PIC simulations and reduced model of confined ionising electron clouds relevant to gyrotrons

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Nonneutral plasmas are of broad interest for antimatter physics, particle accelerators and high power microwave sources such as gyrotrons. Indeed, the study of charged particle confinement is crucial for developing long-term antimatter storage (Penning traps) or to avoid arcing and improve efficiency of particle accelerators and microwave sources. In gyrotrons specifically, operation has been sometimes compromised by the presence of localized trapped electrons (i.e. not belonging to the main electron beam) in the gyrotron gun region [1]. Such trapped electrons can lead to arcing and, in some cases, prevent the electron gun from operating at nominal electron acceleration voltage [2]. The trapping of particles is due to the presence of crossed electric and magnetic fields and has some analogies to a Penning-Malmberg trap. Furthermore, the trapped electrons are believed to cause an increase of the cloud density by ionizing the residual neutral gas (RNG) present in the vacuum vessel, eventually leading to a sudden release of charge by means of an as-of-yet unidentified instability. In fact, there is currently a lack of basic understanding of the trapped electron cloud dynamics and a general study is needed to pinpoint the physical parameters that determine the sudden loss of confinement resulting in arcing events observed experimentally.

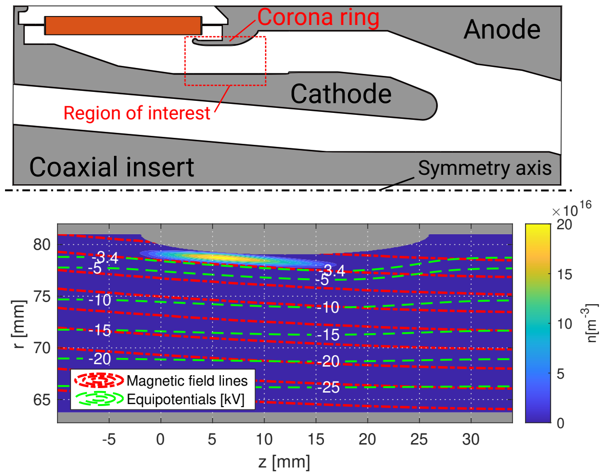

Figure 1: *Top: Geometry of the gt170 gyrotron gun assembly[1]. Grey: metallic components. Orange: Insulator. White: vacuum. Bottom: Approximated geometry and peak electron cloud density and shape reached by the system due to neutral gas ionisation.*

Simulation model, geometry and electron sources

To study this problem, a 2D electrostatic particle-in-cell code assuming azimuthal symmetry has been developed. This code solves the Vlasov-Poisson equation for the electrostatic potential $\Phi(\vec{x},t)$ and the electron distribution function $f(\vec{x},\vec{v},t)$ by using a finite element method for the Poisson equation and a Boris integrator for the particle pusher. The simulation domain considered in this study is an approximation of a specific gyrotron electron gun, represented in Figure 1 (top panel), and known to suffer from electron trapping and leaking currents that prevent its normal operation. This approximated geometry, shown in Figure 1 (bottom panel), consists of a constant radius central cylinder, set at a fixed potential in the kV range, and of an outer cylinder at ground with an elliptic insert to simulate the corona ring of an electron gun. The central cylinder simulates the cathode and the outer cylinder simulates the anode. This leads to the following electric potential boundary conditions: $\Phi\big|_{\text{cathode}} = \Phi_a$, $\Phi\big|_{\text{anode}} = \Phi_b$, $\nabla\Phi\cdot\vec{n}\big|_{\text{otherwise}} = 0$. For the particles, perfectly absorbing boundary conditions are imposed. In addition, electron neutral collisions on Neon atoms are simulated using a Monte Carlo algorithm assuming a uniform background gas at room temperature[3]. The simulated collision processes are elastic and inelastic ionisation collisions that act as an electron source and impose a drag on the electrons. In ionisation events, the created ions are not simulated as they are rapidly lost because of the large Larmor radius acquired at birth by the $E \times B$ drift. Complementary to the electron release by ionisation, an ad-hoc electron source is applied. This source coarsely emulates the background, low-density, free-electrons present in the electron gun region due to field electron emission of the metallic surfaces, or due to ionisation of the RNG by natural background radiation. This volumetric source creates electrons at a fixed rate using a uniform distribution in space and a Maxwellian distribution in velocity with a temperature of 1eV.

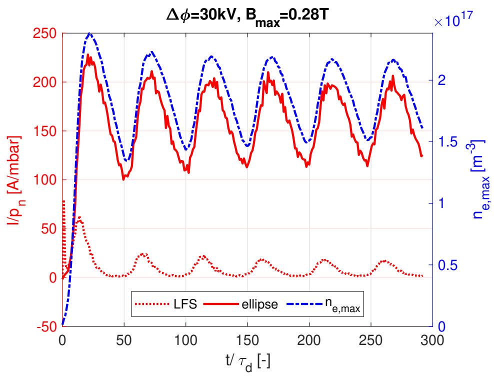

Figure 2: *Time evolution of the electron cloud density and resulting currents on the anode ("ellipse") and on the left open boundary ("LFS").*

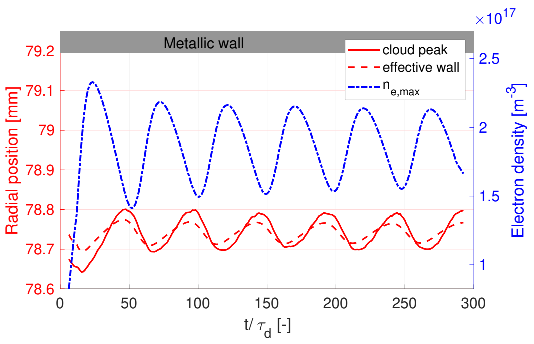

Figure 3: *Time evolution of the electron cloud radial position and of the peak electron density.*

Simulation results

Starting with an empty vessel and using the volumetric source, an electron cloud forms close to the anode as seen in Figure 1. The cloud density increases under the effect of ionisation until losses dominate and the density decrease again. In this geometry the radial losses are dominant, as seen in Figure 2, and are due to the collision-induced radial drift of the cloud which causes the electron Larmor trajectory to intersect with the metallic wall.

As shown in Figure 3, the contact between the center of the cloud and the effective metallic wall causes a fast capture of the electrons on its surface. This capture induces a reduction of the cloud density, and as ionisation is the major source of electrons, the source intensity is also decreased which accelerates the loss of the cloud. Below a density threshold, the new electrons created in the potential well region by the volumetric source can be trapped and the ionisation process is restarted. This whole phenomena causes oscillations in cloud density and radial current, in what could be called *cloud breathing*.

To characterise the average electron cloud density and the resulting current intensity, we performed parametric scans on the externally applied potential bias between the electrodes $\Delta\phi = \phi_b - \phi_a$, the magnetic field amplitude B_{max} and the RNG pressure p_n. For each of these cases we used the same volumetric source term and we looked at the cloud maximum density and the total electron current collected on the boundaries. As can be seen on the results of Figure 4, the potential bias and the magnetic field amplitude have a strong impact on both the electron density and current. The gas pressure has a linear effect on the current but no effect on the density. These last two parameters could then be used to control the radial current.

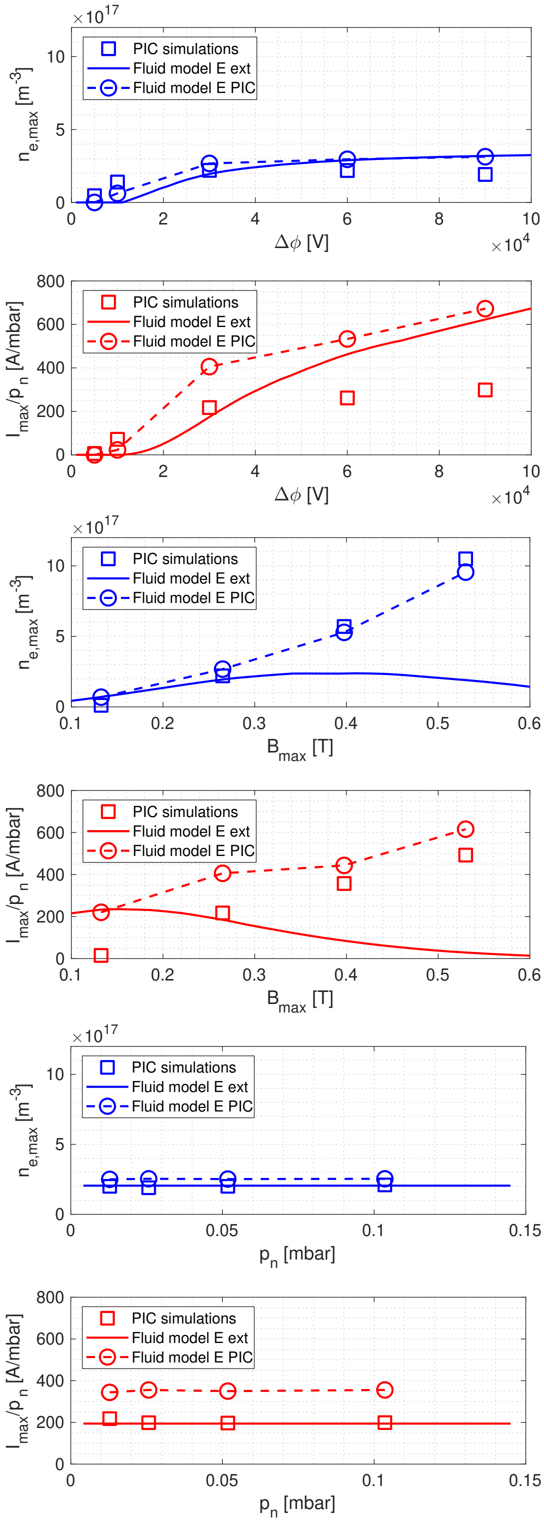

Figure 4: *Maximum density in the cloud and peak collected current on the metallic surfaces for different values of the scanned parameters.*

Reduced fluid model

Using a cold fluid model, a prediction for the time averaged electron density and radial current can be obtained [4]. The time averaged electron density at the position of peak density is predicted with $\omega_{pe,peak}^2 = \Omega_{ce}^2 \frac{<\sigma_{io}v>}{<\sigma_{io}v>+<\sigma_{d}v>}$, where $\omega_{pe,peak} = \sqrt{q^2 n_e/\varepsilon_0 m}$ is the electron plasma frequency, q and m are the electron charge and mass, $\Omega_{ce} = qB/m$ is the cyclotron frequency, σ_{io} is the total ionisation cross-section, σ_d is the effective drag cross-section induced by elastic and inelastic collision processes. For high electron kinetic energies ($E_k \gtrsim 300$eV) the effective drag cross-section for collisions of electrons on Neon atoms is dominated by the effective drag caused by the ionisation source. Under this condition, $\sigma_d \approx \sigma_{io}$ and the plasma frequency becomes $\omega_{pe,peak}^2 \approx \Omega_{ce}^2/2$. This means that for sufficiently strong biases ($\Delta\phi \gtrsim 30$kV) the electron cloud density becomes independent on the bias. Using the same model and assuming only radial losses the radial current is predicted according to $I = \int q\nabla\cdot(n\vec{u})dV \approx -2\pi L r_+ \varepsilon_0 n_n E_r < \sigma_{io} v >$. As seen in Figure 4 there is a good agreement between this model and the PIC simulations when the self-consistent electric field is considered.

Conclusions and outlooks

With this study, we have shown numerically that an electron cloud can form self-consistently by ionising the residual neutral gas present in the vacuum vessel and that oscillations in the cloud density appears. The cloud loss mechanism has been shown to be caused by radial losses induced by the radial drift of the electron cloud. This sink, associated with the ionisation source induce a source-sink feedback loop which causes the oscillations in the cloud density and induced current. To predict the average electron current and density, a reduced fluid model was then briefly presented and verified against parametric scans performed using the PIC code. To confirm the validity of this model in predicting currents in gyrotron guns, simulations with more realistic geometries and comparisons with experimental results are planned.

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