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Designing high efficiency glow discharge cleaning systems

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ABSTRACT

In this paper we present our studies about the choices of anode design and operational regime in order to get high efficiency glow discharge cleaning of the first wall of a fusion device. We analyzed a database of toroidal and poloidal profiles of the ion current density at the wall, measured by electrostatic probes embedded in RFX-mod first wall tiles, taken in different configurations. The ion current at the wall, both global and local, is in fact strictly connected to the cleaning efficiency, since during glow discharge the wall is physically sputtered by the ions. We found that small size anodes and high in-vessel pressure lead to the peaking of the current profile around the anodes locations, and we experimentally characterized this effect. Instead, we found that anode radial position in the poloidal section has negligible effect on current density profile, even when the anodes are placed at the first wall. Finally, the most convenient operational regime, in terms of pressure and current, has been proposed.

1. Introduction

Glow Discharge Cleaning (GDC) is one of the best established techniques used in present fusion devices in order to remove deuterium and impurities from the plasma facing components. At least in its simplest form, with Direct Current (DC) power supply, GDC operation is not compatible with the presence of a magnetic field, that inhibits the discharge, hence in superconducting coils devices DC-GDC cannot be used for inter-shot conditioning; nevertheless DC-GDC is always available in machines, and it is implemented also in ITER [1], as fundamental tool for wall conditioning after maintenance with vessel venting and for tritium recovering after D-T campaigns.

During GDC, the effectiveness of the conditioning of the wall is closely connected to the ion current collected by it, given that in the process the wall plays the role of discharge cathode and undergoes ion sputtering. Maximizing the GD current during the wall cleaning treatments allows to extract at the highest rate the gas trapped in the wall, as experimentally verified in [2]. On the other hand it was also found [2, 3] that in toroidal fusion devices the current does not spread uniformly over the wall: an augmented ion current density at the wall j_{wall} is observed in the vicinity of the anode location at the expense of the value in the other regions. The profile of ion current density was found to be influenced by the in vessel pressure [2], too. The onset of the anode region is due to the fact that in fusion devices the cathode area is much larger than the anode area, typically 2–4 order of magnitudes, and it was seen also in simulations with a recently developed model of GD plasma [4], tested on data from RFX-mod and other devices [3].

The non-uniformity of the j_{wall} profile has a consequence on the cleaning efficiency of the GD system in the sense that the locations of minimum j_{wall} are sputtered at lower rate during the cleaning sessions, forcing to extend the time duration of the treatment. The mitigation of the profile non-uniformity would hence allow shorter cleaning sessions. A different approach could be to take advantage of the profile deformation, placing the anodes close to the regions of the wall where the maximum gas retention is expected so to maximize there the local sputtering. In both cases, the characterization of the factors that influence the j_{wall} profile is of importance because it allows to modulate the current profile as desired.

In the present work we analyze a collection of profiles measured during helium glow discharges at RFX-mod, to experimentally characterize the impact on j_{wall} distribution of the anodes configuration and of the pressure regime. Moreover, we analyzed the voltage required to sustain the current in the different cases, to study in particular how the anodes characteristics must be taken into account when sizing the GD power supply.

2. Experimental tools

RFX-mod [5] is a toroidal fusion device with circular poloidal cross section ($R = 2\,$m and $a = 0.46\,$m). The vessel [6] is fully covered by about 2000 graphite tiles of typical dimension from 100 × 200 mm^2 to

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100 × 150 mm^2, depending on their position, giving a perfect circular-toroidal plasma boundary, without discrete limiters or any other protruding structure: the regular shape of the first wall gives high sensitivity in detecting the effect of any parameter on the j_{wall} profiles during Glow Discharge (GD) sessions and allows a direct comparison of the measures to models, based necessarily on simplified geometry.

The device is equipped with two anodes dedicated to GDs, placed at 180 toroidal degrees each other at ϕ = 52.5° and 232.5° in the toroidal reference frame of the device, that can drive a maximum of 2.5A each. The applied voltage can be up to 1200 V and the power supply is current controlled [6]. The head of the anode is a 10-turns coil of 70 mm diameter and 120 mm total height, made by an Inconel tube (external diameter 6 mm) actively air cooled. For the operation, the antennae are inserted from bottom ports of RFX-mod (at θ = 270° in the poloidal reference frame of the machine, where θ = 0° is the equatorial low field side) up to the center of the vessel minor cross-section, by linear translators with strokes of 1118 mm [6]. For the experiments presented here, a third anode at a different toroidal location (ϕ = 262.5°) was used. It is an electrode designed to bias the edge of the plasma in tokamak discharges at RFX-mod, and it will be hereafter referred to as ET [7]. Its shape is a truncated ellipsoid and it is made of graphite. Its original task did not require cooling since the tokamak discharges are less than 1 s long, hence when used for GD sustainment the maximum current was limited to 0.3A and the session length was kept below 15 min in order to avoid overheating. ET head dimension is 115 × 65 mm^2 and it faces plasma from a bottom diagnostic port at the same poloidal position of GD standard anodes (θ = 270°) [7]. It can be operated with the top of the ellipsoid positioned at the tiles envelope, i.e. the toroidal surface that is tangent to the top of the tiles, or inserted of some centimeters inside the vessel. Drawings of the anodes inside RFX-mod can be found in the cited references [6] and [7].

Ion current density at the wall j_{wall} has been measured thanks to an extensive set of electrostatic probes embedded in the tiles of RFX-mod wall, a toroidal array of 72 equally spaced probes installed at the low field side of the machine, just below the equatorial plane (θ = 340.7°), and a poloidal one of 7 probes at fixed toroidal angle ϕ = 243.9° [8]. Dedicated signal conditioning electronics has been developed, to measure, during the GDs, the saturation current with μA resolution and the floating potential by means of a potentiometric voltage measurement. To obtain that accuracy, the electronics must be floating and hence it is battery supplied and not connected to the RFX-mod acquisition system, probes were disconnected from their standard front end and connected to the stand alone system and battery voltmeters were used for the measure of a couple of probes at a time. Given the laboriousness of the measure, we acquired data only from a subset of 10 to 20 probes, and the set of channels was each time chosen to be the most useful with respect to the objective of the experiment.

3. Results and discussion

The correlation of the j_{wall} profile with anode geometry, position and material and with the GD operational parameters total anode-cathode current (I), voltage (V) and in vessel pressure (p) was explored in a series of GD sessions. Whenever adequate number of measurements was available, close to the anode and far from it, the current density profile was fitted by a Gaussian curve centered at the anode(s) position(s) summed to a flat baseline to give width and height of the anode peak and value of j_{wall} far from it. After verifying that, at least in the current range explored at RFX-mod, the j_{wall} profile measured at different currents scaled stiffly with the current, in some cases the profiles have been rescaled to the total current so to highlight the effect of a given parameter on the shape of the profile. As a reference for the estimation of the distortion of the profile in the different explored configurations we considered the average current profile $<j_{wall}> = I/36$ A/m^2, where I is the total anode-cathode current and 36 is the RFX-mod wall total area: $<j_{wall}>$ is the current density that would be collected by any portion of the wall if the current I would be uniformly spread over it. In the case of profiles rescaled to the current $<j_{wall}> = 1/36 = 0.028$ m^{-2}. The anodes configuration and the GD plasma parameters during the sessions analyzed in this paper are described in Table 1. In the table, the position of the head of the active anode in each experiment is given by two numbers: the first is the distance of the head from the center of the poloidal section, the second is its distance from the wall envelope, hence from the top of the surrounding tiles. The reference point for the position of the electrode is the center of the coil in the case of the standard RFX-mod anodes, which are coils of total height of 12 cm as stated above, whereas it is the top surface in the case of the ET electrode.

Table 1
Summary of anode setup and operational parameters for the glow discharge sessions analyzed in this paper.

	Anode(s)			GD plasma		
Figure	Size (m^2)	Material	Distance from the center of the poloidal section/ wall (m)	*p* (Pa)	*V* (V)	*I* (A)
1(a)	2 × 0.042	Inconel	0.00 / 0.46	0.63	484	2 × 1.27
1(b)	0.005	Inconel	0.00 / 0.46	0.65	594	0.92
1(c)	0.007	Graphite	0.32 / 0.14	0.37	419	0.25
2(a)	0.005	Inconel	0.00 / 0.46	0.41	800	0.92
			0.23 / 0.23	0.41	824	0.92
			0.32 / 0.14	0.41	792	0.92
			0.34 / 0.12	0.41	760	0.92
			0.39 / 0.07	0.41	850	0.40
2(b) 2(c)	0.007	Graphite	0.32 / 0.14	0.36	240	0.25
			0.46 / 0.00	0.36	419	0.25
3	2 × 0.042	Inconel	0.00 / 0.46	0.21	745	2 × 1.39
				0.26	637	2 × 1.35
				0.63	484	2 × 1.27

3.1. Dependence of j_{wall} profile on anode characteristics

Fig. 1 compares the rescaled current density profiles measured with three different anode configurations. In the experiment of the top panel (a) we used the standard anode setup: two Inconel GD antennas, located at the toroidal angles 52.5 and 232.5° and placed at the center of the poloidal section. The total area of the two heads is 0.084 m^2, large compared with typical RFX-mod port dimension of 0.01 m^2, thanks to their spiral shape described in Section 2. Since preliminary measurements showed that, when using two equal anodes driving the same current, the j_{wall} profile around the two is identical, we concentrated the available channels around one of the anodes and in a region far from it. In the center panel (b) we used only one standard GD anode that had been partly coated by an insulating boron-carbon film during previous boronizations, one of the standard wall conditioning techniques used at RFX-mod [9]. The residual conductive portions of the head were the two bushings at the bottom of the spiral, for a total area of 0.005 m^2, as determined by electric resistance measurements on the antenna during inspection. The fact that the bushings were the only parts which conduct current during the sessions was confirmed by camera images of the anode during GDs, showing anode light emission concentrated around them. In the case of the bottom panel (c), the ET electrode (head area 0.007 m^2) was used. It was inserted at its maximum inside the vessel to be in a position as similar as possible to the other two cases.

The comparison of the (a) and (b) panels shows that in the case of smaller anode area (b) the rescaled profile is characterized by larger current collected at the wall (the cathode of the system) in the region around the anode. Since the power supply is current controlled and hence the total current collected by the cathode is fixed, the current collected elsewhere (the baseline) is lower, 0.011 m^{-2} in the profile (b) against the 0.019 m^{-2} of the profile (a), giving rise to a less uniform j_{wall} profile. The presence of a peak of j_{wall} close to the anode is foreseen whenever the anode area is significantly lower than the cathode one

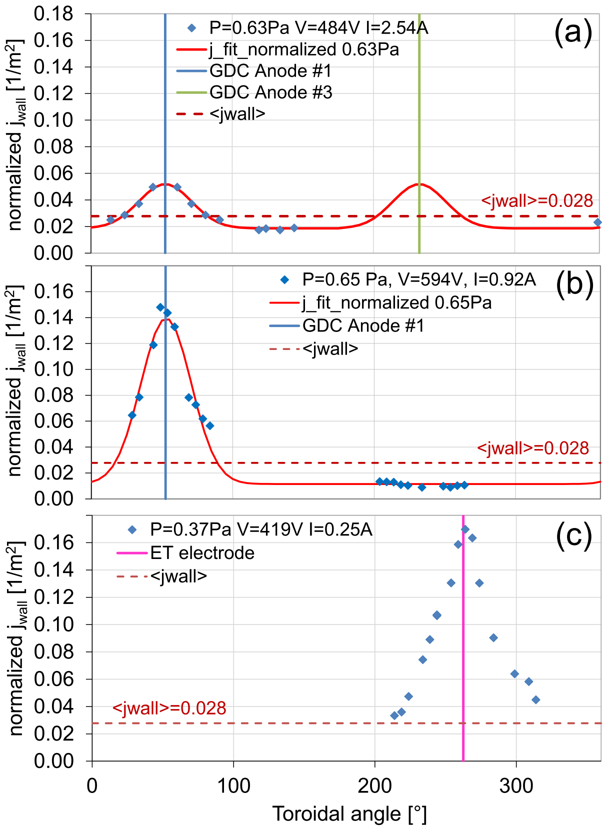

Fig. 1. Density profiles of ion current at the wall j_{wall}, rescaled to total ion current, for three different anodes setup: (a) two full size standard Inconel anodes, total area 0.084 m^2; (b) one Inconel anode with active surface reduced to 0.005 m^2; (c) one graphite anode of 0.007 m^2 area. In the panels, data, anode toroidal positions, average j_{wall} and, when available, fit curves are shown.

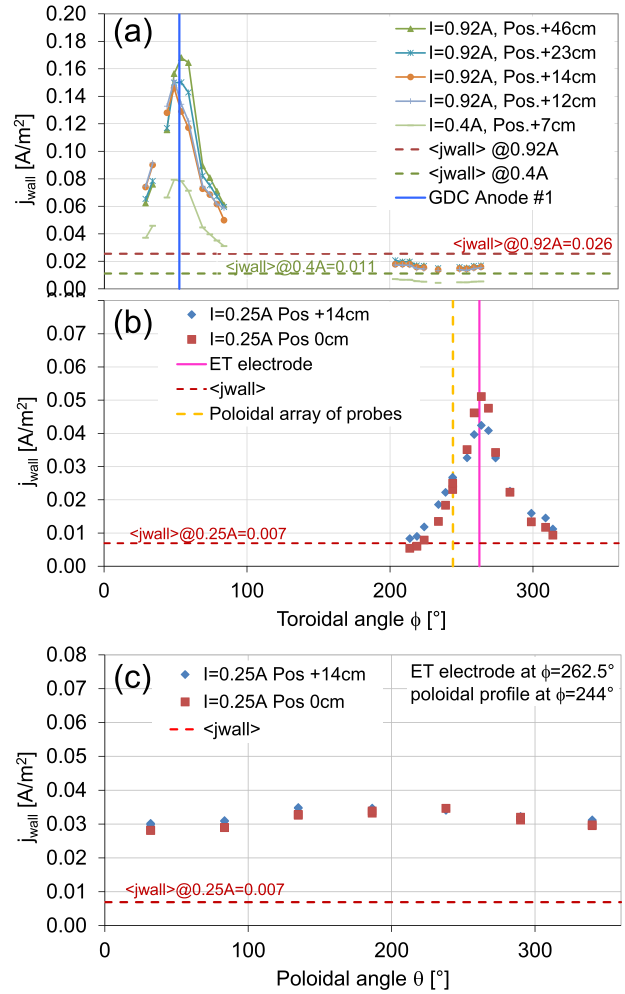

Fig. 2. Toroidal and poloidal profiles of j_{wall} with anodes at different radial positions in the poloidal section. The legend reports the position of the anode head with respect to the wall envelope. In panel (b) the toroidal position of the poloidal array of probes used for the profile in (c) is shown as vertical dashed line.

(like in all fusion experiments), and comes from the arise of a voltage drop at the anode, which induces augmented ionization around it, in order to sustain the current. For example, this effect is explained in [4] and is included in the model of GD plasmas presented there. It is hence reasonable to speculate that the difference in anode area in (a) and (b) causes the observed difference in the two profiles, even if we cannot exclude that the number of active anodes (two in (a) and only one in (b)), regardless of their area, can play a role. At present we do not have data to verify the second issue, but we intend to study it in future work. On the contrary, the rescaled profiles measured with anodes of similar size but different materials, shape and operated at different currents (panels (b) and (c)) look similar.

The comparison of the three profiles suggests that anode area is a key parameter that can be suited in the design phase of a GD system to influence the profile shape.

We report here that, in the case of small anode surface, its temperature during operation became an issue because the same current had to pass through smaller electrode area: for example, visible camera images showed that the conductive part of the anode used for the profile in Fig. 1(b) became incandescent, suggesting that it heated up to hundreds of Celsius degrees and that the cooling system was under dimensioned for the small area case. On the contrary, we didn't experience any problem in breakdown with small anodes, provided that they were inserted in the vessel at least of some centimeters. The case of electrode placed at the wall is described and discussed in Section 3.4.

3.2. Dependence of j_{wall} profile on anode position in the poloidal section

Another aspect we wanted to investigate is the impact on the j_{wall} distribution of the radial position of the anodes in the poloidal section. Some devices (and RFX-mod is among them) operate with the GD electrodes placed by manipulators at the center of the section just before the cleaning session and afterwards retracted for plasma operation, whereas other experiments have fixed anodes integrated in the first wall. In the latter case it is easier to install multiple anodes to totalize large area, because they do not need dedicated ports and manipulators, and the system is ready to be switched on at any time, saving operational time, but as far as we know it has never been studied if anodes at the edge enhance local effects and j_{wall} profile distortion.

In RFX-mod we measured the current density profiles in GDs sustained by one of the standard RFX-mod anodes placed at different positions in the poloidal section (Fig. 2(a)), starting from the standard setup, in which the anode is inserted from below up to the center of the vessel, to +7 cm over the wall. We used the Inconel anode partly insulated described in Section 3.1., that we recall to be a coil of total length of 12 cm where the only conducive parts are the bushings at the bottom of the coil. The operation with extracted anode is not foreseen in RFX-mod hence the positioning of the antenna has never been calibrated and we estimated that the placing error was as high as +/−2 cm. During standard operation, when the anode is in the center of the section at +46 cm over the wall, that error is negligible, but when we operated with extracted electrode it became an issue: at the extreme tested position the conductive bushings were at +1 cm +/−2 cm over the wall tiles, and hence could have been even inside the port. For such a reason, at the most extracted position we halved the current to keep the voltage low and to reduce the risk of electric discharges between the anode and the tiles or port edges. To confirm the results we then used the ET electrode, whose positioning is precise within 0.5 cm and whose top surface is flat, similarly to the tiles one, to repeat the last part of the scan. In that case we measured both the toroidal and the poloidal j_{wall} profiles (Fig. 2(b) and (c) respectively) with the top of the electrode at +14 cm and 0 cm with respect to the wall, and a current of 0.25A. When the top of the electrode is at 0 cm +/−0.5 cm over the wall tiles, it is well aligned to the surrounding tiles and mimics a fix anode installed at the wall among the tiles. The poloidal profile was measured at toroidal angle $\phi = 244°$, about 20° far from the anode. All the profiles of Fig. 2 are absolute (not rescaled to current) and scale in a correct way with the current reported in Table 1. Fig. 2 shows that the j_{wall} profile was very little affected by the radial position of the anodes, and it kept its shape even when the ET electrode was positioned at the wall. The poloidal profile was identical with the electrode inside the vessel or at the wall. It is also interesting to highlight that the measured poloidal profile is flat.

3.3. Dependence of j_{wall} profile on in-vessel pressure

The dependence of the j_{wall} profile on the in-vessel pressure was already seen on preliminary measurements at RFX-mod [2] and also modeled [3, 4], and it was found that low pressure mitigates current profile deformation. For the present work, profiles have been reconstructed in a more accurate way than in the past since we set up more channels and more accurate measurements thanks to the new signal conditioning. Fig. 3 shows the comparison of three profiles at different pressures. In this case GD was operated with two standard anodes fully conducting. As in Fig. 1, the profiles have been rescaled to the measured current so to highlight the only effect of pressure. High pressure gives peaks around the anodes that are more intense and wider: at $p = 0.21$ Pa the peak height and 1/e full width are 0.046 m^{-2} and 24° respectively, whereas at $p = 0.63$ Pa the same quantities are 0.052 m^{-2} and 38°. The increase of ion current collected around the anode at high pressure causes a significant decrease of the baseline, that drops from 0.024 m^{-2} at 0.21 Pa to 0.019 m^{-2} at 0.63 Pa. The two profiles, at 0.21 and 0.63 Pa, are representative of the ion current density distribution in two different regimes of RFX-mod GD plasma, at low and high pressure, that will be shown in the next section to differ also from the point of view of discharge sustainment.

3.4. Operational regime, anode setup and j_{wall} profiles

During GD sessions, the operational parameters I, p and V are in general not independent. When current is feedback controlled, like in RFX-mod, the voltage needed to sustain the discharge changes with pressure according to characteristics curves in the p-V plane, which are shown in solid symbols in Fig. 4 for our device, in the standard plant

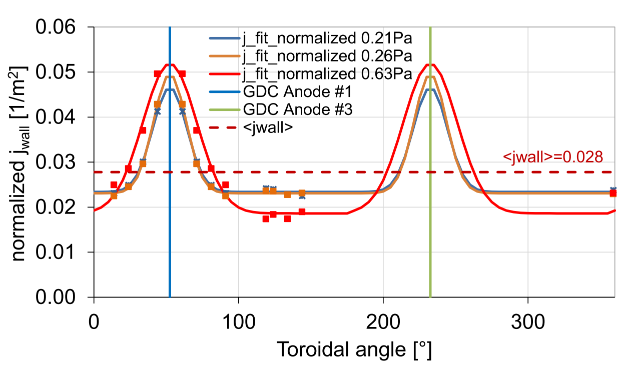

Fig. 3. j_{wall} profiles rescaled to current for three different operating pressures 0.21, 0.26 and 0.63 Pa. Two full size standard anodes were used.

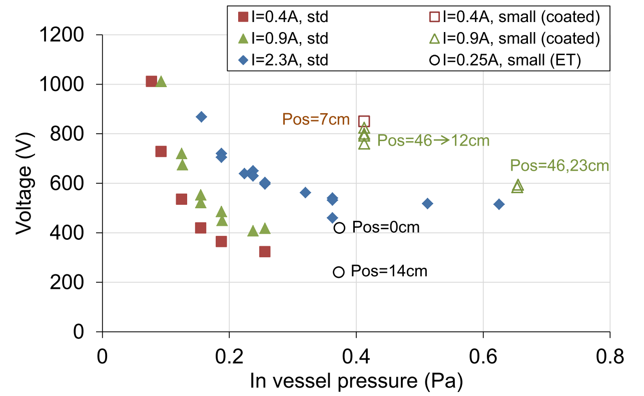

Fig. 4. Operational parameters in the p-V plane for different values of current. Solid symbols refer to glow discharges sustained by large standard RFX-mod anodes placed at the center of the poloidal section (+46 cm), open symbols by small anodes at different radial positions.

configuration (with two full size anodes) and for some different values of current. In the figure, the points correspond to different GDs done in different times but the same curves can be drawn by changing the pressure during single glow discharges. The figure, in particular the p scan at 2.3A where the explored range is wide, shows that the voltage required to sustain a given current remains the same over a large range of pressure, but when p goes below a threshold (weakly dependent on current) the voltage rises steeply as far as pressure is lowered. The threshold value is likely dependent on the geometry of the specific device. The rise of the voltage at low pressure comes from the mechanism that sustains the glow discharge: the charges that allow current circulation are generated by secondary electrons emitted by the cathode and accelerated in the cathode sheath, the region in front of the cathode where most of the anode-cathode voltage drop is located. When pressure is low, the density of neutrals (by far the prevalent species in the GD plasma, that is characterized by a ionization fraction of the order of 10^{-4}) is low and the energy of the secondary electrons must rise to generate enough charges to sustain the discharge. The system hence requires higher and higher voltage to the power supply as pressure decreases, until the pressure becomes too low and the discharge is no more sustainable by the power supply. At fix pressure, instead, the voltage is trivially proportional to the driven current. We made also a tentative estimation of the energy of the ions collected by the electrostatic probes, by biasing the probes at the voltage that zeros the collected current. We interpreted the bias voltage as an effective stopping power for the ions, representative of their average energy. We got that at low pressure, despite the anode-cathode voltage is higher, the energy of the ions is lower. These observations indicate that the pressure regime below the threshold is not favorable for wall conditioning purpose, though at low pressure the j_{wall} profile is more uniform, as shown in Section 3.3.: in fact it requires high voltage to sustain the current, and hence it limits the maximum achievable I in the power limits of the supply, but it gives less energetic sputtering ions. The best operational regime for an efficient wall cleaning is at pressure close to the threshold, not too low otherwise the energy cost to drive the current is uselessly high, not too high to keep the j_{wall} profile more uniform. At such pressure, the operating current should be maximized within the plant limits in order to maximize the sputtering rate, that is trivially proportional to current [2].

We observed in RFX-mod that any modification of the anode setup has an influence on the operating condition of the discharge, and in some cases on the breakdown conditions.

In Fig. 4 the open symbols correspond to GDs performed with small electrode area, the symbol shape corresponding to the current. At given pressure, at 0.4 and 0.9A, the voltage needed to sustain the current is about doubled when the anode is small. At 0.25A we do not have data with full size anodes, but the ordering of the characteristic curves with current suggests that it is lower than what measured with small electrode (the open black circles). Small anodes, hence, not only induce a distortion (as defined in Section 3) of the j_{wall} profile, but also alter the sustainment conditions of the discharge and increase the power requirements.

The open symbols in the figure refer to the sessions with the anodes at different radial positions (some of them were analyzed in session 3.2.). We can hence characterize also the impact of anode location on the operational regime. The voltage is only slightly affected by the anode position, except when the ET electrode is placed at the wall, when we observed a significant increase of the stationary V: the voltage rose from 240 to 420 V for the same current of 0.25A. Differently from what happened when the electrodes, standard or ET, where inserted of at least some centimeters inside the vessel, with the ET electrode at the wall we also observed high voltage requirement at breakdown and we had to rise ionization filament current to start the discharge. Anyway we are confident that the need of power at breakdown can be mitigated by proper placing of the ionization filaments, that in the experiments with the ET electrode were far from the its location.

Our measurements show that the sizing of the power supply of a GD plant must take the characteristics of the anodes into account. In RFX-mod, for example, if we want to design a new GD system that operates with anodes placed at the wall but removable through the ports, that limits their size to the typical port aperture of about 0.01 m^2, we would rise the present power supply maximum voltage of 1.2 kV to about 2 kV to account for both the anode size reduction (anode/cathode ratio from 10^{-3} to 10^{-4}) and the anode poloidal position.

4. Conclusions

The j_{wall} pattern has been measured with either one or two working anodes, with anodes of different size and material and with anodes placed at different heights with respect to the wall, from the center of the poloidal section down to the wall edge. A working pressure scan was also performed. The role of the anode area has been enlightened and j_{wall} non-uniformity has been characterized in terms anode area, even if the impact of anodes number is still unclear. Anode size and radial position were also found to impact on the p-V characteristic curve of the discharge.

Experimental results presented in this paper give some guidelines for the design of an efficient glow discharge plant for fusion devices. Total anodes area as large as possible should be foreseen, in order to mitigate the deformation of j_{wall} profile. For example, in RFX-mod the ratio of anode to cathode area of 10^{-3} gives a j_{wall} baseline, far from the anodes location, which is 70% of the average value that would be if current was uniformly spread over the wall, but with a ten times smaller anode the baseline value drops to 40% of the average, implying that the same cleaning can be obtained only by doubling the GD time duration. Small anodes have a further drawback, since they were found to require more electric power to sustain the current, limiting its achievable value. To facilitate design and operation, the anodes can be placed at a fix position at the wall: we have shown that this can be done without affecting the ion current distribution over the wall, even if a small increase in terms of electric power requirements was observed and should be taken into account when designing the supply system. Finally we have shown that, once the system is fixed, the power supply capabilities can be exploited in the most effective way by working at pressure close to the threshold value below which the voltage to sustain the discharge rises: at lower pressure the maximum obtainable current is lower, at higher pressure the ion current distribution over the wall is less uniform. At such pressure, the current should be maximized since the sputtering rate is proportional to it.

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