Main design features of the Rh-based first mirror developed for the ITER CXRS core diagnostics

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The ITER core charge exchange recombination spectroscopy, which contains five in-port optical mirrors, is intended to transfer the visible light emitted by interaction of the plasma with the diagnostic neutral beam to the corresponding spectrometers. The first mirror (M1) is a key and the most vulnerable component of the diagnostics. In order to provide the required mirror lifetime, maintainability and structural integrity, M1 is composed of special materials, i.e. it is made of a thin 1 mm single-crystal rhodium (ScRh) plate diffusion bonded to a specially matched WCu substrate. A rhodium nanocrystalline coating (NcRh) can be an option.

The main mirror features are:

-optical surface dimensions: 86 mm×170 mm; ScRh of 0.8÷1 mm thickness (≥10 µm for the NcRh coating if selected);

-adjustability with 3 (2 rotations and 1 translation) DOFs (degrees of freedom);

-cooling via mechanical contacts;

-the mirror is cleanable with about 100-500 procedures of 60 MHz plasma discharge.

The paper presents the evolution of the M1 design developed for the optical layout updated in 2018. The design is supported by multifield thermal, electromagnetic and structural analyses and uses experimental data of R&Ds made by Forschungszentrum Juelich, Germany. The study confirms the workability of the proposed mirror design.

Keywords: ITER, diagnostic mirrors, first mirror, mirror cleaning, single crystal rhodium, ScRh

1. Introduction

The first mirror (M1) is one of key components of the in-port ITER CXRS-core diagnostics (charge exchange recombination spectroscopy) located in the vacuum vessel upper port #3 and composed of a set of five optical mirrors transmitting the visible light emitted by the interaction of the plasma with the diagnostic neutral beam (DNB) to the corresponding spectrometers. The most vulnerable mirror is obviously the first one that is subjected to erosion and intensive impurity deposition.

The diagnostics layout front part is shown in Fig. 1. The layout updated in 2018 assumes that the M1 is attached to the front guard unit (FGU) ensuring operational mirror stability and minimal complexity of the remote handling maintenance. The pre-assembled M1&FGU unit is fixed to the upper port plug shielding module (DSM) which serves as an optical bench for the first three optical mirrors. The M1&FGU water pipes and RF&gas lines of the cleaning system and are also mounted on the DSM.

Due to the current M1 location near the first wall, the DFW (diagnostic first wall) has a considerable impact on both the M1 geometry and its assembly procedure. The M1&FGU design should take into account main generic DFW&DSM approaches like an access available, common assembly directions, gaps and the required neutron shielding.

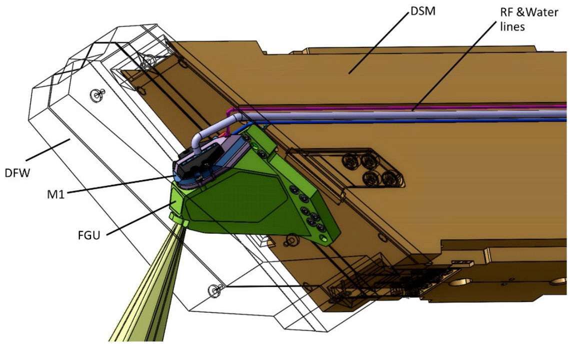

Fig. 1. Front part of the CXRS core diagnostics

The paper describes the most important M1 features implemented into the first mirror design allowing:

-successful integration of the M1 into the upper port plug (UPP) generic layout and the updated CXRS optical layout [1];

-high positioning stability provided with the mirror at the operation and dwell time;

-acceptable thermal & mechanical distortions keeping the project functionality of the optical system;

-proper structural capability under thermal, mechanical, inertial and electromagnetic loads;

-suitable resistance to erosion conditions including cleaning;

-compatibility with a cleaning procedure (RF induced plasma discharge of 60 MHz);

-highest reliability level.

The M1 design proposed is based on the concept of an indirect cooling via mechanical contacts with insulation pads. Preliminary thermo-mechanical analysis has confirmed the feasibility of the mirror concept. Main results of the analysis and specific R&Ds performed have been included also in the paper. However, it is to be noticed, that physical and dielectric properties of AlN and/or Shapal Hi-M ceramics damaged to ~0.3 dpa have to be specified and taken into account more precisely in the future.

2. Main mirror design preconditions

The evolution of the CXRS-core first mirror design is based, in general, on the following background:

• M1 lifetime	20 years (with cleaning)
• Assembly precision	<±0.1 mm, <±0.1 mrad
• Allowable distortion at operation	±100 fringes (±31.6 um)
• M1 positioning tolerances	<±0.2 mm, <±3 mrad
• M1 positioning operation stability	<±1 mm, <±1.5 mrad
• Remote handling category	ITER RH class 2
• Mirror cleaning data:	
-Plasma discharge	60 MHz, 1 kW max.
-Electrical insulation	2 kV
-Working gas, pressure	Ar and ~10% H_2, H_2 and~20% Ar; 1÷6 Pa
-Voltage U_{BIAS}	~100 V
-RF line impedance	<50 Ohm

Despite the fact that the single crystal molybdenum (ScMo) is widely used in ITER first mirrors design of other diagnostics, a single crystal rhodium (ScRh) is proposed as a reference material for the CXRS first mirror [2,3] since a high transmission of the optical system is essential.

Moreover, the ScMo and ScRh comparative test [4] and DSRM (Doppler-shifted reflectance measurements) of Rh mirrors [3,5] performed at FZJ (PSI-2 facility) have confirmed a suitable sputtering resistance of ScRh and the indispensable property that the specular reflectivity of Rh does not degrade at high temperature levels.

The crystal orientation is not defined finally yet. If a ScRh plate selected, the candidate crystal orientations can be [111] and/or [110] ([3,6]).

A rhodium nanocrystalline coating (NcRh, thickness ≥10 μm) can also be an option, if its feasibility is demonstrated and the corresponding testing is performed.

Main concern about the bulk Rh using was a significant decay heat of 30 W/cm^3 [4]. KIT neutron analysis performed precisely for ITER 500 MW plasma scenario predicts the considerably decreased average Rh decay heat of 1.23 W/cm^3 and the total nuclear heating of 1.1 W/cm^3. A thicker plate can be used, if required (from the functional or technological points of view, for example). The average neutron heating of other mirror structural materials is in the range of 0.42÷1.55 W/cm^3.

Another item influencing both the mirror performance and the lifetime is particle fluxes coming from the plasma. The incident neutral particles flux, which reaches the M1, has been estimated by the Monte-Carlo and EIRENE codes at FZJ. The calculated incident heat flux due to D/T atoms on M1 is relatively low and varies from 0.05 to 1.2 kW/m^2 depending on the mirror surface location and plasma scenario.

3. Main mirror development results

The developed CXRS first mirror design, shown in Fig. 2, is composed, in general, of the integrated M1 unit and the supporting flange.

The first mirror assembly is fixed to the top of the FGU (Fig. 1) providing the mirror with the required positioning stability. The fixation is done via a supporting flange (Fig. 2) with the help of a bolts/pins interface ensuring the repeatability of the FGU&M1 relative positon. The proposed approach provides the possibility to repeat the mirror initial position after disassembly without the mirror re-adjustment.

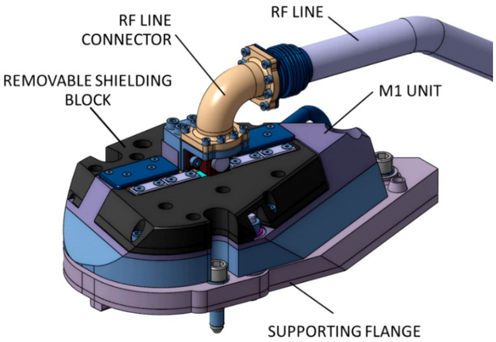

Fig. 2. CXRS-core first mirror

A set of three spacers with spherical joints is used for the connection of the M1 unit to the supporting flange providing the required M1 adjustment capability (Fig. 3). The spherical joints allow the required mirror rotation around the mirror middle point. Additional translation in vertical direction can be achieved by fitting the spacer's thickness.

Taking into account the results of [2], a special attention is paid to the mirror distortion, which, in general, is a sum of mechanical and thermal components. The first member is minimized by elimination of structural overconstrain (the classic 3 points attachment mentioned above). The second part is the mirror thermal distortion which is minimized by means of an adequate match of the thermal expansion coefficients (CTE) of the reflecting and substrate materials. The CTEs adjustment is verified with dedicated R&Ds made at FZJ (see below).

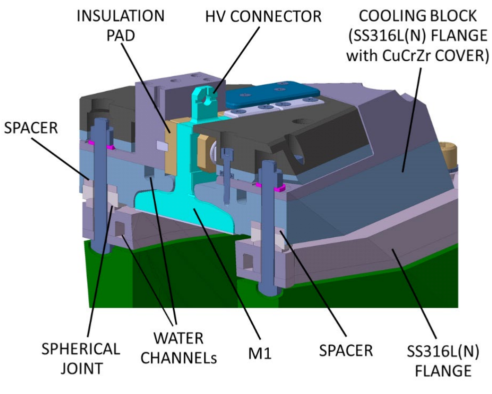

Fig. 3. First mirror assembly cross-section

Finally, the mirror itself is designed of a substrate made of WCu (W(80%)/Cu(20%) wt.) composite with bonded reflecting layer made of thin ScRh plate of 0.8÷1mm×86mm×170mm (Fig. 4). Because of the unconstrained thermal expansions of the bonded part, residual stresses in the substrate after bonding can be neglected.

WCu composite is selected due to the following useful material properties: the proper CTE, good dimensional stability, high thermal conductivity and good machinability [9].

The mirror substrate (Fig. 4) is a part electrically insulated from the ground to 2 kV during cleaning, and it is grounded during ITER plasma operation. Where no direct contact is present, a gap of 1÷2 mm is provided all around (Fig. 3).

The proposed mirror design is robust, and allows to use both the single-crystal and nano-crystalline approaches.

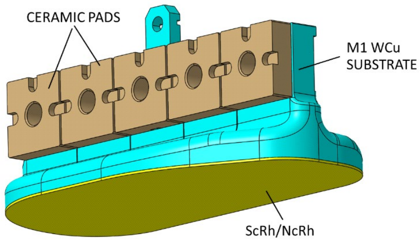

Fig. 4. M1 substrate with ScRh layer/NcRh coating and ceramic pads

The substrate is attached to the cooling block with the help of AlN-based ceramic pads (AlN or Shapal Hi-M ceramics of 10 mm thickness). In order to achieve reliable thermal mechanical contacts, the pads are arranged in the direction perpendicular to the hottest mirror surface.

The cooling block is made of stainless steel 316L(N)- IG to provide the structural integrity and bonded CuCrZr cover to ensure an adequate mirror cooling capability. The cooling block is cooled by a water running through the channel formed in the holder steel plate.

The cooling water is supplied by the UPP diagnostic water loop. In order to simplify the water flow, the M1 and the FGU have series of water interconnections. In order to minimize M1 maximum temperature, the coolant comes at first to the M1 assembly, and then, it goes to the FGU.

The expected maximum temperature of the mirror under neutron heating is ~182°C (Fig. 5). The estimated irregularity of the optical surface is not exceeding 8.7 μm, which is far below the limit indicated above.

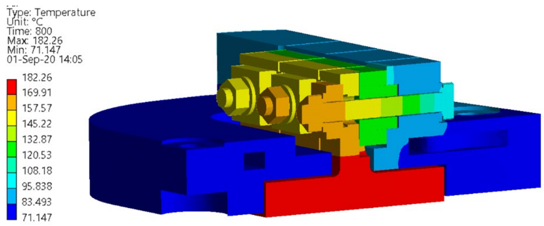

Fig. 5. Mirror temperature distribution under neutron radiation, °C

The RF feeding line of the cleaning system is out the consideration here. However, in order to define preliminary the interface between the M1 and the RF line, a special RF connector is developed (Fig. 2). It is composed of inner and external conductors, i.e. a high voltage (HV) copper inner line (pipe of ~d8 mm) laid inside the Cu coated Shapal Hi-M ceramic elbow. It can be connected via bellows to a Spinner-like rigid RF line (EIA 7/8'') [7] keeping structural integrity.

The coupled-field analysis results show that due to difference in the thermal expansion of the substrate, insulating pads, cooling block and bolts, the initial bolt preloading is partially reduced during operation and baking. One can see (Fig. 6) that the initial bolt preload of 20 kN is lost by ~23 % with the repeatedly applied mirror heating (Fig. 6).

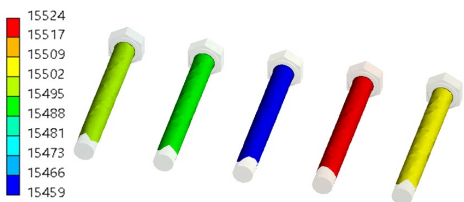

Fig. 6. Bolt preloading degradation during operation, N. Initial preload is 20 kN

It is not a critical point for the current heating intensity, but such kind of structure can require the use of spring disks if the mirror heating is above ~350°C.

Due to the heating, the average pad's contact pressure of 25 MPa goes down to ~20 MPa. The coupled-field analysis shows that, in spite of the mirror thermal distortion and degraded preloading, the required contact areas and relatively high contact pressure (Fig. 7) are kept during structure operation.

In order to verify and confirm the materials selected for the mirror substrate, the measurement of the CTE values have been performed in the temperature range of 20°C÷900°C.

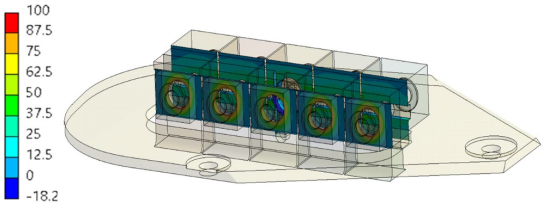

Fig. 7. Ceramic pads mechanical contact pressure distribution at operation, MPa

Dilatometry was used for determination of the relative elongations of bulk W and WCu specimens. The corresponding thermophysical data of Rh [8] and the comparative thermal expansion testing results are summarized in Fig. 8.

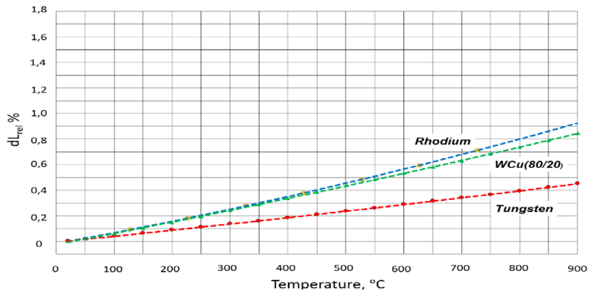

Fig. 8. Comparative data on the thermal expansions of M1 substrate materials

One can see that the temperature elongations of Rh and WCu materials match to each other. It does confirm the expected thermomechanical compatibility of the selected mirror materials.

Another issue of the mirror approach is the reliability and mechanical feasibility of the interconnection between the ScRh plate and WCu composite. The best connection was achieved by means of a diffusion welding. ScRh and WCu samples (disks of ~d20 mm) were bonded by applying a uniaxial pressure of 100 MPa at 700°C during 180 min.

Focused ion beam (FIB) and metallography examination results, shown in Fig. 9, indicate the high quality of the bonded connection. It is to be noticed that the used joining parameters have been also defined to avoid a single crystal recrystallization which was checked after the bonding.

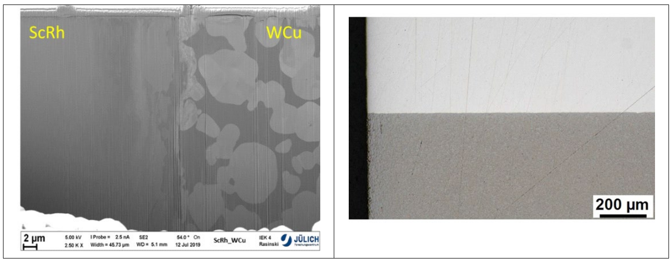

Fig. 9. Results of FIB (left) and metallography (right) examinations

The mechanical properties of the joint were verified with a shear test. The test of 10 samples performed at room temperature reveals an average shear strength of the joint of 233.3 MPa. Such positive test outputs confirm the high quality of the performed ScRh/WCu connection.

4. Discussion and conclusions

-The updated CXRS-core first mirror design basing on the use of ScRh plate bonded to a special WCu substrate is shown with highlight of its key features. The results of the analyses confirm the perfect feasibility of the mirror design.

-The mirror is attached with the required adjustment of 3 DOFs (two rotations and one translation) providing after exchange the recovered initial mirror position without readjustment.

-The developed design is compatible with in-situ repetitive cleaning. The mirror is supplied with the required insulation, gaps and RF feeding line connector.

-The best ScRh/WCu joint is achieved with diffusion welding resulting in the average shear strength of 233.3 MPa.

Several issues are still to be verified/confirmed with special R&Ds:

-Absence of an arc/discharge formation in the gaps and at the mirror backside;

-Contact ceramic surfaces in terms of wearing, especially, the contact surfaces with WCu part. The use of disk springs and an interstitial layer;

-The bonding with a uniaxial pressure and/or HIP (high isostatic pressure) with the use of large-scale samples of WCu and ScRh.

Acknowledgments

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