# Development of high power window prototypes for ECH&CD launchers

**R. Heidinger*[,1a], I. Danilov[1a], A. Meier[1a], B. Piosczyk[1b], P. Späh[1a], M. Thumm[1b,2]**
**W. Bongers[3], M. Graswinckel[3], M. Henderson[4], F. Leuterer[5], A.G.A. Verhoeven[3], D.Wagner[5]**

[1] *Forschungszentrum Karlsruhe, Association FZK-Euratom,*
*(a) Institute for Materials Research I, (b) Institute for Pulsed Power and Microwave Technology.*
*P.O. Box 3640, D-76021 Karlsruhe, Germany*
[2] *Universität Karlsruhe, Institute of High-Frequency Techniques and Electronics,*
*Kaiserstr. 12, D-76128 Karlsruhe, Germany*
[3] *FOM Institute for Plasma Physics "Rijnhuizen", Association EURATOM-FOM ,Nieuwegein, The Netherlands*
[4] *CRPP, EURATOM – Confédération Suisse, EPFL, CH-1015 Lausanne, Switzerland*
[5] *Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*

## Abstract

Torus windows prototypes for Electron Cyclotron (EC) Heating and Current Drive (H&CD) systems are developed for different launcher concepts in accordance with the specific transmission requirements. For ITER, single-disk windows are designed for 2 MW power transmission at fixed frequency (170 GHz) in two variants. For the RS launcher, the remote steering unit is placed close to the torus window in the launcher back-end which calls for a large window aperture (95 mm) to avoid beam vignetting at the extreme steering angles of ±12°. For the FS launcher with the steering mechanism placed in the font shield of the launcher, the aperture and the disk thickness is reduced as the torus window is integrated into a cylindrical waveguide configuration with an inner diameter of 63.5 mm. The reduced absorbed power and cooling paths allow to consider indirect cooling as an alternative to edge cooling which eliminate the risk of tritium contact to the cooling water in case of crack formation in the diamond disk. For the multi-frequency torus window at ASDEX- Upgrade (aperture: 80 mm), a double disk configuration is realised with the disk separation of 5 mm, fine tuneable over ±1 mm. Prototypes of the high power windows were manufactured. First results of the current thermo-hydraulic and of the mm-wave performance tests support the feasibility of the concepts. For the ITER torus windows, the tool development is described which provides on-site replacement by automated cutting and welding tools.

*** Corresponding author:**

**Roland Heidinger, Forschungszentrum Karlsruhe, P. O. Box 3640, 76021 Karlsruhe, Germany,**

**e-mail: roland.heidinger@imf.fzk.de; phone: +49 (7247) 822042, fax: +49 (7247) 824567**

## 1. Introduction

Electron Cyclotron (EC) Heating and Current Drive (H&CD) systems are key components in nuclear fusion technology as localised and steerable deposition of high power mm-waves contributes essentially to plasma start-up, plasma heating, shaping of current profiles, and plasma stabilisation. At ITER, it is foreseen to inject a total of 20 MW mm-wave power at a fixed frequency (170 GHz) and the first tritium confinement in the mm-wave launchers will be formed by CVD diamond windows [1]. As a result of the materials development for fusion technology, large area CVD diamond disks have become commercially available which are the basis for the development of high power EC windows with a transmission capability of 2 MW due to their unparalleled combination of ultralow mm-wave absorption and outstanding thermal conductivity [2]. For the control of plasma instabilities, it is required that the mm-wave launcher can target a localised beam to the q=3/2 and q=2 flux surfaces which will be achieved by angular steering in the poloidal direction. Resulting from the work of the “ECHULA group” of EU associations (ENEA/CNR Milano, CRPP Lausanne, FZK Karlsruhe, FOM Rijnhuizen, IPP/IPF Garching/Stuttgart), an initial reference design for the ECRH Upper Launcher was developed on the basis of the remote steering (RS) concept called the “3/8 RS launcher model” [3]. However, this configuration was becoming marginal for the steering ranges required for operation at different plasma scenarios (i.e. ITER plasma scenario 2, 3 and 5) because of adverse consequences for the focalisation of the beams. Thus the main emphasis in the design work has been redirected towards the front steering (FS) design as it is at present the only steering option that meets the ITER stabilisation requests [4]. For a frequency controlled mm-wave deposition capability, a step-tuneable Electron Cyclotron wave system is under construction at ASDEX Upgrade [5]. For this advanced technology, a torus window has to be realised for mm-wave transmission at 4 selected frequencies between 105 – 140 GHz capable of handling up to 1 MW mm-wave power.

## 2. Torus window for a remote steering launcher

In the classical waveguide configuration adopted in the initial 3/8 RS reference launcher model, the RS launcher is characterised by movable mirrors in the launcher back-end that direct the mm-wave beams with an input steering range of ±12° through the CVD diamond window and an isolation valve into a square corrugated waveguide, which transposes the input angle to the front-end for final targeting into the plasma by fixed front mirrors. The wide steering range introduces particular operational issues into the window design, like an asymmetric window housing (including the cooling chamber) with especially flexible attachment to the window unit with a large aperture metallic cuff. This allows to avoid significant scraping off in the steered beam and to limit the tensile stresses on the cuff and the disk provoked by the pronounced off axis transmission (cf. Fig. 1).

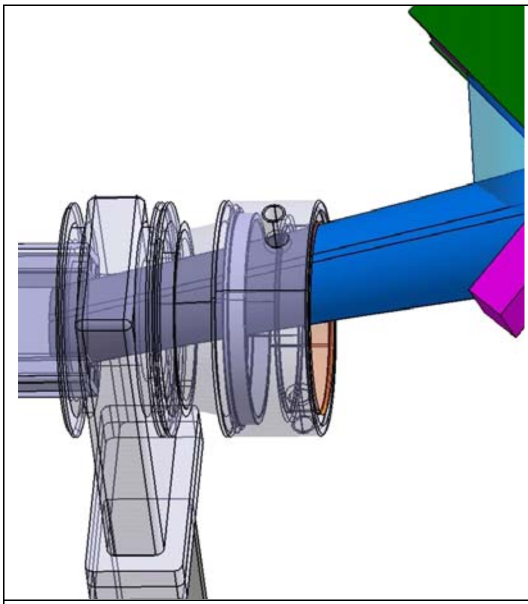

**Fig. 1: Path of the mm-wave beam through the torus window of the 3/8 RS reference launcher at steering angle +12°( beam extension shown is 3.5 times the Gaussian beam radius)**

A RS torus window design was developed based on a CVD diamond disk of 106 mm diameter integrated into a window housing providing an aperture of 95 mm. Thermo-mechanical analysis by FEM ("ANSYS") showed for the chosen egde-cooling with component cooling water that for a conservative level of mm-wave absorption of 1800 W, all materials in the different parts of the window unit can be expected to stay in the elastic regime even at the extreme 12° steering angles,. Peak principal stress in the diamond disk of about 95 MPa are well below the critical limit of 120-150 MPa [6].

A first RS torus window prototype was manufactured to demonstrate the feasibility of the concept (Fig. 2). The window unit was integrated into the mock-up beam line at FOM Rijnhuizen and the transmission characteristics were analysed with a custom-made network analyser system that allows with a dynamic range around 130 dB [7]. The potential interference of the window housing with the beam incident from the remote steering unit was analysed by varying a gap between the window flange and the waveguide (extension) flange, which was set to simulate the isolation valve. The Gaussian content was extracted from the measured power profiles by fitting the measured intensity with the help of the ideal Gaussian profile. It could be shown the power loss due to beam scrape-off is below 1% consistent with a safety factor of 3 relative to the beam radius in distance to scattering metallic parts [8]. The high power transmission characteristics were studied at the coaxial gyrotron test stand at FZK [9]. The modest mode purity required a filtering which provide for the window testing a RF beam of power of 170 kW with more than 97% Gaussian content and a pulse length 6.68 ms. It was shown that the RS-window prototype did not affect the mm-wave antenna pattern (in terms of the Gaussian beam content), did not provoke arcing even in air, satisfied vacuum specifications and did introduce any parasitic vibrations to the RS launcher while operated with circulating cooling water [10].

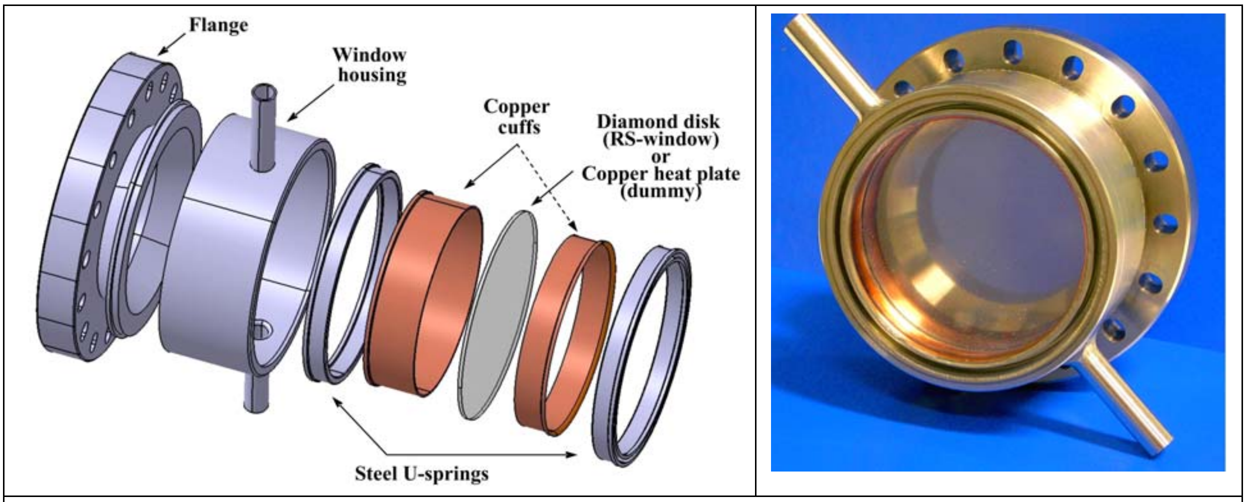

**Fig. 2: The RS torus window prototype shown as an explosion drawing (left) and as the manufactured window unit (right)**

The design specifications and analysis of the cooling system for the RS torus window were experimentally verified by thermo-hydraulic and pressure tests on the RS window prototype and on window dummies in which the CVD diamond disks was substituted by a (heated) copper disk. In these experiments, an elastic behaviour of the copper cuffs (no residual deformations) was observed up for a pressure in the cooling loop of up to 1.6 MPa was which was twice higher then the critical water pressure specified on the basis of the previous stress analysis. The pressure drop of the coolant through the RS window prototype was 0.6% (6 kPa) (for a flow rate of 10 l /min and pressure of 1 MPa) which is falls much below the pressure drop in the test set-up. The temperature profile in the disks did not differ for the horizontal and vertical arrangement of the coolant feeds, thus excluding gravitational effects. Also it was found that the cooling efficiency entered into a flat dependence on the water flow rate above 5 *l*/min was is a less demanding condition than at that obtained from the thermo-hydraulic modelling during the design development.

## 3. Torus window for a front steering launcher

The mm-wave beam in front steering (FS) launcher propagates along the circular waveguide axis. Thus there is no shift of the beam spot on the disk surface. This allows simplifying the window design as compared to the RS steering case: a symmetrical arrangement of the window cuffs can be used. As the window aperture can be reduced to 63.5 mm, the thickness of the CVD diamond disk can be reduced to 1.11 mm ("3-half wavelengths") as compared to 1.85 ("5-half wavelengths"). The shorter absorptive path in the disk reduces the absorbed power from 1800 W to 1100 W for a 2 MW beam at 170 GHz and a "guaranteed" dielectric loss tangent of $4 \cdot 10^{-5}$. Taking into account the gain in cooling scenario which is even increased by the shorter cooling paths in the disk, the standard cooling at the disk edge may potentially given up in favour of indirect cooling. This would eliminate the risk of tritium contact to the cooling water in case of crack formation in the diamond disk. The two cooling concepts were experimentally combined in the design of the FS window prototypes (cf. Fig. 3). A first unit ("ER7_1106": aperture 55 mm) was formed with a non-resonant disk (65 mm dia. x 1.25 mm) by which the brazing technology was proven. The next step was the manufacturing of a close to size unit (ER6_172: aperture 65 mm) with a resonant disk (70 mm x 1.11 mm), yet as before still with CVD diamond of modest dielectric loss level ($\tan\delta \approx 10^{-4}$). For both units, the required tolerance to overpressure of 0.2 MPa could be proven both by simulation and experiment (cf. Tab. 1). As the pressurising test of the cooling systems up to 3 MPa was also positive, the experimental study of the cooling performance will be have to decide on the preferred choice among both cooling concepts and the final design of the FS window prototype which will be based on a low loss disk ($\tan\delta \approx 2\text{-}4 \cdot 10^{-5}$) with dimensions (75 mm dia. x 1.11 mm) suited for a window aperture of 63.5 mm.

Tab. 1: Experimental study and theoretical analysis of the overpressure tolerance of the FS torus window prototype

| Window unit | Pressure | Experiment | FEM analysis | |
|---|---|---|---|---|
| | | Deformation [μm] | Deformation [μm] | $\sigma_{max}$ [MPa] |
| ER6_172 | 0.1 MPa | 19 ±1 | 22 | 47 |
| | 0.2 MPa | 39 ±1 | 44 | 93 |
| ER7_1106 | 0.1 MPa | 10 ±1 | 12 | 32 |
| | 0.2 MPa | 21 ±1 | 24 | 65 |

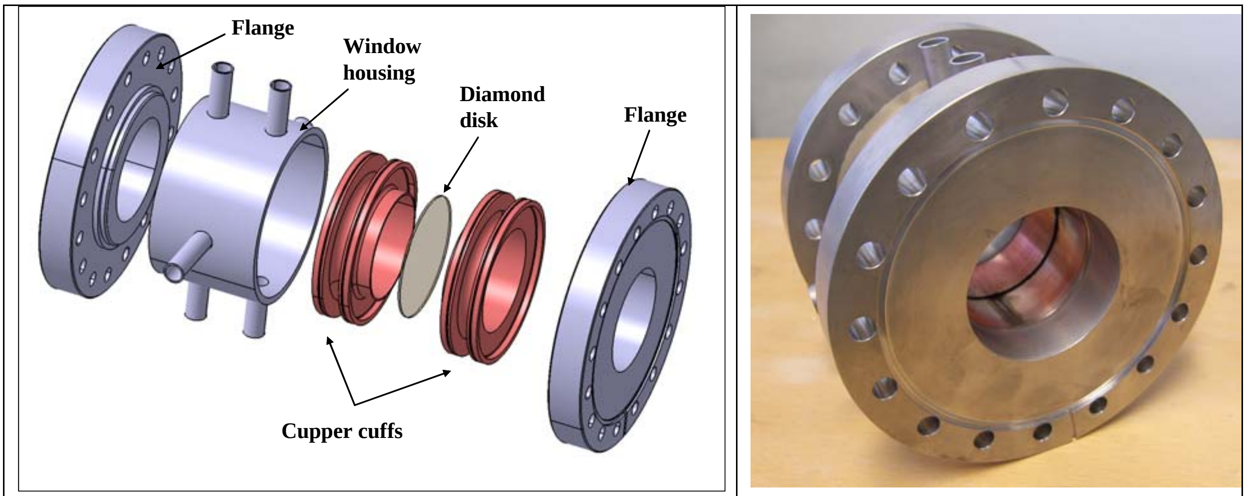

**Fig. 3: The FS torus window prototype shown as an explosion drawing (left) and as the manufactured window unit (right)**

### 4. Torus window for a step-tuneable launcher

The beam lines for advanced multifrequency ECH system at ASDEX-Upgrade (Garching, Germany) will operate for 1 MW power levels at 4 distinct frequencies of ~105…140 GHz. Whereas the thickness of a single-disk diamond window can be chosen such that the minimum reflection condition for the radiofrequency (RF) power can be met at the boundaries of the frequency interval, for the targeted intermediate frequencies (around 115 and 125 GHz) high power reflection will occur due to non - resonant conditions. In double disk arrangement (nominal window thickness in our case: 1.803 and 1.820 mm, resp.), Fabry-Perot resonances, which strongly depend on the disk separation, create a more structured spectrum (cf. Fig.4). Thus minimum reflection conditions are not only met for resonant thickness but also for distinct intermediate frequencies which can be selected by fine tuning the window separation. In order to cope with the typical frequency drift of high power gyrotrons (≈ 100 MHz), the basic disk separation had to be kept small (i.e. 5 mm) with a setting tolerance of about 10 µm over setting range of – 1 mm to 1 mm.

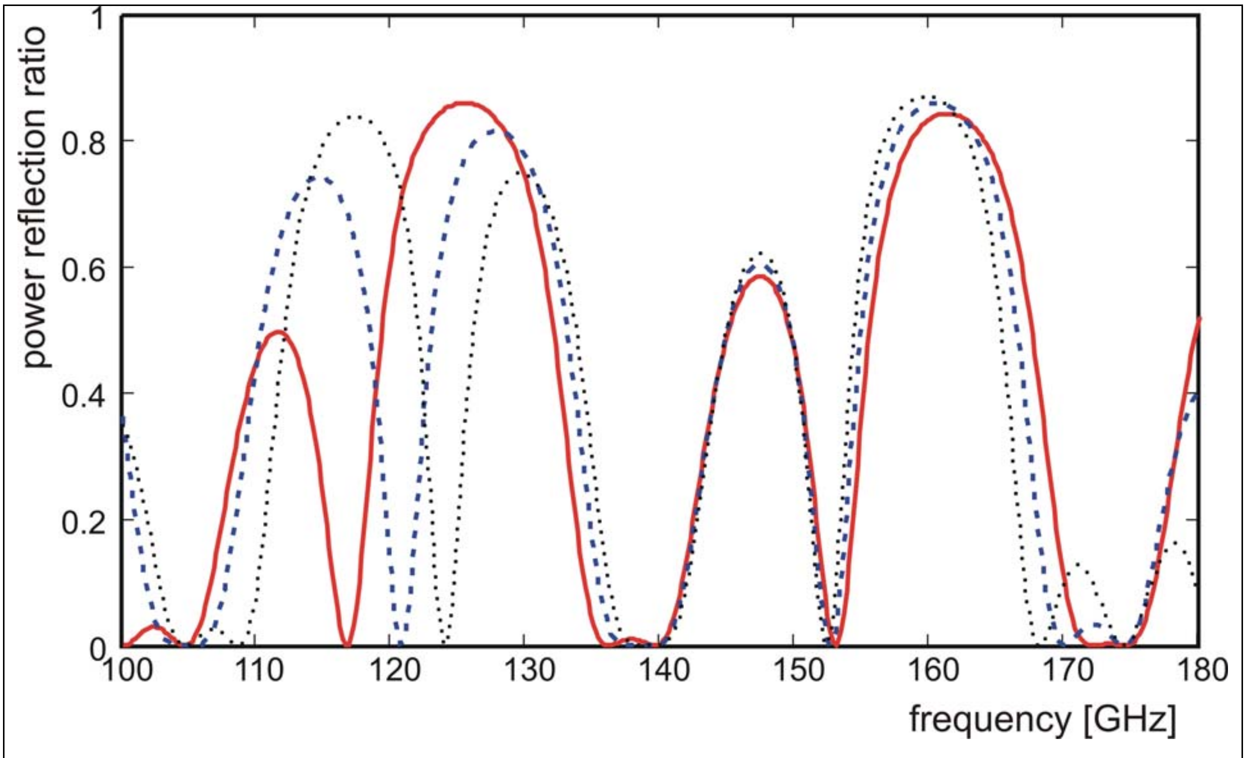

**Fig. 4 The power reflection characteristics of the double disk torus window for step-tuneable launcher at ASDEX Upgrade, calculated for the basic disk separation of 5 mm (dashed) and the minimum and maximum settings of 4 mm (solid) and 6 mm (dotted).**

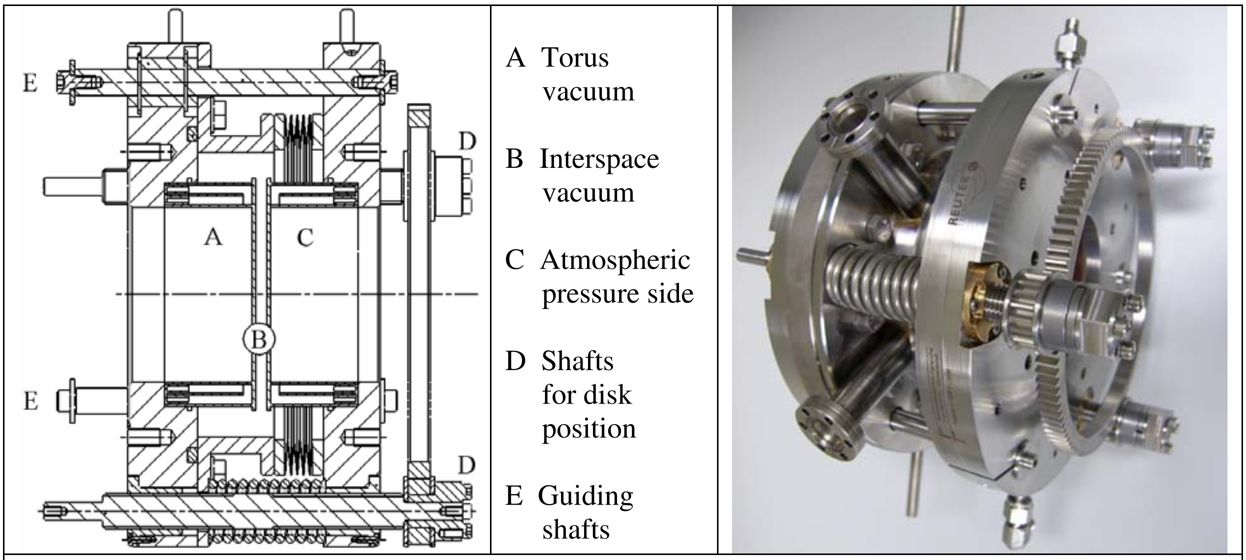

**Fig. 5: The tuneable torus window prototype shown as a cut-away (left) and as the manufactured window unit (right)**

The tight requirements for the disk separation can be satisfied by a novel direct face cooling cooling concept (cf. fig. 5). Essentially, the double disk window is composed of the two window structures and the housing. Each window structure consists of one diamond disk to which the two copper rings are brazed at one face (cooling cuffs) and which are brazed in a second step into a steel flange containing the cooling tubes and connections to the housing. The housing ensures fine tuneable adjustment of the window separation. Spring forces provide the counteracting mechanism to allow the displacement between vacuum and atmospheric pressure sides.

The original manufacturing was impeded by diamond failure before final brazing of the second structure which turned out to be caused by fitting of the not fully concentric shape of the inner and outer cuffs into the stainless steel flange. A design change in which the fitting area in the flange was taken over by a more flexible copper insert removed this critical issue. The manufactured tuneable torus window prototype fulfils vacuum conditions in the disk interspace (better $10^{-5}$ mbar) and water tightness of the cooling system and is presently under preparation of cold tests.

## 5. Tools for in-situ replacement of ITER torus windows

Automated cutting was successfully demonstrated at a dummy of the RS torus window prototype with a slightly oversized commercial tool TSS-NG 168 (cf. Fig. 3). Yet this allowed identifying the type TSS-NG 141 with a working area of 73 – 141.3 mm to be suited for the RS window design and the type TSS-NG 114 with a working area of 60 – 114 mm to be suited for the FS window design. The outer dimensions of the tools (220 mm and 193 mm resp.) exceed the diameters of the window housings by

100 mm and 90 mm resp., which means that a perimeter of 50 mm has be reserved around each window for giving access to the tool.

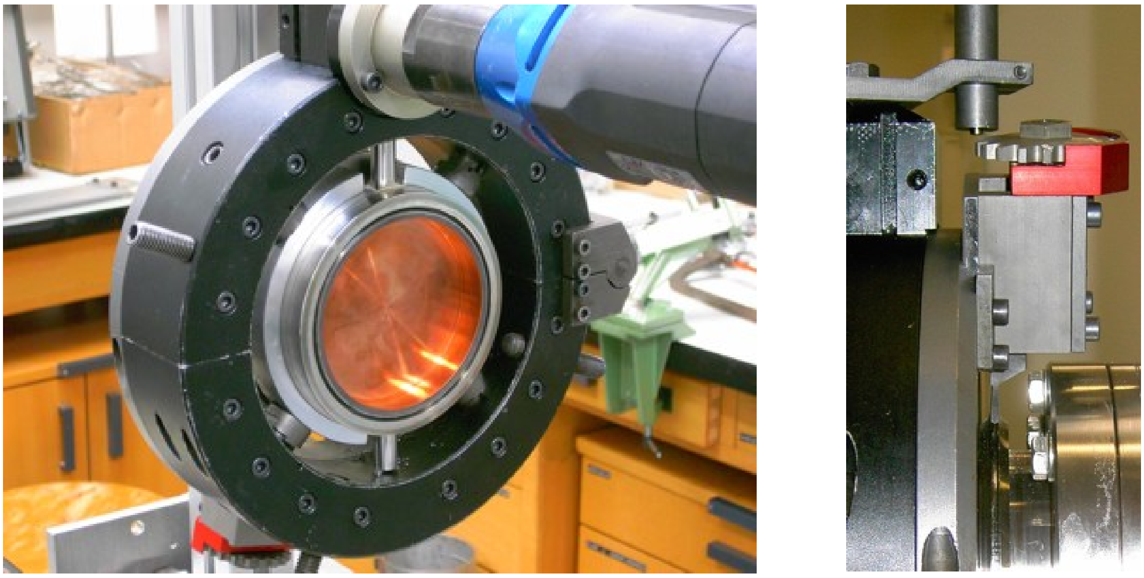

**Fig.6 A dummy window structure for the torus window of the initial RS reference laucher with positioned automated cutting tool(left) and the blade acting on the lip welding of the flange connection to the window socket (right)**

Tests of automated welding were performed with a modified commercial tube-to- sheet weld head (Model 96 of Arc Machines; Much, D). Following the goal of reducing the size of the window socket for the RS torus window in order to gain reserves for beam steering angles with respect to beam vignetting at the window housing, the welding area was shifted close to the window housing, for which a minimum attachment zone for the welding tool of 40 mm was to be reserved (cf. Fig. 7). Therefore a special modification was ordered at the tool manufacturer which was compatible with the tube-to-sheet configuration characteristic for the narrow joint of the window to the isolation flange (cf. Fig.8). Metallographic analysis of the welds showed that the best weld characteristics showed that the reliable welding depths down to 2.3 mm can be obtained. From the actual design of the “Γ” shaped lip, the potential for seven window replacements at the socket could be deduced which is fulfilling any reasonable ITER window replacement scenario.

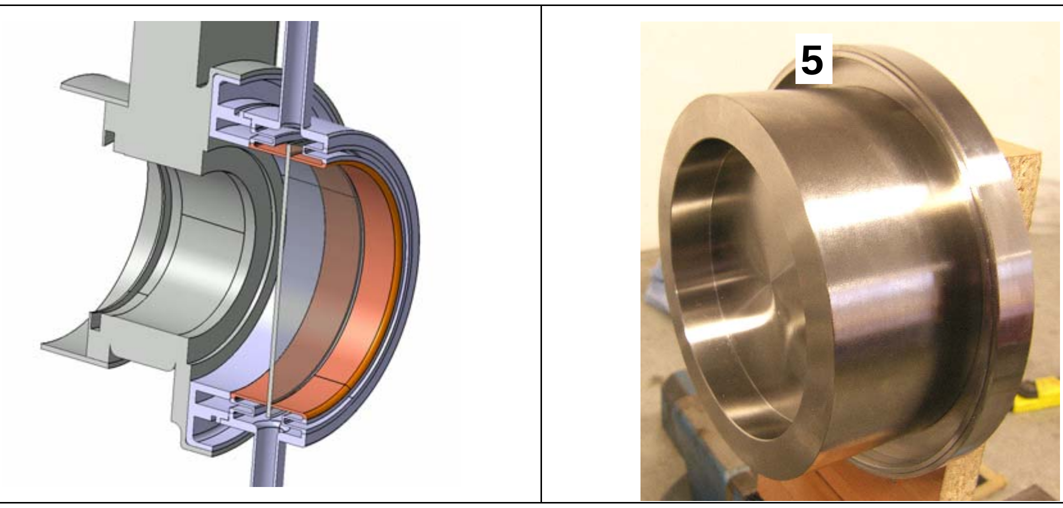

**Fig. 7: The RS torus window design with reduced distance to isolation valve/waveguide entrancence (left) and corresponding window dummy for testing of automated maintenance tools**

**Fig. 8: Adapted commercial orbital welding tool for the automated welding of Γ- shaped welds in the geometry adapted for the short socket version of the RS torus window**

### Summary and outlook

Prototypes of the high power windows were developed and manufactured successfully. In the course of the ITER torus window development, the prototype for the RS torus window was installed and tested in the high power / short pulse tests and it could be shown that the beam quality was not degraded by the torus window unit with respect to the beam amplitude and the Gaussian beam content over the full steering range of ± 12°. Alternatively cooling concepts (edge and indirect cooling) could integrated in first FS window prototypes, and the immanent experiments on the relative cooling performance are left over to decide on the final design of the FS torus window. The goal of reducing the size of the window socket could be achieved including the development of the related automated cutting and welding tools. The tuneable torus window prototype for ADSEX-Upgrade was realised on a double disk window configuration with a specialised face cooling that allows to achieve window separations of 4 … 6 mm. Cold tests are still to successfully conducted prior to its integration at the plasma experiment.

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