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Validation of Negative Ion Beam Space Charge Compensation

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1) Introduction

2) Basic equations (and assumptions)

3) Implementation with Comsol MP

4) Results

5) Conclusion and references

Abstract or Executive summary:

The Space Charge Compensation (SCC) of Ion Beams is considered to be a key ingredient of the transport in drift regions of high current ion beams, both positive as H+ and negative as H- beams envisioned in the Neutral Beam Injectors envisioned for the ITER tokamak. The SCC phenomena consists in the accumulation of a background charge that nearly completely balance the beam space charge, allowing transport of parallel beams without external focusing or acceleration. Even if a 1D radial model is well known, 2D or 3D model are necessary for realistic beam estimates. A 2D fluid model was recently implemented with the help of Comsol Multiphysics simulation tools. This model shows that even if radial SCC flow well stabilizes, H2+ may flow axially back into the accelerator and this unwanted flow may be reduced by another electrode. Here a related Monte Carlo tools to confirm the fluid model prediction is presented. Electric field is obtained by solving Poisson equation by CM , with space charge density due to particles, and by computing field at each particle position by post processing. Secondary particles are generated within the beam volume and their motion is followed by explicit leapfrog time integration until they reach boundaries. Due to the large number of particles necessary, computation time is much more longer the fluid model, even if .somewhat more stable. Code largely benefit from parallelization of Comsol MP routines, even if some careful programming is required for efficiency. Result confirm that the positive background charge has a larger radius than the beam (as firstly emphasized by fluid model) and that axial flow does exist near electrodes (as also predicted). For typical beam profiles, SCC background is plotted. Electron density is small, and possible burst release mechanism are also investigated.

1) INTRODUCTION:

The Space Charge Compensation (SCC) phenomena is the formation of a secondary plasma (due to accumulation of slow reaction products) which helps the propagation of a high density particle beam

Mechanism: gas ionization by primary beam $\underline{H^-}$ or $\underline{H^+}$

$$\underline{H}^{\pm} + H_2 \rightarrow \underline{H}^{\pm} + e + H_2^+ \qquad (1)$$

$$\underline{H}^{-} + H_2 \rightarrow \underline{H}^{0} + \underline{e} + H_2 \qquad (2)$$

$$\sigma_2 = 3 \times 10^{-20}\ \mathrm{m}^{-2}\ (\text{for } 100\ \mathrm{keV}$$

Fast particle are underlined; second reaction provides no slow product. For first reaction

$$\sigma_1 = 2\times10^{-20}\ \mathrm{m}^{-2}$$

slow products : electron temperature T_e= 3 to 5 eV

and H2+ ion temperature = parent H2 (0.2 eV)

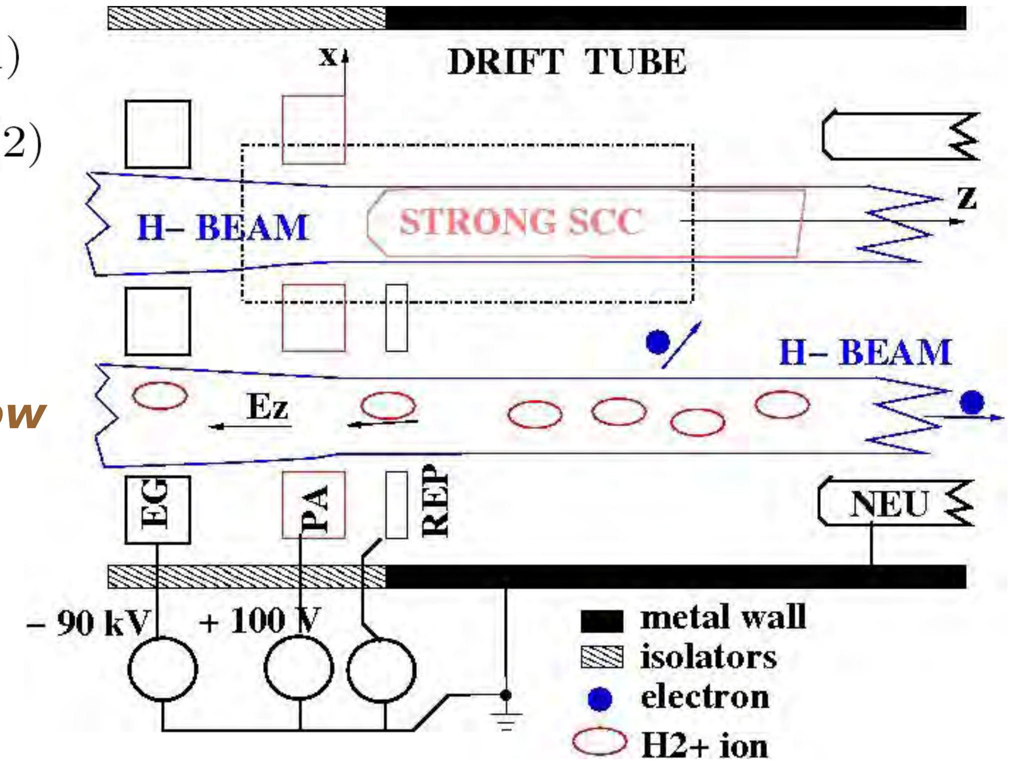


Fig 1: Geometry of the drift tube; two beamlets are shown; simulation region of the fluid model is the dashed rectangle (from MC+PV, Comsol 2010, Paris)

Necessary conditions for space charge compensation (from radial 1D model, Holmes 1989, Soloschenko 1998):

1) gas density n_g sufficient

2) region with no applied electric field (otherwise secondary plasma will be swept away)

3) enough beam radius

1D predictions: SC compensation is 101 +/- 2 % , primary beam self-potential φ (-1 kV scale) is completely shielded, residual φ order of $+T_e/e$

SCC happens also for positive primary beam; is slightly less complete (say 99.5%); still valuable to save focusing elements, for example the IFMIF low energy beam transport (LEBT); see 3D Monte Carlo simulations (Chauvin, 2008)

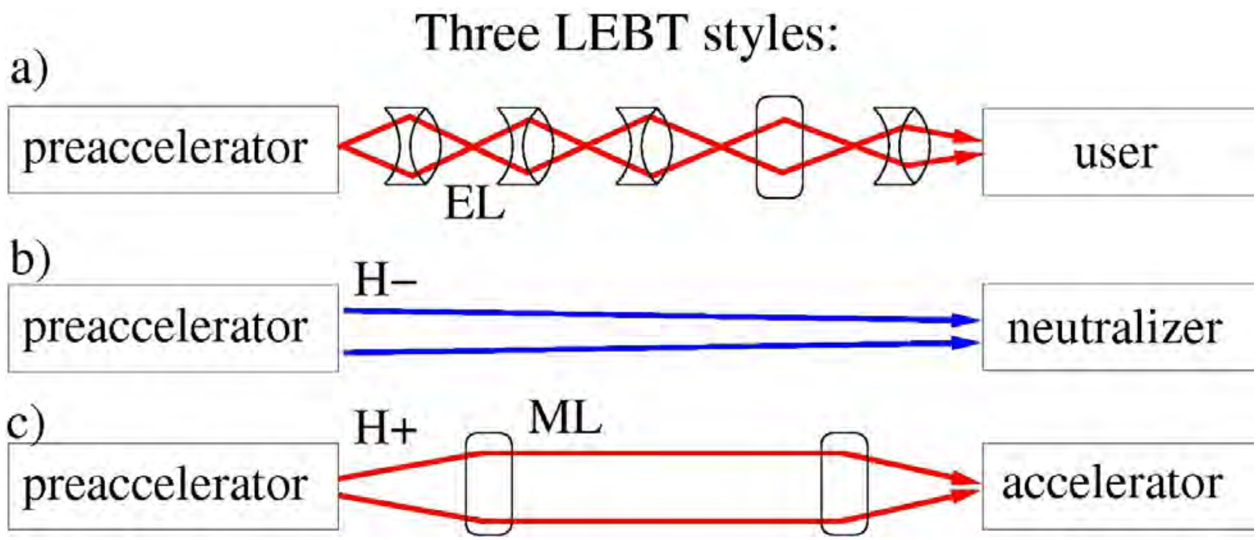


Figure Comparison of LEBTs without (case a) and with SCC (b and c); ML= magnetic lenses; EL= electrostatic lenses)

2) BASIC EQUATIONS (AND ASSUMPTIONS)

Average primary beam density n_0, for example $n_0 = 8.2 \times 10^{13}\ \mathrm{m}^{-3}$

Primary beam density $n_{H-} = n_0 n_b(x)$

Secondary ion density $n_2(z, x, t) = n_{H_2^+}$

here 2D model: z beam axis, x transverse direction

$$-(\epsilon_0/e) \triangle \phi = n_2 - n_e - n_0 n_b \equiv n_0 n_a$$

where n_a is the scaled charge of all particles.

Monte Carlo: secondary ions are create with random speed (Ti = 1 eV) and random position, with rate density

$$R_s = \mathrm{d}n_2 / \mathrm{d}t = n_g n_0 n_b(x) \sigma_1 \qquad (6)$$

Monte Carlo: motion eq. is simple, but is applied to many macroparticles, each with its own speed, so computation is long (this paper)

$$m_2\, \mathrm{d}_t \mathbf{v} = q_2 \mathbf{E}(\mathbf{x}) \quad , \quad \mathrm{d}_t \mathbf{x} = \mathbf{v} \qquad (7)$$

dusty plasma like → $m_2 = w_2 m_{H2}$ $\qquad q_2 = w_2 e$

w_2 the number of ions which each macroparticle represents;

Fluid model: motion of particles is averaged, so that eq. is more complicated, but we have one velocity (MC+PV, 2010)

Our basic idea: solve fluid and Monte Carlo model in the same Comsol MP environment and compare them

Kinetic model: all particles are considered in the phase space (equation looks like fluid model, but computation time is longer than Monte Carlo model)

Parameters used in these simulations:

incoming H^- velocity v_b $\quad v_b = 4.4 \times 10^6$ m/s

Number of macroparticles 160000, $\quad w_2 = 1.1 \times 10^6$

acceleration potential $\quad U_b = 100$ kV

gas density $\quad n_g = 2 \times 10^{18}$ m^{-3}

beam profile: square, trapezoidal, gaussian, parabolic

$\int n_b(x)\,\mathrm{d}x = 2r_b$ **= beam average width =** $2r_b = 8$ mm

$$
\begin{aligned}
n_{b1} &= \Theta(r_b - x') \\
n_{b2} &= \max(0, \min[1, \tfrac{1}{2} + (r_b - x')/\delta_b]) \\
n_{b3} &= \exp[-\tfrac{1}{2}(x'/\sigma_b)^2] \qquad (10) \\
n_{b4} &= \max(0, 1 - (c_4 x'/r_b)^2)
\end{aligned}
$$

with

$\sigma_b = r_b(2/\pi)^{1/2} \qquad c_4 = \frac{2}{3}$

δ_b is the thickness of the region where n_{b2} goes from 1 to 0.

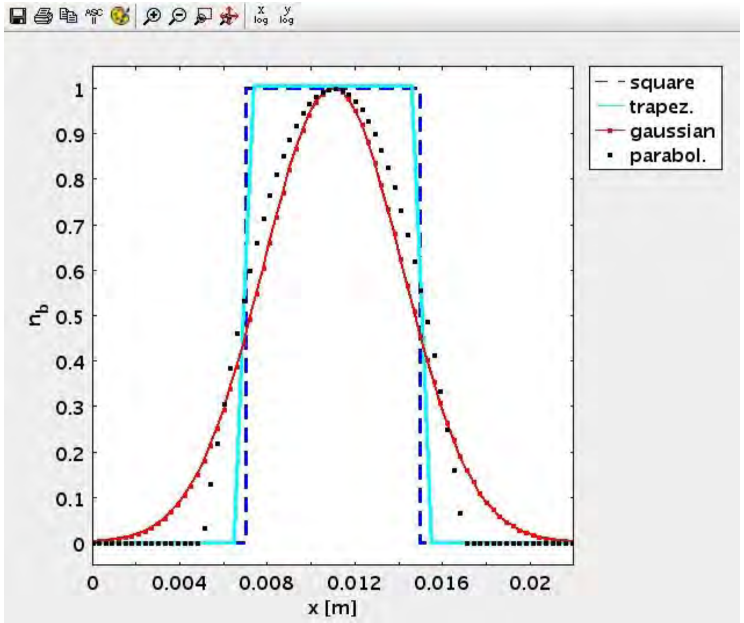


Figure: types of density profile

2.1) Boundary condition for potential $u=\varphi$ and particle flow

Upper and lower side: far away tube condition (to save on simulation domain area) -> Mixed Neumann

$$i_w \cong 1/w \quad \text{and} \quad \mathbf{n}\cdot\nabla u = -i_w u \qquad (8)$$

Right side $z=z_h$: beam exit in perfect axial equilibrium, so $E_z=0$,

Eq 8 with $i_w=0$ (Pure Neumann)

Left side: beam input and metal grid at φ_{PA}: mixed Dirichlet:

$$0 = R = (\phi_{PA}-\phi)\Theta(|x-\tfrac{1}{2}L_x|-r_h, w_h) \quad (9)$$

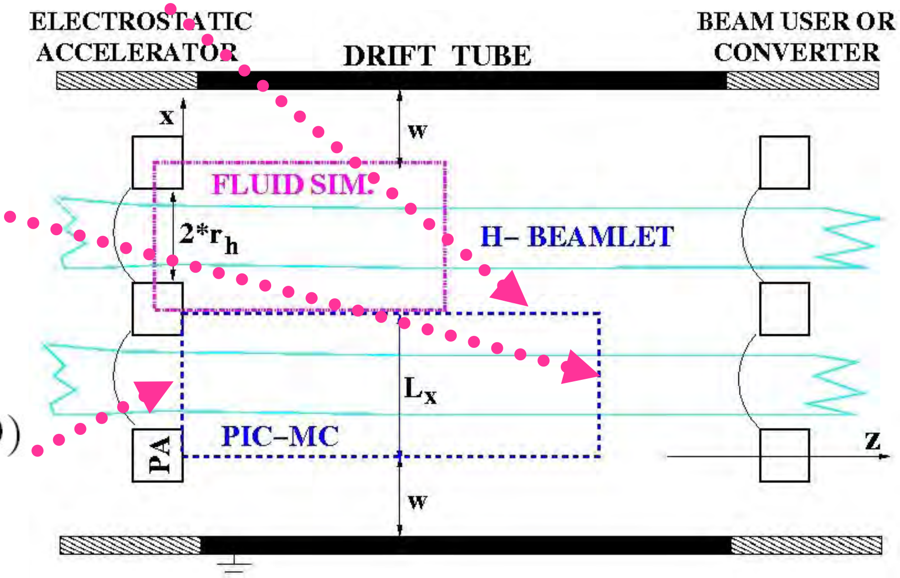


Figure: comparison of simulation domains for fluid and Monte Carlo model

Right side: all particle reflected: $F_c=1$

The boundary condition for particle flow at $z = z_h$ is free symmetric and specular flow; that is, when a particle exit with velocity (v_z, v_x) another one is injected with initial velocity $(-v_z, v_x)$; this is consistent with the Neumann condition for ϕ, since it maintains an uniform SCC at this boundary.

Upper, lower, left side: fraction of reflected particles $F_c=0$

3) IMPLEMENTATION:

Motion integrator: **leapfrog**

Poisson solver **femlin (Comsol MP):**

Space charge teller: **user defined function* dens for femlin**

Field teller: **postinterp (Comsol MP)**

***dens(x,y) must be written with care, as a simple table lookup function for speed. No elegance. Otherwise, speed decreases. A 'teller' function is a function that transmit information between main subtask**

Debye length, from 1.4 to 0.5 mm

$$\lambda_D = (\epsilon_0 T_e / e^2 n_0)^{1/2}$$

Lattice spacing $h_x = 0.17$ **mm**

Number of macroparticle per cell >> 1

$$dt < \lambda_D / v_e$$

Here dt=1.2 ns for H_2^+ and electrons

Smoothing distance

$$w_s = 5 h_x = 0.85 \text{ mm.}$$

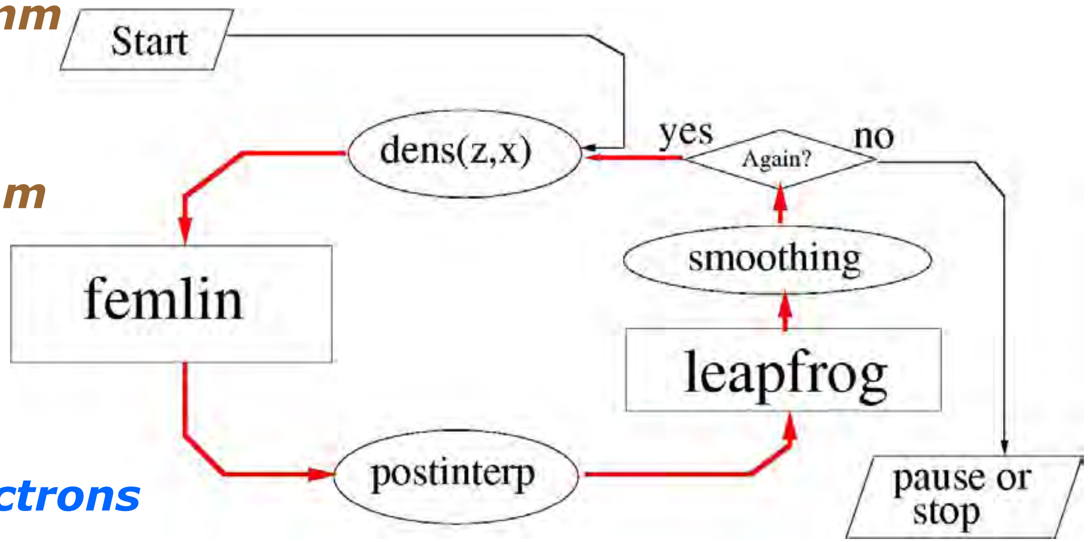


Figure: The solution cycle repeated each dt=1.2 ns

note that cloud of ions diffuses out the primary beam

Smoothing is adjusted not to increase the ion diffusion

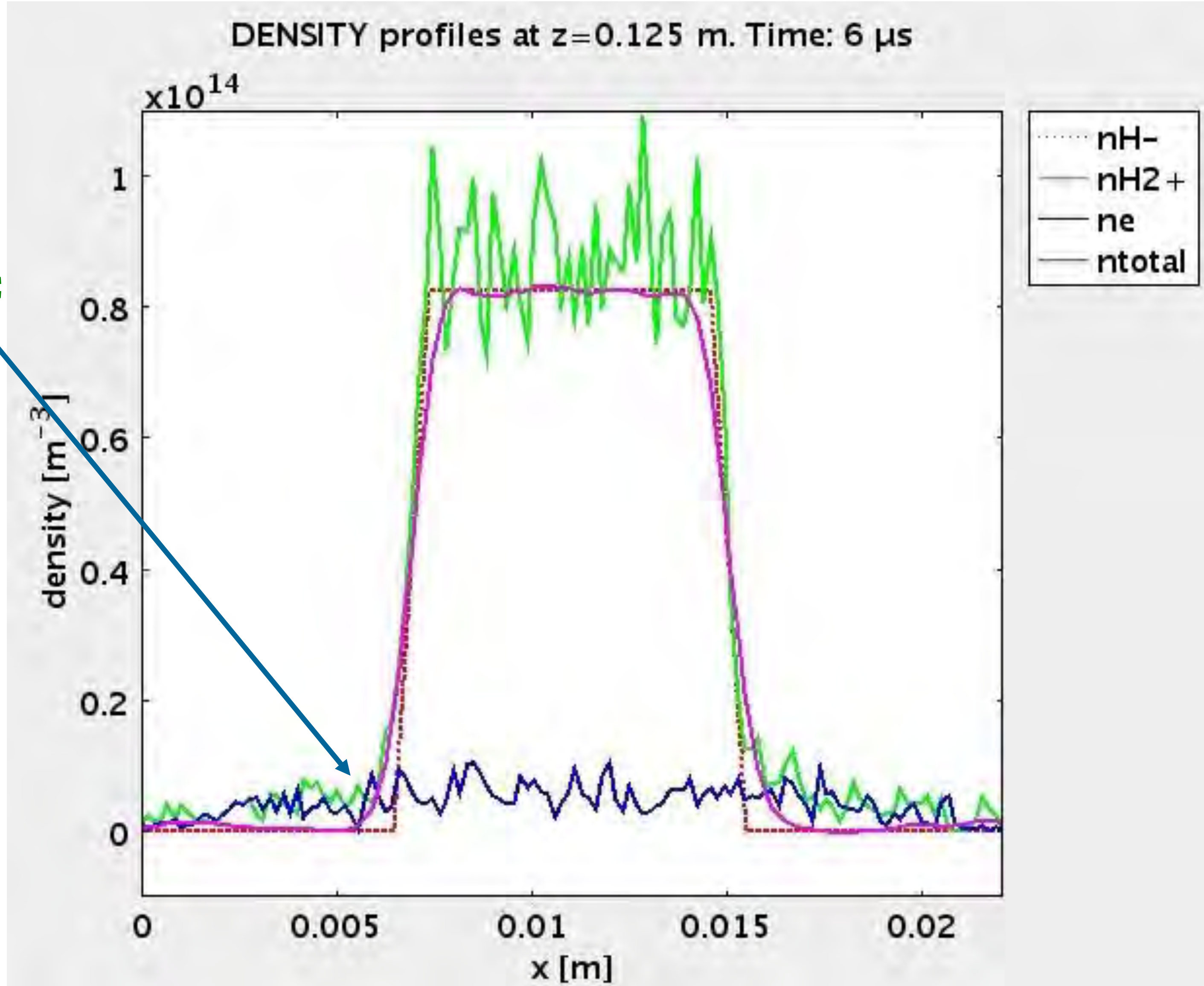
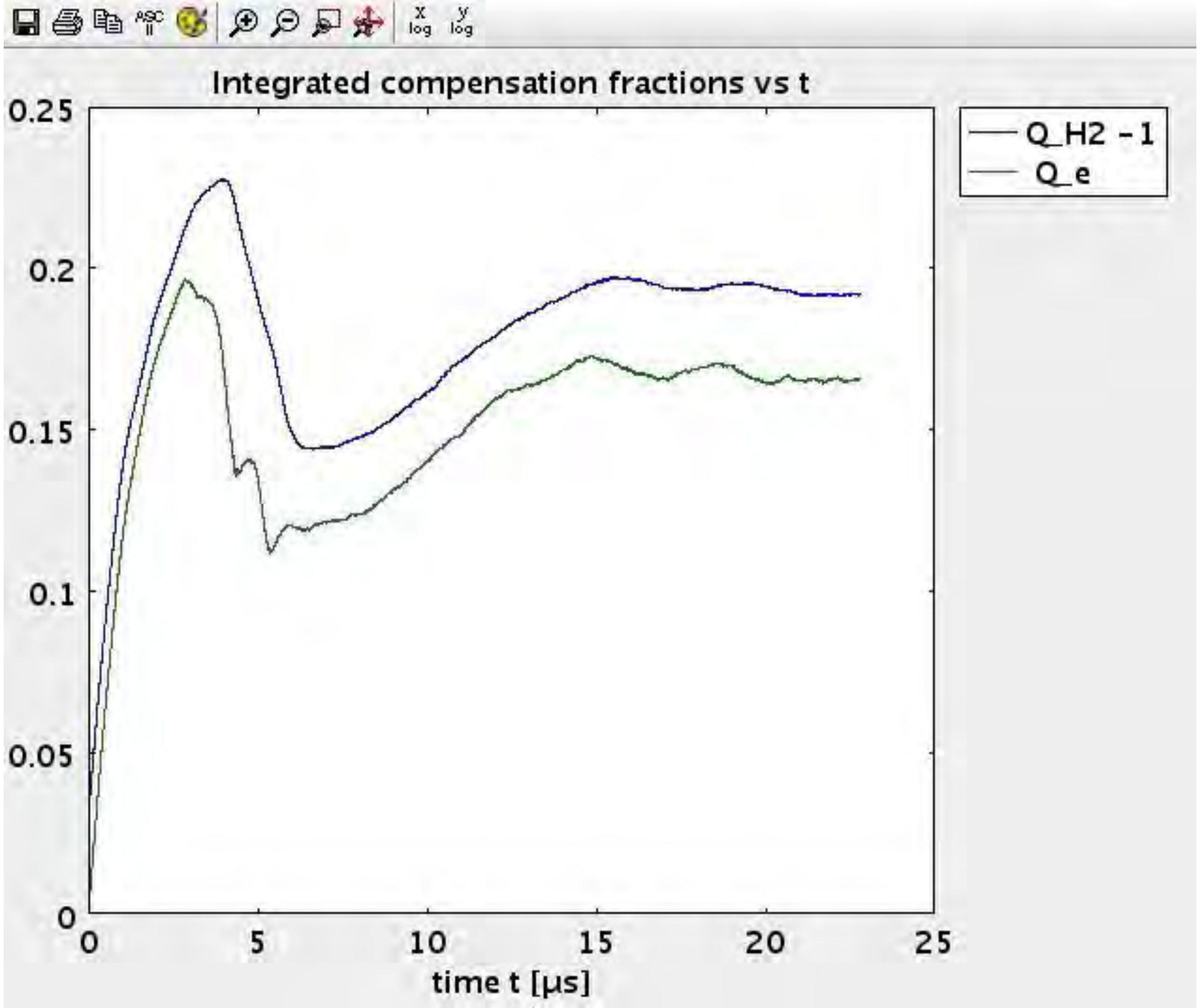


Figure: comparison of densities at $z=z_h/2$. Here ntotal is the smoothed result of $n_{H2+} - n_e$

4) RESULTS:

After an initial overshot (whose shape may depend on artificial starting condition), a much lower evolution to a noisy equilibrium is observed

Overshot shape is still preliminary



$$Q_e(t) = \int n_e(z,x,t)\,\mathrm{d}x\,\mathrm{d}z/(2r_b n_0) \qquad (5)$$

$$Q_2(t) = \int n_2(z,x,t)\,\mathrm{d}x\,\mathrm{d}z/(2r_b n_0) \qquad (4)$$

Figure: evolution of the integrated compensation fraction Q_e and Q_{H2+}

Other evidences of evolution to a noisy equilibrium after a transient; continuous window averaging over 30 iteration is here used.

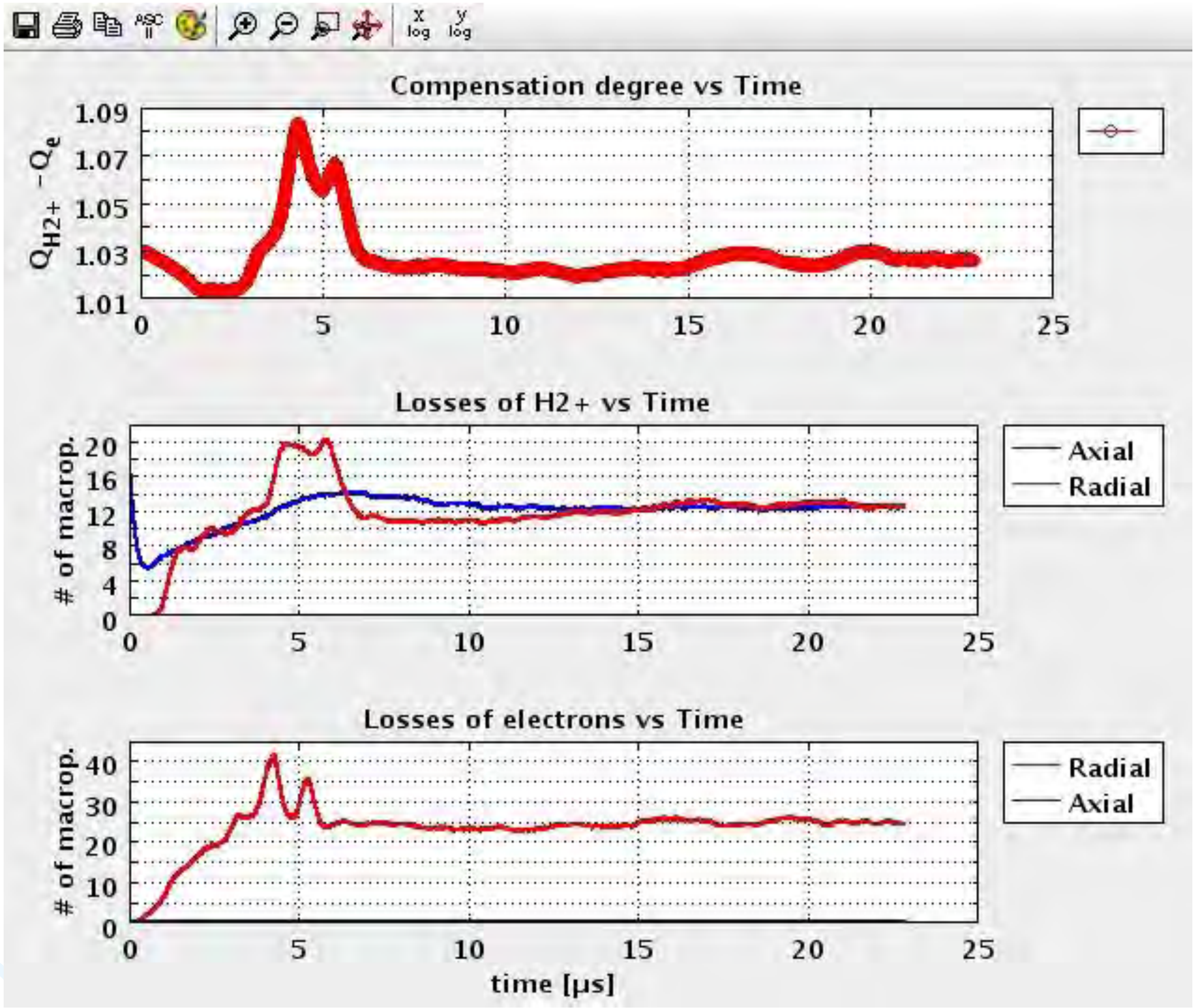


Figure: A macro code plot a graphical summary of macroparticle losses, subdivided in radial (through upper and lower boundary) and axial (through left boundary)

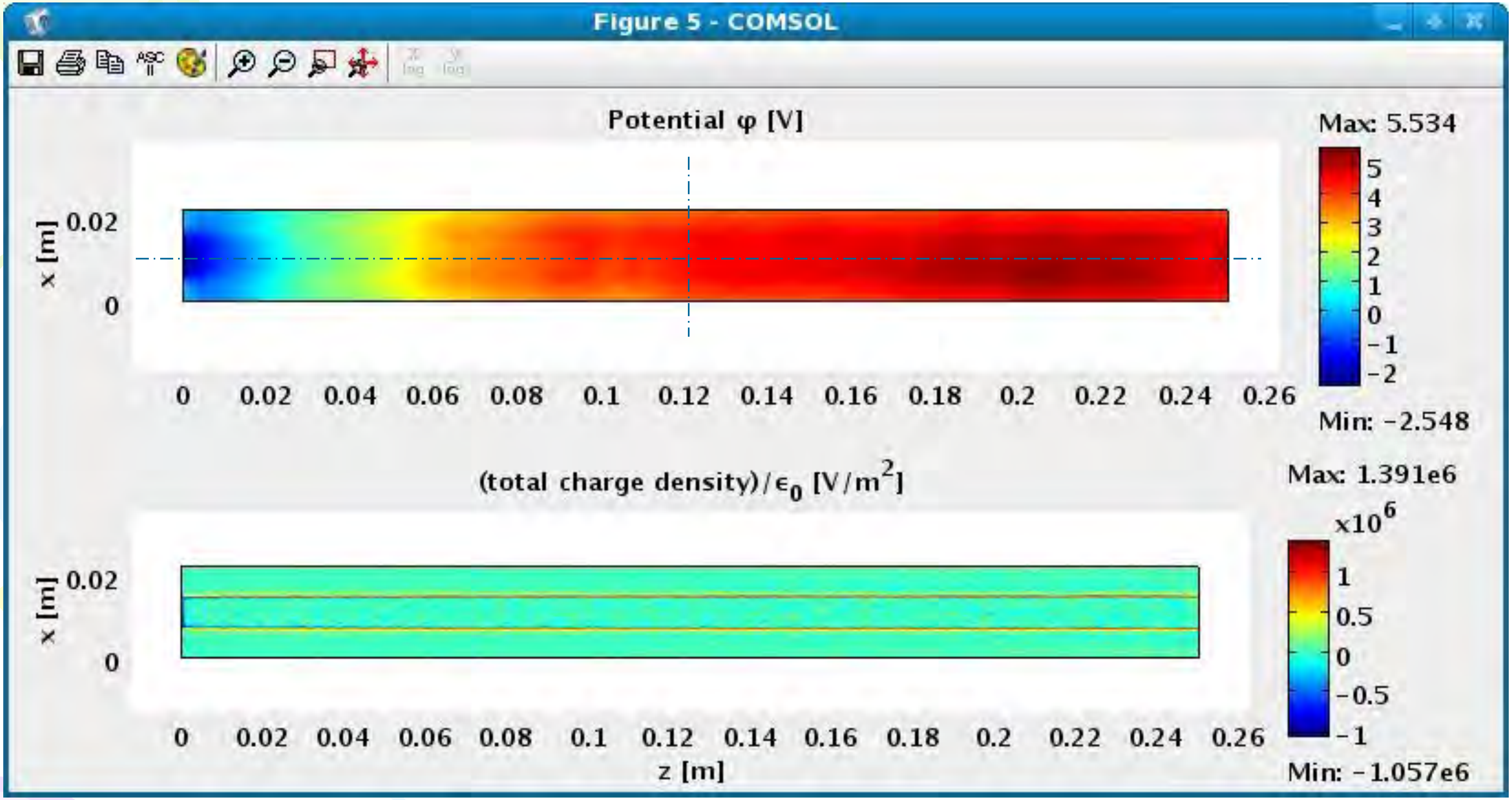
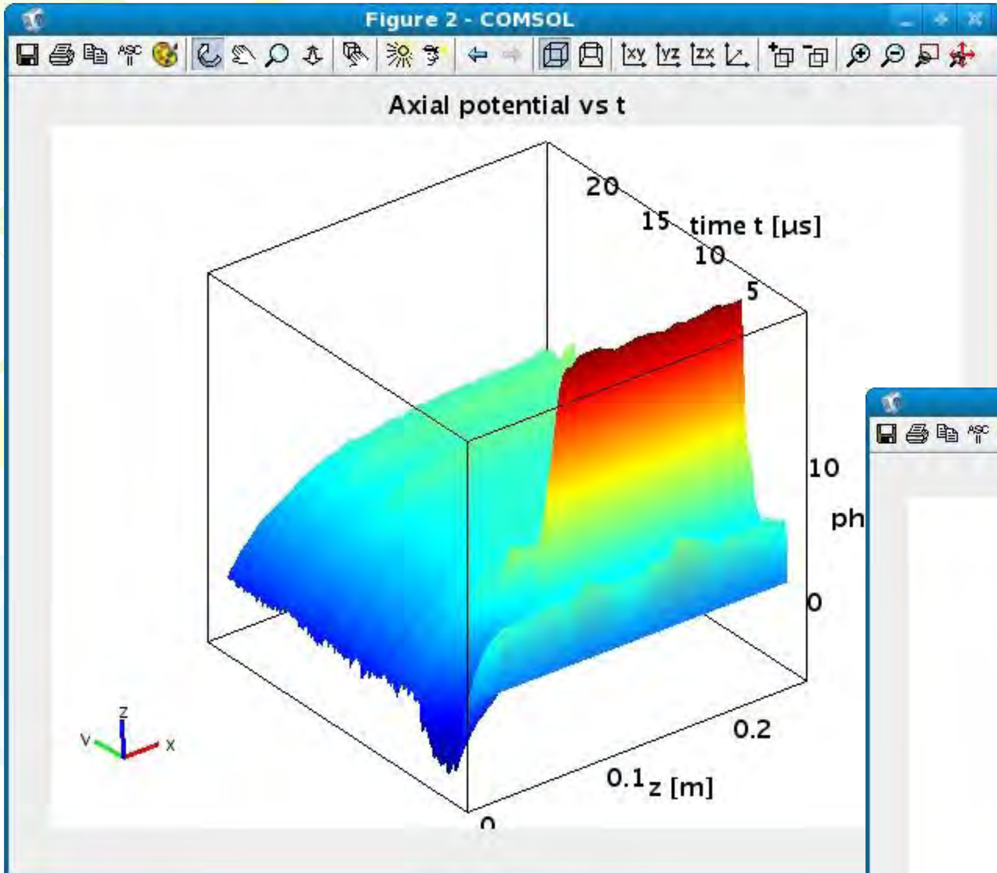


Figure: surface plot of potential and charge density; the potential φ evolution on the section lines the section lines (radial and axial) here dot-dashed is shown on the next slide



Conclusion: even if agreement with fluid model is fair, some noise around equilibrium is apparent and electron density is not negligible

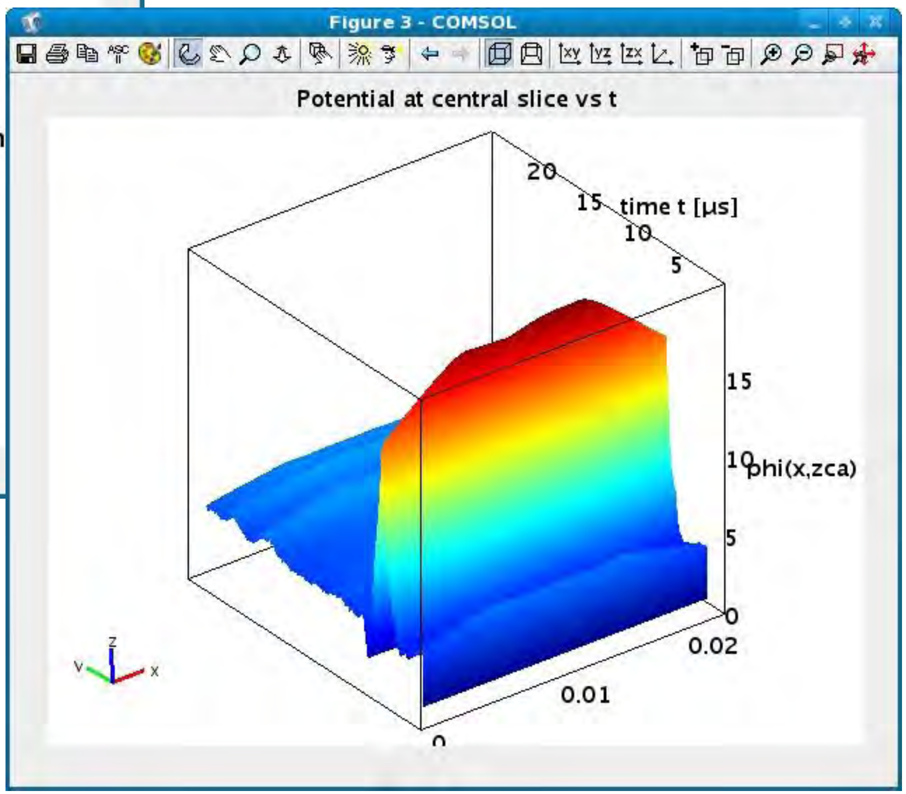


Figure: Evolution of the axial section potential: after the initial overshot, some damped waves are observed before equilibrium is reached

Figure: Evolution of potential on the radial section

Paper references (of course, SCC literature is much wider)

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