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

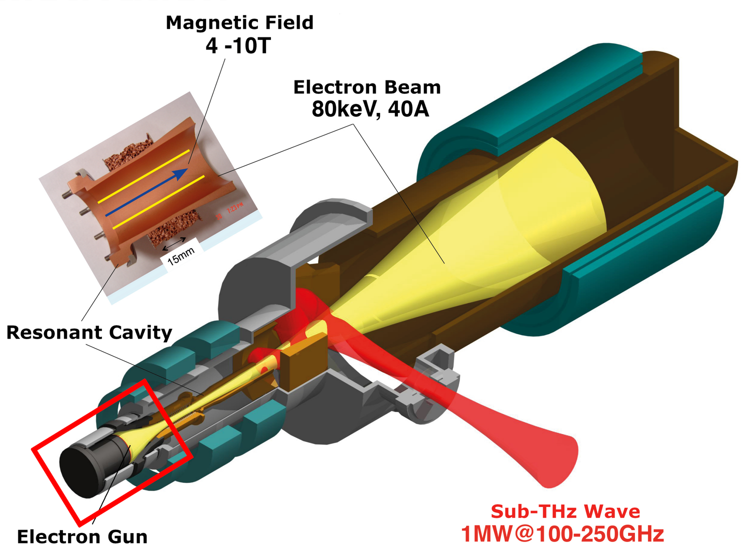
G. Le Bars[1], J.-Ph. Hogge[1], J. Loizu[1], S. Alberti[1], F. Romano[1], A. Cerfon[2], J. Genoud[1]

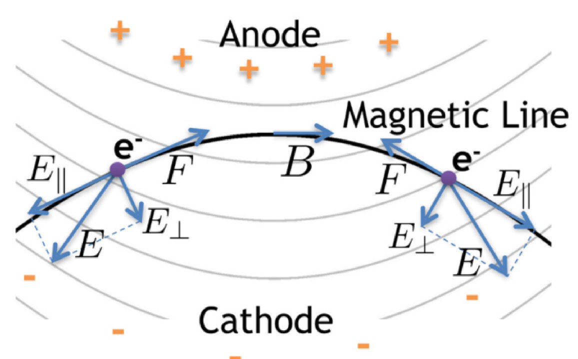
[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland
[2] Courant Institute of Mathematical Sciences, New York University, New York, NY 10012 USA

Abstract

We investigate electron trapping in gyrotron electron guns with a 2D PIC-MC code. The results of parametric scans using an approximated gyrotron geometry with externally applied electric and magnetic field and accounting for electron-neutral collisions are presented. The simulations are compared with and successfully described by an analytical reduced collisional fluid model.

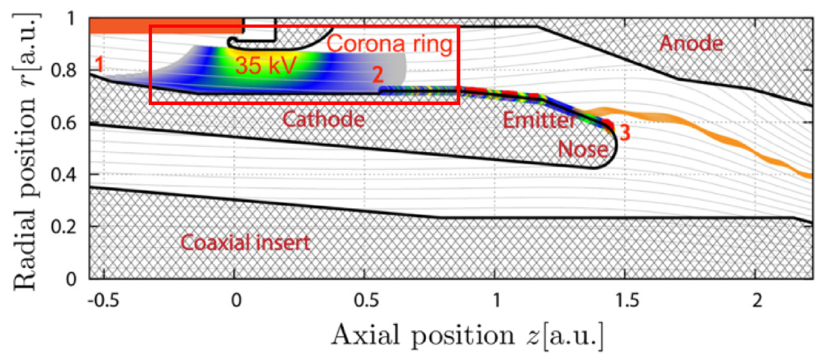
Motivation





Electron trapping in gyrotron electron guns

Experimental studies of prototypes for ITER 2MW coaxial gyrotron (gt170) have shown the presence of electron trapping in the electron gun region that can lead to arcing and potential inoperability of the gyrotron [1]. Further studies have linked this trapping to Penning-like potential wells created by the double crossing of magnetic field and electric equipotential lines [2].



ITER 2MW magnetron injection gun geometry (first prototype) [2]

- Problem: lack of basic understanding of this phenomena which prevents its control
- Question: which key parameters can be tweaked to eliminate these damaging currents?

PIC-MC simulation model

Vlasov-Poisson equation for solved Φ and f using a 2D (r,z) particle-in-cell code with a finite element method for Poisson and a Boris integrator for the particle pusher.

$$\left[\frac{\partial}{\partial t} + \vec{v}\cdot\frac{\partial}{\partial \vec{r}} + \frac{q_e}{m_e}\left(\vec{E} + \vec{v}\wedge\vec{B}_0^{ext}(\vec{r})\right)\cdot\frac{\partial}{\partial \vec{v}}\right] f = C_{e,n}(f)$$

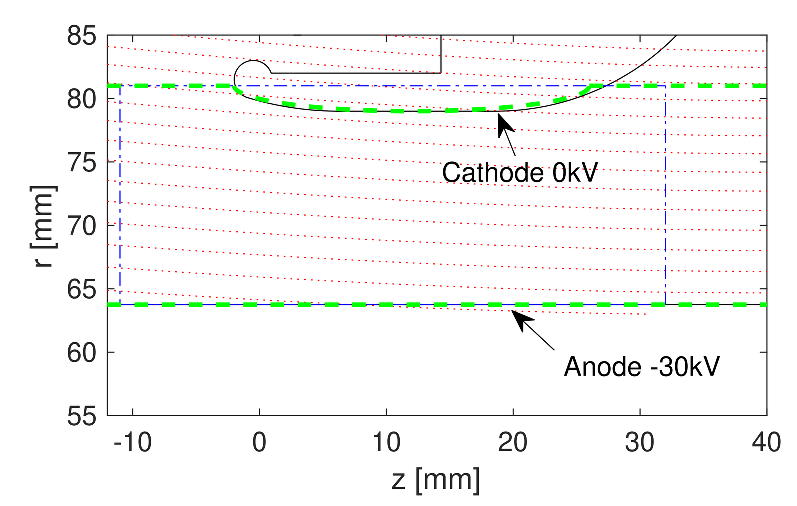
$$\nabla^2\Phi(\vec{r},t) = -\frac{\rho}{\epsilon_0} = -\frac{q_e}{\epsilon_0}\int f(\vec{r},\vec{v},t)d^3\vec{v}$$

$\mathbf{C_{e,n}(f)}$: electrons elastic and inelastic (ionisation) collisions on residual neutral gas simulated with Monte Carlo algorithm [3].
The following electric potential boundary conditions are imposed:

$$\Phi\Big|_{coaxial} = \Phi_a, \quad \Phi\Big|_{anode} = \Phi_b, \quad \nabla\Phi\cdot\boldsymbol{n}\Big|_{otherwise} = 0$$

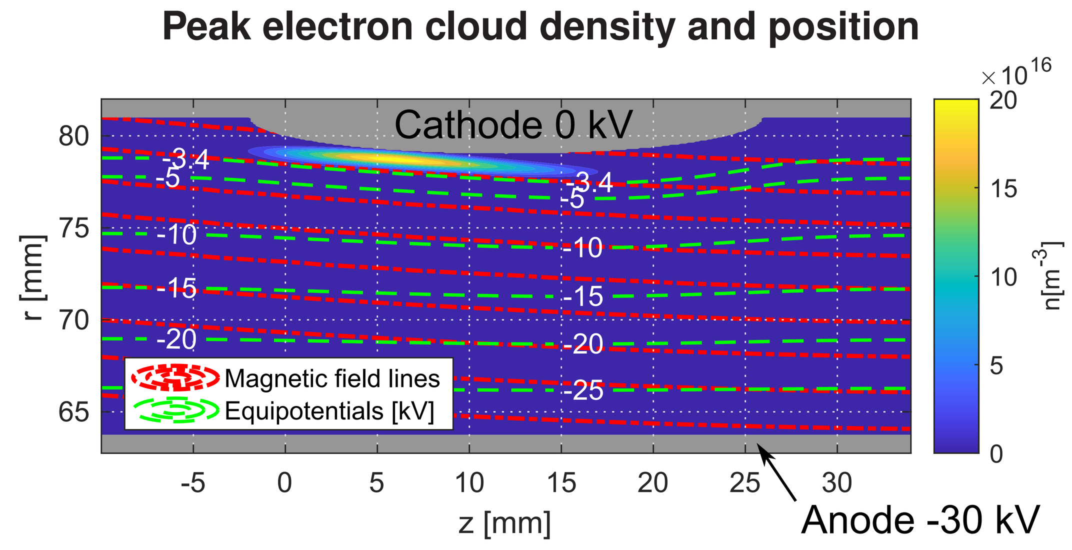
For the particles, perfectly absorbing boundary conditions are assumed.
Typical run time: 36h on a 36 cores node.

Approximation of complex electron gun geometry



- Filled black line: geometry of the original gt170 gyrotron gun assembly [2].
- Dashed green: approximated geometry used in the simulation.
- Dot dashed blue: simulation domain.
- Dotted red: magnetic field lines.

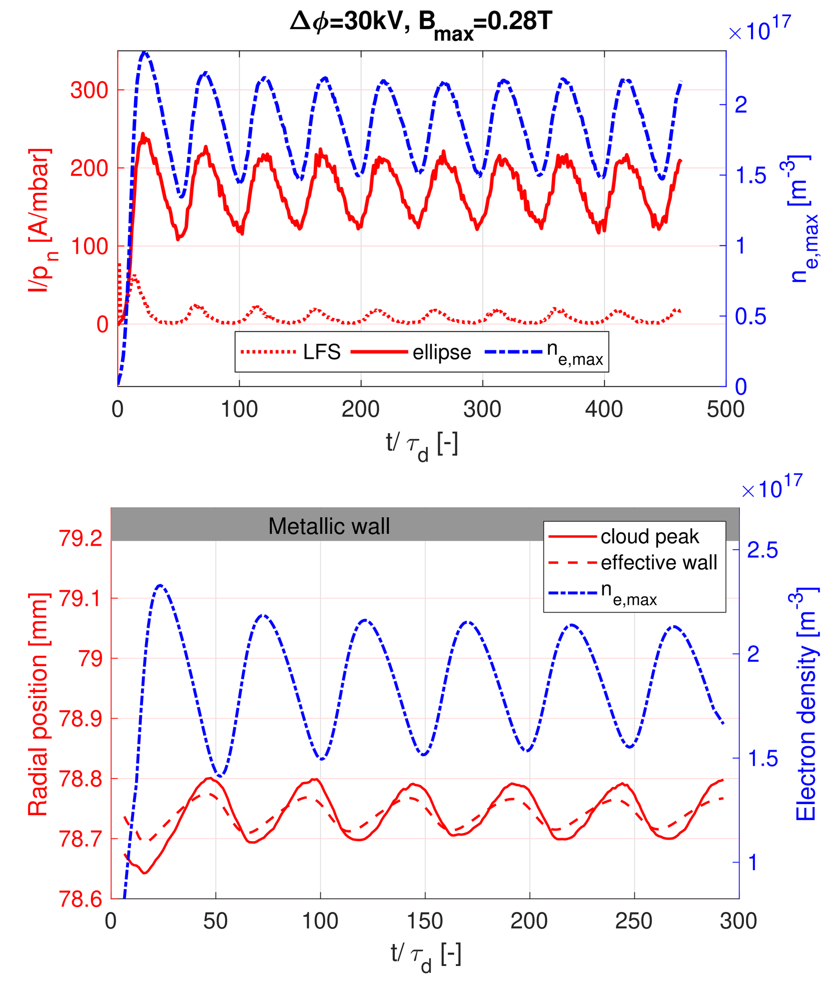
Electron sources



- Neutral gas background ionisation by electron-neutral collisions.
- Volumetric electron source spanning full domain
  - Low intensity compared to ionisation.
  - Constant in time.
  - Maxwellian in velocity ($T_e = 1eV$).

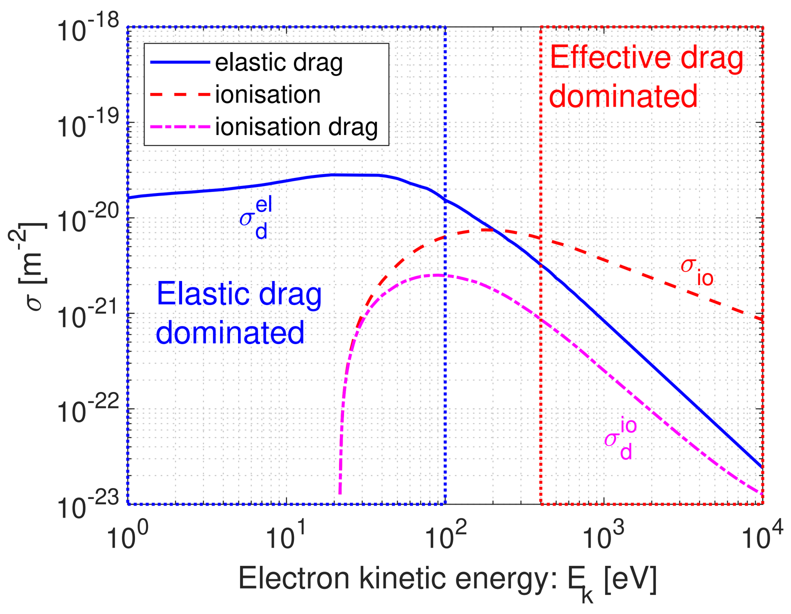
Cloud formation and evolution

1. Initial low density cloud loaded in presence of neutral gas and low intensity source.
2. Some electrons are trapped in the potential well.
3. They ionise the neutral gas.
4. Most created electrons are trapped → increase in cloud density.
5. Few created electrons are not trapped → weak axial losses at low field side (LFS).
6. Collisions induce azimuthal drag → impose cloud radial drift.
7. Electron cyclotronic trajectories intersect the wall → strong radial loss on the ellipse.
8. The cloud is quickly depleted.
9. The volumetric source restarts the process.



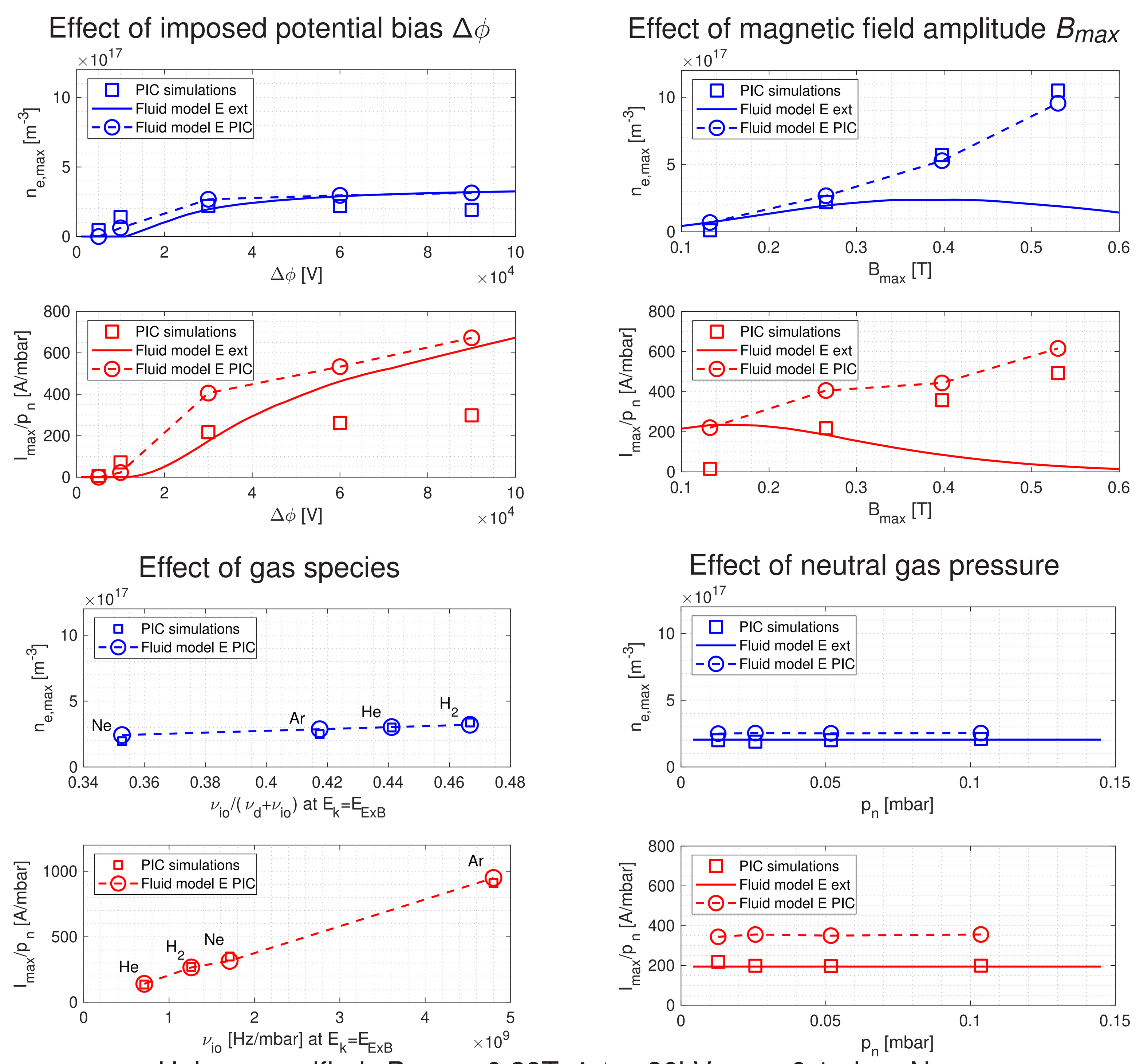
Reduced fluid model

- A cold analytical collisional fluid model [5] predicts the time averaged electron density:
$$\omega^2_{pe,peak} = \Omega^2_{ce}\frac{<\sigma_{io}v>}{<\sigma_{io}v> + <\sigma_d v>}$$
- For high e^- kinetic energies ($E_k \gtrsim 300$eV):
$\sigma_d = \sigma_{io} + \sigma_d^{el} + \sigma_d^{io} \approx \sigma_{io} \rightarrow \omega^2_{pe,peak} \approx \Omega^2_{ce}/2$
- The same model assuming perfect axial confinement predicts the radial current:
$$I = \int q\nabla\cdot(n\mathbf{u})dV \approx -2\pi L r_+ \epsilon_0 n_n E_r < \sigma_{io}v > .$$
- $E_k \approx m(E_r/B_z)^2/2 \rightarrow$ model depends on E_r.



- Using only vacuum electric field gives erroneous predictions because E_r is function of n_e.
- A self-consistent description of E_r is needed.

Parametric scans



Unless specified: $B_{max} = 0.28$T, $\Delta\phi = 30$kV, $p_n = 0.1$mbar, Neon

Conclusions & Outlooks

- An electron cloud forms self-consistently close to the elliptic electrode.
- Radial losses due to radial drift caused by electron-neutral collisions.
- Axial losses are negligible.
- Oscillations in cloud density and electron current are observed.
- An experiment is being designed and built to validate these results
- Two collision regimes depending on electron kinetic energy can be identified which lead to two regions of bias dependencies.
- Magnetic field and electric field have strong impact and could be used to avoid currents.
- The reduced fluid model has good agreement with the PIC simulations.
- More realistic geometries will be considered and compared to experimental results.

References

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