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EC22

Appearance and analysis of a reflecting coating damage

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Abstract. Eight reflecting gratings are installed into the plasma facing wall of ASDEX Upgrade (AUG) in order to provide a controlled second pass through the plasma centre in 140 GHz heating scenarios with reduced single pass absorption. Four of these gratings are machined out of W1.4901 steel and coated with tungsten to increase the reflectivity. During plasma operation three of them worked very well, only one showed a strong correlation between the launcher On-time and an unusual increase in plasma radiation. After completion of the 2022 experimental campaign, this tile was carefully inspected. Traces of local melting were visible and the tile was examined with a scanning electron microscope to determine the surface material composition. The image of backscattered electrons revealed that tungsten is missing locally and along some of the ridges of the complex topology of this grating. Within these areas, the steel surface started to melt, which is in accordance with the assumption, that an intact tungsten coating indeed prevents the steel from melting. The damaged tile is currently being replaced and we have implemented two measures in order to prevent such damage on the new tile. The first measure is to consequently finish all machining steps before the coating procedure. This is because a mechanical damage of the coating before the installation could not be ruled out. The second measure is to control and minimize the surface roughness after machining and before the coating procedure. It turned out that the roughness was up to 3 microns in the past, which seems to be too high for the desired quality of this particular coating. We have tested and developed an electropolishing procedure to decrease the surface roughness to the order of 1 micron and keep the grating topology as precise as possible.

1 Introduction

For the typical experimental situation at ASDEX Upgrade (AUG) and using a launched wave frequency 140 GHz, using O-Mode 2nd harmonic (O-2) polarization (B_0=2.5 T) can be beneficial, because it allows one to operate at plasma densities significantly above 10^{20} m^{-3}, at the cost of reduced single pass absorption [1], however. The O-2 absorption can be optimized with the launching angle [2] and it depends on the electron temperature T_e. At AUG it may be necessary to implement a start-up procedure in order to achieve high enough T_e of the order of a few keV, before the O-2 mode heating can be applied efficiently. The absorption is then routinely evaluated with the TORBEAM code [3].

In order to handle the shine through, reflecting gratings [2,4] are installed on the Heat Shield, i.e. the plasma facing wall on the inner column of AUG. The gratings are designed to refocus the beam and redirect it for a second pass through the plasma centre, from the high field side towards the low field side. Altogether, this two-pass scheme significantly increases the total absorption [4], further passes are usually neglected. All AUG electron cyclotron resonance heating (ECRH) launchers are now equipped for this scheme [5]. The gratings are coated with tungsten in order to increase the reflectivity. Two of them, machined out of graphite and tungsten coated, are in service since 2009. Two similar gratings came into operation in 2017 and 2018, and they do not show degradation.

The four gratings, which were installed more recently in 2019 and 2020 are machined out of W1.4901 VWHHO ³3´ IXOO QDPH-2) ;and &U:0R9 coated using a molybdenum interlayer (thickness d_{Mo}=0.5 µm) and tungsten (d_W=10 µm). The decision to use this particular steel on the Heat Shield was part of a material research program. Three of the coated steel gratings to date do not show traces of degradation. Th UHPDLQLQJ RQH µ5¶ UHIOHFWRU IR will be discussed in the following, was used in the campaign 2020/2021 normally, but showed unexpected behaviour in the 2021/22 campaign.

2 Experimental setup and observations

For the two-pass configuration and geometry of all AUG ECRH launchers, as well as overview and general visualization, please refer to [5]. In figure 1 we show the two gratings, which are designed to handle the shine through of the double launcher in AUG segment 14.

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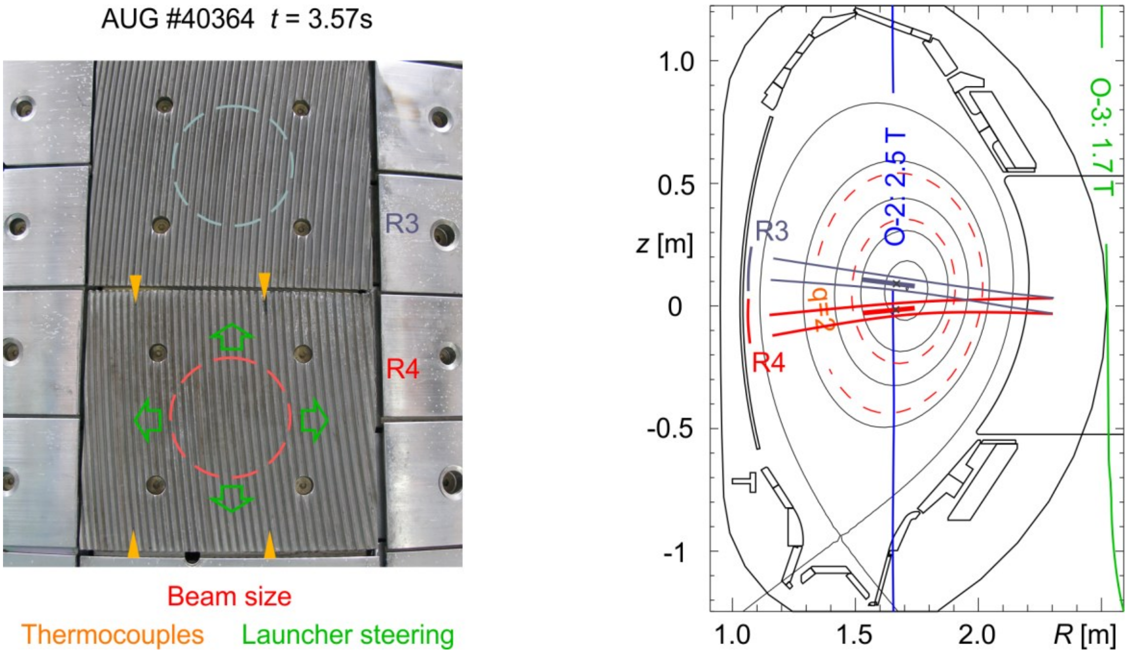

Fig. 1. Left: Reflecting gratings R3 and R4 mounted on the AUG Heat Shield. Right: Schematic AUG vertical cross section visualisation of beams propagating towards R3 and R4 [3]. Absorption zone (O-2) near the center of the plasma (cf. contour lin Simulated shine through beam size and steering/ranges possibilities are indicated in the photo on the left by coloured arr

2.1 Single-pass model beam propagation

The size of the model shine through beam in front of the grating R4 can be approximated with a Gaussian beam radius $w=4$ cm, based on TORBEAM [3] simulations. The maximum intensity in the centre of the model beam is $I_{max} = P_S / (\pi w^2/2)$ where P_S is the total shine through beam power. In order to give an overview of intensities just in front of the grating, and function of T_e in the absorption zone, Table 1 shows simulation results of AUG experiments, where O-2 was used.

Table 1. Single pass shine-through simulation [3] for beam-line No. 4 in various AUG experiments, sorted by T_e in the absorption zone. I_{max} was evaluated near the grating R4 and assuming a Gaussian beam width $w=0.04$ m.

AUG # shot N° time	T_e [keV]	Launched [kW]	Shine through	I_{max} [MW/m^2]
#40364 t=3.57s	4.4	750	25%	74
#40422 t=2.88s	2.4	790	41%	129
#40422 t=3.01s	2.2	790	44%	137
#40422 t=3.08s	1.25	790	61%	190
#40422 t=3.14s	0.8	790	75%	236

Assuming a shine through intensity of 100 MW/m^2 on average together with a maximum AUG pulse length of 10 sec, the beam energy per area may reach up to 1000 MJ/m^2 locally. For uncooled steel we use a maximum energy limit of 6 MJ/m^2, which corresponds roughly to $\Delta T = 1500$ K and a thickness of $d = 1$mm.

Comparing the energy limit with the beam energy, it becomes clear that the beam absorption << 1% is mandatory at the reflecting surface. In literature and for a given frequency of 140 GHz we find values in the UDQJH « IRU VWHHO > @ DQG tungsten [7]. This is why we consider the tungsten coating essential.

2.2 Experimental findings

We regularly check the two-pass heating scheme by using launchers with O-2 mode polarization one after the other in a 1 MA plasma discharge. The thermocouple response on the appropriate reflecting grating can be used to verify the consistency of the beam steering. In one of these tests (AUG #40422) we noticed very strong plasma radiation, correlated with the operation of launcher 4 in O-2 mode (figure 2). It could be verified that the increase in plasma radiation was due to an increasing tungsten content. The total plasma radiation surpassed the total heating power, so that finally the plasma cooled down and terminated. After this incident we suspected a coating damage on the reflecting grating R4 and did not do any further experiments with shine through on this reflector.

2.3 Annual in-vessel inspection

When the experimental campaign 2021/2022 ended, the reflector R4 was inspected. A droplet of melted material was visible on the top of one ridge near the lower left mounting hole. Photographs of this grating, before and after the damage occurred, are shown in figure 3. The reflector was removed and brought into the laboratory for further investigation.

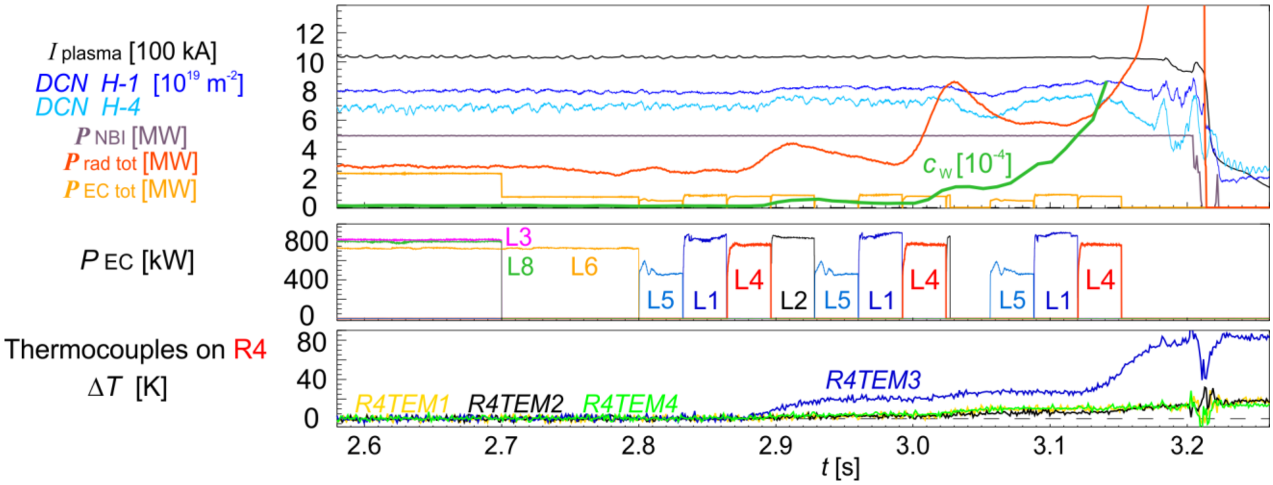

Fig. 2. AUG experiment #40422, March 11th 2022. In the beginning, three ECRH launchers (L3, L6, L8) with X-2 mode heating, a 5 MW of neutral beam injection (NBI) were used. The line integrated interferometer signals (DCN) indicate, that the plasma densit is indeed around 10^{20} m^{-3} (sightline length approx 1m, flat profile). At t=2.8s all X-2 mode heating is switched off and four launc with O-2 mode heating are tested one after the other. The significant rise in the total plasma radiation ($P_{rad\,tot}$) correlates with th operation of launcher L4 only. The tungsten content c_W of the plasma rises from 10^{-5} in the beginning up to 10^{-3} at t=3.15s. One of th thermocouples (R4TEM3) indicates a significant local temperature rise on the grating (R4) (rate approx. 1K/ms at t=3.15 s).

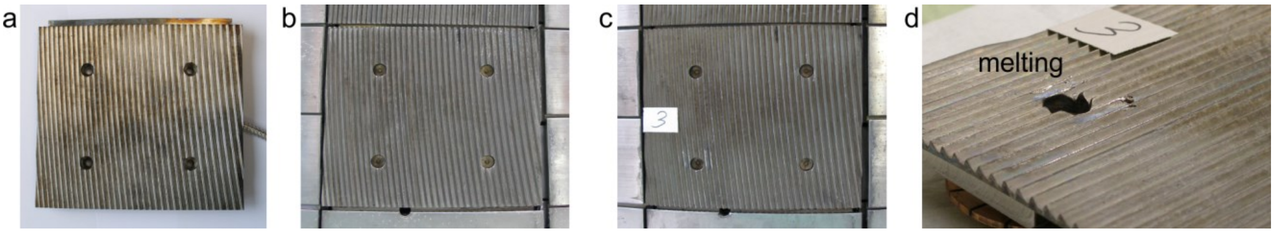

Fig. 3. Photos of the reflecting grating R4: a) July 2020 before first installation, b) August 2021, after the 2020/21 cam c) September 2022 in the vessel, d) in the lab, zoom of damaged region.

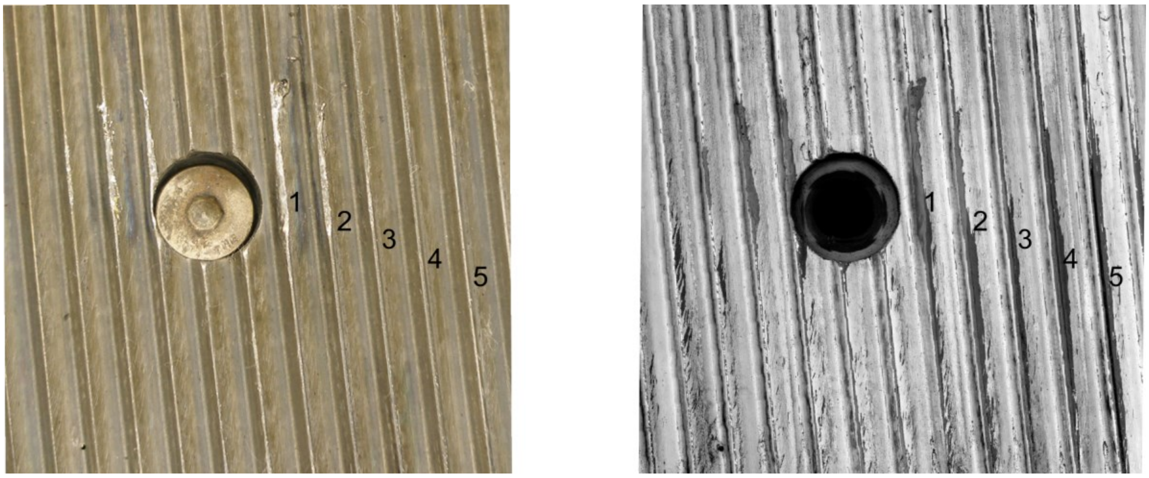

Fig. 4. Photograph (left) and image of backscattered electrons (right) of the damaged region. The contrast (right) ref material composition: bright areas are tungsten covered, darker areas are without tungsten. For orientation, the ridges of t are labelled with numbers, starting near the mounting hole. Obviously, the coating is missing in stripes, elongated along t ridges.

3 Surface analysis

The melted droplet (figure 3d) was removed and the tile cleaned. In order to measure the material composition on the surface, the tile was investigated with a scanning electron microscope and an imaging technique for backscattered electrons was applied (figure 4).

Tungsten is missing along the top of several ridges. It is not possible to recognize this in the visual inspection. Some of the labelled ridges (figure 4) were examined more closely, namely the 4th ridge (figure 5) and the 2nd ridge (figure 6), where melted zones, zones without tungsten and zones with tungsten are very close together. Energy dispersive spectroscopy was applied in order to identify particular elements (cf. figure 6).

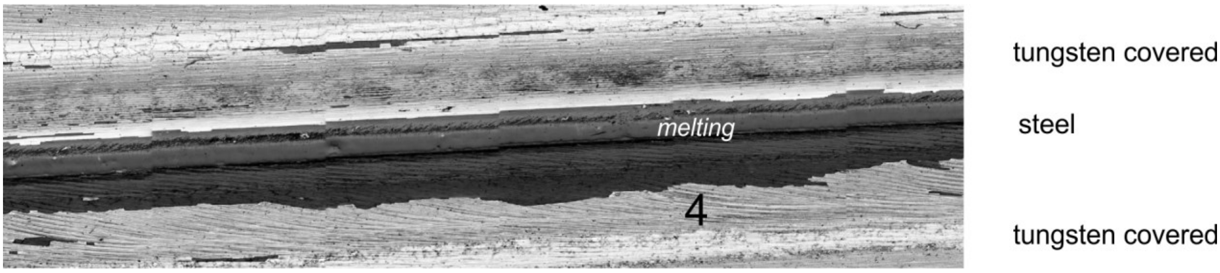

Fig. 5. Image of backscattered electrons: zoom on 4th ridge from figure 4 right, rotated by 90 deg. The steel started on the top of the ridge, where the tungsten coating is missing.

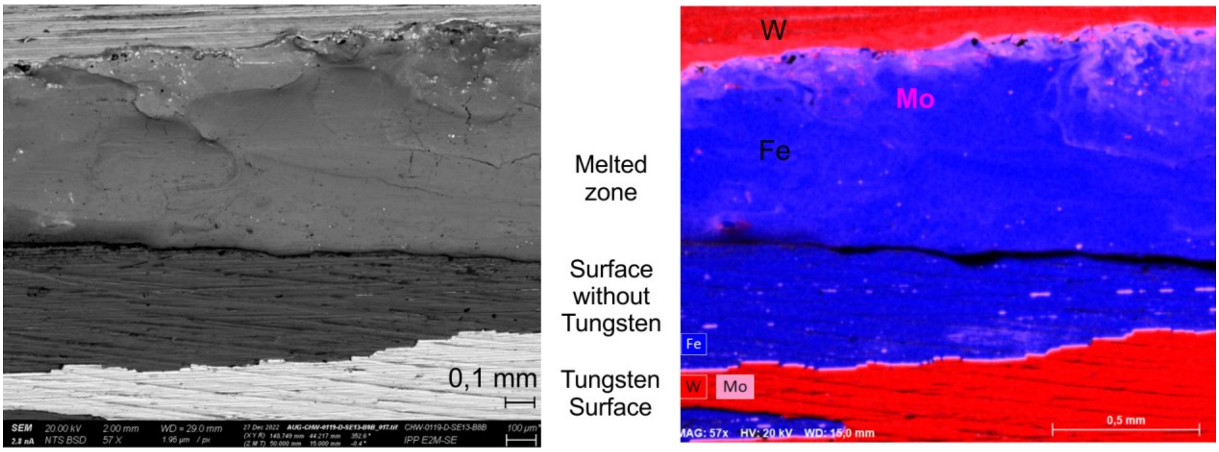

Fig. 6. =RRP RQ WKH ULGJH RI WKH JUDWLQJ QHDU SRVLW-scattered electron Right: Principal component on the surface, identified by energy dispersive spectroscopy (EDS). The molybdenum interlayer visible at the edges, where the tungsten came off.

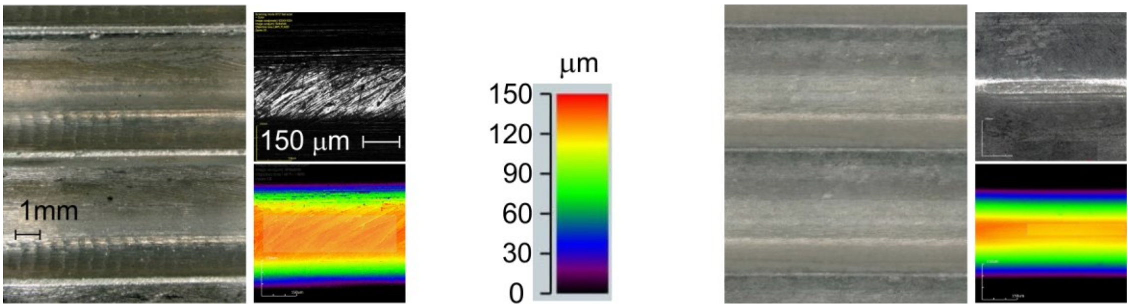

Fig. 7. Roughness Ra Before and after the electropolishing procedure. Left: Overview on a region containing thre ridges and exemplary zoom on the top of one ridge (small photo on top). The contour plot below visualizes for the roughness measurement. The measurement is done in a region, where the ridge top is approximately planar. Measurement result Ra = 3 ± 0.5 µm (unpolished).
Right: Electropolished grating. The regions on the tile are not exactly the same as on the left, but it is clear surface roughness has changed. Measurement Result Ra = 1.2 ± 0.5 µm (electropolished).

4 Discussion

We discuss a probable explanation for the given observations: The steel surface was exposed on some of the ridges, due to an initial and possibly mechanical damage. In one of the experiments, probably #40364 with significant shine through, the steel started melting, at first unnoticed during the operation. At the edges of the melted zone the coating lost stability and adhesion and it was removed by the heating in #40422, this time with a highly visible fingerprint in the spectroscopic measurement systems of AUG.

With respect to future improvements: the risk of an initial damage and adhesion have to be discussed. A strict finishing of all machining steps before the coating process should reduce the risk of accidental damage. Adhesion in general can be improved by avoiding strong curvatures ($r < 1$ mm). When discussing the adhesion of this particular coating with a thin molybdenum interlayer, the surface roughness may play a role. A direct tungsten coating on steel is not favorable. The original roughness is larger than the thickness of the interlayer. A surface roughness smaller than the interlayer thickness is desirable.

5 Outlook and possible improvements

We could reduce the surface roughness by treatment in an electropolishing bath (for stainless steel). Using different samples, we tested for the onset of a measurable polishing effect in order to preserve as much of the grating structure as possible. Our conclusion was to use a treatment time of 2 min, and a current density of 6 kA/m^2 (applied voltage 20V). The result on a new tile can be seen in figure 7. We note that the surface is not planar and that the roughness measurement Ra as given in figure 7 is, therefore, an upper limit. This newly prepared tile is intended to replace the damaged R4 in the upcoming experiment campaign.

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