DEVELOPMENT OF AN INSIDE-GAP PLASMA GENERATOR FOR WALL CLEANING APPLICATIONS
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1. Introduction

Fuel accumulation in the wall, critical for long term operation of a fusion machine, is even more prominent for surfaces with grooves and voids, due to increase of surface area and co-deposition in the gaps. The inter-tile spaces have dimensions in the 3-6 mm range, but the slit widths in the castellated tiles are much smaller. For example, Be tiles from JET have castellated blocks of 6 x 6 mm with a groove deepness of 6 mm and 0.6 mm slit width. In the case of ITER, castellation in cells of 10 x 10 x 10 mm with slits of 0.5 mm was proposed for the vertical target of the divertor. Various cleaning techniques already approached, like laser, flash-lamp, oxidation and glow discharge have the drawback of limited access in narrow spaces. The adequacy of sub-atmospheric radiofrequency discharges for discharge cleaning of inter-tile spaces and gaps in castellated tiles, based on the capability of low pressure radiofrequency discharges to spread and burn in narrow spaces, is reported.

The project aims at the elaboration of a laboratory scale I*nside*-G*ap* P*lasma* G*enerator* (IGPG) device, compatible with scanning operations, and the assessment of its cleaning capabilities. For the reported period the objectives were related to the design and building up of an IGPG tool at laboratory scale, supporting scanning of castellated surfaces with its plasma column and the assessment of the cleaning potential of IGPG device in the case of planar and inside gap surfaces.

2. Results and discussion

2.1. Feasibility of plasma generation inside gaps. Operation domains

By assuming that the cleaning process is supported by the presence of plasma in the proximity of the co-deposited wall, the problem which has to be solved is the plasma sustaining inside the small gaps. A critical condition for plasma existence is that the given volume offers enough room for sheath development. Namely, the minimal condition to be fulfilled in order to allow the discharge penetration inside the small gaps is D (size-width of gap) $\geq L_{sh}$ (plasma sheath thickness). The problem of plasma development inside the gap is then translated into finding solutions to handle the sheath thickness for becoming smaller than the gap width. Roughly, the order of magnitude of the sheath thickness is given by the Debye length, which scales with plasma parameters as $\lambda_d \sim (T_e/n_e)^{1/2}$. They (T_e, n_e) can be handled through the injected RF power and pressure because, in the given ranges of those parameters, the increase of power increases the electron density (via increase of the ionization rate) and the increase of pressure decreases the electronic temperature (via thermalization of electrons by collisions with the cold gas).

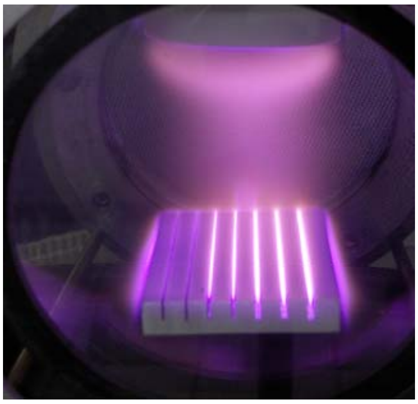


Figure 1. Image of discharge penetration inside grooves having different widths

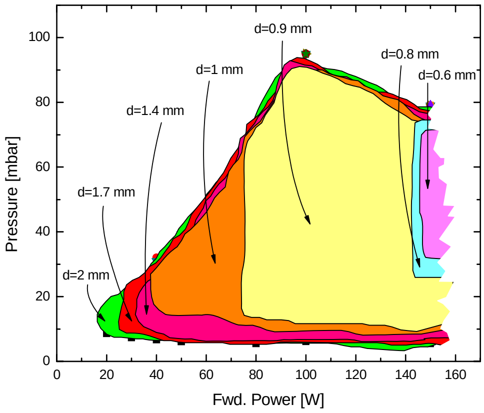


Figure 2. The operation domains in power pressure space (argon, various gap widths, distance 60 mm)

A dedicated set-up for investigating the conditions in which the discharge is operating inside small gaps was built-up. From the examination of the power and pressure values for which the discharge penetrates into the gaps of various widths size (see Figure 1) the operation domains in the pressure- power coordinates were obtained. The domains are defined by the areas enclosed inside by the polygonal figures connecting the points corresponding to appearance and disappearance of plasma in the gaps. The graphs in the Figure 2 show, that going towards narrow spaces and larger distances the domains are less extended. Such as, the discharge in gaps of 0.6-0.8 mm was obtained for a pressure range of 25-80 mbar, but only at power values larger than 150 W. Also, Figure 2 allows determining the widths for which the discharge simultaneously coexists in more than one grove. For example, the point characterized by a pressure of 120 mbar and a power of 50 W is situated inside the domains corresponding to d=0.9, 1.0, 1.7, 2.0 mm, but the plasma does not penetrate inside the gaps of 0.8 and 0.7 mm (the point in discussion is outside the existence domains corresponding to those sizes). Similar experiments performed with nitrogen discharges show that inside gap operation in nitrogen is more restrictive than in argon: no discharge was obtained in gaps narrower than 0.9 mm, and the pressure window is in the zone 1-14 mbar.

In addition to these studies, electrodes from other materials, like iron were used, but not noticeable differences were obtained compared to the aluminum electrodes.

2.2 Inside-Gap Plasma Generator (IGPG) tool at laboratory scale

2.2.1 The design of IGPG tool

The IGPG consists of a water cooled movable electrode, mounted in a vacuum chamber, which can be placed at various distances from the castellated surface. The electrode design is shown in Figure 3. It is made as a brass cylindrical chamber, water cooled inside, with a radius of 20 mm. On one side the electrode is covered by an insulating Teflon jacket which prevents the discharge spreading on its backside. The electrode is supported by a long arm, which is used to perform the translation movement along the castellated surface. The arm is made from more tubings, enclosed each into the other having various roles: i) the smallest contains the water cooling pipes and is connected to the RF supply; ii) the next one as diameter is a glass tubing having insulating role; iii) the next one is a stainless steel grounded tubing having the role of screening, so the RF field does not escape outside, preventing the discharge burning around the arm.; iv) the last one is glass made and is greased allowing the low friction translation movement.

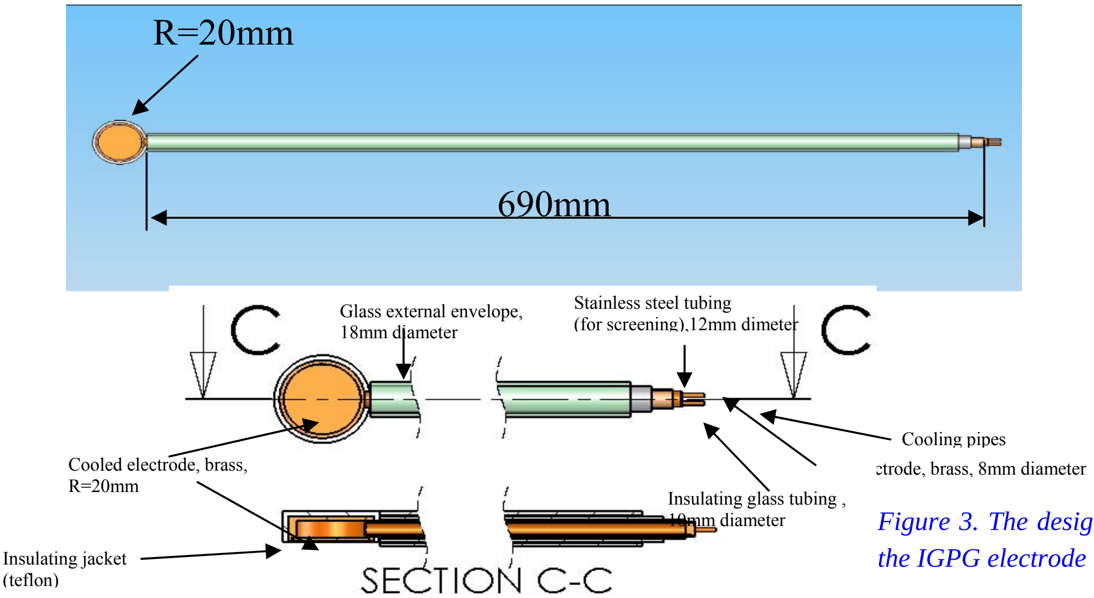


Figure 3. The design of the IGPG electrode

2.2.2 The IGPG system and the block diagram

The block diagram of the setup and the parameter ranges are presented in Figure 4.

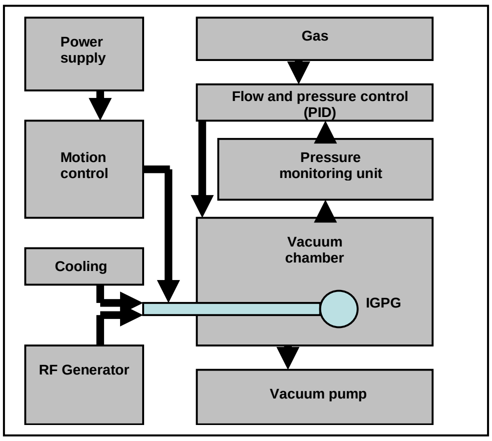


Figure 4. The Block diagram of the IGPG system;

The parameter ranges:

RF power:	10 -200 W, 13.56 MHz
Gas:	Argon
Mass flow rate:	1-7000 sccm
Pressure range:	1-400 mbar
Water flow rate (cooling rate):	0.3 l/min
Translation speed:	0- 16 cm/min
Distance IGPG-surface:	18-45 mm

A schematic view and an image of the IGPG setup are presented in Figure 5. In Figure 6 are presented images of the plasma operation with the electrode placed in the front of a castellated surface. It should be noticed the formation of the plasma column in front of the electrode and the penetration of the discharge inside the gaps. During the experiments it was checked out that this plasma column moves together with the electrode, while keeping the discharge inside the gaps, which was one of the main objectives of the works for the above mentioned period. The translation speed was in the range 0-16 cm/min.

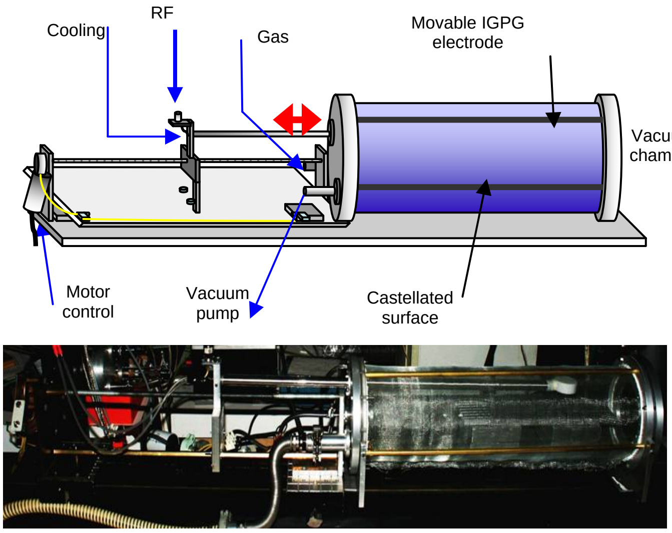


Figure 5. The schematic of the IGPG setup (top) and its image (bottom)

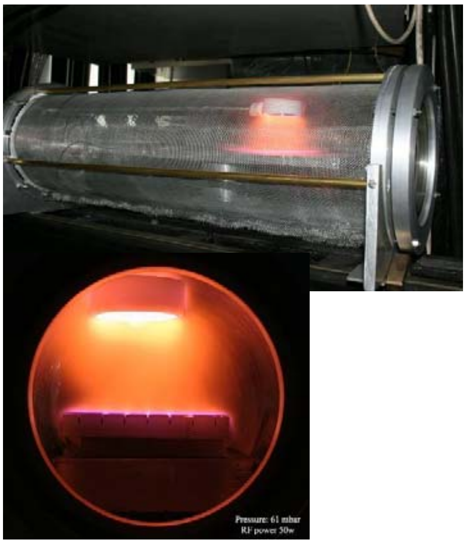


Figure 6. Images of the IGPG tool in operation

2.2.3 Heating and sputtering

The actual IGPG device has a cooling circuit with water flow rate of 0.3 l/min which allows continuous work with maxim power of 200 W. In order to use higher power better cooling will be necessary. Although sputtering was not investigated in detail, since no changes of the polishing degree of the electrode were visually observed after hours of operation, an indication of low sputtering degree was obtained.

2.3 Assessment of the potential of the realized tool in cleaning of planar and inside gap surfaces

2.3.1 The removal rates for graphite made castellated surfaces

The removal rates were determined by gravimetry. A castellated surface was machined in a graphite bloc and submitted to IGPG treatment (Figure 7). The mass was measured after various treatment times. From the mass decrease the removal rate was calculated. The obtained value was 2.24 10-4g/min. Nevertheless, this experiment does not provide distinctive values for the removal rate on the flat upper surface and removal rate inside the gap.

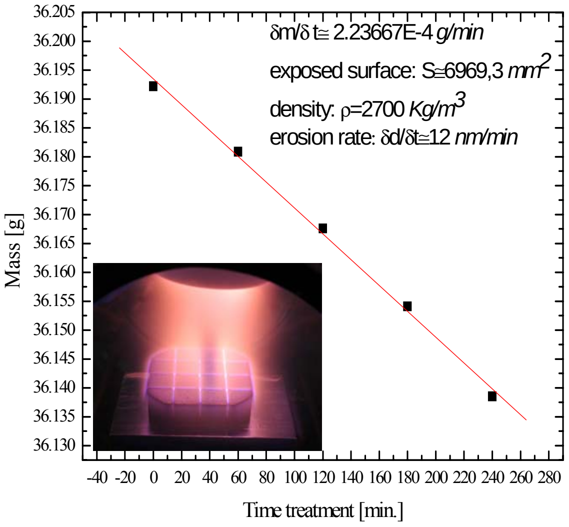
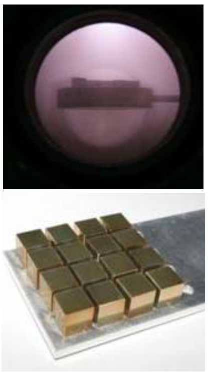


Figure 7. Determination of removal rates of castellated graphite material (parameters: pressure 37 mbar, distance 50 mm, RF power 30 W, argon gas flow 600 sccm); inset: image during treatment

2.3.2 Assessment of inside gap cleaning of castellated surfaces

Castellated pieces which can be mounted and dismounted from separate parts were designed and machined. The parts consisted of optical polished aluminum cubes (Figure 8) and were vacuum coated with amorphous hydrogenated carbon by Plasma Assisted Chemical Vapor Deposition Technique (PACVD). The coating was realized on all cube's sides in a PACVD reactor, with argon plasma injected with acetylene. An image of

Figure 8. The assembling of castellated surfaces from parts



the castellated substrate during the deposition process, taken through the reactor window is shown in Figure 9a. An image of the coated castellated substrate is presented in Figure 9b.

Figure 9. a) Al substrate during the deposition process on one side of the cubes; b) Overall coated assembled castellated specimen

The coating thickness, as measured by Atomic Force Microscopy and ellipsometry, was 1.2 µm. The coated assembled castellated specimen was submitted to cleaning by IGPG in conditions of discharge generation inside the gaps. The cleaning process is exemplified by the image in Figure 10a, and the image of the resulted specimen after a determined cleaning time is shown in Figure 10b, from which it may be noticed the cleaning effect of the discharge.

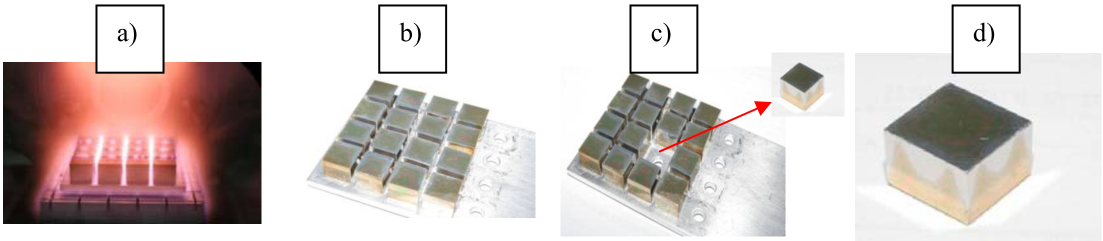
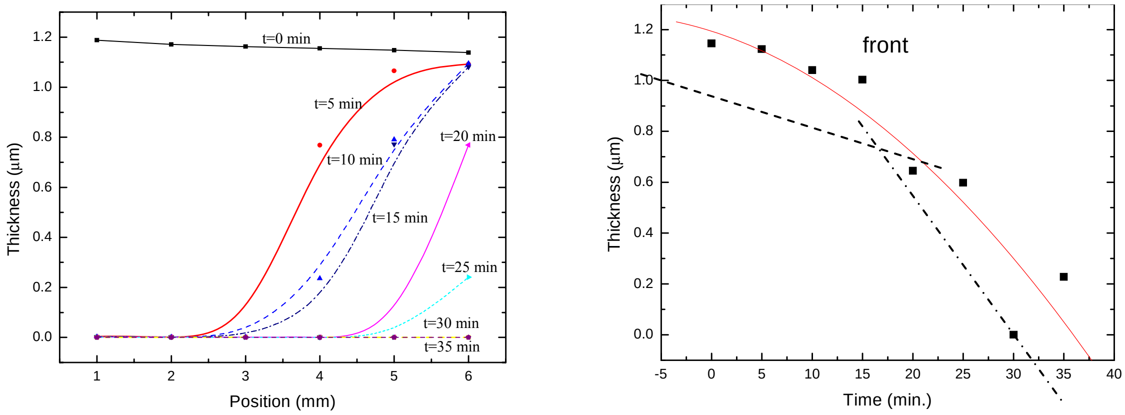


Figure 10. Image of the cleaning process and image of partial cleaned assembled and disassembled castellated piece

The quantitative measurement of the material removal was performed with the ellipsometric technique. In this technique the change in polarization (given by the polarization angles Ψ and Δ) of an incident linearly polarized light beam, after the reflection on a layer coated substrate, is converted into layer thickness (d). In order to obtain time dependent removal rates, after cleaning at various times, the castellated piece was disassembled (see Figure 10c) in cubes. A separate cube (Figure 10d) was chosen for quantitative measurement of the cleaning process. The obtained dependence of the thickness of the un-removed layer upon the position (i.e. upon gap deepness) for different times is shown in Figure 11a, while the dependence of thickness upon time for the front side is shown in Figure 11b. It is seen that in less than 5 minutes the layer, initially 1.2 µm thick, is completely removed up to 3 mm deepness. In this portion the removal rate is about 0.24 µm /min. As concerning the front side the removal rates varies between 0.01 and 0.04 µm /min.



Figures 15a) Dependence of layer thickness upon deepness, on the lateral side and for different treatment times; b) Dependence of layer thickness, on the front side, upon the time

Thus, the potential of the IGPG tool for cleaning surfaces inside gaps was demonstrated. The highest removal rates are obtained at the gaps upper margins, which is very convenient because the co-deposited layers on the real castellated tiles are thicker in these regions.

2.5 The phenomenon of discharge self-structuring (discharge segmentation)

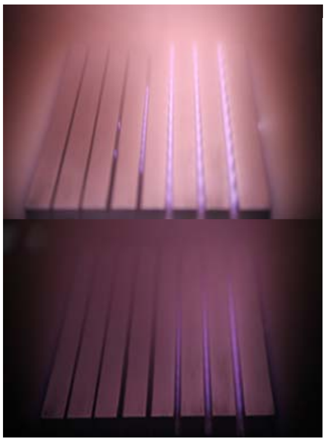


Figure 16. Image of inside argon gap discharge working at 70 W, 34 mbar, 600 sccm: a) continuous power,; b) same parameter values but pulsed operation, duty cycle= 31.6%, T_{on}=11.8 ms, T_{off}=25.5 ms

During the experiment an unexpected difficulty appeared, which can be a drawback of using IGPG tool for tiles cleaning. The difficulty is related to the phenomenon of discharge structuring. Shortly, it consists of the breaking of discharge uniformity inside the gas and the appearance of a series of small discharges spatially separated. This phenomenon is described by the images in Figure16a. The origin of this phenomenon is not known, and can be a source of intensive research in the gas discharge physics. Nevertheless this is an undesired effect and its prevention is of paramount importance. As the position of the separated small discharges is power dependent, experiments have been performed with power modulated discharges. Indeed by pulsing the RF discharge the inside gap discharge uniformity is improved, as observed in the image in figure 16b.

3. Conclusions

A laboratory scale Inside-Gap Plasma Generator (IGPG) setup was designed and built-up. It consists of a water cooled movable electrode, mounted in a vacuum chamber. The setup operation is assisted by a motion control system, RF power supplying system, pressure control system, cooling system. The simultaneous movement of the plasma column and inside gap plasma generation was demonstrated. Contact areas of plasma column with the castellated electrode of 10 cm^2 were obtained, simultaneously with discharge maintaining in gaps of 0.8 mm width.

Experiments were performed in order to assess at laboratory scale the effectiveness of the IGPG tool in modification/removal of carbon from surfaces. In a set of experiments the removal of carbon from graphite surfaces with a rate of 2.2×10^{-4} g/min (equivalent of thickness 0.012 µm /min) was obtained in non-optimized conditions. Another set of experiments was performed on a castellated assemble (1.5 mm gap width), vacuum coated with amorphous hydrogenated carbon. The thickness profile inside the gaps, at different treatment times, was measured by ellipsometry. It is proved that the cleaning process is effective, the removal rate depending on deepness: the cleaning proceeds faster at the upper gap margins (about 0.24 µm /min for the first 2 mm), where in fact the co-deposited layers on real tokamak tiles are thicker.

A phenomenon of plasma structuring (discharge segmentation) inside gaps was observed, and experiments proved that by discharge power modulation it can be avoided.

Suggested further work

The IGPG cleaning is very promising, as it is effective both on large area and in localized places, as gaps. Further work is necessary to optimize the removal rate, for example by changing gases and using gas mixtures, including oxygen and nitrogen, and using higher power variants (with more intensive cooling). Moreover, the study of the processes responsible for the observed cleaning effect is necessary. The IGPG can also act on carbon containing powders existing in gaps.

Publications

1. **C. Stancu, I. Luciu, R.E. Ionita, B. Mitu, G. Dinescu** , "*Operation Domains of an Inside-Gap RF Discharge"*, Proceedings of the 28th International Conference on Phenomena in Ionized Gases, July 15-20, 2007, Prague, Czech Republic

2. **C. Stancu, M. Teodorescu, E. R. Ionita, T. Acsente, G. Dinescu,** *"Inside-Gap RF Discharge Generator for Cleaning Applications"*, Book of Abstracts, 14th International Conference on Plasma Physics and Applications, September 14-18, 2007, Brasov, Romania, poster presentation.