Laboratori Nazionali di Legnaro (Istituto Nazionale di Fisica Nucleare)

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Drifts and non uniformity in H-/D- sources with Plasma Ion Funnel extraction

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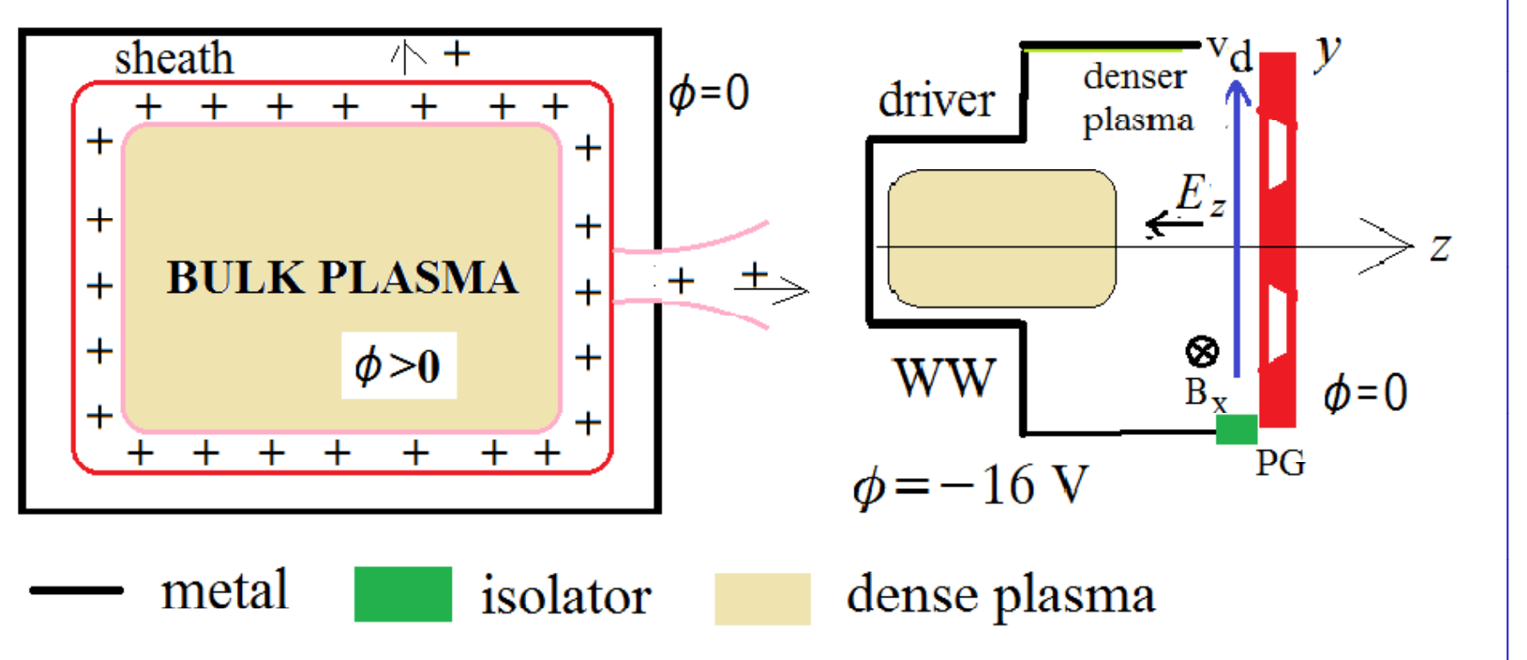
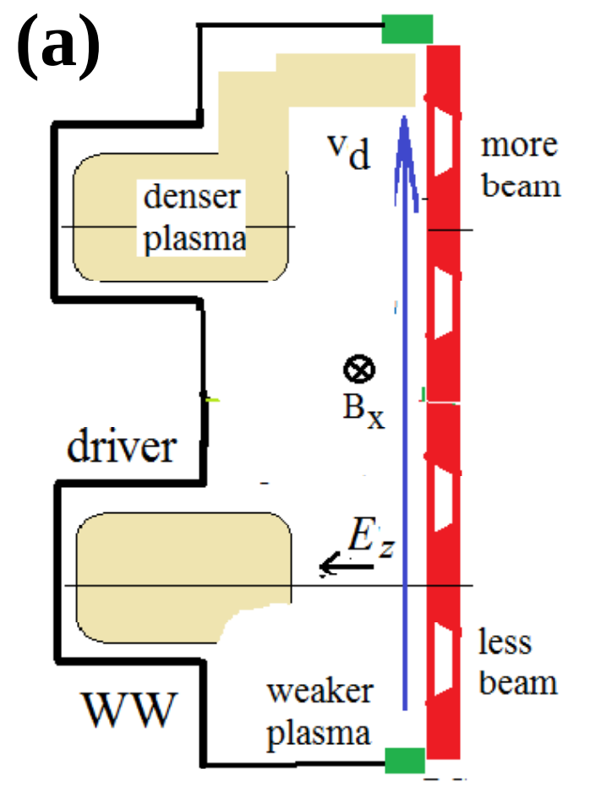
Abstract: The H- multiaperture ion sources requested by NBI for fusion researches need fair plasma uniformity on those apertures placed on in the so called Plasma Grid, both to facilitate perveance matching of all beamlet and to balance erosion of caesium layer in long pulses. The flow of particle drifts (with vd= E x B) due to both the magnetic filter (Bf), needed in the extraction region to reduce electron density temperature, and to the extraction electric field, forms a pileup with resulting top/bottom plasma asymmetry. The plasma density, however, can be controlled by funnel electrodes and bias plate (BP) with proper polarization. Assuming that filter current flows vertically, as in SIPDER, and in designs for MITICA and DTT (Divertor Test Tokamak), we have Bf horizontally directed and vd vertically directed, say in toward bottom to fix ideas. In smaller sources, pile up is less important, but non-uniformity of plasma near walls is proportionally more important. The variety of experimental results and conditions suggest a long and careful discussion. Several remedies were proposed, based on modification of the E x B pattern, to reduce plasma flow accumulation at specific points (source bottom) . In the funnel concept, the BP is supplemented by many electrodes inside the extraction region. Voltages among PG, BP, funnel and wider plasma chamber walls, as well Bf, are key parameters. Due to the large computation size of the full problem, several approximate simulation methods were used. 3D simulations with no space charge have shown good ion extraction condition for preventing direct electron co-extraction. An empirical model for plasma sheath and space charge is also solved in 2D (using nonlinear multiphysics solvers) and a discussion on drift trajectories that mostly confirm similar 3D results is introduced. Comparisons with other fluid models in the literature considered. Effects of wall conditions are also critically discussed.

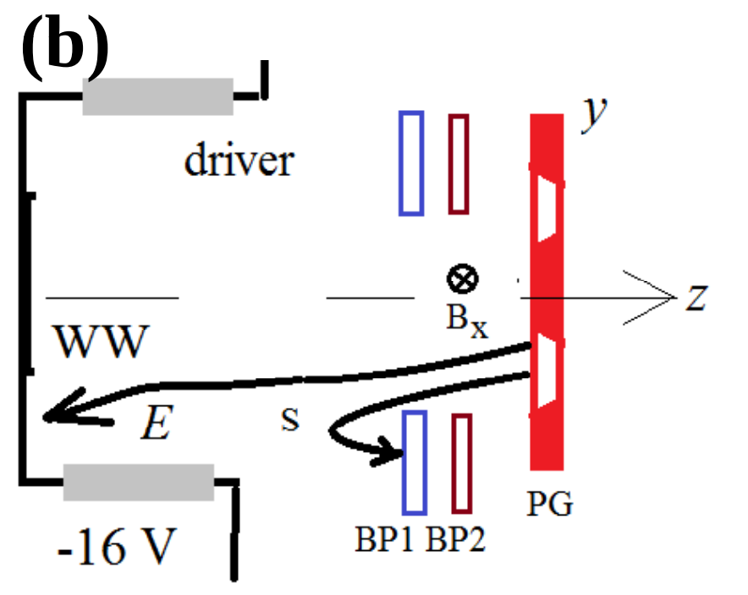
I. INTRODUCTION



Plasma ion source must develop sheath potentials to balance electron and positive ions (ion+) flows to walls. This greatly help ion+ extraction and the source plasma chamber can be a simple box with one beam extraction hole. For negative ion (ion-) plasma chamber must be divided into many (2 or more) electrodes, and a magnetic filter is needed to prevent electron extraction. So drift motion v_d appears

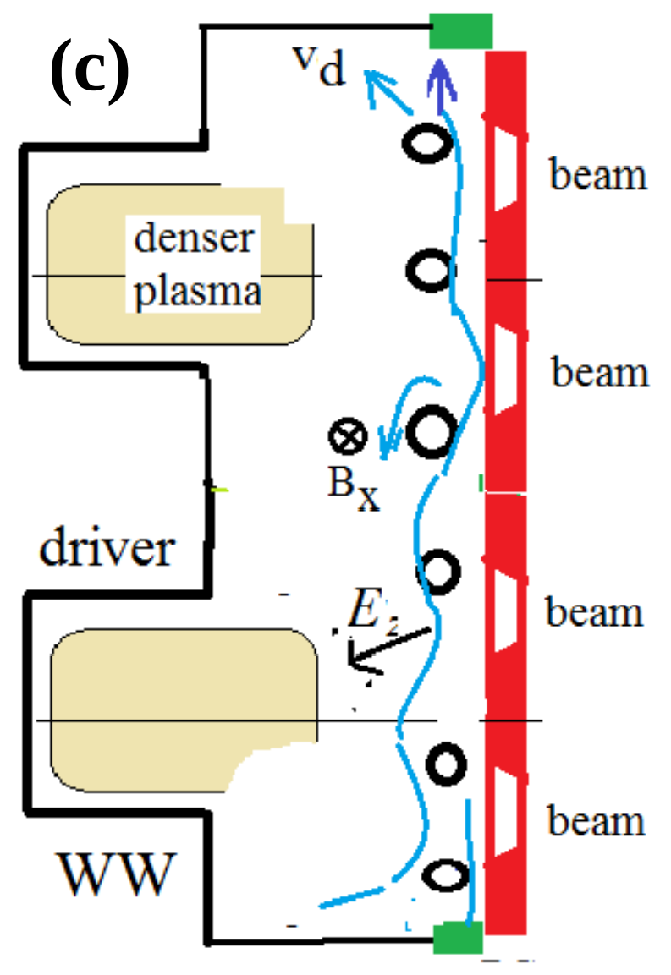
$$\mathbf{v}_d = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$





NIO1 double bias plate

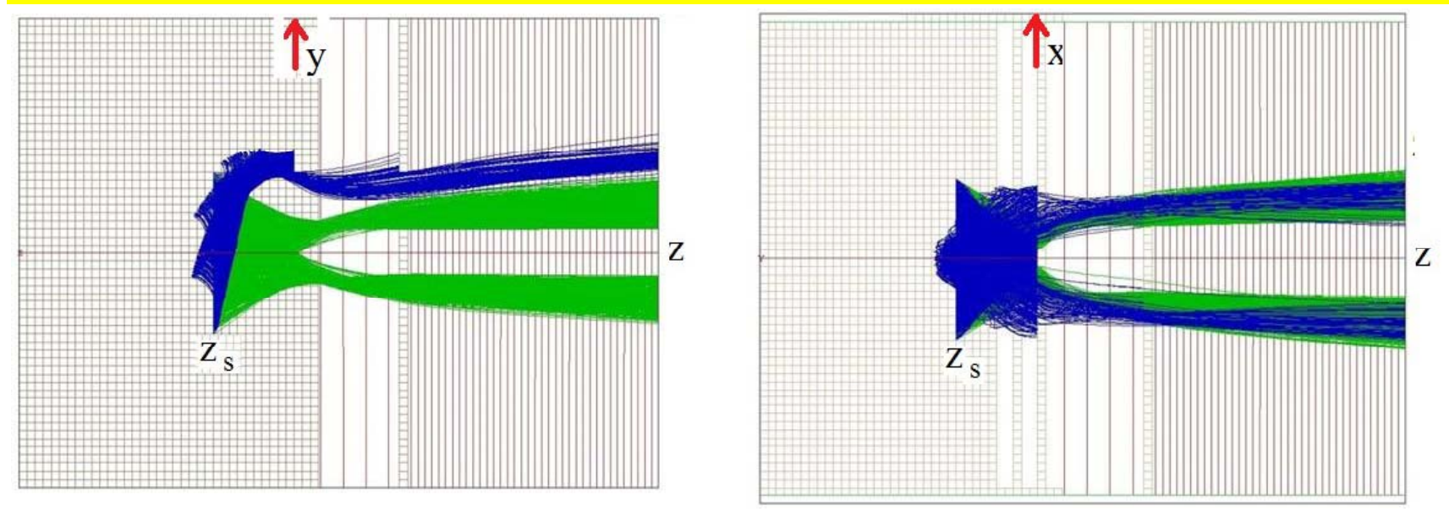
(a) an uniform drift flow (as sketched) can move plasma between drivers so plasma density is no longer uniform top/bottom; (b) to perturb drift flow direction, more electrode can inserted (see NIO1 example), Other setups: potentials rods [3-5,11], funnels[9,20], see -> Long range drift are hopefully hindered by local vorticity and screening from electrodes



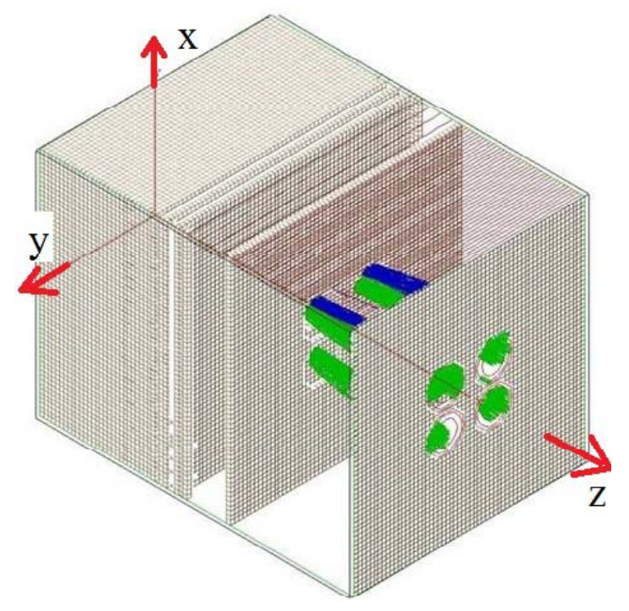
II. PURE RAY TRACING

A first illustration of efficacy of **PIF** (Plasma Ion Funnel) electrodes comes from simple 3D ray tracing, which is limited to regions with very weak plasma

II.a Source with 4 extraction holes in rectangular geometry without PIF



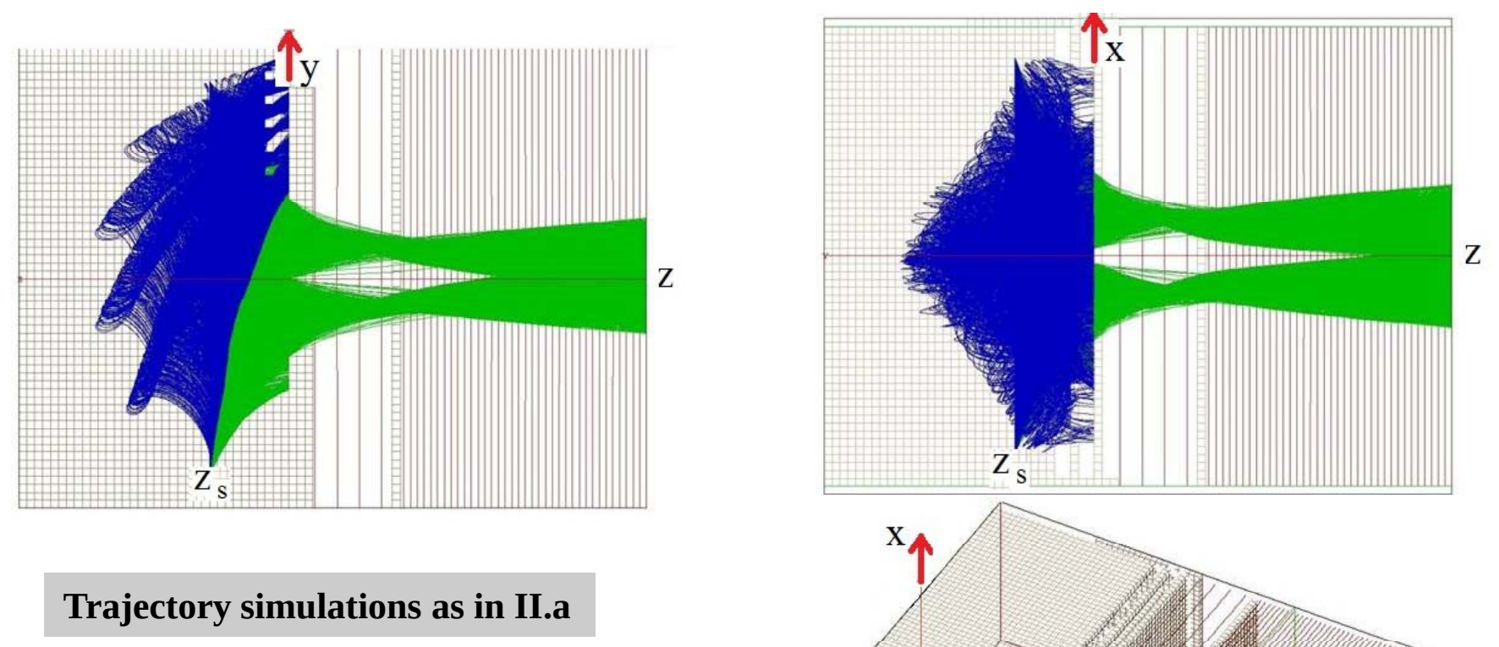
Trajectory simulations with B_F=6 mT and V_{PG}= 60V (→E=20 kV/m); $V_S=V_{BP}$= 0; Eki=0.5 eV; The x starting positions: 26 mm, inside a circumference of d=20 mm on the (y,z) plane (e^-, blue; D^-, green):



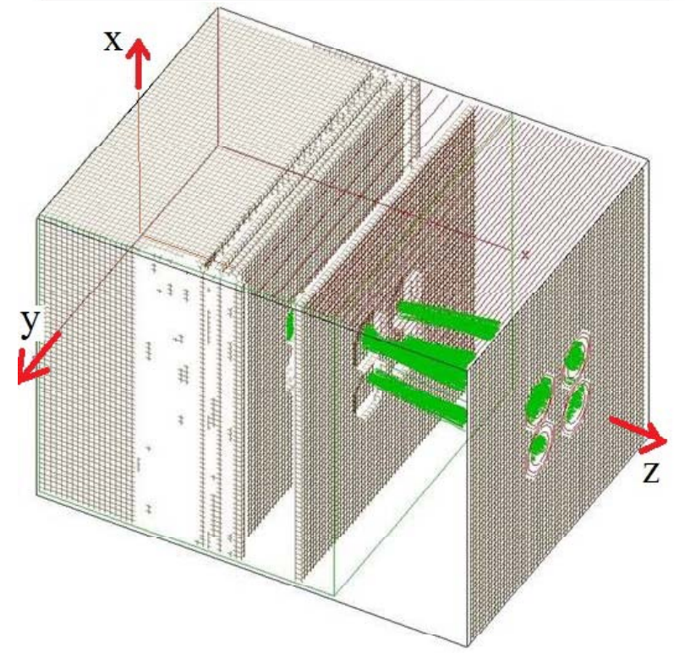
Note: (i) The PIF electrodes on the BP, which are not visible, have squared instead of ring Shapes; (ii) with no PIF configuration the simulations show e^- co-extraction and ExB drifts effect

A rough SIMION model of a MaMug source type in rectangular geometry (like in ITER) is here proposed to study D- and e- trajectories starting from the source plasma sheet region (note: unfortunately, the volume amount considered for was limited by SIMION calculation capability →A rectangular geometry model with only 4 extraction holes could be used)→

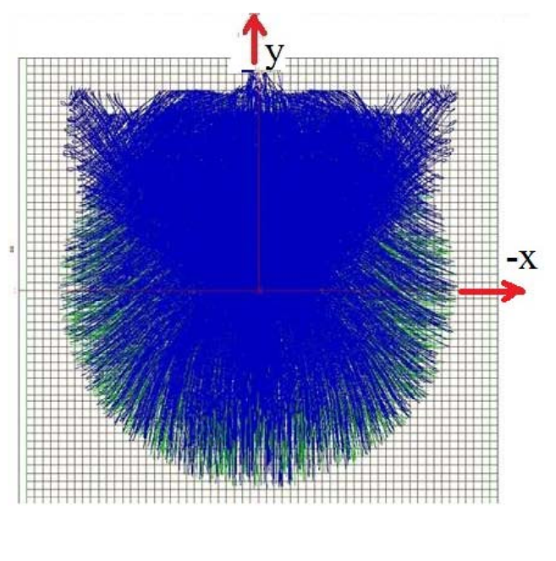
II.b Simulations for the same case but with PIF electrode configuration



Trajectory simulations as in II.a



Note: (i) with PIF electrodes, no e^- co-extraction is present and ExB drifts have tilted direction and spread towards the source back . (ii) In the plane yz the e^- ExB drifts do not continue beyond the simulation volume.



Charged particle trajectories simulations for particles starting from the source extraction region have shown that PIF configuration could avoid the e- co-extraction. The case without PIF electrodes with the same BF and VEG (extraction potential), instead, have e- coextraction with a bigger ExB drifts effect.

III MODEL FOR RESIDUAL PLASMA POLARIZATIONS

We consider only the extraction region part of the plasma $z_1<z<0$, where T_e is small and about constant; n_{e0} be a reference density for example n_e at $z=z_1$

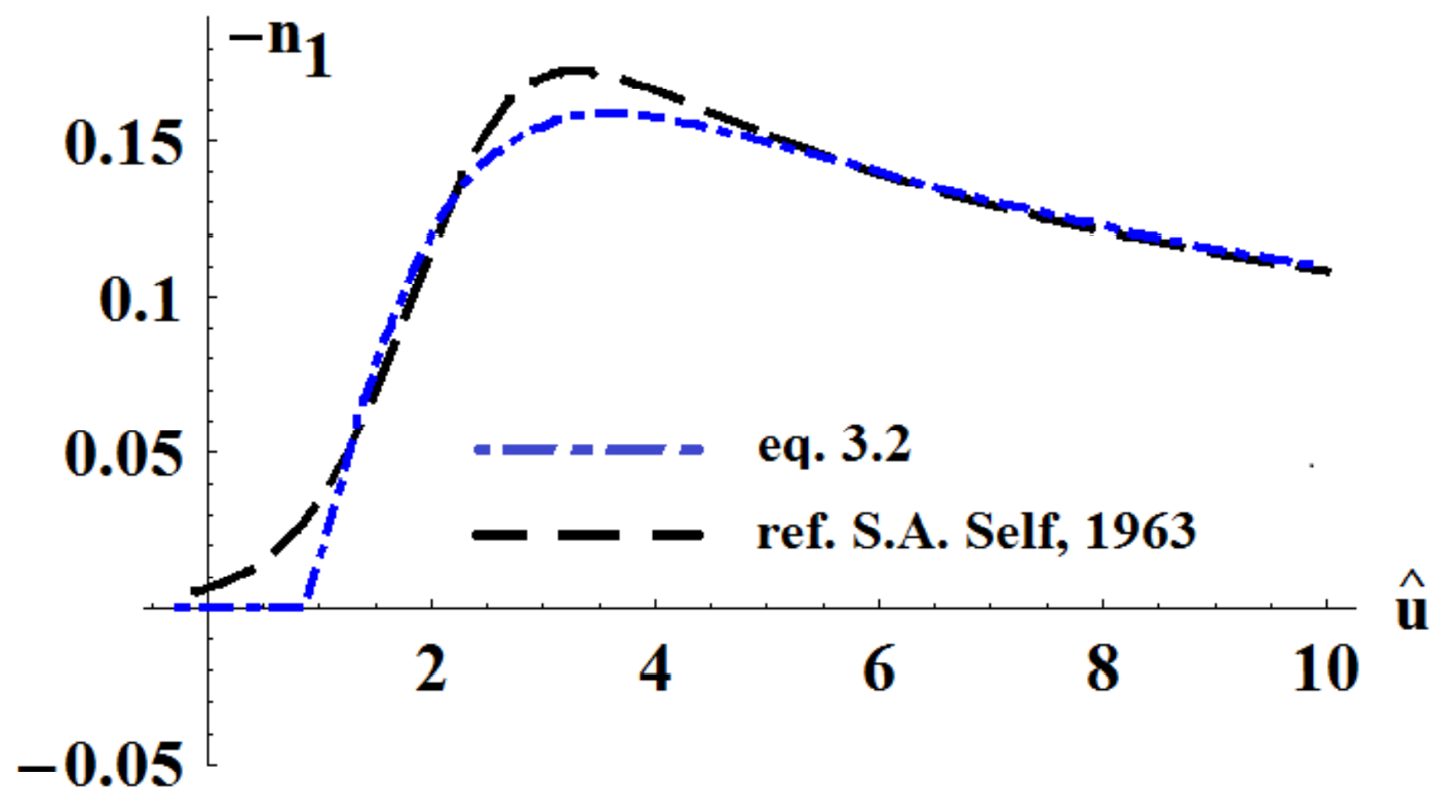
$$u = e\phi/T_e \qquad n_+ \equiv n_i/n_{e0}$$

$$n_- = (n_e + n_{H^-})/n_{e0}$$

In this dimensionless quantities Poisson eq. becomes

$$-\lambda_D^2\, \Delta u = n_+ - n_- \equiv n_1$$

Debye length $$\lambda_D = (\epsilon_0 T_e / e^2 N_{e0})^{1/2}$$



In principle n_1 calculation requires a kinetic and collisional model. But we can use a smooth approximation of a 1D kinetic solution of the complete plasma equation [12,14]; that is

$$n_1(u) = -\frac{c_0}{2}\frac{1+\tanh(\hat{u}-u_m)}{[u_a^2 + (\max(0,\hat{u}))^2]^{1/4}} \quad , \quad \hat{u} - u_p \tag{3.2}$$

plotted above, with c_0=0.344 and u_p the average of u at ion starting positions z_s .

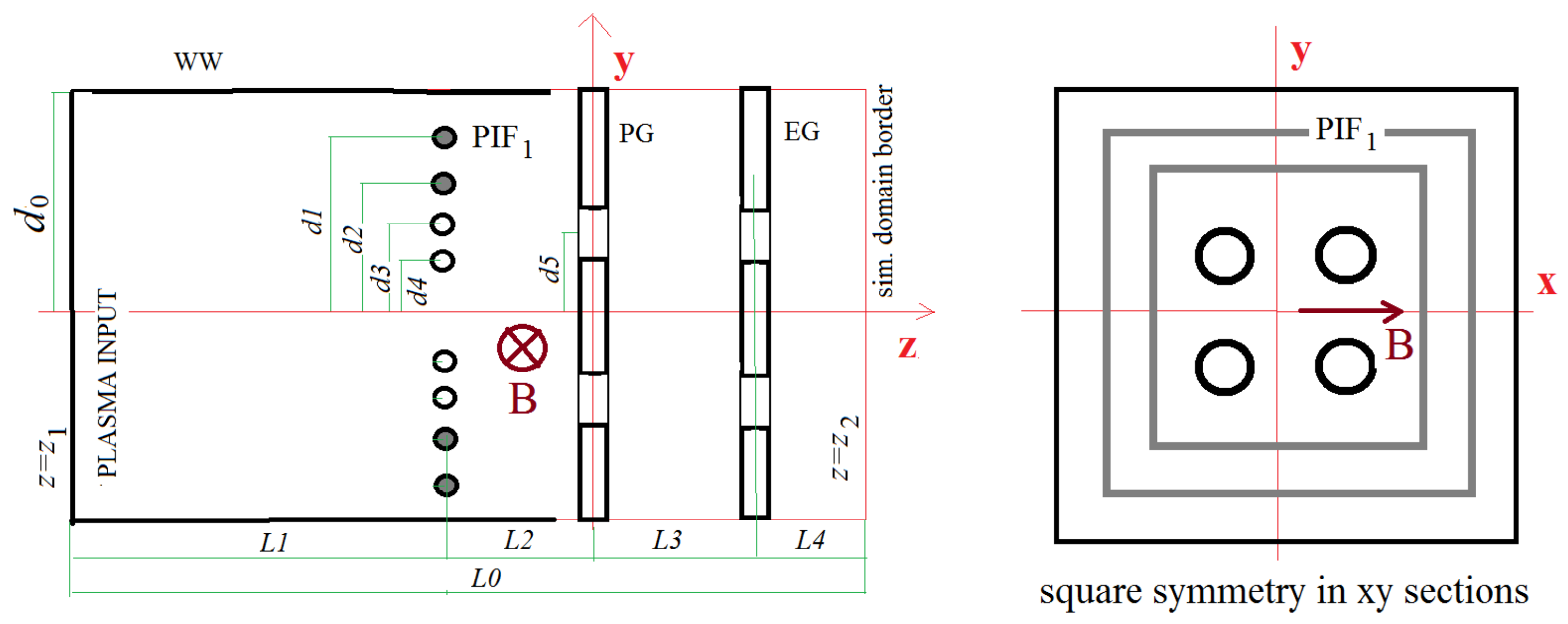
Apart from wider wall (WW), boundary conditions (bc) are fixed potentials at electrodes (funnel, BP) and Neumann bc at isolator and gap. At WW, for mesh economy, we exclude standard sheath from simulation domain and correct potential $-V_b$ by known sheath voltage drops:

$$u_w = \frac{e}{T_e}(-V_b + \phi_d + \Delta\phi) = -\frac{eV_b}{T_e} + f_1 + f_2 .$$

We have f_1=0.854 and

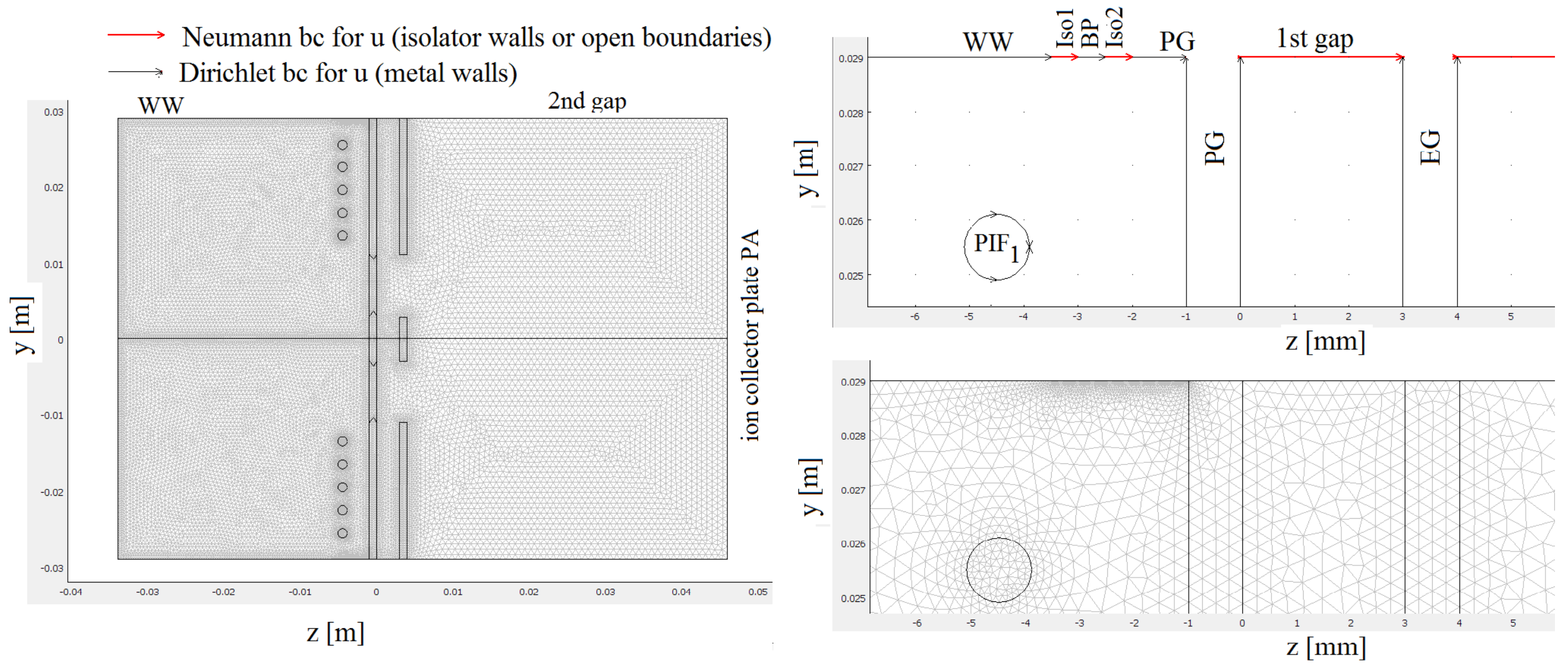
$$\phi_d = f_2(T_e/e) \quad , \quad f_2 = \tfrac{1}{2}\log(M_i/2\,\pi\, m_e)$$

In our example, V_b = 16 V, T_e = 1 eV, and f_2 = 4.1, so that $u_w = -11$..



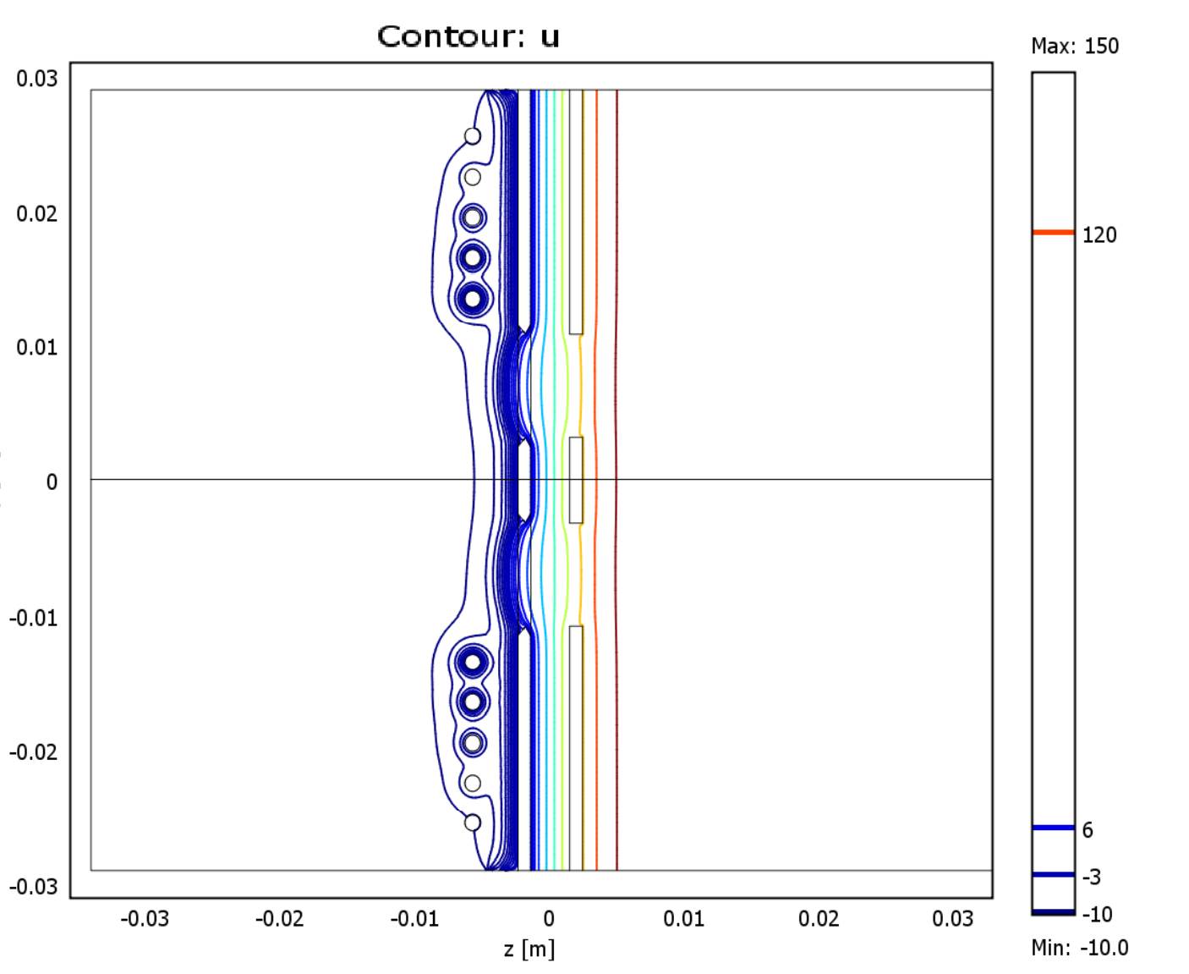
square symmetry in xy sections

3D geometry (a) yz section, with z the beam axis (b) xy section, note 4 extraction aperture

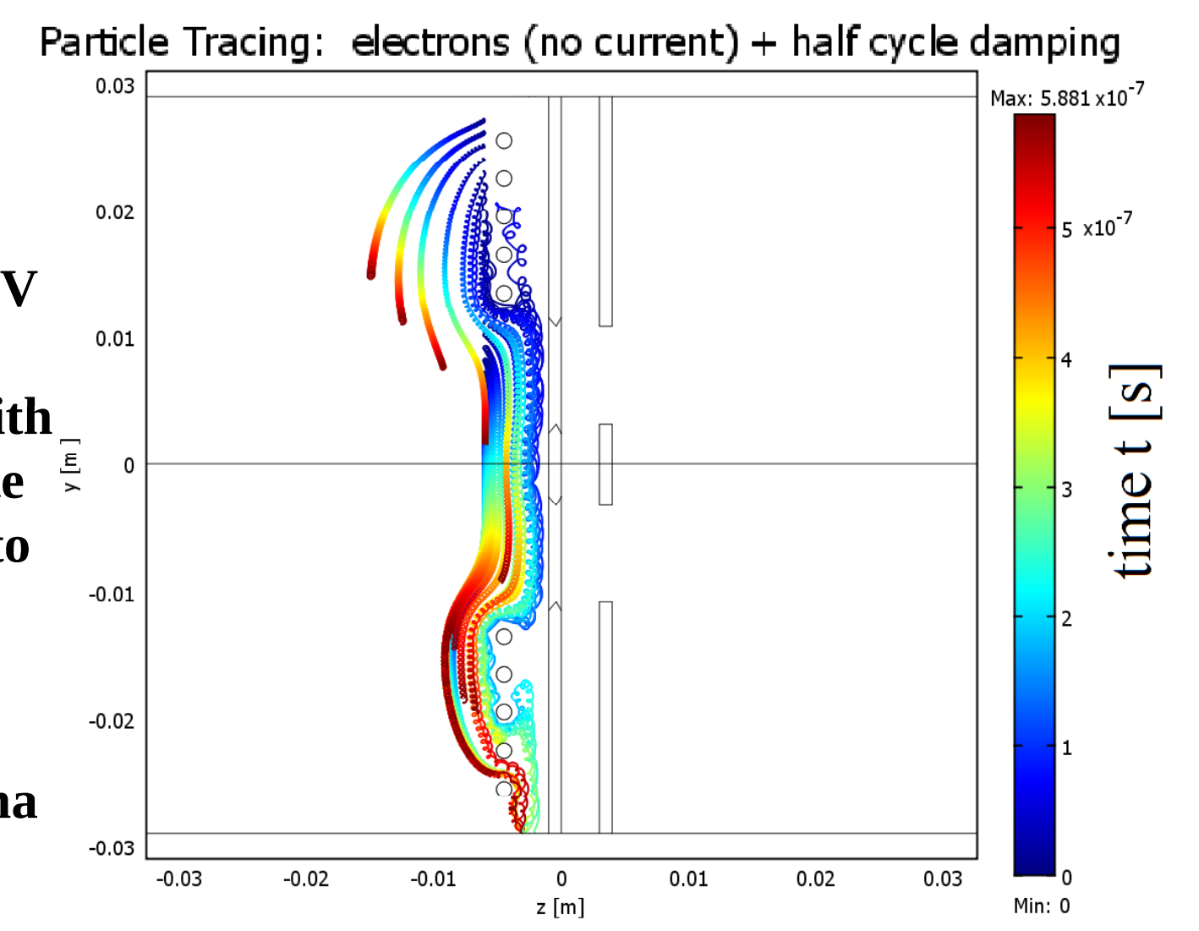


(a) overall view of the mesh; EG is the extraction grid; (b) detail of upper border, with isolator walls ISO1 and ISO2; note the wall segment connected to PG; (c) mesh refinement near ISO and BP border, region where plasma equipotentials concentrates

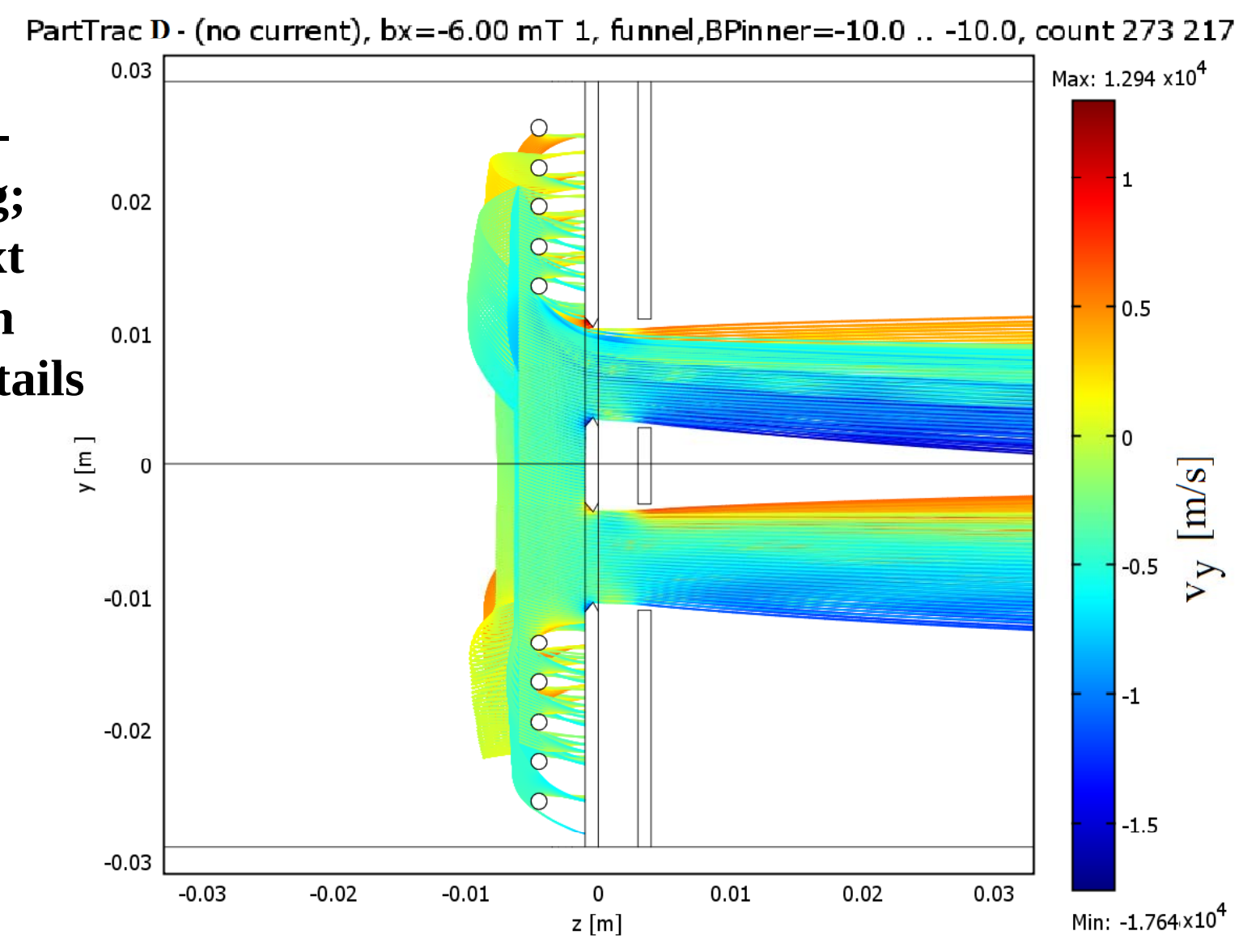
IV. RESULTS



Equi-potential lines, eg. u-level

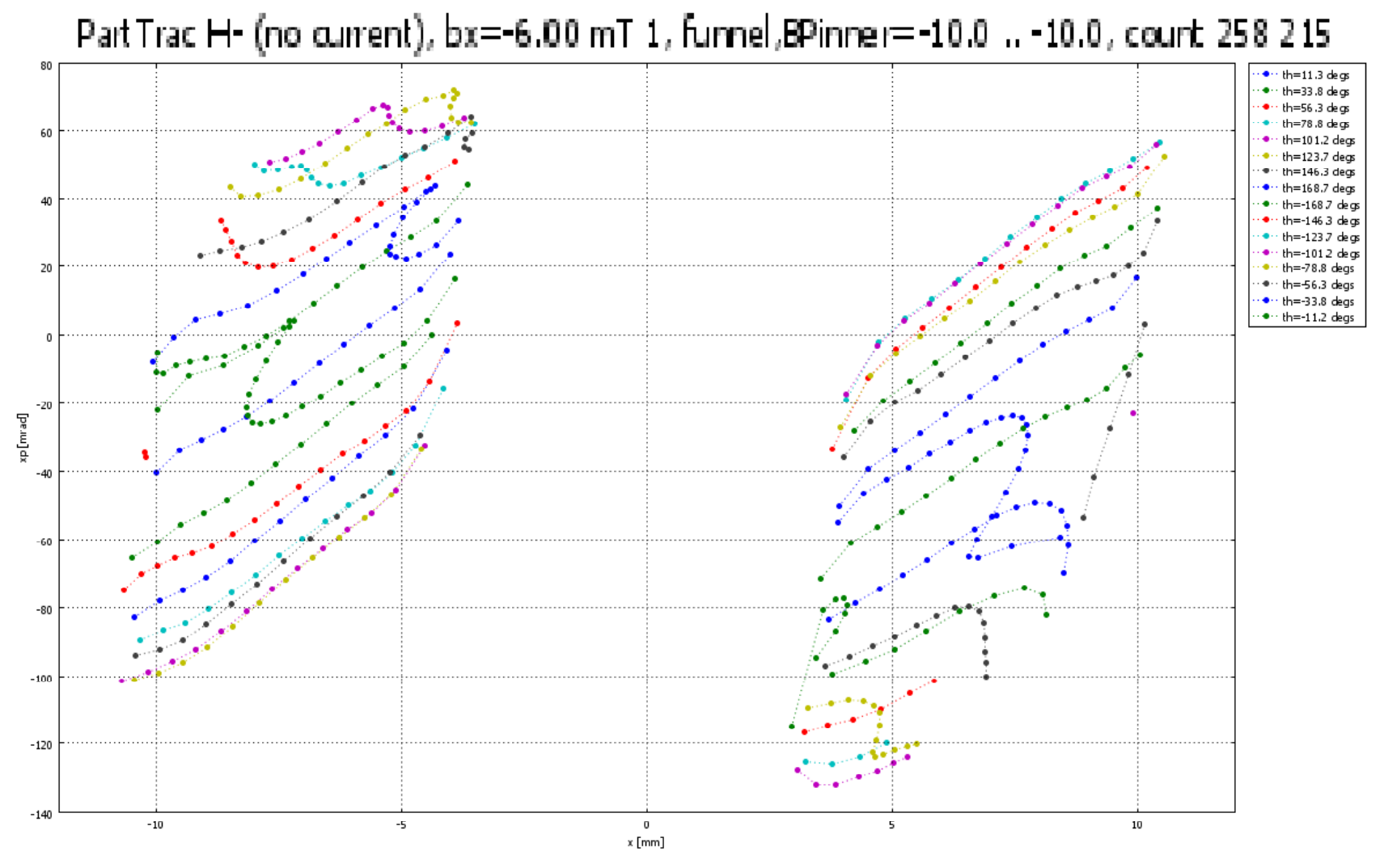


Electron drifts, with z_s=-6 mm, and initial energy 0.1 eV and heat exchange with plasma. Note flow bends to follow u-levels, and few e- go inside plasma



D- ray-tracing; see next caption for details

IV.b Extracted ion emittence



Ion emittance plot y-y' at z = 0:025 m, from previous figure; D- starts from z_s =-6 mm, with y_s =[-43:43]/2 mm and θ_s as labeled (ions with same θ_s are joined by dotted lines as visual guidance). Points can be inscribed into 2 ellipses (as expected); note slight top-down c ellipses count asymmetry; due to electrode placement (to be improved)some ellipses parts are still missing

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