Assessment of the new ITER GDC system performance

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Introduction

In ITER, glow discharge conditioning (GDC) will be used to prepare in-vessel component surfaces prior to machine start-up and following any maintenance procedures requiring in-vessel access. It is also considered as one option for partial tritium recovery following experimental campaigns in the nuclear phase. For a number of reasons, it has recently been decided to relocate the ITER GDC system from the lower lateral (divertor level) access points to outer midplane and upper lateral ports. This in turn requires a redesign of the system and the use of a new concept for the GDC electrode head, with the aim to achieve reliable and safe breakdown of the GDC discharges and to obtain an as uniform as possible distribution of the ion flux onto the first wall, i.e. adequate coverage of the plasma-facing components.

To address these problems, laboratory tests of a mock-up of the proposed anode system have been performed in a small scale reactor and a 2D multi-fluid model of the glow discharge has been developed based on the model [1]. This paper presents the results of both a gas breakdown study performed with the ITER anode proxy and preliminary benchmarking of the model against experimental results obtained in the test reactor in terms of wall current densities, plasma potential, electron density and temperature.

1. Experimental set-up

An existing test reactor at CEA/IRFM [2] was modified for the experiments. The vacuum vessel has a volume of 0.8 m^3 and an inner wall surface of about 5 m^2. A generator supplies 2.8 kV – 1 A DC power to the anode, the aim being to reach a similar level of current density onto the surface with respect to the wall current densities foreseen for ITER during GDC. The working pressure p ranges from a few 10^{-7} mbar up to 0.10 mbar. Gas flow is feedback controlled by the pressure, measured by means of a baratron capacitance gauge. The discharge has been operated either in He, Ar or H_2, the latter being of primary interest to ITER.

In ITER, the flat plate anode concept which is now being developed will be at best located flush with the Diagnostic First Wall (DFW) front surface with relatively narrow gaps separating the high voltage electrode from surrounding structures (Figure 1a). Typical dimensions of the planned anode are 20 x 30 cm, with gap width ~3 cm. GDC discharges can be sustained if the electron mean-free-path $\lambda \sim p^{-1}$ is comparable to the typical dimension of the vacuum chamber. For the laboratory tests, a scaling factor F = 5 has been used corresponding to the ratio of the ITER minor radius (d_{ITER} = 2 m) to the test chamber radius (d_{TEST} = 0.4 m). Hence $p_{TEST} \cdot d_{TEST} \approx p_{ITER} \cdot d_{ITER}$. Given the scaling factor, a 4 x 6 cm stainless steel anode of 0.8 cm thickness has been designed to mock-up the ITER anode. It is mounted on a moveable support and surrounded by a proxy of the DFW surface with the 7 mm wide gaps in between (Figure 1b).

A second anode is used for the model benchmarking. It is a stainless steel cylinder, 2 cm thick, with diameter of 4 cm, installed at the bottom of the vessel, on axis. This allows a moveable Langmuir probe, inserted from the top of the chamber, to make a full vertical scan of the plasma column and retrieve the axial dependence of the main discharge parameters. The probe is a thin cylindrical wire at the end of 1 m long ceramic rod which can be fully immersed into the plasma. Several disk probes are fixed on the wall to measure the ion current density.

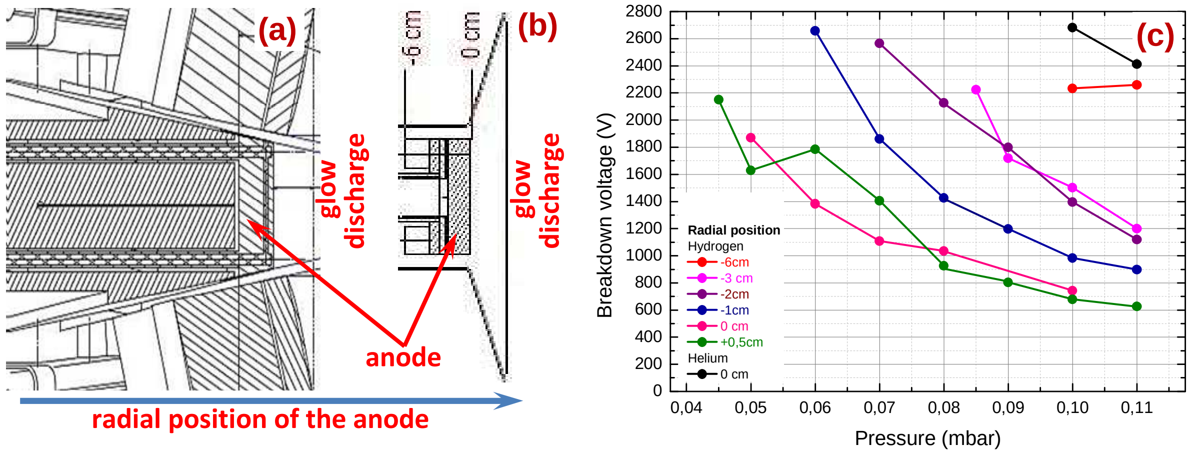

Figure 1. The ITER anode design (a), the tested mock-up (b) and gas breakdown curves in H_2 and He (c).

2. Tests of the mock-up of the ITER anode

The DC breakdown voltage was measured as a function of gas pressure and distance between the anode and the DFW proxy (Figure 1c). Breakdown could be reliably obtained with the anode flush with respect to the DFW for pressures between $5 \cdot 10^{-2}$ and 10^{-1} mbar in the test chamber, i.e. $10^{-2} - 2 \cdot 10^{-2}$ mbar in ITER. Higher pressures lead to lower breakdown voltage, following Paschen’s law [3]. Moving the anode into recessed positions with respect to the DFW proxy at a fixed pressure results in increasing breakdown voltages; in the case where the anode is more than 6 cm recessed, no breakdown was possible below 2.8 kV for the pressure range studied. Breakdown in helium also requires elevated anode voltages, as expected from the higher ionisation potential of He compared to H_2.

No parasitic plasma was formed in the gaps between the anode and the surrounding metal frame, indicating that the ~3 cm gap envisioned around the ITER anode should ensure safe GDC breakdown.

3. GDC model validation

The 2D multi-species fluid model, describing electrons, ions and neutrals by separate sets of fluid equations, is used to model a steady-state glow discharge in the cylindrical geometry. The secondary electrons emitted from the wall by ion impact are accelerated through the cathode fall and enter the plasma as a mono-energetic electron beam at several hundreds of eV. These fast electrons are trapped in the potential well formed by the cathode fall existing at all wall surfaces in the chamber and are slowed-down in collisions with the neutral gas before joining the low-temperature (0.5-5 eV) Maxwellian electron fluid. In order to capture this behaviour, the model includes both fast beam-like and thermalized populations of electrons.

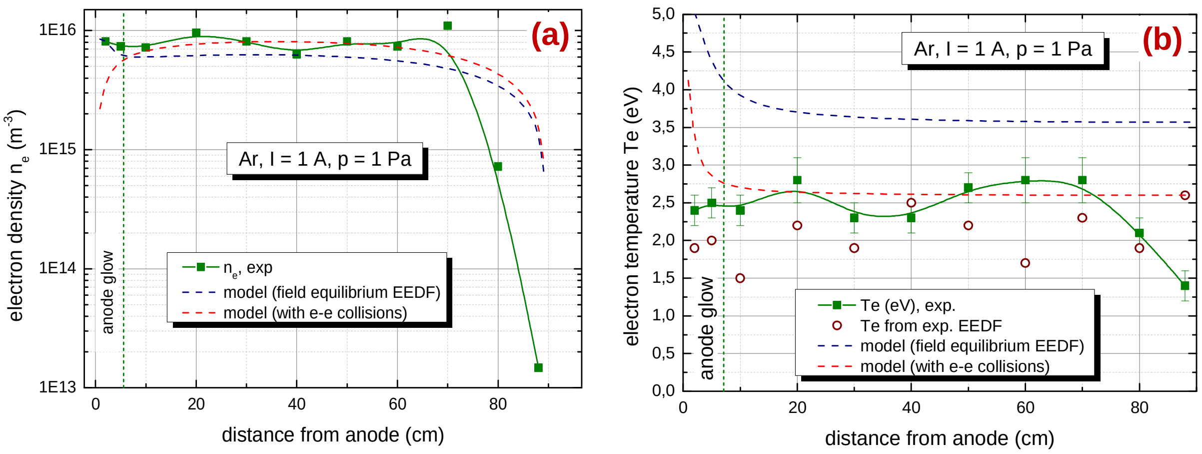

Figure 2. Electron density n_e (a) and temperature T_e (b) profile along the axis in the Ar glow discharge (1 Pa, 1 A).

Numerical simulations have been attempted first for argon GDC, which can be described by a much simpler set of species and reactions than in the case of hydrogen: fast and bulk electrons, Ar^+ and Ar. Figure 2 compares the electron density, n_e (a) and temperature, T_e (b) measured in the test chamber with the 2D fluid model simulations. There is good agreement for n_e throughout most of the vessel (Figure 2a). In the case of T_e, the calculated value in Ar depends strongly on the assumptions for the electron energy distribution function (EEDF). The best accordance with experimental data is found for the field-equilibrium EEDF, accounting for both e-Ar collisions and e-e Coulomb collisions, with the resulting $T_e \sim 2.6$ eV (Figure 2b).

The modeling scheme for H_2-GDC involves the following species: fast and bulk electrons, H^+, H^{2+}, H^{3+}, H and H_2. The calculated and measured values of n_e in the negative glow region are comparable and range between 5 and $9 \cdot 10^{15}$ m^{-3} (Figure 3a). On the other hand, the calculated bulk T_e (Figure 3b) is around 0.3 eV in most of the vessel, which is a factor 2-3 lower than the experimental value.

In both cases (Ar or H_2), the code predicts steep gradients in the anode glow region, but this is found experimentally in neither n_e, T_e nor plasma potential. The H_2 simulations show that the size of the anode glow region is very sensitive to the model assumptions regarding the ion dynamics. When neglecting H^+ ions, the anode glow becomes unrealistically large.

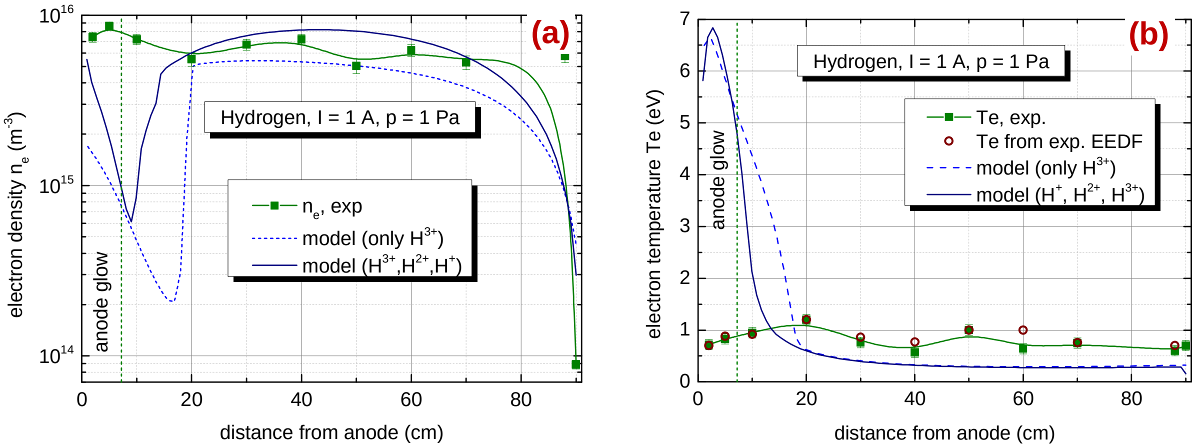

Figure 3. Electron density n_e (a) and temperature T_e (b) profile along the axis in the H_2 glow discharge (1 Pa, 1 A).

The calculated wall ion flux density ~10^{18} $m^{-2}s^{-1}$ (~0.2 A/m^2) is in good agreement with that obtained experimentally for the same conditions at the same location on the chamber wall.

4. Conclusion

Gas breakdown tests with a mock-up of the proposed ITER GDC anode in H_2 and He have been performed in a dedicated test chamber, showing that the envisioned 3 cm gap around the anode should ensure safe breakdown of D_2-GDC. No parasitic plasmas were observed in the gaps or behind the anode. A strong dependence of breakdown voltage with anode recess behind neighbouring surfaces is found, showing that such recesses should be avoided in ITER.

A 2D multi-fluid model of the GDC plasma has been benchmarked against experimental data for argon and hydrogen in the cylindrical geometry of the test glow discharge chamber. Plasma parameters have been measured by means of Langmuir probes, with typical values $n_e = 8\cdot 10^{15}$ m^{-3}, $T_e = 2.5$ eV and $V_{plasma} = 380$ V in Ar, and $n_e = 5-9\cdot 10^{15}$ m^{-3}, $T_e = 0.5-1$ eV and $V_{plasma} = 390$ V in H_2. Experimentally determined plasma density and temperature are reproduced by the model with similar trends in the negative glow region and discrepancies within a factor of 2-3. Despite some disagreement in the vicinity of the anode, the model of the hollow cathode glow discharge can be considered validated for the negative glow region of H_2 and Ar plasmas. This is the key region determining the distribution of the ion fluxes to the tokamak first wall; therefore the present model is approved for simulation of the likely degree of GDC uniformity in ITER with a fixed number of GDC electrodes.

References

[1] G. J. M. Hagelaar, G. Fubiani and J.-P. Bœuf, Plasma Sources Sci. Technol. **20** (2011) 015001.
[2] D. Douai *et al.*, Journal of Physics: Conference Series **100** (2008) 062034.
[3] Yu. P. Raizer, “Gas discharge physics”, Springer (1991) 134.