Boronisation research plan

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December 24, 2024

1 Short overview

Amount	kind of samples	need	project	TOMAS days
12	hydrogen doped graphite	Test ICWC vs ECWC	W7-X	12
6	hydrogen doped boron-coated graphite			
2	boron-coated graphite			
12	Boronized tungsten, doped with deuterium	test efficiency of IC vs EC vs GD	ITER	12
4	Pure tungsten, doped with deuterium			

2 Scientific relevance and reasoning

W7-X

Glow discharge in H_2 plasma and ECWC in He plasma have been actively used on W7-X to condition the wall and it's effects have been reported ([2],[4] and EUROFUSION WPS1-PR(16) 16175). However, ECWC is only able to deposit power near the fundamental, as such the EC wall conditioning is inhomogeneous. ICWC shouldn't have this kind of shortcoming and should provide a more efficient cleanup[3]. as a preparation to the eventual usage of ICWC in W7-X it should be investigated how ECWC and ICWC compare both in outgassing from pure graphite and from boron-coated graphite (as both are possible PFMs in W7-X). To this end baseline ECRH experiments need to be carried out on TOMAS, as well as ICWC experiments to compare to as to draw conclusion to W7-X.

ITER

It has quite recently been decided that ITER will not have a Berillium wall but a tungsten wall, experiments have been carried out at JET with an "ITER-like wall"[1] which was, at the time, a Berillium wall. The author is unaware of any published wall conditioning experiments carried out on tungsten walls, as such

the proposal is to compare all 3 ITER available wall conditioning schemes using both boronized tungsten, as regular boronization will be done. As well as pure tungsten experiments to gain information on de-trapping of exposed tungsten.

3 TOMAS setup and days estimate

3.1 W7-X

As mentioned in EUROFUSION WPS1-PR(16) 16175, ECWC outgassing follows a time law, this law needs to be measured on TOMAS to show that it is equiped to compare IC and EC, after which the same kind of experiment needs to be carried out to determine the IC time law and scale difference. To get a W7-X relevant condition, the IC frequency will be set to 38MHz, mimicking the minority heating and the second harmonic heating scenarios. The power level will be kept as high as possible whilst the electron density will be kept to the one observed at W7-X (reflectometer measurements), the plasma species will be Helium to have a more distinct signal from the removed hydrogen.

The exposures will all keep these same settings and vary in time to make a time-outgassing relation possible. 6 samples will be used to do the EC discharges, grouped as 2 each to make error estimation possible. After which 6 samples will be used to do the IC discharges.

As W7-X also boronizes their walls (monthly), IC experiments will also be carried out on 6 boronized graphite samples. as the EC-IC relation should already be established from previous experiments, this should give additional insight into the de-trapping efficiency of boron. As the rapidity of boron erosion under plasma operation is still an open question, this will also be measured using the remaining 2 samples.

3.2 ITER

6 Boronized tunsten samples will be used for ICWC estimates, 4 for ECWC estimates

4 Thickness and density estimation

We wish to know how the various wall conditioning schemes affect the boronized PFM, to this end we need to know both the thickness of the boron layer before and after the exposures, as well as it's density. We want to know the density as to see how it is dependent on the substrate and to infer how many atoms got sputtered.

4.1 Boronized Tungsten

My proposal for measuring the thickness of the boron layer is to use three methods, the first two methods concern a general estimate of the thickness

whilst the third would be sample-specific. We first half-coat one sample by applying sticky tape during coating and peeling it off afterwards, enabling the first method: the use of a profilometer to determine the jump in height. The second method which we'll also apply on this half-coated sample is the use of a SEM either by drilling small holes in the coated surface and determine the thickness that way or looking at the side of the sample. The third method is to use the ellipsometer in the mirror lab, this last method is also what we'll be using for the normal samples, it is however good to have many thickness estimates of the half-coated sample as we'll need it later and as it's a good check to see if the ellipsometry measurements are accurate. Note that most of these techniques (especially the ellipsometry) will only be possible if the tungsten surface is polished properly.

To now measure the density we'll perform ion beam analysis on the half coated sample. To see how this works, please allow the following train of thought: After analysing the experimental data from the IBA (ERDA) we'd know that there are x amount of B^{10} atoms per cm^2 and y amount of B^{11} atoms per cm^2 on the surface of the sample, using the mass of both of these isotopes and the measured thickness (of which we have 3 independent measurements), we can infer the density:

$$\rho = \frac{1}{d \times 1cm^2} \left(x \times \text{massa } B^{10} \text{ isotope} + y \times \text{massa } B^{11} \text{ isotope} \right) \qquad (1)$$

Assuming this density to hold for the other samples, we can infer how many atoms were sputtered from the change in thickness which we'll measure using ellipsometry.

4.2 Boronized Graphite

My proposal for measuring the thickness of the boron layer on graphite would be to use two methods, we'll also be using the half-coated sample enabling the use of a profilometer. The second method which we'll apply in conjunction is by using the ellipsometer in the mirror lab, note that the SEM wouldn't be able to see the difference between carbon and boron and is thus not possible to use here. We then proceed as mentioned for tungsten, inferring the density using IBA.

5 Doping estimation

As we'd later want to measure the outgassing efficiency of the various wall conditioning systems, we'd like to dope the samples with some atoms (e.g deuterium) and measure the concentration before and after the various wall conditioning schemes. We'll probably measure these concentrations using ERDA.

6 Exposure: Erosion rate

We'd like to expose the samples to either hydrogen, helium or mixed hydrogen and helium. Each under different wall conditioning regimes, either Glow Discharge, Ion Cyclotron Wall Conditioning, Electron Cyclotron Wall Conditioning or ICWC and ECWC at the same time. We'll first do some spectroscopy to see the amount of impurities in our plasma (if any are visible, our spectrometer is quite low-resolution). And then expose the pure boron to test the erosion rate with different powers.

6.1 ICWC

In TOMAS the IC creates both neutrals and ions, mostly with energies below 1keV. The frequency at which we may couple is still uncertain, ideally we'd like to go as high as possible which would be a 50MHz plasma, but for now we were only able to go up to 42MHz. As magnetic field we will use 0.114T (2000A input current) and power-wise we'd like to do a ramp, with values 1500W, 3500W and 5500W of injected power. Limiting the pressure to 10^{-4} mbar during the discharge of the 1500W, maintaining the same base pressure (not the neutrals pressure) for the higher powers. I.e when the penning gauge indicates 10^{-3} mbar without IC and 10^{-4} mbar with IC at 1500W, we'll be doing 5500W for the same 10^{-3} mbar gas (however this system is still under consideration). Whilst the powers we'll use are very small compared to larger devices, due to the way everything is measured, as will be mentioned, it might be possible to extrapolate to bigger devices. ICWC at TOMAS is a monopole working in a mode conversion scheme, as such most of the particles evenly spread to the wall. This enables us to extrapolate measurements performed by the RFEA (retarding field energy analyser,able to measure the ion distribution) and ToF-NPA (Time of Flight Neutral Particle energy Analyser, measure neutral distribution) to the full vessel and use it as a prediction on how the sample will be eroded. Unfortunately the retarding field energy analyser (RFEA) seems to have some hickups for the moment when doing IC discharges which we'll try to fix over the next couple of weeks. If it's not properly fixed when experiments are carried out, we will have to either rely on simulations to determine the amount of ions and their energies in the plasma or correlate the electron density and temperature to the ion density and temperature (if at all possible) or correlate the neutrals to the ions (e.g assuming pure charge exchange).

6.2 ECWC

Efficiency of ECWC for fuel removal has been less investigated in current devices but as it will be used for conditioning in JT-60SA and W7-X, there is an upsurge in interest. We don't expect any 10eV< energy neutrals, as such the main player of outgassing and erosion will be ions. As mentioned we either need some kind of RFEA measurements to estimate the erosion rate/simulate or somehow correlate the electron density and temperature to the ion density and temperature.

6.3   ECWC+ICWC

These sometimes are used in conjunction, so we'll also do exposures with these, note that the erosion rate will drastically increase. The max combined power should be around 11kW of injected power, we may scale as: 1.5kW EC + 1.5kW IC, 3.5kW EC + 3.5kW IC, 5.5kW EC + 5.5kW IC, or total = 3kW, 7kW and 11kW of power. We have tested 10kW already so this all seems possible. I'd do the combined erosion after the IC and EC as we'll have a more concrete idea of what to expect.

6.4   Glow Discharge

Even though GD is falling out of favour due to superconducting magnets not being easy to turn off, we'll do some exposures if time permits, with the same pre-measurements as IC.

7   Extrapolation to larger devices

If we can simulate the particle flux, using e.g a modified version of the tomator code, and the thus implied erosion using a BCA (Binary Collision Approximation) code such as rustBCA, we might be able to verify the erosion prediction and have confidence that this kind of code may work on bigger devices.

It is also possible that some mechanisms are dominant and easily scalable, for example, it might be that the IC sputtering is mainly caused by the RF sheath formed in front of the antenna. The RF sheath induced sputtering may scale logaritmically with power, if this is also the case with the sample erosion, we can be confident that it's the main sputtering candidate and thus easily scalable to other antenna's (by simulating their sheath).

8   Exposure: Outgassing efficiency

This is for much later, after all the erosion estimations have been done, but under all the previously mentioned techniques, we'll use the same measurements and estimate the outgassing rate by constructing a sample with the same amount of doping in the BCA simulation.

References

[1] D. Douai, S. Brezinsek, H.G. Esser, E. Joffrin, T. Keenan, S. Knipe, D. Kogut, P.J. Lomas, S. Marsen, I. Nunes, V. Philipps, R.A. Pitts, M. Shimada, and P. de Vries. Wall conditioning of jet with the iter-like wall. *Journal of Nuclear Materials*, 438:S1172–S1176, 2013. Proceedings of the 20th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices.

[2] A Goriaev, T Wauters, R Brakel, S Brezinsek, A Dinklage, J Fellinger, H Grote, D Moseev, S Sereda, O Volzke, and W7-X team. Wall conditioning at the wendelstein 7-x stellarator operating with a graphite divertor. *Physica Scripta*, 2020(T171):014063, mar 2020.

[3] T. Wauters, H. P. Laqua, M. Otte, M. Preynas, T. Stange, P. Urlings, Y. Altenburg, D. Aßmus, D. Birus, and F. Louche. Ion and electron cyclotron wall conditioning in stellarator and tokamak magnetic field configuration on wega. *AIP Conference Proceedings*, 1580(1):187–190, 02 2014.

[4] Tom Wauters, Andrei Goriaev, Arturo Alonso, Juergen Baldzuhn, Rudolf Brakel, Sebastijan Brezinsek, Andreas Dinklage, Heinz Grote, Joris Fellinger, Oliver P. Ford, Ralf König, Heinrich Laqua, Dmitry Matveev, Torsten Stange, and Lilla Vanó. Wall conditioning throughout the first carbon divertor campaign on wendelstein 7-x. *Nuclear Materials and Energy*, 17:235–241, 2018.