Prototype Manufacturing and Testing of Components of the ECH Upper Launcher for ITER

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The main purpose of the Electron Cyclotron Heating (ECH) Upper Launcher at ITER is to provide local current drive in order to control plasma instabilities with the main focus on the stabilisation of neoclassical tearing modes (NTMs) and the sawtooth instability. The injection of 20 MW mm-wave power at 170 GHz is guided into the plasma by a mm-wave system which is installed in 4 of the 18 upper port plugs of the ITER vacuum vessel. The structural system of these so-called Upper Launchers, housing the mm-wave system, consists of two units, namely the blanket shield module (BSM) which forms the plasma facing component and the launcher main structure with removable internal shield blocks. It has to be designed for rough operation conditions as nuclear heating and enormous mechanical loads during plasma disruptions (EM-loads). The development of the structural design is accompanied by computational analyses, prototype manufacturing and prototype testing. Especially for structures with complex geometry, the optimum manufacturing route has to be determined regarding both technical and economical aspects.
On the basis of a characteristic section of the BSM (called BSM corner prototype) different manufacturing routes were evaluated. The front part of the BSM is exposed to volumetric nuclear heating of up to 3 W/cm^3 and to guarantee sufficient cooling it is designed with a double wall shell, which allows heat removal by internal meandering cooling circuits. Concerning the requirements on leak tightness, mechanical strength and geometrical precision, manufacturing of a double wall structure with internal cooling channels is a main challenge. Two BSM-corner prototypes were manufactured one by brazing of semi-finished parts and the other one by Hot Isostatic Pressing (HIP) and dedicated tests regarding pressure loss and cooling efficiency were performed. For the experimental part the Launcher Handling and Test Facility (LHT) at KIT was used to test prototypes under ITER relevant conditions. The results were compared with appropriate calculations and numerical FEM/CFD analyses performed with respect to flow characteristics, heat transfer and pressure loss of cooling water.
In this paper the experience obtained on prototyping is presented and the importance of prototyping for design validation is pointed out.

1. Introduction

For stabilisation of neoclassical tearing modes, four Electron Cyclotron Heating (ECH) launchers will be installed in the upper ports of the ITER vacuum vessel [1]. This will be achieved by injection of up to 20 MW power at 170 GHz into the ITER plasma. Each launcher penetrates the vacuum vessel and the blanket up to the first wall. It must be designed for rough operating conditions as nuclear heating and very high mechanical loads during plasma disruptions. The mm-wave system, which consists of two rows with four waveguides each and a quasi optical mirror system with front steering mirrors is integrated into the Upper launcher. The mechanical system of the launcher consists of the blanket shield module (BSM), forming the plasma facing component and the main structure with internal shielding. To ensure protection and precise positioning of the mm-wave system, it has to be integrated into a rigid and accessible structure. The development of the Upper Launcher is organized by a cooperation of EURATOM associations (ENEA/CNR Milano, CRPP Lausanne, KIT, FOM Rijnhuizen, IPP Garching/IPF Stuttgart) and covers the mm-wave system, the diamond windows, the structural system and maintenance issues.

Design development and validation of the structural system is accompanied by computational analyses (EM- and thermo mechanical loads, neutronic analyses, computational fluid dynamics (CFD) analysis) and manufacturing tests [2]. Analyses and tests are related to design feasibility, prevention of residual stresses, contour accuracy and thermo-hydraulic behavior and were performed for selected components.

2. Basic configuration of the Launcher and selection of prototype components

The ECRH Upper Launcher is attached to the port flange of the vacuum vessel. Its outer structure can be split into two units, the Blanket Shield Module (BSM) and the main structure (main frame) (*FIG. 1a*). Both units are connected via bolted joints, which allow axial dismantling. Depending on the expected heat loads, the launcher components are designed as double or single wall elements. The front section of the main frame, which is exposed to enhanced heat loads, consists of a double wall area. The rear part, which needs no active cooling is designed as a single wall. The closure plate forms the primary vacuum boundary and the tritium barrier. Behind the closure plate is a double wall socket (which serves as heat source during baking process) and a support flange. The isolation valves and diamond windows *(FIG. 1.b)* are located prior to the closure plate (an alternative location with both placed further from the port plug is under discussion). Main functions of the structure are the housing of the mm-wave system and of shielding elements as well as the separation from neighbouring components. The launcher is designed as a cantilever, thus a very rigid system is required to guarantee structural integrity. The UL, in accordance with other vessel components, is made from 316L(N)-IG stainless steel.

a) b)

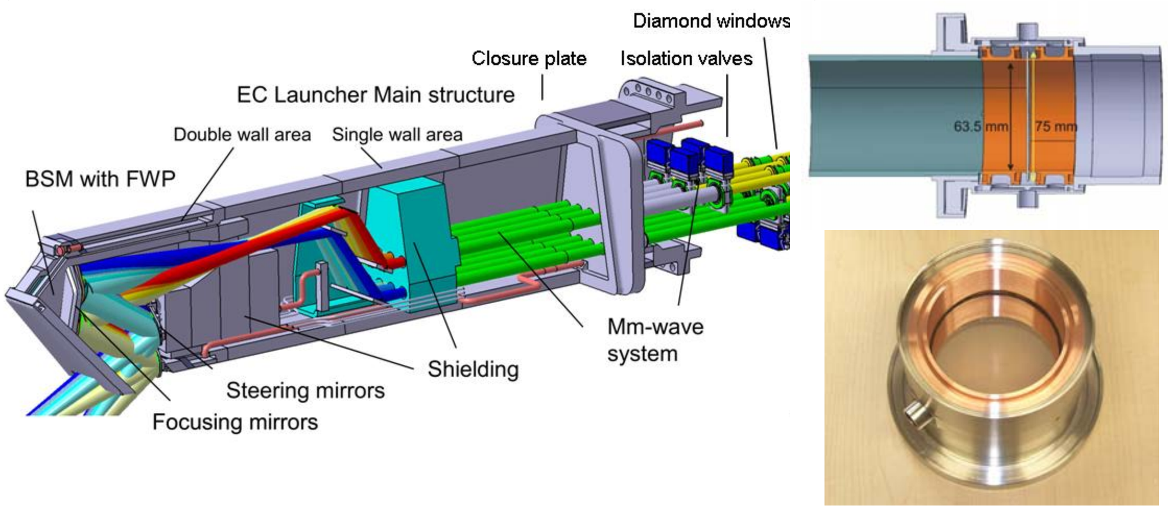

FIG. 1. a) Overview: main components of the ECRH Upper Launcher, b) Diamond torus window concept and prototype.

The BSM as the plasma facing component is exposed to volumetric nuclear heating up to 3 W/cm^3 [3, 4]. It is designed as a double wall structure, which allows active cooling by means of pressurized water. Therefore a wide range of mechanical and thermo mechanical properties as well as leak tightness have to be fulfilled. As the manufacturing of a cooled double wall structure is challenging, it was decided to investigate the manufacturing of two BSM prototypes and to perform tests dedicated for design validation (e.g. experiments on shock cooling). Details are described below.

The single wall section of the mainframe is currently designed to consist of 3 segments which have to be welded together. Accurate and safe welding of such massive components is not a standard process and therefore first prototype manufacturing tests have been recently started [5].
The performed experiments show that manufacturing results are dependent not only from the raw material itself but from its history (e.g. manufacturing route and manufacturing temperatures) and from the surface finish. As the launcher is an in vessel vacuum component these properties also play an important role for the outgassing behaviour of the launcher. Experiments regarding this topic were started and within this paper first preliminary results are presented.
Additionally diamond window development is under investigation and prototypes are manufactured and tested. Details could be found in [6].

3. Launcher Handling and Test facility - objectives and configuration

As shown before the ECH Upper Launcher consists of different and partial very complex components with individual design requirements. Therefore a Launcher Handling and Test facility (LHT) is built up at KIT which provides an infrastructure for testing of different prototypes. It allows an experimental validation or a better knowledge of the significance of results obtained by design tools like numerical simulations. Strategies for acceptance testing can be developed and will be used as an input to procurement, manufacturing, testing and delivery to ITER. The LHT (*FIG. 2*) provides a full scale experimental site with a water loop providing ITER blanket water parameters for normal operation (temperature from 100°C-150°C and a pressure up to 3 MPa), and bake out conditions (temperatures up to 240 °C and a pressure up to 4.4 MPa). Further components of the LHT are a rack to fix the prototypes and a control and Data Acquisition unit (CODAC). Additionally it offers a remote handling area to enable experimental testing of remote handling procedures. The construction of the prototype rack can be easily adapted to integrate new prototypes. A BSM flange prototype was manufactured which serves as mechanical interface to the test objects, e.g. to the BSM corner prototype.

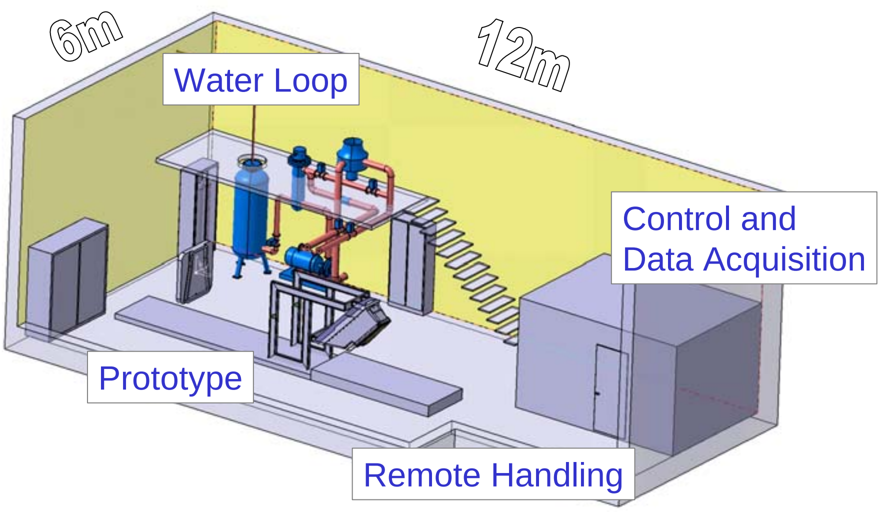

FIG. 2. Schematic configuration of the Launcher Handling and Test facility (LHT).

4. Manufacturing of double wall structures

There are different concepts for manufacturing a double wall structure. One concept is the machining from a massive body. The machining of circular channels in a massive steel block can be done by a combination of deep drilling and welding. Using this concept, a first simple mock up was manufactured and tested (see 4.1).
In a second step the more complex BSM corner prototypes were fabricated using further approaches: Brazing and Hot Isostatic Pressing (HIP). For the Braze-route machined single parts were joined by a brazing in a furnace (4.2). The manufacturing of complex structures using the HIP route is based on a diffusion welding process or sintering of metal powder at high temperatures and high pressure (4.3).

4.1 Mock-up with drilled cooling channels

For a simplified Mock-up, four channels (D~22 mm, distance = 100 mm) were drilled into a massive steel plate (*FIG. 3a*, *b*). Apart from water in- and outlet, the open channels were connected at their end and then closed by welded plugs. Different operation modes of the water circuit were tested and the effect of the cooling channels was visualised by infrared mappings (*FIG. 3c*). The experiments show that especially in region with high nuclear heating small distances between the drilled channels are necessary to avoid hot spots and high thermal stresses. These stresses due to heat expansion are critical for the welded areas.
The machining of massive parts results in a good mechanical strength, but the high number of required welds is critical. Additional the complexity of the shape is limited.

a) b) c)

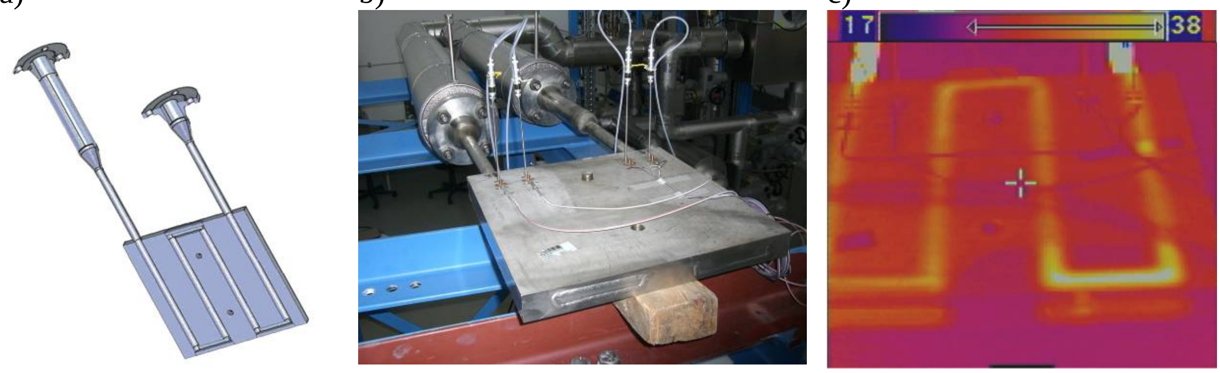

FIG. 3. Mock-up with drilled cooling lines: a) Catia-model, b) mock-up with connections to cooling circuit and c) thermal mapping.

4.2 BSM corner prototype (brazed)

Another approach for manufacturing double wall structures is the welding/brazing technique, which was investigated for the BSM corner prototype. Prefabricated parts of the corner prototype (outer and inner wall section, flow ribs, cover plate, flange) were assembled by brazing (*FIG. 4*). Prior to the brazing process in a vacuum furnace (12h at 1050°C) the parts were laser spot welded for a proper positioning. Tensile tests with dedicated specimens of the joints show good mechanical properties. Also the leak tightness of the brazed joints fulfils the requirements.
A critical issue of this technique is the proper positioning of the individual parts hindered by the thermal expansion at brazing temperatures. However, this issue can be relaxed by minor

design modifications. For full-size applications as the BSM, brazing furnaces with extended capacities are required.

a) b)

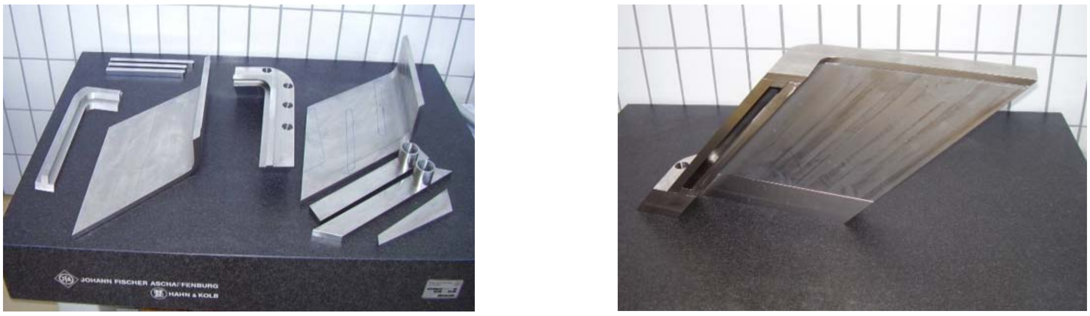

FIG. 4. a) Machined parts for brazing and b) brazed BSM corner prototype

4.3 BSM corner prototype (HIP)

In principle there are two basic methods for manufacturing of complex structures by Hot Isostatic Pressing. Firstly, the diffusion welding of machined parts and secondly the sintering of metal powder. For both concepts a welded and evacuated capsule is required which is placed into the HIP device.

To identify the appropriate method, simplified test samples were manufactured. In *FIG. 5* the schematic layout of the test samples for both methods is shown. The inner capsules must be removed by etching, while the outer capsule (in case of sintering) can be removed mechanically. The sintering of powder metal enclosed in a ferritic capsule turned out to be the optimum manufacturing route and therefore it was used for the HIP-BSM corner prototype.

a) b)

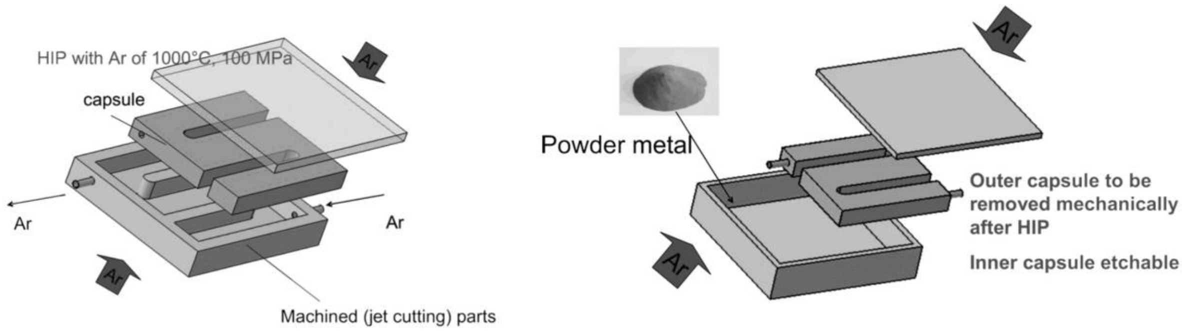

FIG. 5. Schematic layout of the test samples for a) diffusion welding and b) powder metal sintering by HIP.

Capsules based on a 3D-CAD-model were fabricated and filled with metal powder. After evacuation, they were hot isostatically pressed at a temperature of 1000°C and a pressure of 100 MPa, followed by removal of the capsules and final machining of the outer surfaces. In a second HIP-diffusion welding process the double-wall section (*FIG. 6*) was tied to the flanges. The final product showed generally good quality with rough surfaces of the flow channels. The rough surface (created by the spherical metal powder) gives an advantage regarding heat transfer efficiency.

a) b)

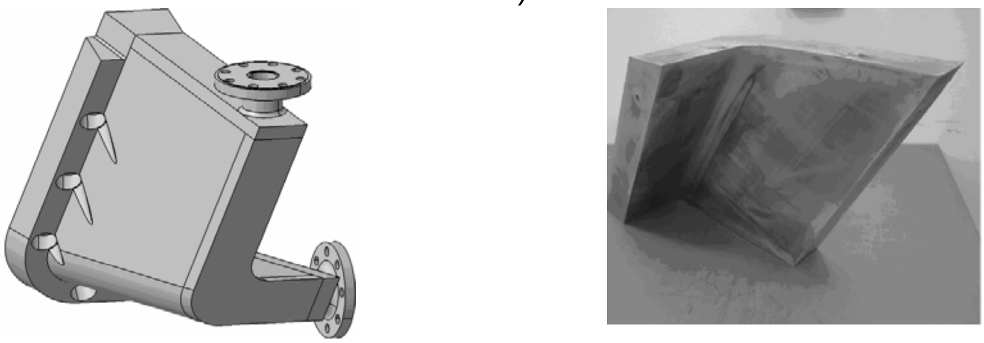

FIG. 6. a) BSM corner prototype model and b) the double wall body manufactured by HIP.

5. Prototype testing - BSM corner prototype

The HIP-prototype was chosen for testing and its integration into the LHT was realized by the massive flange mounted to the rack (*FIG. 7. a*). A series of thermocouples were contacted to selected points on its surface and an infrared camera allowed the observation of the whole prototype. As the BSM is located close to the plasma it has to withstand very high heat loads, thus effective cooling is mandatory. This can be achieved by a proper cooling design with an adequate geometry and small distance between the cooling channels. For evaluation of the cooling design/system, CFD simulations (fluid dynamic model) are the major tool. But crosschecks with experiments are necessary to check the simulation for its suitability and significance for further design improvements.

Therefore shock cooling experiments were performed with the BSM prototype. The structure of the prototype was heated up by feeding water at 95°C. After reaching the equilibrium water with a mass flow rate of 3 kg/s at 25°C started to flow into the system and the temperature decrease was monitored. The CFD simulation showed a slightly faster temperature decrease which is due to the characteristics of the real inflow: at the very beginning hot water is still inside the piping, while the mass flow rate does not suddenly reach its maximum, as it is in simulation. But besides this effect the simulation results come very close to the experiment including details like nearly stationary turbulences with higher temperatures and best cooling in the high flow regions. The decrease rates of the temperature are comparable and the experimental temperature distribution monitored by the infrared mappings is adequately reflected by the temperature map of the simulation (*FIG. 7 b, c*). This indicates that the heat exchange process is well simulated by CFD, so it is considered to be a good tool for design and validation of the BSM/FWP cooling system.

a) b) c)

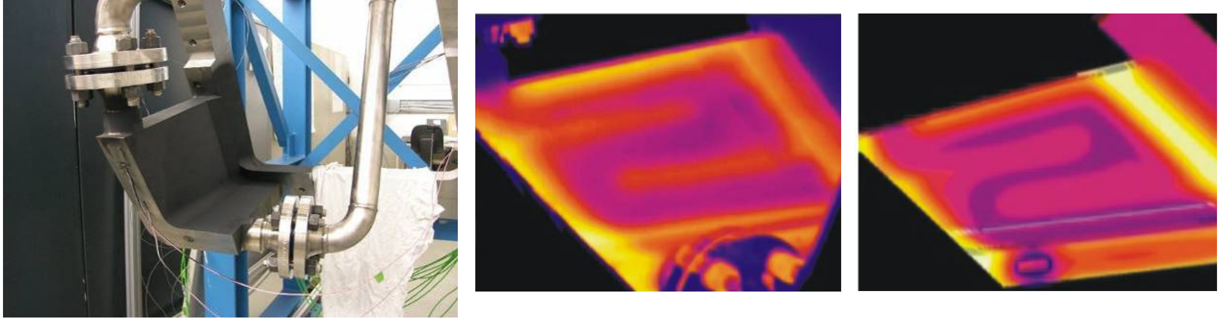

FIG. 7. a) BSM corner prototype mounted to the flange prototype and connected to water circuit, b) temperature map from infrared measurement and c) from simulation (after 80s shock cooling).

6. Outgassing Measurements

Outgassing can be defined as the evolution of gas from a solid or liquid in vacuum. As released gas contaminates the ITER plasma, outgassing must be limited for materials inside the vacuum system. Outgassing limits are specified in the ITER vacuum handbook for all components according to their position in the vacuum quality classification [7]. The UL is a torus primary vacuum component and the limits are very strict. As shown before, the HIP process is one of the preferred manufacturing routes for the Launcher structure, but outgassing data for hot isostatically pressed stainless steel are not available in literature yet and so experimental measurements are necessary in order to verify the compliance with the limits.
The outgassing rate of a surface depends on the exposure time to vacuum, temperature, surface finish of the material, cleaning method of the surface and other factors and therefore experiments were started to investigate this issue. Stainless steel samples were manufactured by rolling, rolling with additional solid HIP and HIP from metal powder. Two surface treatments were applied (*FIG. 8.a*) to the different specimen. The samples were made of AISI 316LN and AISI 317LMN steel, since the ITER steel is expensive and not a standard material.
For vacuum measurements of gas release a variant of the dynamic method was used [8] and *FIG. 8b* shows the experimental setup. The vacuum chamber is formed by a quartz tube passing through an oven and is connected to the pumping station and to the vacuum gauges (including quadrupole mass spectrometer). Measuring partial pressures of the released gas and doing blank and sample runs, the specific partial outgassing rates of the samples were calculated (typical gas species: H_2, H_2O, CO/N_2, O_2, Ar, CO_2/N_2O). As an example *FIG. 8c* reports the specific outgassing rate of hydrogen q_{H2} as a function of the pump-down time at T = 100°C. The curves for the two samples manufactured by rolling respectively by rolling with additional solid HIP are very close. Only for higher pumping time there is a small difference. The obtained results revealed that the dimensions of the samples were too small to appreciate the effect of the HIP method on the outgassing rates; so higher sample/chamber volume ratio must be taken into account. It was observed that for the sample with rills the outgassing value is about 4 times higher than that of the polished sample. Since the outgassing values were calculated per unit of the real area (taking into account the surface roughness) of the samples, the explanation for this is not the increased surface but would be the structural change of the surface that the material undergoes when the rills are generated.
The results were only preliminary and as a consequence cannot be compared to the outgassing limits yet. Future work aims to make further improvements of the experimental setup.

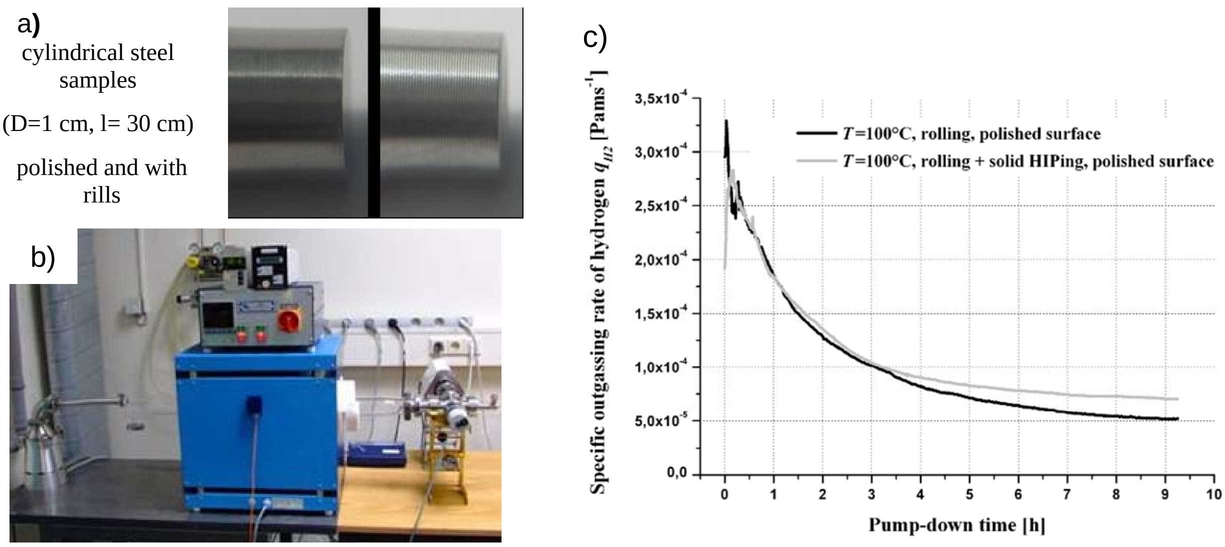

FIG. 8. a) Typical samples, b) experimental set-up c) effect of HIP on the specific outgassing rate.

7. Summary

The design development and validation of the ECH Upper Launcher is based on analytical and numerical calculations as well as on prototype tests.

Manufacturing routes were checked by the constructions of simplified mock-ups and prototypes to identify the optimum manufacturing route. A first mock-up with a very basic design was followed by BSM corner prototypes, which were good indicators for suitable manufacturing techniques. The manufacturing of the complex double wall structure is sophisticated. Combination of drilling and welding causes distortions and has a limitation in terms of geometrical complexity. Brazing requires precisely manufactured parts which have to be positioned exactly after applying braze and during the whole brazing process. The more complex the structure, the higher is the risk for errors during mounting and brazing, which can result in insufficient tightness. An elegant method to realize complex structures is given by HIP. The BSM corner prototype manufactured by HIP presently defines the favourite manufacturing route – at least from the technical point of view. Several manufacturing variants are possible such as complete processing from powder or by diffusion welding of preformed parts. Also a combination e.g. with drilling and wire eroding is possible.

A CFD simulation was performed to reproduce the shock-cooling experiment made on the BSM corner prototype in the LHT facility. The comparison between the results and the measurements shows that the CFD model is able to reproduce the heat exchange process during the shock-cooling event. Therefore the simulations are considered as a good tool for design improvement of the BSM/FWP cooling system.

Acknowledgments

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