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Feasibility study of the DEMO divertor target baffles

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ABSTRACT

The divertor is one of the key components of a Tokamak fusion machine since it must be capable to exhaust both particles and power. Since the CAD model has been released the DEMO Outboard Vertical Target baffles (OVT) represent one of the most challenging components both from the design and fabrication technology point of view. It is infact exposed to intense neutron damage and high heat fluxes and has a very narrow radius of curvature (around 100mm compared to the radius of 500mm of ITER ones). Within the Work Package Divertor (WP-DIV 2021-2027) the EUROfusion Consortium launched a dedicated R&D task to explore the fabrication of the component itself. ENEA that is involved in the R&D technology activities of the target PFCs for the WP-DIV will study two alternative joining technologies with the aim to design and manufacture a mock-up made by a curved CuCrZr cooling pipe and Tungsten monoblocks joined to the pipe itself. The first technology is the well assessed Hot Radial Pressing (HRP) while the second one will be the brazing through an interlayer material between the pipe and the monoblocks. This paper reports the results of both joining technologies by means of Non-Destructive Examinations (Ultrasonic Testing) to give preliminary feedback on a suitable and industrially scalable manufacturing process.

1. Introduction, objectives, and methodology

This paper reports the manufacturing activities performed in the ENEA-Frascati laboratories to explore the fabricability of the EU-DEMO Outer Vertical Target baffles (OVT).

The reference design of the plasma facing units of the DEMO divertor is a ITER-like design having a CuCrZr cooling pipe (OD: 15mm - ID:12mm) covered with Tungsten (W) monoblock joined to the pipe by means of an OFE-Cu 1 mm thick interlayer [1]. This design has been verified for the high thermal loads expected in fusion reactor divertor through intensive experimental campaigns in linear devices with electronic, ion or plasma sources and the suitable fabrication processes for both diffusion [2] and brazing [3] manufacturing processes have been qualified in the framework of the qualification activities for the ITER divertor production.

However, the poloidal profile of the EU-DEMO divertor unit requires a very tight baffle curvature radius; while the ITER curvature radius is about 500 mm, in EU-DEMO the radius is much smaller, and, for the OVT baffle, reaches 107 mm (at the tube axis). A verification of the applicability of the developed production processes even in the case of so tight radius of curvature has become necessary and ENEA, that is involved in the R&D technology activities of the target PFCs for the WP-DIV [4], studied two alternative joining technologies with the aim to qualify manufacturing processes of plasma facing units with: diffusion bonding by Hot Radial Pressing (HRP) and brazing with GEMCO as brazing alloy.

The activities has been carried out by the following steps:

- development of a detailed CAD drawing considering the gap requirements for joining and for assembly of the components;
- mock-up preparation:
  - pipe bending;
  - monoblocks procurements;
  - design and fabrication of the brazing tools;
  - welding process;
- fabrication of 1 dummy mock-up by HRP to assess the main aspects of the manufacturing process, like the thermal cycle in the oven, the high pressure equipment and the internal tooling;
- manufacturing of 1 mock-up by HRP;
- manufacturing of 1 mock-up by Brazing;

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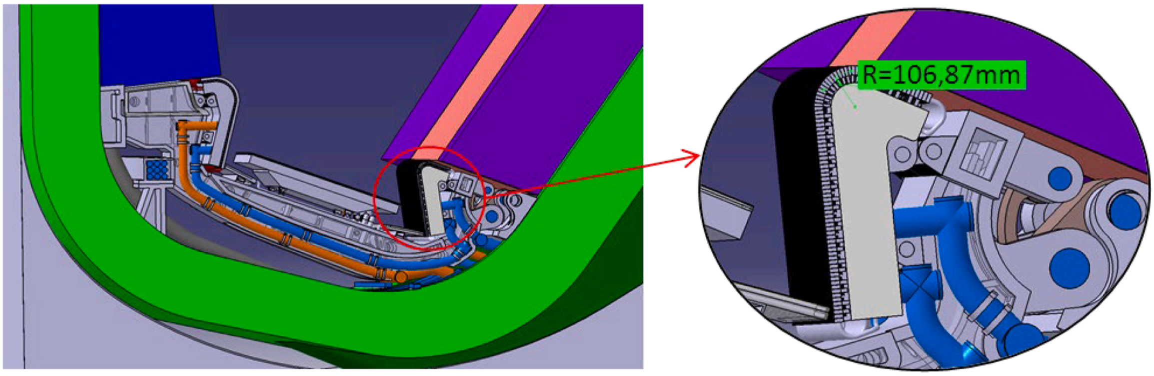


Fig. 1. DEMO CAD design (2022) showing bending radius value for the OVT baffle.

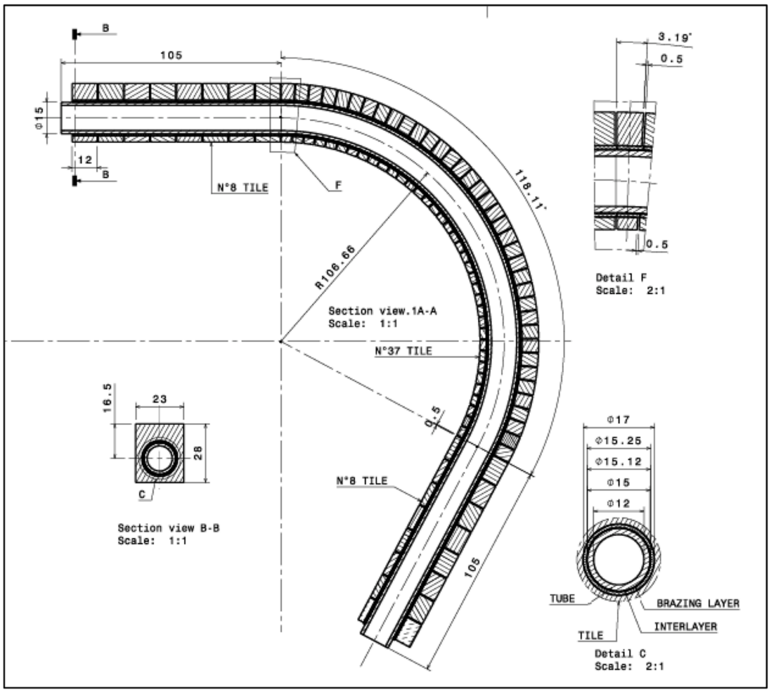


Fig. 2. ENEA design of the OVT baffle for assembly and manufacturing.

- mock-up examination by performing non-destructive examinations: Ultrasonic Testing (UT), to evaluate the joining quality and dimensional check to verify the achieved tolerances.

2. Modelling of the system

DEMO CAD model and OVT baffle design.

The CAD model of the EU-DEMO divertor used as starting point is the conceptual design developed in 2022 [5] and showed in Fig. 1. In this model the bending curvature radius for IVT baffle is 223.9mm while for the OVT baffle is 106.8mm.

The feasibility study of the DEMO Divertor target baffle started with the engineering of the conceptual design (see Fig. 2) of the baffle targets taking into account the followed geometrical constraints:

- plasma facing surface preserved;
- respect of the distance between the tube axis and monoblocks upper surface;
- monoblock hole diameter: 17mm;
- cooling pipe: O.D. 15mm;
- interlayer between W monoblocks and pipe: about 1 mm (ITER-like)
- Gap between monoblocks in the axial direction 0.5mm at the plasma side.

Fig. 2 shows an overall view of the result obtained where it can be clearly observed that in the curved area of the baffle the axial dimension of the monoblock has been reduced to respect the straight one. Furthermore, as can be observed in detail F the axially opposite faces of the monoblock are not parallel to each other. In fact, in the ITER baffle the maximum gap between each monoblock at the plasma side is 1.2 mm but, even using this value in the DEMO baffle the monoblock faces would be in interference in the opposite side. Therefore, the monoblock faces were designed not parallel in the same monoblock, but parallel between a monoblock and the adjacent one of the followed monoblock resulting in a uniform gap fixed at 0.5mm.

The choice of the axial width of the monoblock does not only derive from design requirements, but also from technological constraints as the need to assemble the monoblocks on the curved tube before the joining process. The dimensions of the monoblock that can be acted upon to allow the assembly of the monoblocks on the curved pipe are the axial width and the diameter of the hole of the monoblock. A reduced width and a large hole diameter facilitate assembly, but, on the other hand, a

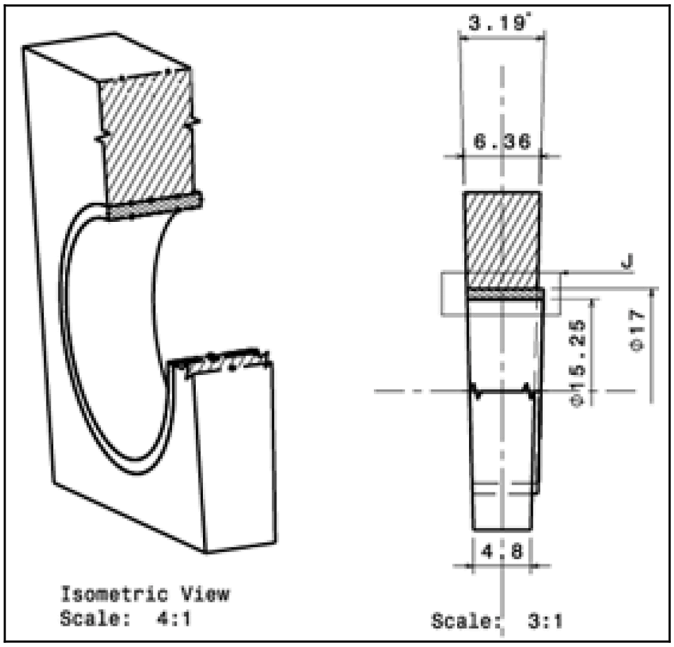


Fig. 3. ENEA Technical drawing for the manufacturing of the monoblocks.

reduced axial dimension increases the number of monoblocks and therefore the number of gaps which represent a danger for possible overloads on the monoblock edges due to the plasma incidence, and a too large hole diameter determines a gap between the surfaces to be joined that may not be recovered during the process and that is responsible for shrinkage stress during cooling down.

The technical drawing for the monoblock procurement was therefore done taking in to account these aspects: Fig. 3 shows the one for the application by brazing.

3. Material procurement and qualification activities

A batch of 100 W monoblocks with the Cu interlayer has been procured from the Chinese company AT&M. A batch of 10 ELBRODUR Type HF (CuCr1Zr, delivered in the solution annealed+water quenched condition) pipes has been curved from the Italian company Nuova Saccem s. r.l. (ENEA supplied the straight pipes realized from the Germany company KM EUROPE Metal AG): the pipe bending activities started with one prototype-tube and then with three bending tests to reach the as per drawing radius of curvature (~107mm), trying to avoid ovalization and to preserve the 12mm inner radius. In order to avoid deterioration of the mechanical properties of the CuCrZr pipes, the bending process has been done cold.

3.1. *CuCrZr pipe bending and dimensional check*

The main obstacle to fabricate this component is the tight curvature radius, in fact the first issue is represented by bending the CuCrZr pipe: the bending process must keep the inner/outer diameter and follow the desired curvature.

The CuCrZr alloy has been chosen as heat sink pipe because it has high mechanical properties (high ultimate tensile strength and high yielding strength) and good thermal conductivity. This high mechanical strength (that must be preserved) makes difficult to bend the tube itself, causing the tube to ovalize during bending. The ovalization of the pipe is a threat both for the assembly phase and for the bonding process. The pipe ovalization increases locally the gap between the pipe and the internal hole in the monoblocks being able to prevent the assembly or producing high residual stresses during the cooling phase after the bonding process promoting the onset of detachments. The process used to bend the straight pipes was the cold bending to keep the high mechanical properties of the CuCrZr. Since the baffle has a very narrow bending radius, in agreement with the supplier at first a dummy-tube was bent and then a trial on three additional pipes was performed to improve the bending tools and to reach the drawing values. At the end of this R&D fase, 10 bended pipes were supplied.

The first dummy-tube showed high ovalization that did not allow to assembly the monoblocks and large shift from the designed curvature.

The next three bent pipes sent to the ENEA laboratory were measured using the centesimal Caliper Mitutoyo Absolute.

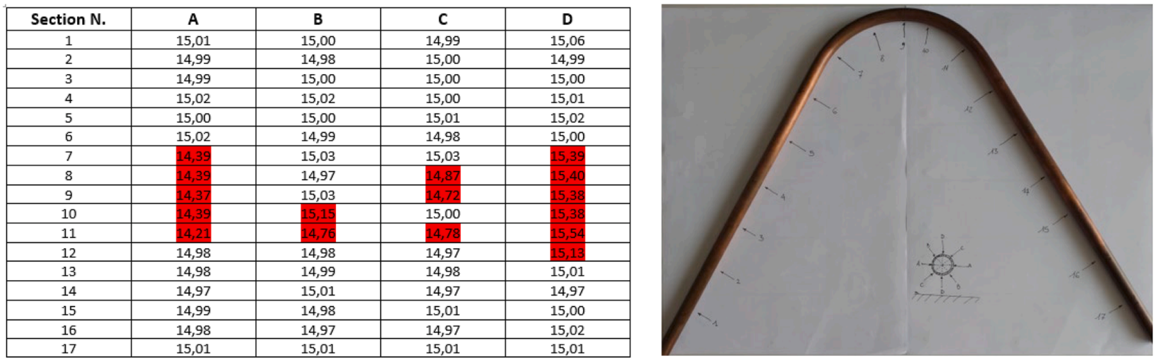
The sections to be analyzed have been identified and are indicated with increasing numbers along the axis pipe. The pipe diameter at each section has been measured along 4 directions (i.e. A, B, C, D).

The nominal diameter of 15mm ± 0.2 was verified along the straight part while in the curved area a marked ovalization has been measured varying from 14.21mm to 15.54mm (see Fig. 4, red colours highlight measures out of tolerance).

The other three trial pipes followed more precisely the curvature of the pipe even if they still showed ovalization in the curvature area (a shrinkage was noted in the horizontal plane with the tube that tends to assume an elliptical geometry with the major axis in the vertical).

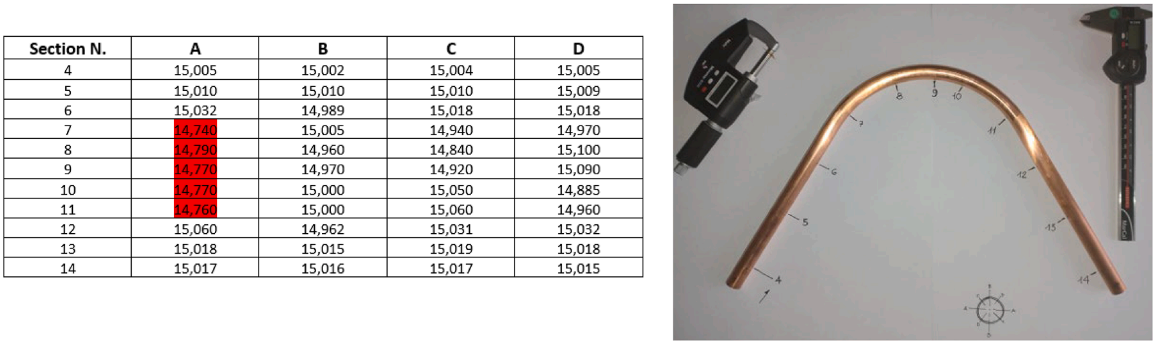
On the final batch supplied (10 pipes) the measurements were performed using a Micrometer in the straight area and a Caliper in the curved one. The measurements performed on 14 sections and still along 4 directions showed that the pipe in the straight area is in the tolerance of the nominal diameter (15mm ± 0.2) and it is strongly improved in the curved area even if it still shows ovalization (below the results of the pipe used for the HRP with red colours that highlight measures out of tolerance, see Fig. 5).

The results showed a shrinkage at the curved area on the horizontal plane, in this zone the pipe has an elliptical geometry with the major axis in the vertical while in the transition between the straight pipe and the curved one the major axis tends to go on the horizontal plane. The



Section N.	A	B	C	D
1	15,01	15,00	14,99	15,06
2	14,99	14,98	15,00	14,99
3	14,99	15,00	15,00	15,00
4	15,02	15,02	15,00	15,01
5	15,00	15,00	15,01	15,02
6	15,02	14,99	14,98	15,00
7	14,39	15,03	15,03	15,39
8	14,39	14,97	14,87	15,40
9	14,37	15,03	14,72	15,38
10	14,39	15,15	15,00	15,38
11	14,21	14,76	14,78	15,54
12	14,98	14,98	14,97	15,13
13	14,98	14,99	14,98	15,01
14	14,97	15,01	14,97	14,97
15	14,99	14,98	15,01	15,00
16	14,98	14,97	14,97	15,02
17	15,01	15,01	15,01	15,01

Fig. 4. Measurements of the diameter using the caliper (it is defined as limit deviation for fine tolerance the value ± 0.10 as per "General Tolerance Table generali ISO 2768").



Section N.	A	B	C	D
4	15,005	15,002	15,004	15,005
5	15,010	15,010	15,010	15,009
6	15,032	14,989	15,018	15,018
7	14,740	15,005	14,940	14,970
8	14,790	14,960	14,840	15,100
9	14,770	14,970	14,920	15,090
10	14,770	15,000	15,050	14,885
11	14,760	15,000	15,060	14,960
12	15,060	14,962	15,031	15,032
13	15,018	15,015	15,019	15,018
14	15,017	15,016	15,017	15,015

Fig. 5. Measurements performed on the HRP pipe of the final batch supplied.

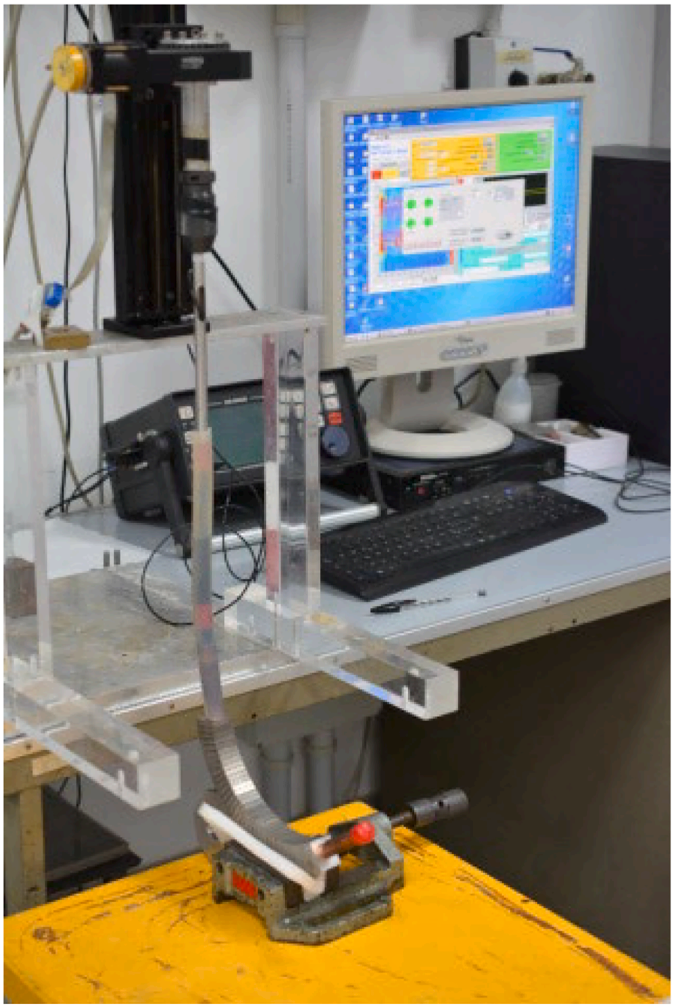


Fig. 6. UT scanning process.

diameter ranges from the minimum value of 14.74mm to the maximum value of 15.10mm. Pipe bending was improved but it still showed ovalization.

3.2. Ultrasonic technique examination

The best UT approach to check the bonding between the pipe and the monoblock is by pulse-echo technique since the UT beam is theoretically orthogonal to the interface to be analyzed. However, due to the dimensions of the UT probe and the radius of curvature of the baffle, this orthogonality cannot be really ensured. Starting from a methodology developed in ENEA [6] and widely used with success for the qualification of processes for ITER ([7,8]) and DEMO ([9,10]) target prototypes and mockups, some particular measures have been implemented in the control equipment to try to minimize the possible signal loss due to the narrow radius of curvature (see Fig. 6).

Fig. 7. Manufactured dummy steel monoblocks.

The Fig. 6 shows the equipment used for these mock-ups. The UT method used is based on a pulse-echo water gap technique. The measurement system consists of an ultrasonic pulser/receiver probe and an automatic handling system with two degrees of freedom, one translation and one rotation, both controlled by an integrated code. The piezoelectric 15 MHz nominal frequency focalized probe is inserted in special plastic probe holder (see [6]) designed to ensure that the distance between the probe and the interface to be analyzed is within its focal length range. This probe holder is placed at the end of a rigid hollow shaft, which allows inserting the probe inside the cooling tube of the mock-up to be analyzed. The mock-ups are fully immersed in water. Signal is acquired along the generatrix of the tube (z direction): probe goes down inside the pipe and acquires the signals, then comes back and rotates of 1 degree (theta direction). The test is completed when the probe comes back at the initial position (i.e. when rotated of 360°). The axial measurement step is 0.08 mm.

All the mock-ups were tested with the pipe axis in vertical position with the ID of the monoblock in horizontal way not upside down. The 0 of the rotation is in the central part of the side opposite the high flux

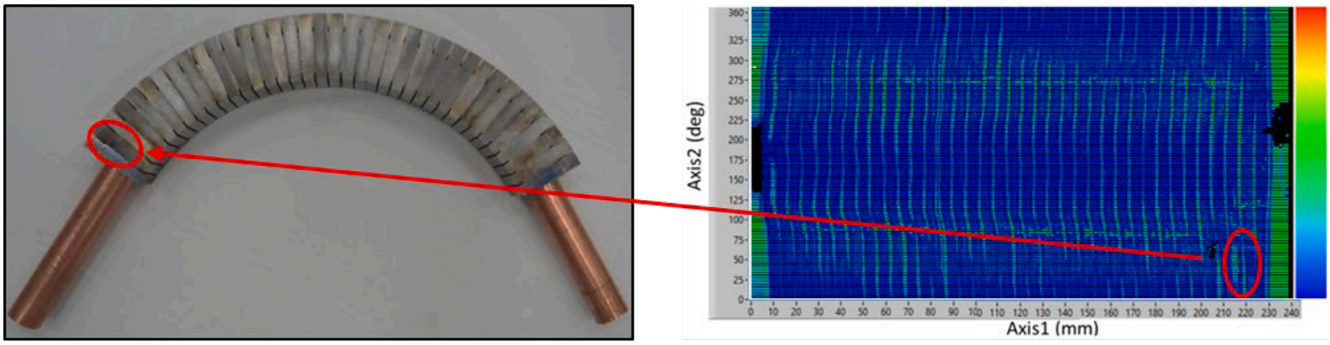


Fig. 8. Assembled pipe with steel blocks after HRP (middle) and UT results after HRP by C-scan (right side).

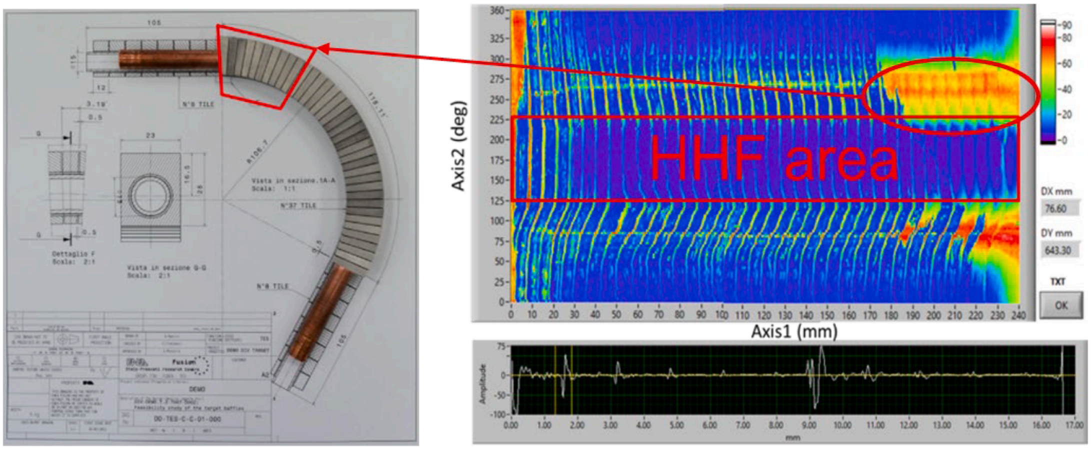


Fig. 9. Baffle mock-up 01 after HRP (left side) and UT results after HRP by C-scan (right side).

face so that the high flux side is in the horizontal band in the center of the plotted area (approximately between 145° and 215°). The 0 of the translation is approximately 5÷10 mm below the first monoblock and the monoblock area is approximately centered.

The results are showed by the C-scan representation.

The C-scan is a map: the horizontal axis reports the axial displacement of the probe inside the pipe (z [mm]), while the vertical axis gives the rotation angle (theta [degrees]). The pixel color gives the maximum amplitude in % of Full Screen Height (%fsh) of the pressure signal, in absolute value, inside of a chosen depth range.

The results of UT examination are reported in terms of C-scan at the pipe/interlayer interface.

3.3. HRP joining pre-test (1st test mock-up fabrication)

A batch of 40 dummy steel monoblocks, having the same overall dimensions as the W ones (with no Cu interlayer, see Fig. 7), was procured to test the tools and furnace parameters. The HRP process [11] consists of a thermal cycle performed at 600°C for 2 hours in a high vacuum furnace, while the contact at the interface between pipe and the monoblock needed to perform the diffusion bonding is made by pressurizing the pipe internally [12].

As explained before, the aim of this dummy mockup realized with the steel monoblocks was to check the whole process equipment, with the same propose, the UT examination was conducted on the dummy with the sole scope of verifying the possibility of using the UT metothod already developed in ENEA for different applications [6] and, eventually, making the specific necessary improvements.

Fig. 8 shows the ultrasonic results by the C-scan representation at the interface between the 37 Steel monoblocks and the CuCrZr pipe. Despite the geometric difficulties of the sample, the results obtained allowed the system's ability to verify the status of the interface to be scanned: the vertical lines of the gaps are fully visible (even if distorted) and distinct from the blue areas of the junction of the monoblocks with the tube.

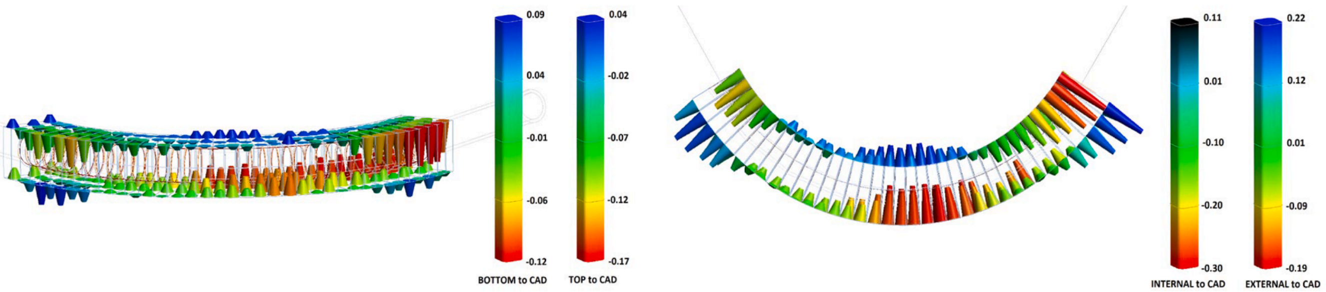


Fig. 10. Horizontal (left side) and radial (right side) deviation of manufactured part (color bar units are in mm).

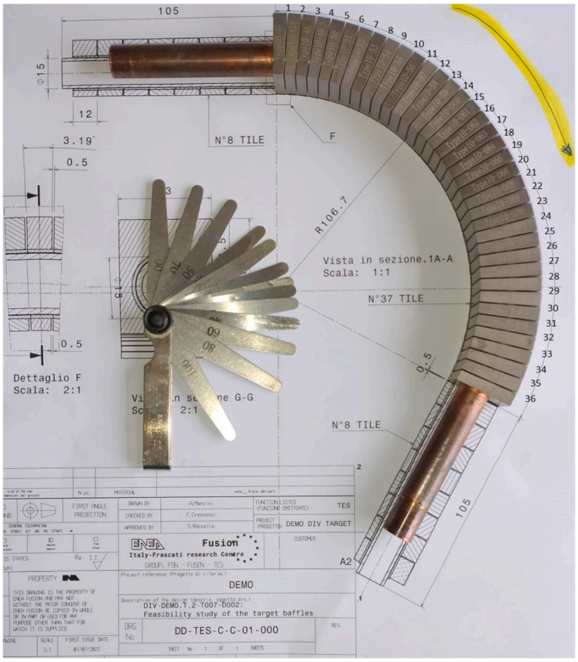


Fig. 11. Identification of the gaps for the mock-up manufactured by HRP.

Despite the absence of interlayer and the little attention paid to the preparatory phase, the UT control surprisingly revealed an excellent junction between the tube and the SS monoblocks: in fact, from the C-scan in the figure, it is possible to observe defective areas on the sides of the mock-up (horizontal lines) and a defect in correspondence with the third block from the left in the figure in the low flow area.

4. Baffle manufacturing processes

4.1. HRP mockup fabrication results

The first W monoblock manufactured mockup was performed using the HRP joining process [11].

Fig. 9 reports the UT results by the C-scan representation at the interface between the 37 Copper interlayer of the W monoblocks and the CuCrZr pipe performed on the fabricated mock-up to check the goodness of the bonding. The results showed that the bonding interface below the high heat flux area has no defects. As happened for the dummy, defects were detected at the end parts of the mockup in the lateral side. A large defect is visible in the first monoblock on the left, while 9 monoblocks are defective at the right end.

A 3d scan of the fabricated mock-up was performed using the Faro CAM2® Edge Arm S/N E09-05-15-30682 (accessories: FaroArm® Calibration Cone and 3mm ceramic Ball Probe “Metrology Works”) and the results are showed in Fig. 10. The deviation from the CAD model was evaluated by the SPATIAL ANALYZER code and a horizontal deviation was found in the range: +0.1mm / -0.17mm and a radial deviation in the range: +0.2mm / -0.3mm.

Although there are no acceptance criteria for these components, the results obtained are indicative of tolerances that can be achieved using this manufacturing process and appear acceptable even considering the lower thermal and particle load in this area of the target.

A measurement of the gap between the W monoblocks plasma side has been also performed by means of blade feeler gauge (see Fig. 11 and Table 1). It can be noted that the gap is in the range of the desired value of 0.5 ± 0.1 mm with a average value of 0.47mm.

4.2. Brazing mockup fabrication results

The brazed mock-up was manufactured with the same procedure fine-tuning in the DEMO target R&D in the frame of the EUROFusion Work Package DIV [13]. The brazing alloy (Gemco) was chosen for the fabrication of the DEMO targets as a compromise between welding performances and low nickel content (a material with a long decay time to be limited in a reactor). The process was performed in a vacuum furnace (~10^{-5}mbar) at 980°C.

Due to the limited availability, the mock-up consisted of just 26 W monoblocks. Fig. 12 shows the W monoblock mock-up after the brazing process.

After the welding process, the UT scan was performed. The results

Table 1
Gap measured for the mock-up manufactured by HRP.

gap ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
gap [mm]	0.45	0.40	0.45	0.40	0.40	0.40	0.40	0.40	0.45	0.45	0.50	0.50	0.50	0.45	0.40	0.45	0.50	0.50
gap ID	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
gap [mm]	0.45	0.45	0.45	0.45	0.50	0.50	0.55	0.50	0.50	0.50	0.60	0.45	0.50	0.45	0.50	0.50	0.50	0.50

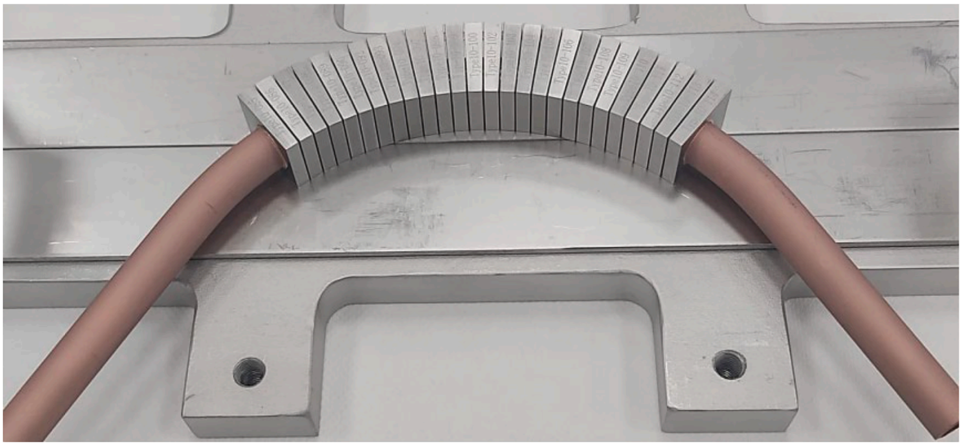


Fig. 12. Mockup after brazing process.

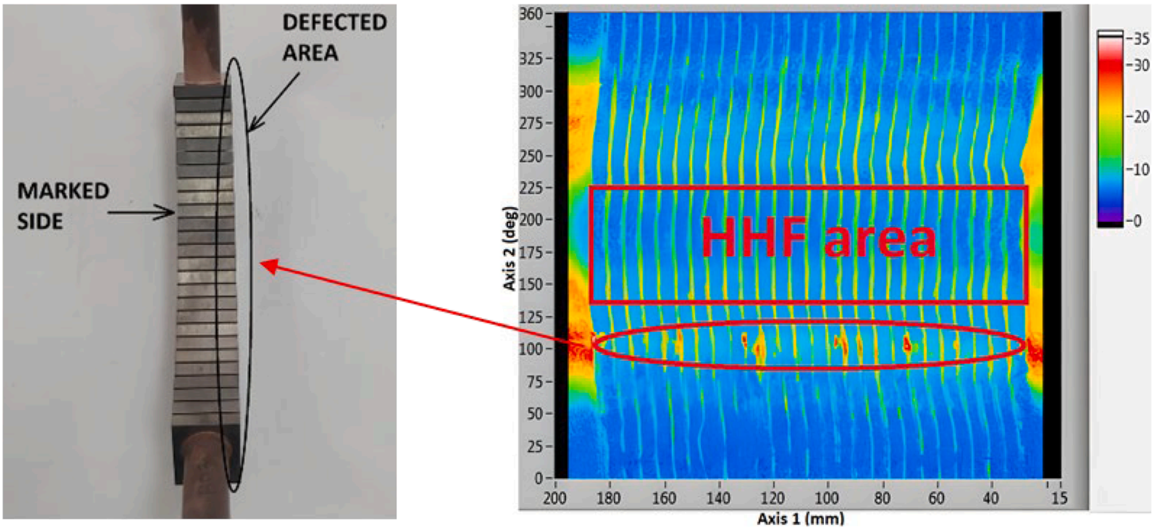


Fig. 13. Baffle mock-up 02 after Brazing (left side) and UT results after Brazing by C-scan (right side).

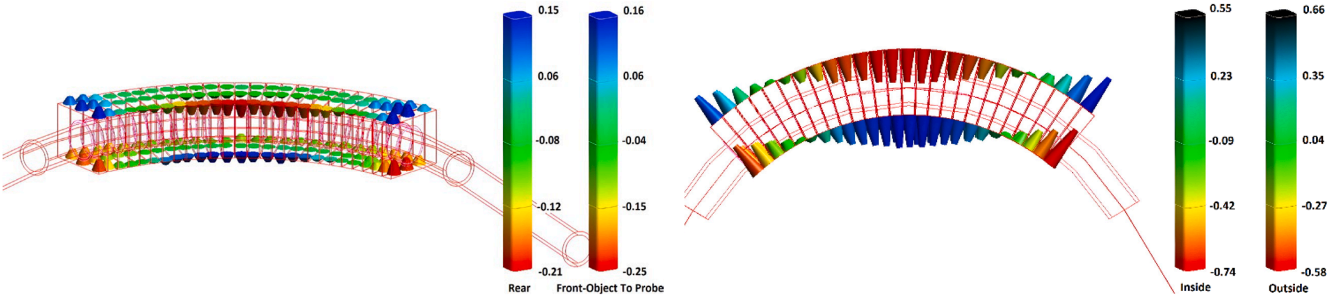


Fig. 14. Horizontal (left side) and radial (right side) deviation of manufactured part (color bar units are in mm).

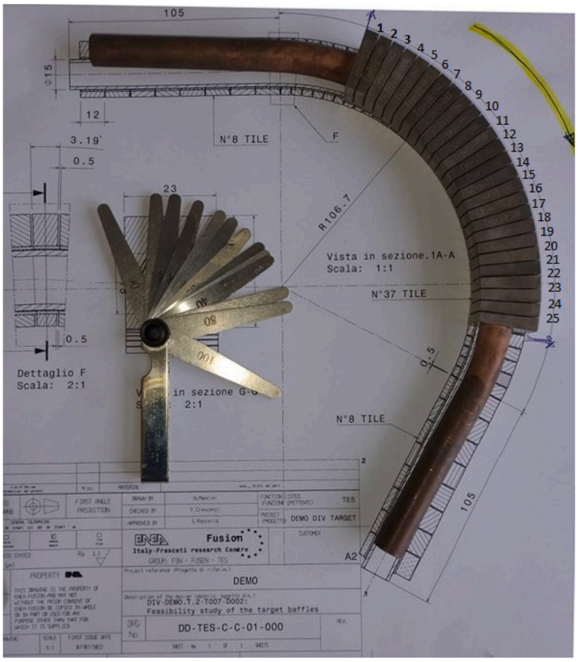


Fig. 15. Measurement of the gap after the Brazing process.

are shown with the C-scan in Fig. 13: small defects were detected located at the lateral side of the monoblocks distributed along the entire axial length of the mock-up. This side corresponds to the mock-up face placed on the furnace plate during the process.

The defects present on only one side do not appear to be related to the ovalization of the tube which seems more critical in the diffusion bonding process. The results of the brazing process appear to be less affected by initial ovalization of the pipe, perhaps, due to the higher temperatures reached by the tube during the process.

Also for this mock-up, the dimensional control was carried out with a 3d scan by the Faro CAM2® Edge Arm S/N E09-05-15-30682 and the deviation from the nominal was verified using the SPATIAL ANALYZER. The deviation from the CAD model was evaluated in the in the range: +0.16mm / -0.25mm of horizontal deviation and +0.66mm / -0.74mm of radial deviation (see Fig. 14). Even though during the brazing process the mockup is free to expand during heating and cooling ramps (so as to remain in a stress-free condition) and there are no imposed mechanical loads as in the case of the HRP process, where high pressure is applied internally to the tube, the final deviation from the nominal is greater than in the HRP case, in particular an increase in the radius of tube curvature is observed.

A measurement of the gap between the W monoblocks plasma side has been also performed by means of blade feeler gauge (see Fig. 15 and Table 2). It can be noted that the measured gaps were below the nominal value of 0.5 mm with values in the range of 0.35 mm and 0.45 mm with an average value of 0.39 mm.

Table 2
Gap measured for the mock-up manufactured by Brazing.

gap ID	1	2	3	4	5	6	7	8	9	10	11	12	13
gap [mm]	0.40	0.45	0.40	0.40	0.40	0.40	0.40	0.35	0.35	0.40	0.35	0.40	0.40
gap ID	14	15	16	17	18	19	20	21	22	23	24	25	
gap [mm]	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.35	0.40	0.40	

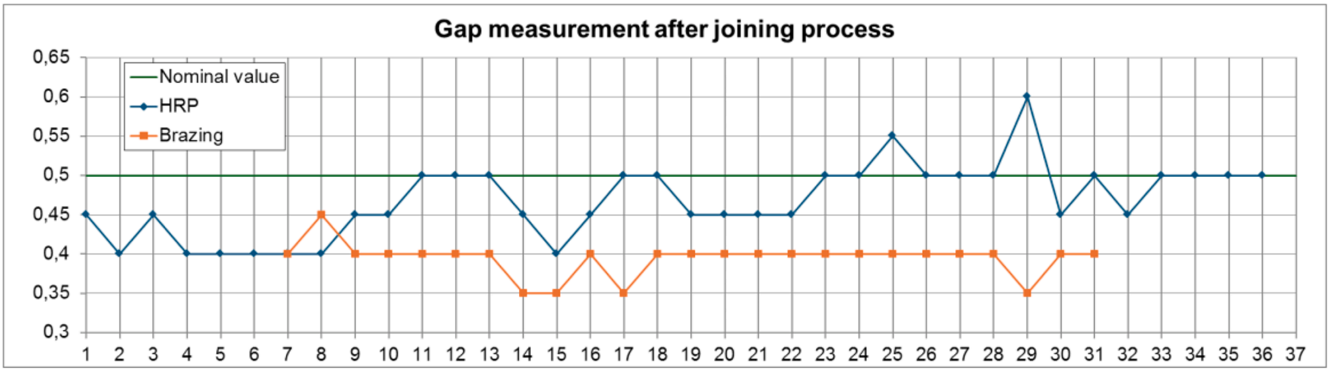


Fig. 16. Gap measurement after the joining process: comparison between the results obtained by brazing and by diffusion bonding.

5. Conclusions

The realization of a detailed CAD of the EU-DEMO targets with the tight bending radius that took into account construction and geometric constraints highlighted the need for extremely small and numerous monoblocks; this, likely, has an impact on production times and costs.

However, strictly related to manufacturability, both the HRP joining process and the brazing performed on the W monoblocks with the OFE-Cu interlayer have given good results. Some problems have been encountered in the realization of these components, however the first attempts are encouraging and the results are positive. Although the use of diffusion bonding has many advantages, such as the greater simplicity and speed of the assembly phases before the welding process and the use of lower temperatures that do not require tempering processes of the alloy tube, the UT examinations after the welding process revealed larger defective areas in the HRPed mock-up to respect the brazed one. The defects detected are located on the lateral sides of the monoblocks at the beginning of the curved part. These areas are those where a greater ovalization of the tube was found downstream of the bending process and a relationship between the ovalization of the tube and the defects found appears plausible. So, in the case of choosing this method, particular attention must be paid to the tube bending process. The tube ovalization problems encountered, even if they are accentuated by the tight radius, are intrinsic to the bending process and can complicate the production process and increase the risk of failure during the production even with larger radius baffles such as those of the ITER divertor.

The gap measurement after the joining processes showed that with in the HRP process the gap the variability range is wider, but the values are distributed more symmetrically and closer to the nominal. In the case of the brazing joint, the gaps are systematically smaller than the nominal value (see Fig. 16).

The dimensional control, instead, revealed a higher precision in the mock-up made by HRP compared to the brazed one. The causes of the excessive distortions of the brazed mock-up must be analyzed and will be part of future activities. Particular attention will be paid to the dimensional analysis of the tubes before the joining process and evaluations of residual stresses in the tubes following cold bending process will be carried out.

The number of samples produced is however too limited to consider the present conclusions as definitive about the advantages and disadvantages of one process compared to the other. Further tests are already underway in order to improve the joining results and the statistics on the dimensional results.

CRediT authorship contribution statement

F. Crescenzi: Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **M. Cerocchi:** Writing – review & editing, Visualization, Resources. **R. De Luca:** Writing – review & editing, Resources, Data curation. **F. Giorgetti:** Writing – review & editing, Resources. **P. Lorusso:** Writing – review & editing, Resources, Investigation. **A. Mancini:** Writing – review & editing, Resources, Data curation. **G. Mugnaini:** Writing – review & editing, Resources, Data curation. **S. Roccella:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **L. Verdini:** Writing – review & editing, Resources, Data curation. **J.H. You:** Writing – review & editing, Methodology, Investigation, 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.

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Data availability

Data will be made available on request.

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