Glow discharge cleaning on ITER

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1. Introduction and background

Glow discharge cleaning (GDC) is a standard tool on tokamaks for wall preparation and conditioning, typically for recovery after vessel venting or following periods of tokamak operation. It is frequently used for recovery after disruptions and often inter-pulse as a means of particle recycling control, particularly in carbon dominated machines. A GDC system is in preparation for ITER [1,2], and is being specified on the basis of experience from current devices.

ITER is a superconducting device and because DC glow cannot ignite with the presence of magnetic field, its use will be restricted to periods in which the toroidal field is absent. It is thus seen on ITER principally as a tool, as on many tokamaks, for preparation of in-vessel surfaces following long periods of maintenance/venting. Unlike systems which operate in the presence of toroidal field (e.g. ion cyclotron wall conditioning [3], or high frequency glow discharge cleaning [4]), DC glow is effective in reaching most surfaces if sufficient line of sight to glow electrodes is provided and pressures are adjusted correctly.

A GDC system for ITER presents a number of design difficulties compared with current devices. The presence of a thick, close fitting, water cooled nuclear blanket with very small inter-module gaps means that placement of glow electrodes on the first wall (FW) itself is challenging. Even if solutions are found, the electrodes would be exposed to intense neutron and heat fluxes and would require the development of reliable concepts for electrical feedthroughs and insulation in a system rated to > 1kV and carrying currents of tens of amperes. The presently favoured solution, using moveable systems through port plugs is also problematic, particularly with regard to the design difficulty associated with electrode heads which must carry water cooling and which must ensure the role of neutron shielding when the head is retracted back into the blanket/port plug penetration. The heat load on the electrodes themselves is also an area of uncertainty and requires more quantitative assessment than has been performed so far.

All of these issues have been highlighted at the recent conceptual design review (CDR) of the baseline ITER GDC system, which consists of 6 toroidally equally spaced electrodes entering through lateral ports at divertor level. The mechanical design required to provide this moveable system is on the limit of feasibility and activity is now being focused on relocation of the electrode system to other areas of the vacuum vessel, in particular in equatorial or upper ports. It is also likely that this relocation will be accompanied by a reduction in the number of electrodes. In this case, the question of cleaning efficiency becomes especially important given the scale size of ITER and the fact that deuterium, where ionization mean-free paths can be shorter than or comparable with the characteristic device size at typical GDC gas pressures (see below), is likely to be the preferred glow plasma species. The glow plasma must wet areas of the FW with sufficient current density to permit reasonable GDC action over sufficiently short time periods, compatible with the foreseen duration of conditioning cycles and to ensure that critical wall areas, particularly those in the midplane regions where plasmas will be limited during early discharge formation, are adequately cleaned. We are thus in the process of developing models to describe the glow discharge plasma which in turn can be tested against experimental results in current devices. This paper outlines briefly the first simple modelling approach.

2. Glow discharge parameters

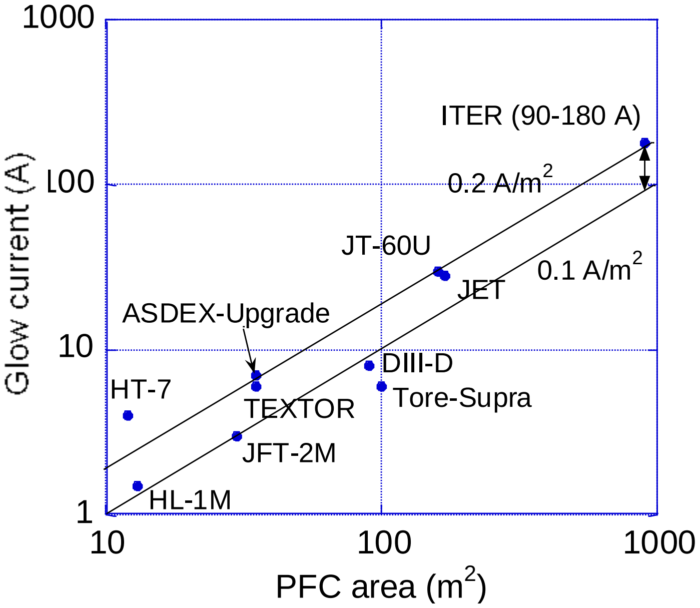

Fig. 1 Glow current vs. PFC area compiled from measurements on current devices

In the current design specification, the ITER electrodes are biased positively (300-1000 V – the glow electrode is thus the anode in the system) with respect to the FW (cathode). The experimental database from present devices suggests that glow current densities at the walls should be in the range (0.1-0.2) A/m^2 (Fig. 1). From this current density, the glow plasma electron density is estimated to be in the range (1.3-2.5) x 10^{14} m^{-3} (assuming T_e =1 eV). The gas pressure in the experiments plotted in Fig. 1 lies between p = 0.05 - 0.5 Pa and since the glow plasma typically has a rather low ionization degree (<1% from the Saha equation), these pressures correspond to neutral densities in the range n_o ~ 0.13 - 1.3 x 10^{20} m^{-3}, indicating the importance of collisions with neutrals. The strong sheath electric field (cathode fall) accelerates ions to the walls so that at impact they carry energies in the range 300-1000 eV. Ion induced secondary electrons are in turn released normal to the wall surfaces and are accelerated back into the plasma. At the expected ion impact energies, the secondary electron yield of beryllium (the ITER FW material) is 0.02-0.04 (electrons/ion) [5].

3. Simple glow plasma model

A preliminary attempt has been made to model the glow plasma with the goal of understanding and offering some predictive capability for the GDC operating range, uniformity and electrode heat load. The approach taken is to follow the trajectory of fast electrons emitted from the FW and accelerated by the sheath voltage, V_s, using a Monte Carlo technique to account for the energy loss and scattering due to atomic and molecular processes and wall reflection.

For simplicity with regard to solving for the static electric field generated by the glow electrode-FW system, the geometry used in the model is a rectangular parallelepiped, measuring 4 m x 8 m x 10 m, corresponding very roughly to a toroidal quarter of the ITER vacuum vessel (Fig. 2). In this sense, the calculations are performed under the assumption that 4 anodes will be the maximum number which can be installed in the ITER system. The anode disk < 0.2 m in radius, is placed at (0 m, 4 m, 5 m). Electrons are emitted from the coordinate point (0 m, 4.2 m, 5 m) (where the dipole electric field is strongest), in the x direction accelerated by the cathode potential fall, to model the first generation of fast electrons. The electric field created in the glow plasma, consistent with a glow current of 50 A per anode and resistivity due to bulk electron-neutral collisions is computed analytically with an electric dipole disk model (anode plate and its mirror image to satisfy the boundary condition: no electric field through FW) and the electron acceleration due to this electric field is taken into account. In this initial approach, the boundary of the simulation domain is taken to be at the plasma-sheath interface on the FW so that the sheath region is ignored. Plasma electrons are reflected at this boundary.

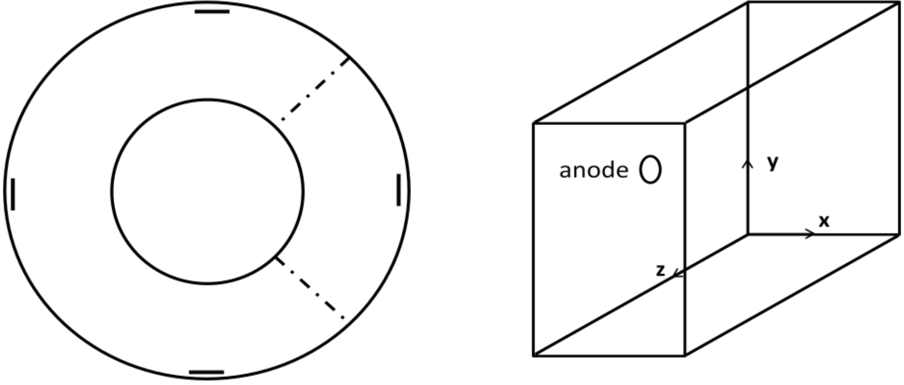

Fig. 2 (a) Top view of ITER with four anodes fixed on the outer wall, and the toroidal quadrant to be modelled.

(b) Schematic of the rectangular parallelepiped coordinate system used, to model the toroidal quadrant of ITER vacuum vessel. The x axis corresponds to the horizontal direction, y vertical and z toroidal direction.

A set of molecular processes are considered including elastic [6] and the following inelastic collisions [7]:

- molecular excitation: e + D_2 ($X^1\sum_g^+$)→ e + D_2^* ($B^1\sum_u^+ 2p\sigma$),
  e + D_2 ($X^1\sum_g^+$)→ e + D_2^* ($C^1\prod_u^+ 2p\pi$)
- molecular dissociation: e + D_2 ($X^1\sum_g^+$)→ e + D_2^* ($b^3\sum_u^+$, $a^3\sum_g^+$ and $c^3\prod_u^+$)
  → e +D(1s) + D(1s)
- molecular ionization: e + D_2 ($X^1\sum_g^+$)→ e + D_2^+ (v) + e
- dissociative ionization: e + D_2 ($X^1\sum_g^+$)→ e +[D_2^+ ($\sum_g$, *and* $\sum_u$) + e] → e + D^+ + D(1s) + e

At each inelastic collision, the energy of the electron is reduced by the energy required for the reaction. At each elastic collision, the direction of motion is randomized. In all cases, after each collision the static electric field once again acts to accelerate the electrons. For each trajectory step ds, if the random number ε ($0<\varepsilon<1$) falls in the interval of [$ds/\lambda_1 + \ldots + ds/\lambda_{i-1}$, $ds/\lambda_1 + \ldots + ds/\lambda_{i-1} + ds/\lambda_i$] (where λ_i is the mean-free-path of the collision process ‘i’), we assume that the collision process ‘i’ occurs.

4. Results

Spatial ionization profiles have been computed as a function of voltage fall at the cathode and gas pressure for fixed glow electrode current = 50 A and deuterium gas species. Fig. 3 shows some example profiles along the z direction (representing “toroidal distance” in this crude geometrical description of the torus quadrant). These calculations show that, as would be expected, the glow plasma is more uniform with higher voltage fall at the cathode and lower pressure. For example, D glow plasmas at (500 V and 0.5 Pa) and (300 V and 0.2 Pa) would be expected to be reasonably uniform over the distances characteristic of the ITER vacuum vessel dimension.

In experiments reported from JET in the mid-nineties (some of the only such measurements reported for tokamak glow plasmas and on which much of the original ITER GDC system specification was based), 4 electrodes were located the top of the main chamber. The ion saturation current in D glow plasmas measured by Langmuir probes at different locations on the main wall dropped significantly toward the bottom of the vessel (distance ~4 m from the electrodes) for p >0.3 Pa and for an anode potential of 300 V [8]. Recent dedicated TEXTOR experiments (half toroidal circumference ~ 5 m) have demonstrated that D glow plasma can be reasonably uniform using a single glow electrode at an electrode potential of 500 V and glow pressure of 0.6 Pa [9].

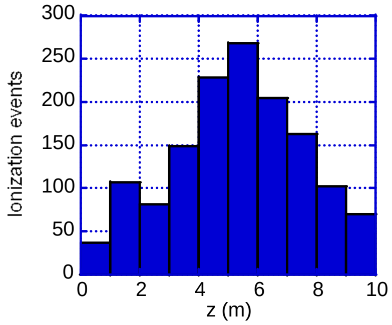

Fig. 3 (a) Ionization profile for V_s = 300 V and p = 0.5 Pa.

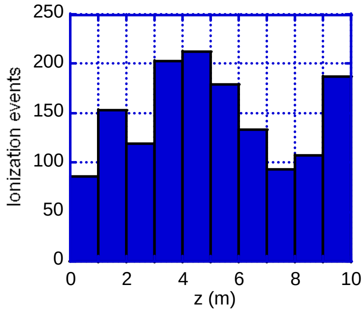

Fig. 3 (b) Ionization profile for V_s = 500 V and p = 0.5 Pa.

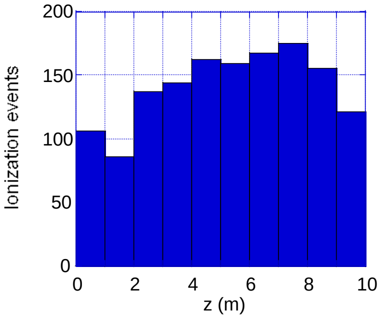

Fig. 3 (c) Ionization profile for V_s = 300 V and p = 0.2 Pa.

5. Summary

A Monte-Carlo calculation of fast electron trajectory and molecular processes has been carried out with ITER-relevant size in an attempt to estimate the possible GDC operation range, profile of the glow plasma and electrode heat load. The results may be summarised as follows: the glow plasma is more uniform with higher voltage fall at the cathode and lower pressure. For example, D glow plasmas at (500 V and 0.5 Pa) and (300 V and 0.2 Pa) are expected to be reasonably uniform with four electrodes distributed uniformly in the toroidal direction. These results are qualitatively consistent with Langmuir probe measurements in JET deuterium GDC plasmas, where significant non-uniformity in the glow wall current density was observed at >0.3 Pa and 300 V. The ion saturation current drops significantly toward the bottom of the vessel (distance ~4 m from electrodes located at the top of the main chamber). These results are also in agreement with recent observations in TEXTOR, where D glow plasma with a single electrode was found to be reasonably uniform over distances of ~ 5 m with 500 V and 0.6 Pa. Future work will include the estimation of the electrode heat load, effect of the electric field on the trajectory of the ions and slow electrons, distribution of initial electron source and the real geometry of ITER.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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