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# Divertor conceptual design of the European Volumetric Neutron Source

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ABSTRACT

The goal of the European plasma Volumetric Neutron Source (VNS), which is a 14 MeV n-source, is to test and validate technological solutions of breeding blankets in an environment representative of a future fusion power plant such as DEMO. One of the assessed magnetic configurations is a tokamak device with a radius of ≈ 2.5 m that produces a D-T fusion power of ≈ 30 MW. The architecture of VNS integrates a single null divertor located at the bottom of the vacuum vessel. The ITER-like divertor is designed to be actively water-cooled for stationary operation and is made up with 36 cassette modules. Each module has a cassette body with a set of plasma facing components (PFCs) with tungsten as plasma facing material. The PFC arrangement is a dome positioned in the central part with reflector plates on both sides located between inboard and outboard target striking surfaces. The selected PFC technological solutions are: the plasma facing units (PFUs) of the targets are armored with tungsten monoblocs bonded onto a cooling pipe made of CuCrZr with an inserted twisted tape, the PFUs of the dome are made up with tungsten flat tiles bonded onto a CuCrZr hypervapotron cooling structure. This paper presents the status of the development of the divertor conceptual design. Preliminary analyses confirmed that the design is compatible with plasma scenarios foreseen for VNS operation.

## 1. Introduction

Today's Technological Readiness Level (TRL) of the breeding blanket, which is a key component of a future fusion power plant, is very low. This situation requires the set-up of an R&D development programme to test, select and validate the most promising technological solutions of a breeding blanket in addition to ITER and IFMIF- DONES [1]. EUROfusion has recently launched a feasibility study to address this critical issue. The proposed test facility is a 14 MeV plasma Volumetric Neutron Source (VNS) which provides an environment representative of a future fusion power plant such as DEMO [2]. One assessed option of magnetic configuration [3] is a medium-size tokamak device with a radius of ≈ 2.5 m and an aspect ratio of ≈ 4.6. D-T fusion power of ≈ 30 MW is generated by D Neutral Beam Injection (NBI) of a power of 42.5 MW plus 10 MW Electron Cyclotron (EC). The goal is the production of a stationary neutron power load at midplane onto the outboard wall of ≈ 0.5 MW/m$^2$, which is the assigned location of the test breeding blanket modules.

The architecture of VNS is a single null divertor configuration with a divertor located at the bottom of the Vacuum Vessel (VV). The position and shaping of the divertor are the results of physics simulations using SOLPS-ITER [4,5]. This paper presents the status of the divertor conceptual design.

Topic: Plasma Facing Component

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## 2. Conceptual design

The divertor consists of the toroidal arrangement of 36 consecutive Cassette Modules (CMs) and is divided into 12 sectors (Fig. 1).

A sector is associated with a Toroidal Field (TF) coil (12 TF coils in total) and corresponds to a toroidal angle of 30°. Each sector comprises a set of 3 CMs: one central CM and two lateral CMs. Fig. 2 shows an overview of the CAD configuration model of a set of CMs.

Each sector is associated with a Lower Port (LWP) for routing feeding pipeworks of each CM. Some of the LWPs are assigned to maintenance (4 over 12) and the others are equipped with vacuum pumps. Fig. 3 shows the CAD model of a CM and the location of the main divertor components. The dimensions are: ≈ 1,5 m long, ≈ 0.85 m high, ≈ 0.5 m wide (toroidal direction). Total weight with coolant is 1475 kg.

The divertor design is an adaptation of the ITER divertor [6] to take advantage of the lessons learned of on-going production of this component to reduce development investment. Plasma Facing Components (PFCs) are positioned on the Cassette Body (CB). The dome is positioned in the central part with reflector plates on both sides located between inboard and outboard target striking surfaces. The functions of the targets are to intersect and neutralize the SOL (Scrape-Off layer) particle fluxes, and to exhaust heat from SOL particles, radiation and nuclear heating. The functions of the dome are to shield the pumping channel of the CB for protecting the VV against neutron flux and radiation, to drive gas flow to the pumping channel while preventing upstream and gas reflux into the plasma at the same time. The pumping channel, which is located in the central part of the CM, guides the gas flow towards the LWP. The functions of the reflector plates are to protect cooling manifolds and pipes against particles, neutron fluxes and radiation, to enhance particle exhaust and to exhaust heat from radiation and nuclear heating.

The concept of integration is based on the same principles as ITER [7]. The CM is connected and positioned in the VV by means of support of fixation at the inboard and outboard. At the inboard side of the CM, a nose-shaped contact plate with spherical surface which, once engaged, constrains poloidal and toroidal displacements but not rotations and maintains the gap to the inboard shielding. At the outboard side of the CM, a wishbone system with removable pins constrains rotation about the radial axis. This solution aims to provide sufficient elastic compliance and static resilience to accommodate the mismatch between the VV and the CM. Rails located below the divertor, which are static supports against gravity loads, allow the guidance of the toroidal transportation of the CMs. This solution should allow the precise PFC positioning and the toroidal movement of the CMs in the VV to the dedicated LWP for maintenance while taking over different loads (electro-magnetic, mechanical, neutronic and radiative) in different operation modes.

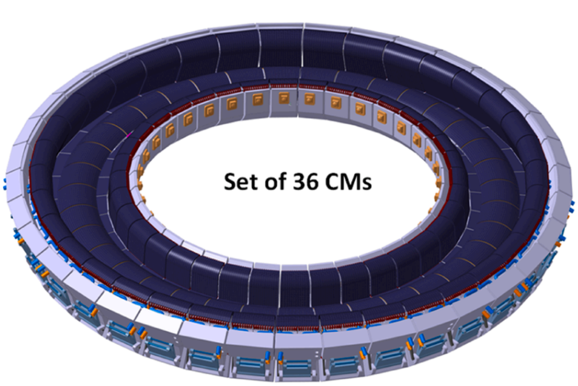


**Fig. 1.** CAD overview of the divertor arrangement.

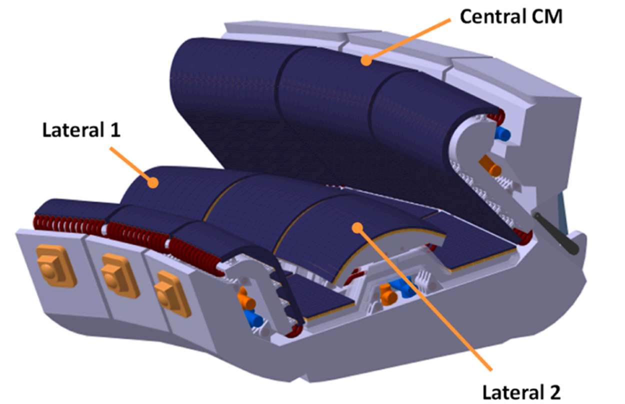


**Fig. 2.** CAD overview of a set of 3 CMs.

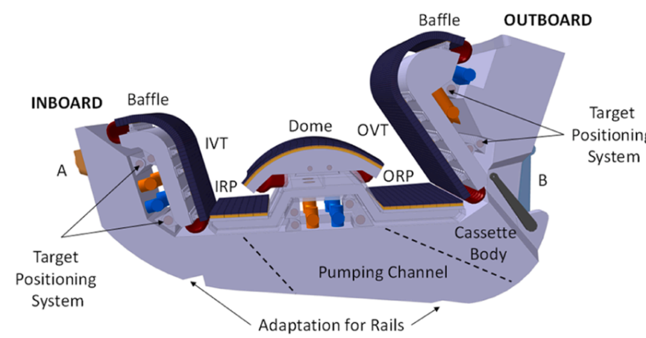


**Fig. 3.** CAD view of the central CM. IRP/ORP: Inboard/Outboard Reflector Plates, IVT/OVT: Inboard/Outboard Vertical Target. A and B are the fixation systems at inboard (nose) and outboard (wishbone), respectively.

## 3. Loading conditions

The highest thermally loaded components are the targets. To reduce local heat fluxes to level compatible with technological capabilities, two solutions are combined: (1) target inclination at a shallow angle of 2–3° relative to the grazing magnetic field [8] and (2) radiative cooling at the target proximity using seeded inert gas such as Krypton or Argon (below an allowed concentration limit to avoid dilution effect). Loading conditions selected for the design are listed in Table 1.

First results of physics simulations estimated much lower peak heat flux density on PFCs than presented in Table 1. Considering the present uncertainties of physics modeling, adequate margins have been introduced for the value of the peak heat fluxes. For instance, the maximal validated value by experiments in operation [9] or in test facility [10] has been selected for the target. The margins related in particular to the W-thickness and cooling conditions will be adapted throughout the design process.

The main heating system is NBI and is assumed to be rapidly switched off in case of abnormal events which may damage PFCs.

**Table 1**
Specified loads on divertor components.

| Loading | Specified Values |
|---|---|
| Volumetric thermal power by nuclear heating | 5.30 MW for divertor<br>0.15 MW per CM |
| Plasma thermal power | 56.7 MW for divertor<br>1.6 MW per CM |
| Peak heat flux density in normal operation | ≤ 10 MW/m² (targets)<br>≤ 5 MW/m² (baffle)<br>≤ 1 MW/m² (dome)<br>≤ 1 MW/m² (RPs) |

Therefore, no slow or short transient peak heat fluxes on the targets are specified.

## 4. Thermal simulation and analysis

The main constraint for the design of the hydraulic cooling circuit is the lack of available space for the welding and re-welding process of the CM inlet and outlet feeding pipes in the LWP, which are connected to the primary heat transfer system. In total six DN50 pipes are placed in each LWP. Fig. 4 schematically shows the resulting hydraulic organization of the CM cooling circuit. The CB distributes cooling between PFCs.

This arrangement defines three groups of PFCs: IVT, OVT, Dome + RPs. The advantage is the theoretical possibility to remove these groups independently of one another in case of maintenance activities.

The selected structural material for the CB, manifolds and pipes is 316Ti [11], which is presently considered as the most reasonable choice due to the level of damage above 20 dpa expected to be experienced in this facility [12].

The PFCs are divided into individual plasma facing units (PFUs). The PFUs of the targets are armored with pure tungsten monoblocs bonded onto a cooling pipe made of CuCrZr with an inserted twisted tape in the straight part. The PFUs of the dome are made up with pure tungsten flat tiles bonded onto a CuCrZr hypervapotron cooling structure [13]. Fig. 5 shows the PFCs only and the number of PFUs by component.

Each set of PFUs is cooled in parallel. Table 2 presents the water-cooling parameters.

The tungsten thickness is selected to reach a maximal surface temperature ≤1000 °C for specified heat fluxes to provide a sufficient margin against tungsten recrystallization. At this conceptual design stage, the final front armor thickness of W-PFC is not fully fixed. In the next stage, chamfering issues [11] and sputtering effects due to fast particles are planned to be integrated in the design.

Preliminary results of CFD analyses are presented in Figs. 6 and 7. Fig. 6 shows several regions with too high local velocity in some connection pipes responsible for high pressure drop. These locations are identified, and these issues can be easily solved. The calculation confirms an adequate coolant distribution among PFCs and sufficient margin to CHF.

## 5. Neutronic simulations

The divertor is exposed to fast neutrons from the plasma core. The high level of neutron flux generates nuclear heating and gamma ray emission. The produced stationary heat is removed by active water cooling. One of the features of the divertor is to reduce the impact of neutrons and gamma on the components beyond such as the VV and magnet systems. The most critical locations are apertures and in particular the pumping channel in the CB and the LWP.

The simulations are related to the strategy of the divertor maintenance. CMs are not repaired in situ in the VV and are transported by dedicated cask to the Active Maintenance Facility. Moving and re-installing CMs means organizing the first action of cutting and re-

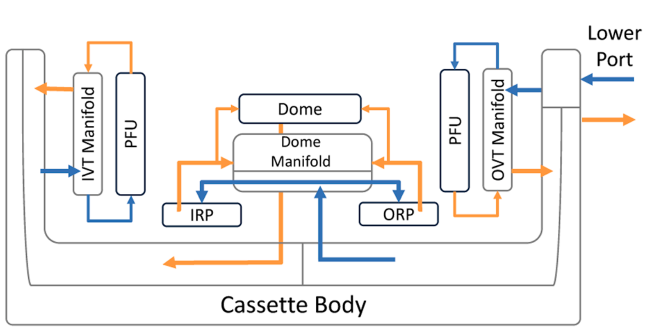


**Fig. 4.** Schematic hydraulic arrangement of one CM.

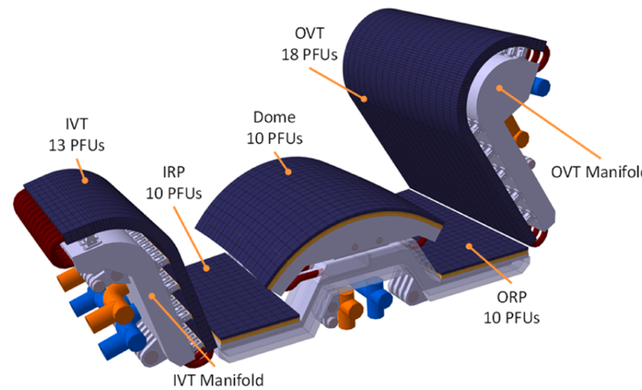


**Fig. 5.** CAD view of PFCs only.

**Table 2**
Water-cooling conditions.

| Parameter | Specified Values |
|---|---|
| Flow rate / CM | 11.3 kg/s |
| Total flow rate for divertor | 410 kg/s |
| Inlet temperature | 50 °C |
| Temperature increase / CM | 35 |
| Inlet pressure | 3.5 MPa |
| Pressure drop / CM | 1.1 |

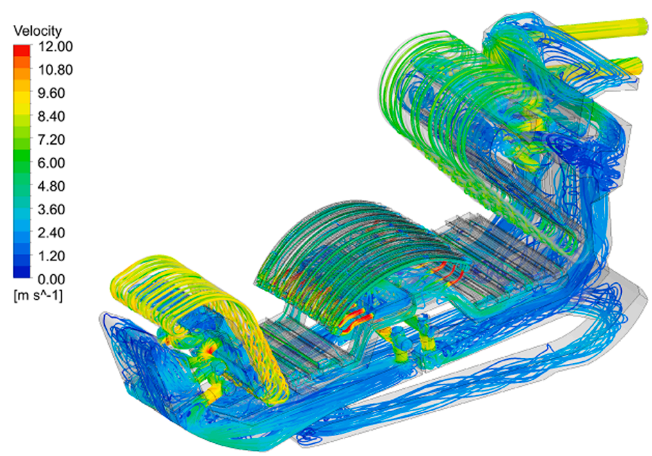


**Fig. 6.** CFD calculations – Velocity distribution.

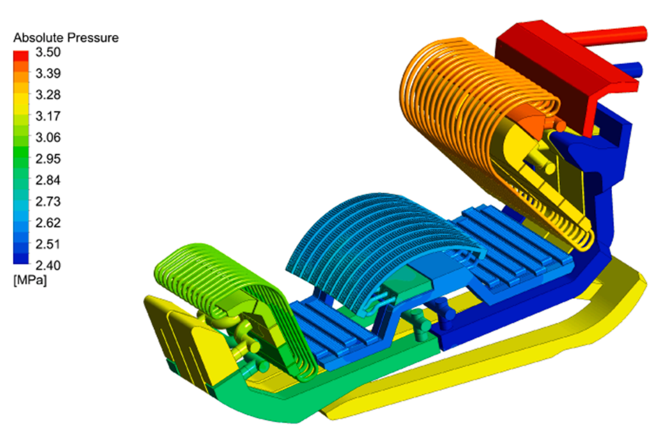


**Fig. 7.** CFD calculations – Pressure distribution.

welding feeding pipes in the LWP.

The identified issue is the accumulation of He content at the foreseen location of rewelding pipes. Beyond a certain limit, which is a function of the pipe material, this work becomes impossible due to swelling and He content.

Despite quality controls, some PFCs might show some defects (for instance, lack of bonding of target monoblocs) detected during the commissioning phase without irradiation. In these conditions, welding activities are not affected. Once irradiation operation starts, the maintenance is managed with remote maintenance tools. A good illustration of the impact of neutronics simulations on the design is the analysis of the re-welding situation at the location of the LWP. Fig. 8 presents the main results of these simulations [14]. The selected conservative He limit for re-welding is 1 appm/FPY [15].

To reach acceptable values, the design of the CB needed to be adapted, as shown in Fig. 9.

The reduction of He in the upper pipe is the combination of (1) an adaptation of the top outboard shape of the CB to form a labyrinth together with the counterpart of the outboard shielding and (2) an integration of a W-block to reduce neutron impact. Another issue is the required shielding protection of the pumping channel of the CB oriented to the LWP. The difficulty was the W-integration compatible with cooling circuit scheme. A W-block is added at the bottom of the CB. In addition, plasma loads on the IRP and ORP could be easily withstood with coated W-pipe.

## 6. Conclusion

The present status of the conceptual divertor design carried out in the frame of the VNS feasibility study is summarized. The design is an adaptation of the ITER design to VNS operating conditions. The multiple preliminary analyses (electro-magnetic, gas exhaust for pumping neutronics, physics, structural, thermal-hydraulic) performed by the different European institutes participating to EUROfusion confirmed that the proposed divertor conceptual design fulfills the VNS requirements. The envisaged operation generates local plasma heat flux densities compatible with existing technological conditions. A new approach is proposed with the integration of W-blocks at different locations to increase the divertor shielding performance (by increasing the W-volume) to better protect the LWP. This study allowed the identification of the rewelding feeding pipes in the LWP as critical for the divertor maintenance. In addition to its main goal focus on the breeding blanket, VNS is an opportunity to validate technological solutions of the divertor (e.g. assemblies in addition to IFMIF-DONES) as well as maintenance tools in the same environment as breeding blankets representative of a future fusion power plant.

## CRediT authorship contribution statement

**J. Boscary:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **P. Vinoni:** Visualization, Software, Formal analysis, Methodology, Writing – review & editing. **D. Marzullo:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **A. Quartararo:** Writing – review & editing, Validation, Software, Formal analysis, Methodology, Visualization. **A. Cufar:** Software, Formal analysis, Visualization. **S. Renard:** Software, Resources. **M. Kannamüller:** Visualization, Software. **S. Wiesen:** Software, Formal analysis, Methodology. **G. Aiello:** Formal analysis. **C. Bachmann:** Supervision, Project administration, Conceptualization, Funding acquisition, Methodology. **D. Leichtle:** Formal analysis, Data curation, Resources. **P. Gallina:** Project administration. **R. Neu:** Project administration.

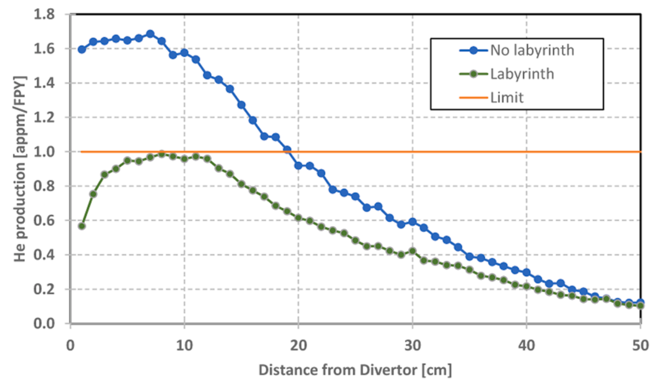


**Fig. 8.** Evolution of He production along the upper feeding pipe of the CM. 0 cm refers to the CB backside. Rewelding location is foreseen between 5 and 10 cm.

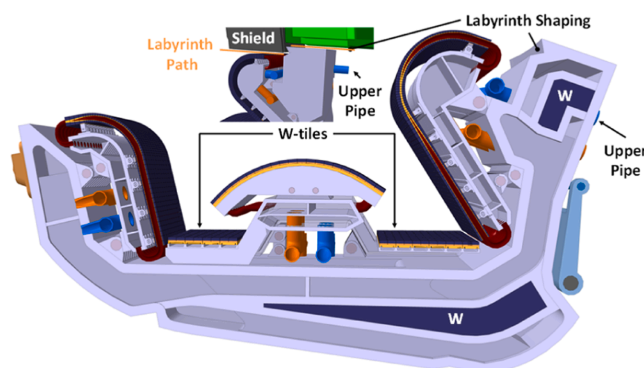


**Fig. 9.** Integration of W-volume to improve n-shielding.

## 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.

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## Data availability

Data will be made available on request.

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