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Summary of the production of the divertor target elements of Wendelstein 7-X

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HIGHLIGHTS

- Completion of the target element production for the water-cooled divertor of Wendelstein 7-X.
- Technology: CFC NB31 bi-layer tiles electron beam welded onto CuCrZr heat sink with swirl tape.
- Production by PLANSEE SE: 973 target elements with ~16, 200 tiles, 44 different quality examinations for 82 manufacturing steps.
- Reliability of the bonding between CFC tiles and heat sink confirmed by high heat flux testing in the facility GLADIS based on a statistical approach.
- Essential recovery of CuCrZr properties after ageing processes (475 °C, 3 h) confirmed by systematic hardness and electrical conductivity measurements.

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ABSTRACT

The realization of the 19.6 m^2 highly heat loaded part of the divertor of Wendelstein 7-X (W7-X) requires the installation of 890 target elements. A target element is made of a CuCrZr copper alloy heat sink armored with carbon fibre reinforced carbon CFC NB31 tiles. The industrial production of the target elements by the Austrian company PLANSEE SE needed 5 years. The successful delivery of a total of 973 target elements (armored with ~16,200 tiles) was based on an efficient quality assurance throughout the production by the manufacturer: 44 different quality examinations for 82 manufacturing steps. It was followed by an intensive quality assessment by IPP: visual inspections, dynamic pressure tests, He-leak testing in vacuum oven, high heat flux testing. The quality of the delivered elements, and in particular the reliability of the bonding between CFC tiles and heat sink, was confirmed by high heat flux testing on the basis of a statistical approach. The essential recovery of CuCrZr properties after ageing processes was confirmed by the measurement of hardness and electrical conductivity. 104 target elements (10.7%) were accepted after repair.

1. Introduction

The installation of an actively water-cooled divertor in the stellarator Wendelstein 7-X (W7-X) is mandatory to achieve stationary power and particle exhaust for a pulse length of up to 30 min [1]. The 19.6 m^2 highly loaded divertor surface is made of 890 individual target elements distributed in ten discrete similar divertor units, two for each of the W7-X five field periods. Each unit has 10 target modules, which are sets of target elements of the same length placed onto a support frame and fed with water from manifolds [2].

A target element is made of a CuCrZr copper alloy heat sink armored with carbon fibre reinforced carbon CFC NB31 tiles. It is designed to remove a stationary heat flux of 10 MW/m^2 on its main area, 5 MW/m^2 at the top end adjacent to the pumping gap and 2 MW/m^2 at the edge tile facing the pumping gap. In 2003 the production was awarded to the Austrian company PLANSEE SE. Four pre-series with the production and intensive testing of ~60 full scale prototypes were needed to improve step by step the initial design. The bi-layer technology which increases the thermo-mechanical performance and lifetime of the bond of the CFC tile to the heat sink was developed [3–5]; a sealing labyrinth and a central fin to prevent a possible by-pass between adjacent channels and ensure the full cooling at the end of the target element were introduced [6]; the design of the tiles protecting the top end

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Table 1
Main characteristics of target elements.

Type	Length [mm]	Max. Width [mm]	Top tiles	Edge tile
1S	594	57	23	1
1A	594	61.5	23	1
1B	595	61.5	23	1
1C	594	60	23	1
2S	572	55	22	1
2B	573	59.5	22	1
3S	320	54	13	
3A	320	58.5	13	
3C	320	59	13	
4S	250	57	10	
4B	250	61.5	10	
5S	361	55	15	1

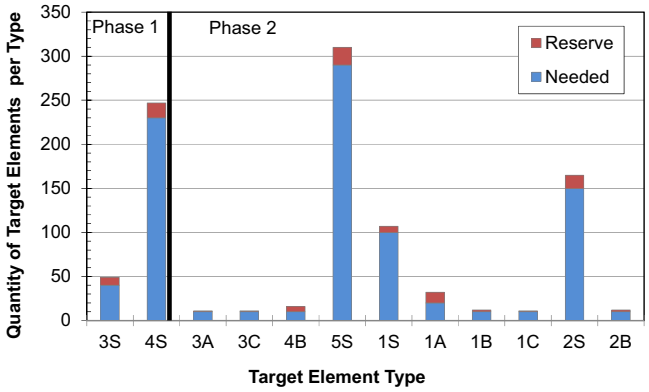

Fig. 1. Quantity of target element per type.

and at the edge was modified [7]; the electron beam welding of the heat sink was optimized; intensive high heat flux (HHF) testing was performed to qualify the 6 different batches of CFC NB31 to be used for the serial fabrication, which have different material properties [8], and to establish a statistical assessment for the serial fabrication based on the results of the pre-series [9]; the repair process of CFC tiles and connector tubes was validated; the quality assurance by PLANSEE SE and reception tests by W7-X were established for the serial production. The result of this extended validation phase allowed the release of the serial production in 2009. This paper summarizes the results of the total production finally completed in 2014 as planned.

2. Production

The production has 5 standard types of target elements with 7 variants for diagnostic integration. Main dimensions are listed in Table 1. The quantity of target elements per chronologically delivered type and the total number of tiles per type are presented in Figs. 1 and 2, respectively.

A total of 973 target elements was delivered, which includes a reserve of 9.3%. The total quantity of delivered armored tiles is ~16,200.

The industrial production was split in two phases, the successful completion of phase 1 releasing phase 2. Phase 1 was the production of 296 target elements of types 3S and 4S, which is 30% of the total production of target elements or 20% of the total production of tiles. These 2 types were selected because of their simplified design: short and no edge tiles. A preliminary step was added for the phase 2 with the first production of 22 target elements of type 1S and 22 of type 5S to validate the manufacturing process of long elements and edge tiles.

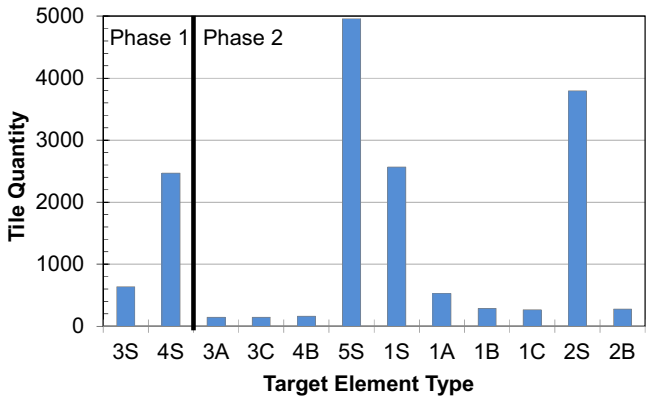

Fig. 2. Quantity of armored tiles per type.

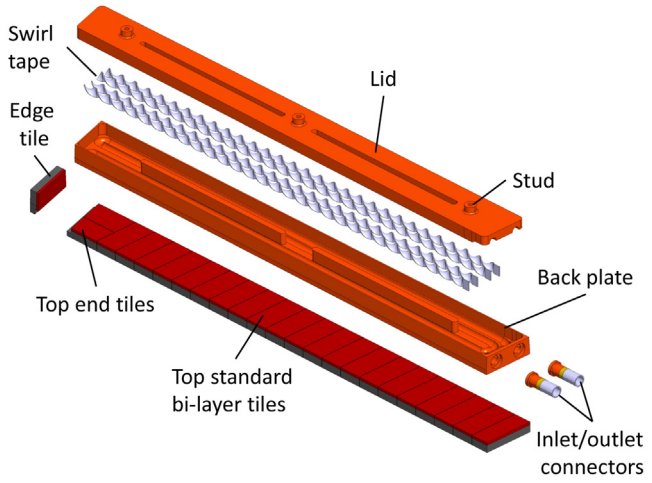

Fig. 3. Main parts of a target element of type 1S.

3. Manufacturing process

The different parts of a target element are shown in Fig. 3 with type 1S. A copper layer is joined by active metal casting to the laser-treated surface of CFC tiles. For each batch, metallography samples verify the copper infiltration specified to remain below 2 mm. After machining of this layer to a thickness of 0.4 mm, each tile is inspected visually and by X-ray. Then an oxygen-free (OF) Cu, 4 mm thick, layer is joined onto the 0.4 mm Cu layer by hot isostatic pressing to produce the bi-layer tiles. Tiles are finally machined to their final dimension: 8 mm CFC plus 3 mm bi-layer. At the final stage, tiles are checked with non-destructive tests (NDTs): ultrasonic inspection for the bond OF-Cu/Cu, X-ray for the bond CFC/Cu, visual inspection (all bonds) and thermography (thermal conductivity of the tiles). 3 types of tiles were produced: top standard (90%), end top (6%) and edge tiles (4%). Defective tiles are not repaired. The quality assurance of the tile is of prime importance for a viable production due to the fact that one defective tile means one defective target element.

The transition between CuCrZr and stainless steel of the inlet/outlet connectors is realized with a 5 mm long nickel adapter. Thick tubes are electron beam welded and then machined to their final dimension (12 mm outer diameter, 1 mm thick) to remove porosities generated by this process. All connectors are the same for all target elements. NDTs are: dimensions, He sniffing leak testing at atmosphere, X-ray and dye-penetration.

The CuCrZr heat sink is made of a lid and a back plate in which half-channels and central fin are machined. They are joined

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