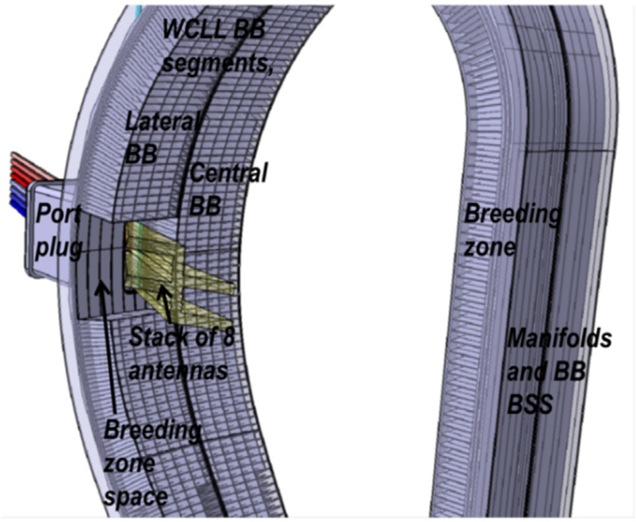

Fig. 4. Stack of 8 antennas in WCLL BB.

opening of 3°; ii) gap of 74 mm at IB4 and 60 mm at IB5, with 2° opening; iii) gap of 60 mm at IB4 and 46 mm at IB5, with 2° opening and guiding tube inserted 200 mm 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 9–12 lines could be sufficient. The computed impact on TBR is marginal: even in the worst configuration (case i) above) the maximal TBR variation is −0.0029 and the Tritium self-sufficiency is guaranteed with sufficient margin. 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 5×10^{-5} W/cm^3. Due to the straight opening neutrons streaming cause an increased dpa level in the VV steel: the cumulate damage on the VV is close to the limit of 0.45 dpa/FPY in the worst configuration (see Fig. 3). The neutron irradiation maximum limit for the DEMO vessel is presently specified as 2.75 dpa (over 6FPY): this would be an irradiation damage limit requiring limited effort to obtain a licensing approval, since this value is already given in RCC-MRx as *negligible irradiation damage dose threshold* (see Ref. [9] A3.3S.33). In ITER it is considered to define the lower dpa limit (0.5–1.0 dpa) to minimize further material verifications requirements (see [9] A3.1S.41). Further design assessment will include the increase of the radiation heat flux onto the VV inner shell through the gaps. If the fuelling line stops at the BSS the pellet will keep a straight trajectory through the BB and the required fuelling performance is impacted. A thorough comparison of a re-optimized injection line stopped at the BSS and a line guided through the BB is on-going: at first the optimum 2D trajectories are computed and compared vs. the reference design criteria, then the engineering integration of the lines is assessed for balancing pro and cons.

3.2. Electron cyclotron launchers

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). 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: the design of the BB thermal-hydraulics, the piping layout and the interfaces with the Balance of Plant, and the RM scheme and machine architecture, which are designed with the principle of removing and handling vertically full BB segments via the upper port. The EC Launchers concepts (developed at KIT and IFP) considered for BB and port integration in 2016 are based on Remote Steering Antennas (RSA). The other concept that is being studied foresees the use of truncated waveguides and Step-Tunable gyrotrons. Until the design review in 2017 the BB integration will focus on the RSA: the port plug and EC launchers 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 port plug 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.

Two 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 through the central segment with partial impact also on the lateral segment. Case ii) has been designed to limit the BB impact to the lateral segment only, with an opening possibly less favourable for the neutron streaming. The stack of 8 antennas as integrated into the WCLL BB (developed at ENEA) [10] is shown in Fig. 4.

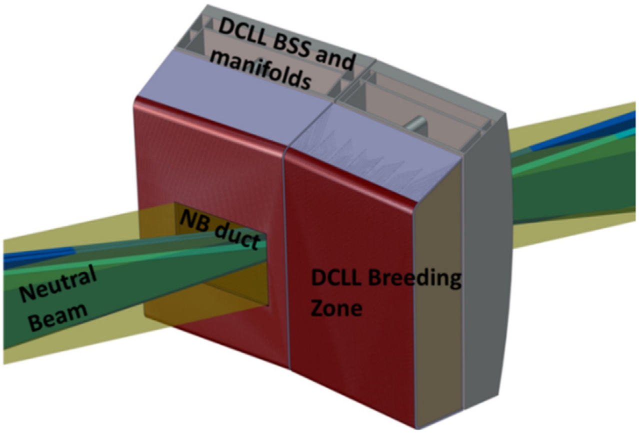

Fig. 5. Front view of two equatorial DCLL BB modules with the integrated NBI.

In Fig. 4 the stack of 8 antennas is integrated in 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 (developed at Consorzio RFX) for BB and port integration foresees an injection angle of 30° with respect to the radial direction and an opening size at the BB of 0.7 m × 0.7 m. 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 smaller tangency angle, the mechanical integration is much easier, with a larger clearance to coils and VV. As for the opening at the BB FW, one option would be to focus the beam at the plasma center, with highest concentration of energy to the plasma, but larger aperture in the BB (up to 2 m × 1 m). Focusing the beam at the middle of the BB FW one ensures a minimization of the beam aperture, but a larger beam section at the center of plasma. The mechanical integration aspects have been privileged and the option with 30° injection angle and the beam focus in the BB with opening size at the BB FW of 0.7 m × 0.7 m has been integrated in 2016.

As for the EC, the NBI integration into the DCLL (developed at CIEMAT) [11] 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. Fig. 5 shows a front view of the two equatorial DCLL BB modules where the NBI is integrated. The design will be further assessed also with neutronic analyses up to the design review planned in 2017. Studies are ongoing 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.

3.4. Other systems

3.4.1. 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 fully compatible with RM requirements (developed at CCFE) [12] is integrated and analyzed in 2016 into a BB (by KIT). 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 IB and OB 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.

3.4.2. Divertor supports

Five different cassette fixation schemes are under design and assessment (by ENEA, IPP Garching). 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.

3.4.3. Diagnostic systems

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

4. Conclusions

In the EU DEMO conceptual design activities individual systems have developed independently their own design based on the EU DEMO baseline defined in 2015: here an effort is made to define a workplan and start the activities for the mechanical integration of IVC. In particular the work focused on: i) defining a schedule for the IVC integration design 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 fuelling systems into the BB and for the BB and divertor supporting structures. As this is the first start of in-vessel integration activities for the EU DEMO, the work focused on the mechanical integration of the main auxiliaries and the BB fixations and on the corresponding neutronic analyses of the 3D openings in the BB. The next steps of the in-vessel integration design shall encompass detailed consideration on the nuclear aspects related to the tritium fuel cycle, detailed thermo-mechanical design and analyses of components working close to the plasma and under neutron irradiation as well as RAMI and safety aspects for BB and auxiliaries. Most of the systems to be integrated are indeed developing specific requirements (expected performance, materials, tolerated heat loads and neutron damages, maintainability).

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom Research and Training Programme 2014–2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] F. Romanelli, A Roadmap to the Realisation of Fusion Energy. Technical Report, EFDA, 2012.
[2] G. Federici, et al., Overview of EU DEMO design and R&D activities, Fusion Eng. Des. 89 (2014) 882.
[3] A. Martin, et al., Design evolution and integration of the ITER in-vessel components, Fusion Eng. Des. 88 (2013) 1955–1959.
[4] D. Marzullo, et al., Design progress of the DEMO divertor locking system according to IPADeP methodology, Procedia CIRP 34 (2015) 56–63.
[5] L.V. Boccaccini, et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. 109–111 (Pt. B) (2016) 1199–1206.
[6] B. Ploeckl, et al., Fuelling technology for DEMO, state of the art, Fusion Eng. Des. (submitted for publication).
[7] F. Hernandez, et al., A new HCPB breeding blanket for the EU DEMO: evolution, rationale and preliminary performances, Fusion Eng. Des. 124 (2017) 882–886.
[8] U. Fischer, et al., Methodological approach for DEMO neutronics in the European PPPT programme: computational tools, data and analyses, Fusion Eng. Des. (submitted for publication).
[9] RCC-MRx, Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN, 2013.
[10] A. Del Nevo, et al., WCLL breeding blanket design and integration for DEMO : status and perspectives, Fusion Eng. Des. 682-686 (2015) 124.
[11] D. Rapisarda, et al., Conceptual design of the EU-DEMO dual coolant lithium lead equatorial module, IEEE Trans. Plasma Sci. (2016) (in press).
[12] D. Iglesias, et al., Remote handling assessment of attachment concepts for DEMO blanket segments, Fusion Eng. Des. 98–99 (2015) 1500–1504.