Preliminary engineering assessment of alternative magnetic divertor configurations for EU-DEMO

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A R T I C L E I N F O

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A B S T R A C T

One of the main challenges in the roadmap to the realization of fusion energy is to develop a heat and power exhaust system able to withstand the large loads expected in the divertor of a fusion power plant. The challenge of reducing the heat load on the divertor targets is addressed, within the mission 2 ‘Heat-exhaust systems’, through the investigation of divertor configurations alternative to the standard Single Null (SN), such as the Snowflake (SF), Double Null (DN), X and Super-X (SX) divertors. This paper focuses on a preliminary engineering assessment of the alternative configurations proposed for the EU DEMO reactor. Starting from the description of the optimized plasma shape developed for each configuration, the 3D geometrical description of the Magnet System and of the main Mechanical Structures (Vacuum Vessel and in-vessel components) is presented. Based on the 3D geometry, the compatibility of the location and dimensions of ports with Remote Maintenance needs is discussed and possible design optimizations are proposed both for the Magnets system and the mechanical structures design. Finally, the various configurations are compared with regard to the engineering and feasibility aspects.

1. Introduction

One of the main challenges in the European roadmap to the realization of fusion energy [1] is to develop a heat and power exhaust system able to withstand the large loads expected in the divertor of a fusion power plant. The Mission 2 ‘Heat-exhaust systems’ focuses on the investigation of Alternative Divertor Configurations (ADCs) such as the Double Null (DN), the SnowFlake (SF), the X (XD) and super-X (SX) divertors as a reliable solution for the power exhaust problem [2]. The current DEMO reactor scenario foresees, as for the ITER plasma shape, a single null magnetic configuration. This is characterized by a single point of null of the magnetic field, consequently the high heat flux from plasma, as well as the high particle and neutron fluence, strike on two divertor vertical targets, which shall be able to exhaust the related high power. ADCs might be beneficial in terms of detachment onset, window and stability, allowing lower separatrix densities and less impurities in the plasma core. They are also studied to offer more flexibility during off-normal events and passive stabilization mechanisms.

Several divertor configuration concepts have been studied as alternatives to the conventional divertor, among which the configurations discussed in this work are the ones relying on the same physics basis as the baseline DEMO Single Null (SN) [3]. Within the EUROfusion Work Package DTT1/ADC, first assessment of possible alterative configurations, discussed in [3], focused mainly on the plasma-physics and plasma-control of ADCs, adopting as reference DEMO SN the baseline configuration developed in 2015 [4].

In the framework of the same EUROfusion workpackage, this paper presents the last activities performed for the alignment of the alternative machine geometries and configurations to the DEMO reference Single Null baseline 2017 [5]. It focuses on the geometrical design and first engineering assessment of the mechanical structures for alternative configurations. According to Systems Engineering principles [6], the requirements for the conceptual design have been defined and an iterative optimization procedure based on parametric CAD models has been assumed for design development. In the next section the design procedure and the design requirements are presented, while Section 3

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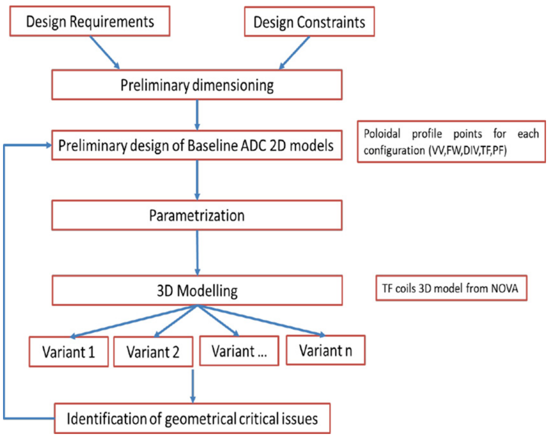

Fig. 1. Design procedure.

discusses the first design iteration for the mechanical structure of DN, SX, SF, and XD, highlighting main design criticisms and giving the inputs for the next design iteration.

2. Problem definition and design procedures

The definition of the ADCs and their geometrical design have been developed according to an iterative optimization procedure, shown in Fig. 1.

Starting from the main design requirements and constraints (described in Section 2.1), preliminary dimensioning is performed and the poloidal profiles of plasma shape, Toroidal Field coils (TF), Poloidal Field coils (PF), Vacuum Vessel (VV), First Wall (FW) and divertor are generated. Basing on these profiles, 2D design is modelled in parametric CAD software and the main design parameters affecting the geometrical definition of the structures are introduced. This parametrization allows for a parametric associative 3D modelling methodology, which gives the possibility to generate possible geometrical variants for each configuration to be assessed from geometrical and structural point of view. Where critical issues are identified, the new 2D geometries are produced and the process restarts iteratively.

2.1. Design requirements and constraints

The design requirements for the 3D building of the mechanical structures come mainly from the 2D optimized geometries developed for plasma control using CREATE_NL software [7] (for plasma shapes and PF coils) and NOVA code [8] (for TF, VV, FW and divertor). These shapes are generated to optimize the alternative configuration respecting the main parameters of the DEMO baseline SN configuration, as it is assumed as the starting point for the development of the ADCs. With respect to the previous version published in [3], this work starts from new 2D geometries generated to align the ADC machine geometries and configurations to the DEMO Single Null baseline 2017 [5].

The most significant variations of the DEMO 2017 SN baseline respect to the 2014 SN baseline were related to:

- a reduction of the TF coils from 18 to 16 with a consequent increase of the TF radial dimension (due to the maximum ripple constraint)
- increase of the reference elongation from k (95%) = 1.55 to k (95%) = 1.65
- increase of the machine major radius from $R = 8.76\,\mathrm{m}$ to $R = 8.94\,\mathrm{m}$

The DEMO SN baseline 2017 have been realized assuming an aspect ratio of 3.1. The 2D and the 3D geometries of the DEMO SN baseline are shown in Fig. 2.

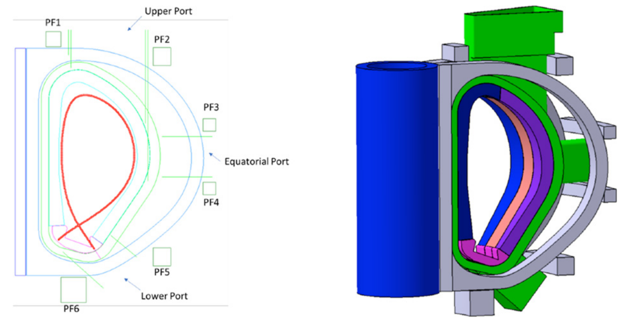

Fig. 2. DEMO Single Null baseline 2017.

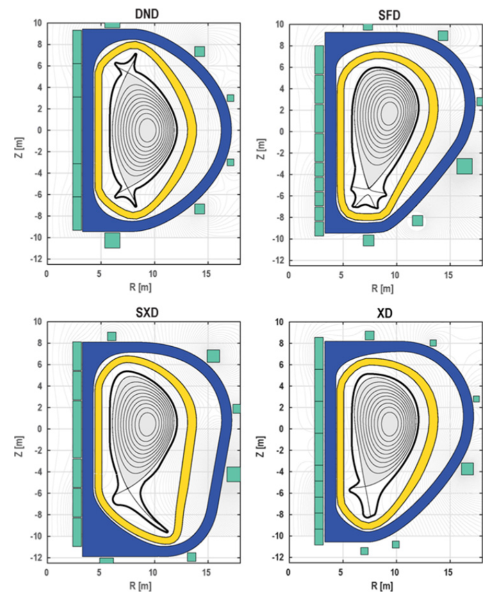

Fig. 3. ADCs 2D geometries form NOVA.

The alternative configurations are designed with the same major radius, aspect ratio, elongation and at the same plasma current parameters as the reference single null. The resulting preliminary 2D geometries from NOVA optimization code are shown in Fig. 3.

Assuming these profiles as design requirements (2D shapes) to be fulfilled, the 3D design activities are carried on considering the main high-level requirements affecting the mechanical structures. While the poloidal profile of the VV is required to be consistent as much as possible with the 2D shapes generated from NOVA, the main design constraint affecting the development of the 3D design of ADCs are the position of the PF coils and the dimensions of the TF coils, since ports allocation and dimensioning are bound to them. On the other side, the ports are affecting the maximum dimension of the in-vessel components to be replaced through the lower port (divertor) the vertical and the equatorial port (blanket), so they become the main constraint for the in-vessel components segmentation. Ports dimension shall also consider the need of Outer Intercoil Structures (OIS – see Fig.7), which shall be dimensioned so that the TF coil system will be able to withstand the out-of-plane loads.

The general DEMO plant requirements [9] are assumed as reference requirements also for the development of the ADCs geometries. In particular, the remote maintenance (RM) scheme shall foresee the minimum number of replacements of the in-vessel components to maximize the plant availability. This means that the segmentation of the in-vessel component shall be minimized, aiming, as for the DEMO baseline RM scheme, to replace three divertor per lower port and five blanket segments per upper port (3 outboard and 2 inboard segment per sector) [10].

Starting for the described requirements and constraints, the baseline CAD models for each ADCs tokamak machine have been developed, as described in next section.

3. Alternative divertor configurations. 3D design

Starting from points given by 2D geometries and requirements presented in Section 2, poloidal profiles relative to the DN, the SF, the SX and the XD configurations have been obtained as reference to develop four baseline 3D models. Each model is made up by following components:

- Vacuum Vessel shells and ports
- First Wall and divertor (obtained by the same set of point)
- Toroidal Field Coils
- Poloidal Field Coils

The 3D design activities have been developed according to the Systems Engineering principles. As designed and parametrized, the 3D CAD models developed are useful as first "master concept model" (see [11]) to be used for further analyses and shape optimization in the next design iterations.

3.1. TF coils modelling

For all the configurations, the 3D TF coil geometry was output automatically from NOVA, including:

- TF Casing
- Winding Pack
- Intercoil Structures (combined with the casing)

The TF casing was generated from the 2D layout defined by CREATE_NL code, while the 3D dimensions were taken from the process run [14]. The winding pack was split into graded sections as detailed in [15].

Preliminary analysis of the coils showed that the inter-coil structure had a large influence on the stress results vs. the length optimized TF geometries generated in NOVA. The preliminary analysis concluded:

- The outer intercoil structure should be maximized in length and thickness in order to stiffen the system against out of plane loading
- The inner intercoil structure should maximize the contact between the TF coils to distribute the radial compressive loads
- There is a minor reduction in stress by moving the outer intercoil structures towards the plasma

These conclusions resulted in further analysis focused on maximizing the inner and outer intercoil structures with the positions being governed by the PF coil positions. The minor reduction in the stress shown by moving the outer intercoil structure towards the plasma was not included due to potential manufacturing difficulties and the outer intercoil structures remained at the center of the casing in the 2D plane. The thickness of the outer intercoil structure was limited to 0.2 m, basing on the technological issues related to weldability and assembly operations.

3.2. Double null configuration

The Double Null configuration is an up-down symmetric configuration presenting X-points at the top and bottom and corresponding divertors [16]. Consistently, up-down symmetric geometries have been developed. The 3D design of a single 22.5° sector is shown in Fig. 4.

The lower X-point location and volumes are similar to the SN configuration, so the resulting divertor design closely matches the SN divertor [12,13], in terms of distances of the vertical targets from the X point, grazing angle and poloidal incidence angle.

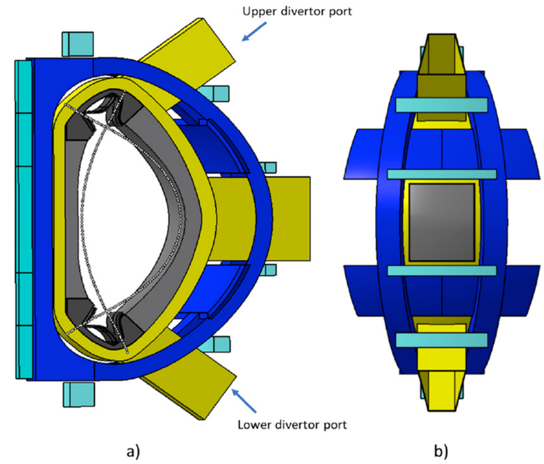

Fig. 4. DN configuration. a) Poloidal plane view, b) radial view.

The VV ports have been designed considering minimum clearances with TF, PF and inter-coil structures. The results are a lower and an upper port sized to allow for the replacement of respectively the lower and the upper divertor. Six divertor cassette (3 upper and 3 lower) per sector are foreseen and their poloidal profile is designed to support vertical target, allow for vacuum pumping (through the same divertor ports) and Remote Handling (RH) replacement. The equatorial port is needed to allow for blanket replacement. This will require detailed studies for blanket segmentation in next design iteration. Fig. 5 shows a poloidal cross section with main VV dimensions (a), the dimensions of equatorial (b) and the dimensions of the divertor ports (c).

3.3. Super-X configuration

The super-X configuration is generated increasing the major radius of the divertor targets, in order to increase the total flux expansion towards the target [17]. The main constraint to the divertor target radius is represented by the curvature in the divertor region of the toroidal field coils. Fig. 6 shows the 3D design of a single 22.5° sector.

As shown in the poloidal cross section (Fig. 6a), the outer divertor target is located at the higher possible radius consistently with the TF coil geometries and the minimum thickness required for VV. This reduces the space for the divertor cassette in the outer strike point area and, on the other hand, results in a bigger divertor poloidal profile. Fig. 6a shows how the cassette thickness in the outboard area is quite small (~ 300 mm) to accommodate vertical target, cooled cassette body

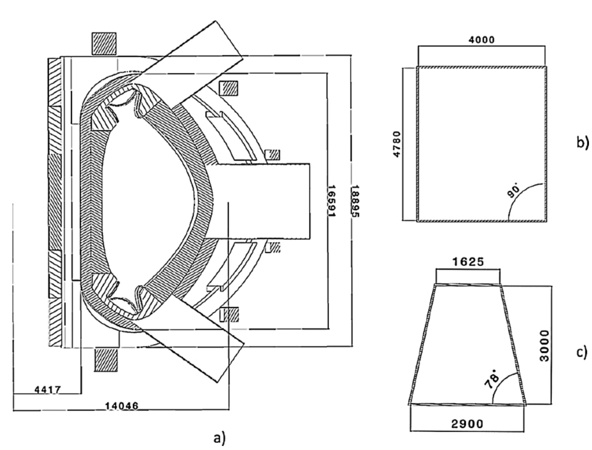

Fig. 5. Overall dimensions of DN configuration. a) VV and TF overall dimensions, b) equatorial port dimensions, c) divertor ports dimensions. (dimensions are in mm).

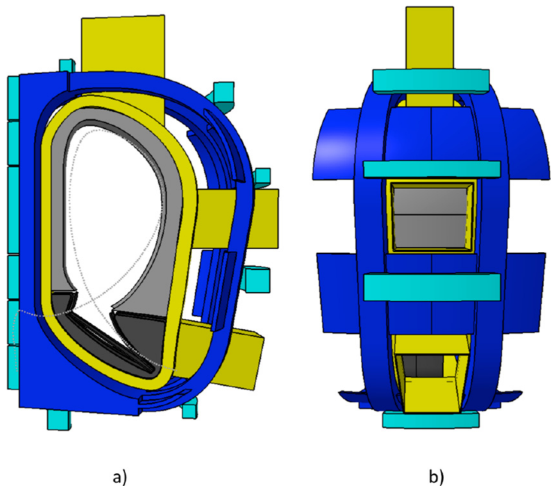

Fig. 6. SX configuration. a) Poloidal plane view, b) radial view.

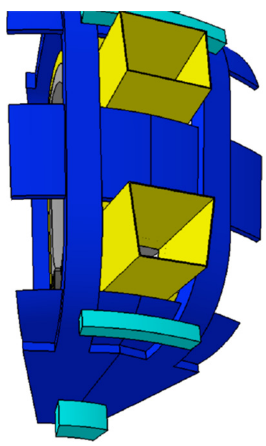

Fig. 7. Outer intercoil structure in the divertor area.

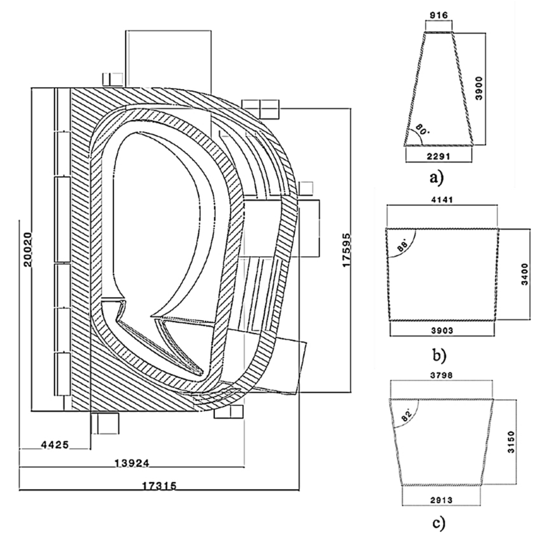

Fig. 8. Overall dimensions of SX configuration. VV and TF overall dimensions, a) upper port dimensions, b) equatorial port dimensions, c) lower port dimensions. (dimensions are in mm).

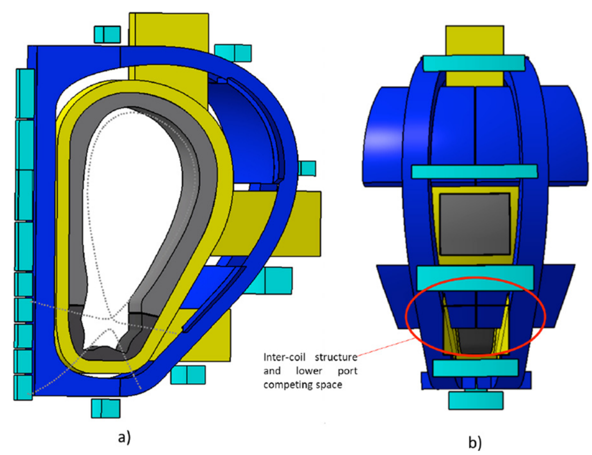

Fig. 9. SF configuration. a) Poloidal plane view, b) radial view.

and appropriate RH interface. As input for next design iteration, to avoid this subject, the VV shape should be changed at the outboard in order to get more space for divertor. This would allow also the design of proper cassette-to-VV fixation system (and relative toroidal rails) to be assessed for divertor RH compatibility.

As for the DND configuration, VV ports have been designed considering minimum clearances with PFs, TFs and outer inter-coil structures. The divertor lower port results too small compared with the divertor poloidal dimensions. This does not allow, in the first iteration design, for divertor replacement through this port. The design parameters identified to be optimized in the design process are the poloidal dimension of the inter-coil structure between equatorial and lower port and the possible reduction of the divertor poloidal profile. Fig. 8 shows a poloidal cross section with main VV dimensions (a) and the dimensions of ports (upper (a) equatorial (b) and lower (c)).

3.4. SnowFlake configuration

The snowflake divertor concept is based on a second order null point [18]. This splits the separatrix around the null into six legs with two enclosing the confined plasma and four divertor legs [3]. Fig. 9 shows the 3D design of a single 22.5° sector.

For the SF configuration there are two competing requirements affecting the design for the lower port. The first one requires a bigger divertor to accommodate the four targets, while the second one foresees a smaller space between PF5 and PF6. For this reason, a horizontal lower port for divertor remote handling could represent a good solution, if allowed by the inter-coil structures. Currently, considering the inter-coil structures generated for TF toroidal loads from NOVA, the inter-coil structure between PF4 and PF5 does not allow for a reasonable horizontal lower port dimension. Two possible corrective actions have been identified for next design iteration:

- reduce intercoil structures between PF4 and PF5 by ~1000 mm poloidally. In order to compensate such reduction an additional intercoil structure could be added between PF5 and PF6.
- Investigate the possibility to have the four divertor targets to be replaced independently each other, the two upper through the equatorial port and the two lower through the lower port. This solution would help maintaining a bigger inter-coil structure between PF4 and PF5, but it will reduce the plant availability since the divertor replacement will result more time-consuming. It shall be carefully evaluated considering the potential Full Power Year operation capability (FPY) of each target.

The upper port results suitable to blanket removal with the same scheme of the DEMO reference SN baseline. Fig. 10 shows a poloidal cross section with main VV dimensions and port dimensions

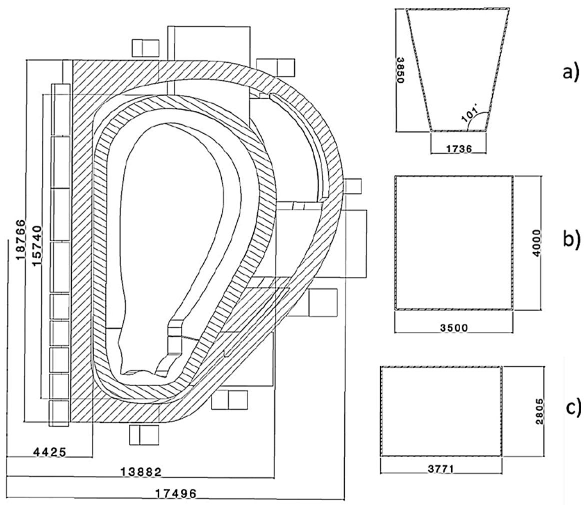

Fig. 10. Overall dimensions of SF configuration. VV and TF overall dimensions, a) upper port dimensions, b) equatorial port dimensions, c) lower port dimensions. (dimensions are in mm).

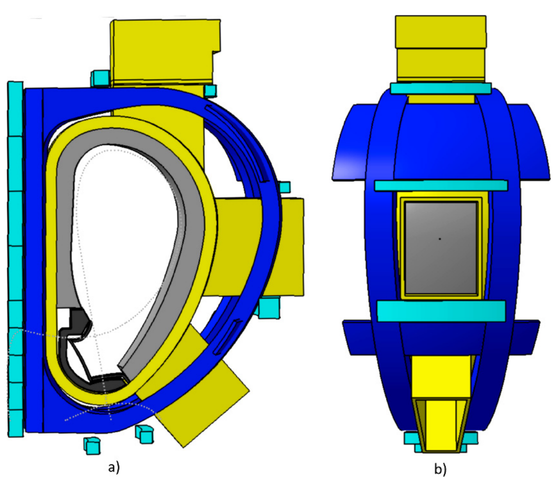

Fig. 11. XD configuration. a) Poloidal plane view, b) radial view.

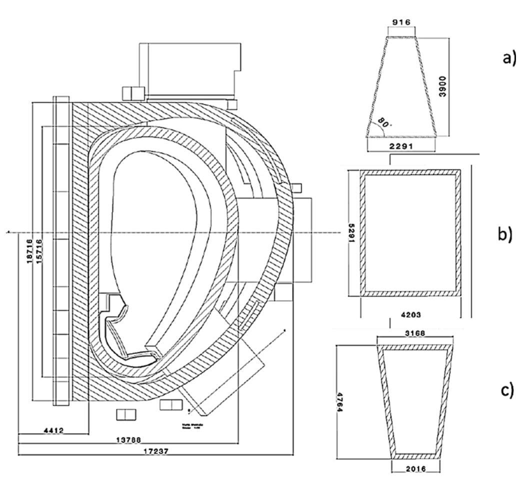

Fig. 12. Overall dimensions of XD configuration. VV and TF overall dimensions, a) upper port dimensions, b) equatorial port dimensions, c) lower port dimensions. (dimensions are in mm).

3.5. X divertor

The X divertor (XD) concept [19] relies on a flaring of flux surfaces near the divertor targets. Fig. 11 shows the 3D design of a single 22.5° sector.

The design process has been carried on basing on the same considerations of the configurations previously described. As for SF and SX configurations the upper port allows for blanket RH with same scheme of DEMO SN baseline configuration. The divertor presents general dimension similar to the SN baseline and the lower divertor ports dose not presents main criticism for divertor replacement. Overall dimension and ports profiles are shown in Fig. 12.

4. Conclusion

In this paper the design procedures and first 3D building of the Alternative Divertor Configurations studied for pawer exhaust in DEMO are presented. Following Systems Engineering principles, an iterative design optimization procedure as been assumed. In this work the first mechanical design iteration is presented, highlighting the main design criticisms and the inputs for the next design iterations. According to the DEMO SN baseline configuration model, first 3D configuration models for DN, SX, SF and XD are presented. The design activities focused mainly on the compatibility of VV and in-vessel components design with RH requirements. While the DN requires a different RH scheme for blanket than the DEMO SN reference baseline (removal through the equatorial port instead of upper port), the SX, the SF, and XD configurations can allow similar RH scheme, even if ports and divertor dimensions requires further review in next design iteration, competing mainly with PF location and OIS dimensions.

CRediT authorship contribution statement

Domenico Marzullo: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Roberto Ambrosino:** Conceptualization, Writing - review & editing, Project administration, Supervision, Funding acquisition. **Antonio Castaldo:** Conceptualization, Methodology, Writing - review & editing. **Giuseppe Di Gironimo:** Visualization, Project administration. **Samuel Merriman:** Methodology, Writing - review & editing.

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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