Ionization of the Gas Curtain of the BGC and tracking of ions and electrons at the HEL

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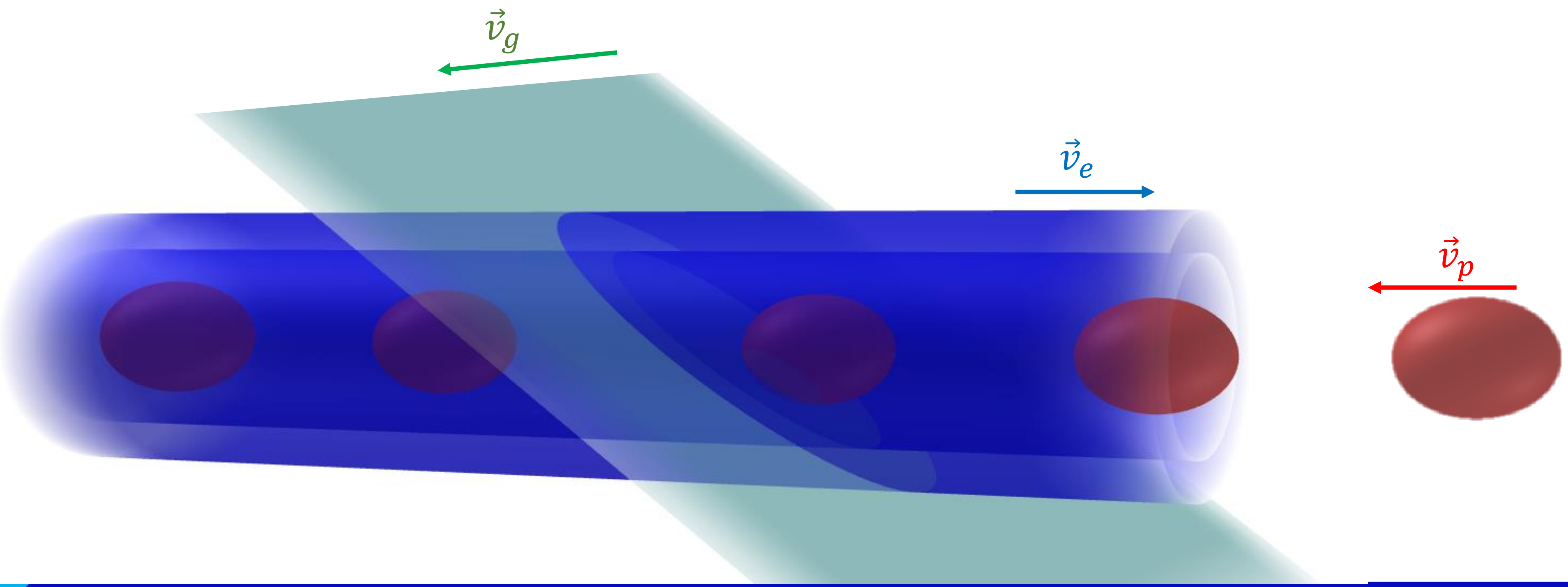
Outline

- Introduction
- Electric and magnetic fields of electron beam
- Fields of the proton beam
- Particle tracking
- Ions accumulation
- Conclusion

Introduction

- The gas (Ne) sheet is used to measure beams overlap and cross section.
- Side effect - it creates electron-ion pairs.



Proton beam parameters

σ_x, σ_y	306 µm
σ_z	8.3 cm
Q	$3{,}25 \cdot 10^{-8}$C (Gauss)
E_p	7 TeV

Electron beam parameters

I_e	5 A (uniform)
E_e	10 keV
r_0	2,5 mm
R	5 mm

Gas sheet parameters

ρ_g	$8 \cdot 10^{16}\ m^{-3}$ (uniform)
v_g	$800\ m/s$
Thickness	2,2 mm
Tilt angle	45°

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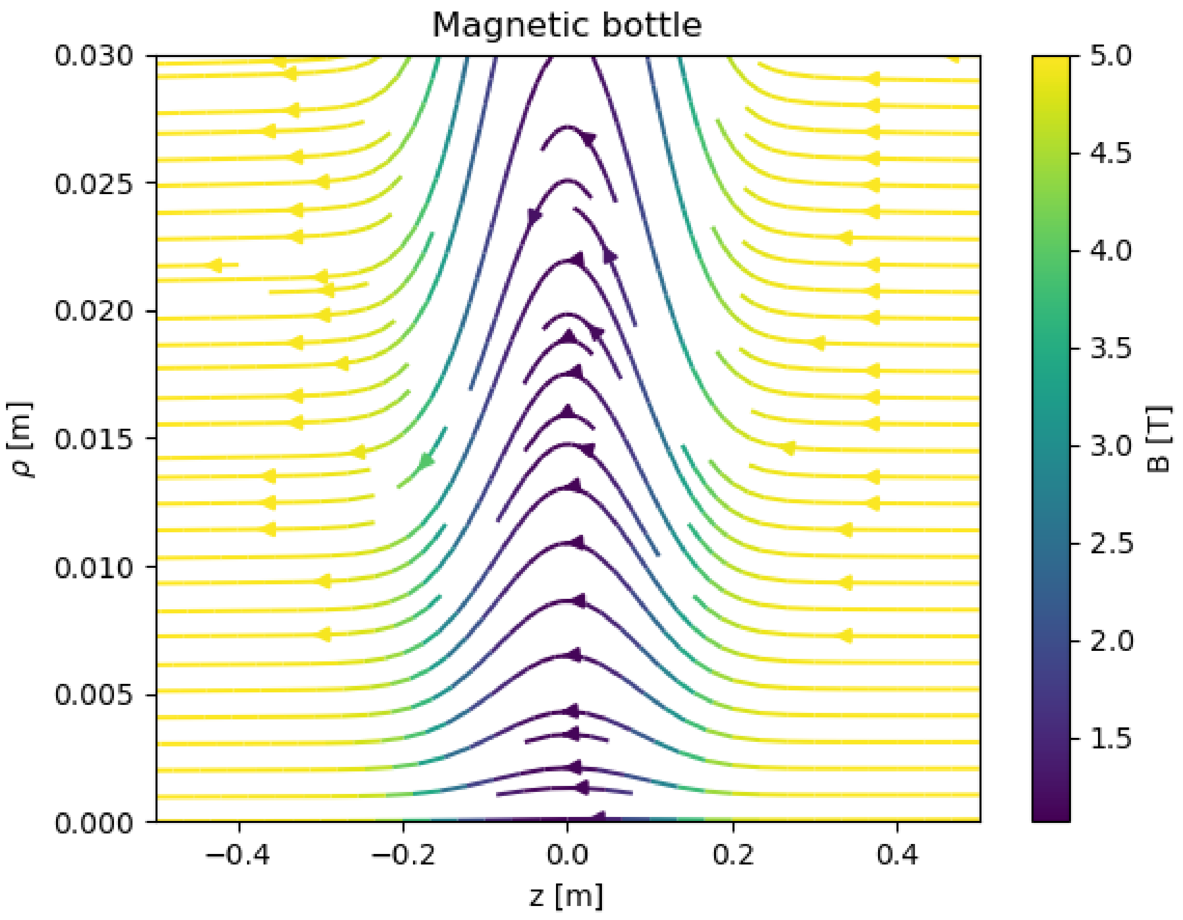
Magnetic "bottle"

- The external B field is weaker in the gas location.

- The magnetic lines form the "bottle" structure.

- It is possible to have the ionised particle trapped inside "bottle".



Goals

- Study ionised particle movement.
- Study distribution of the ionised particles in BGC.
- Can the ionised particles escape from the BGC location?
- Are the additional clearing electrodes needed?

How does the used code work?

- Using Runge-Kutta 4th order method.

- Simulated in the cylindrical volume $\mp 1{,}7$ m (center @ gas sheet) and 3 cm in R.

$$\begin{cases} \dot{\vec{p}}(t) = q\left(\left[\vec{v}(t) \times \vec{B}(\vec{r},t)\right] + \vec{E}(\vec{r},t)\right) \\ \dot{\vec{r}}(t) = v(t) \\ \vec{p}(t) = \dfrac{m\vec{v}(t)}{\sqrt{1 - \dfrac{v(t)^2}{c^2}}} \end{cases}$$

- Electromagnetic field from external magnets, proton and hollow electron beams.

- Each ionized particle is tracked independently.

External field interpolation

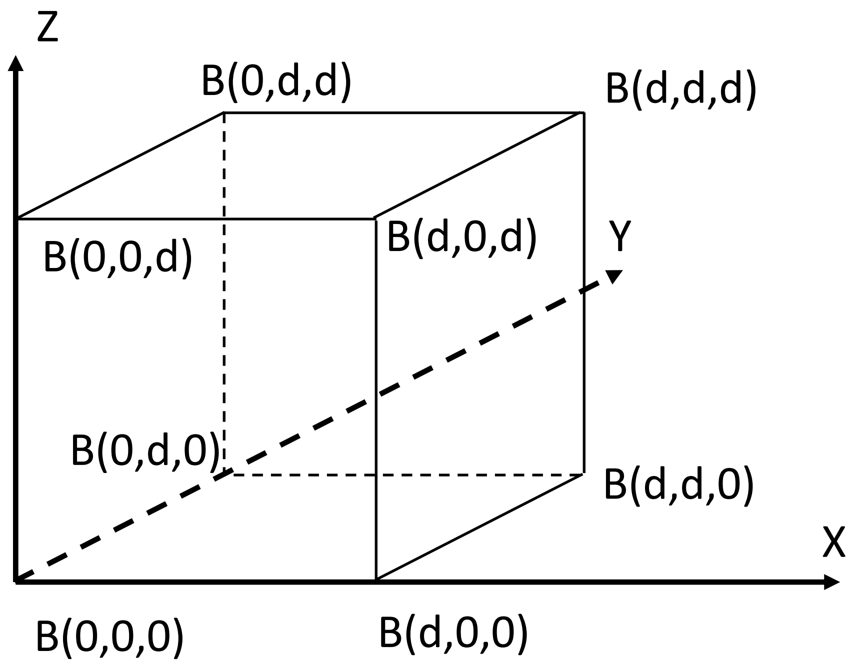
- The external magnetic field map was kindly provided by Sameed.

- Interpolation by the following formula:

$$B(x,y,z) = A_1xyz + A_2xy + A_3xz + A_4yz + A_5x + A_6y + A_7z + A_8$$

A_i are determined by solving linear equation.

d - mesh step (d = 1 cm in our simulation)



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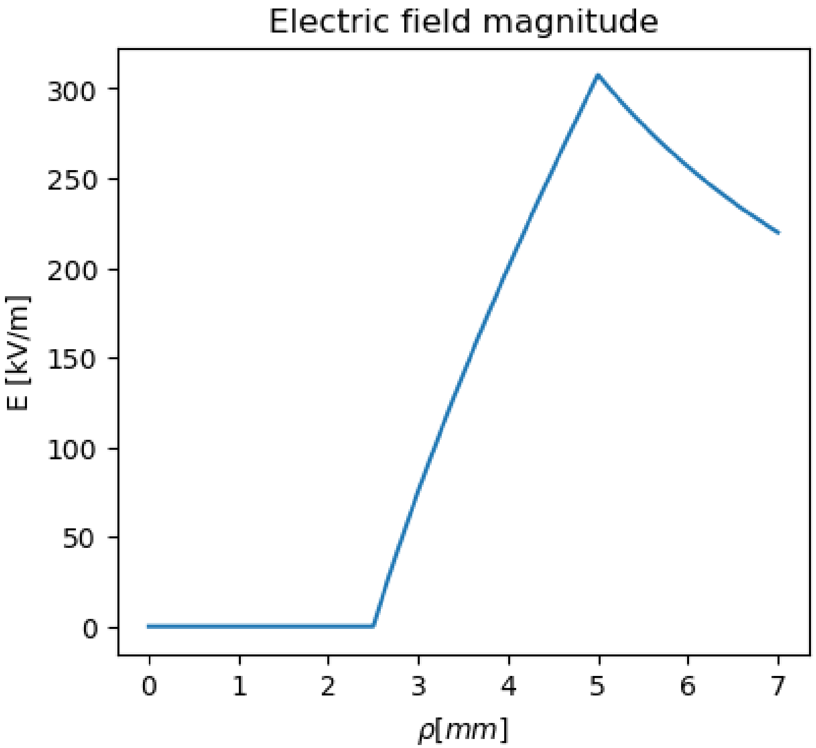
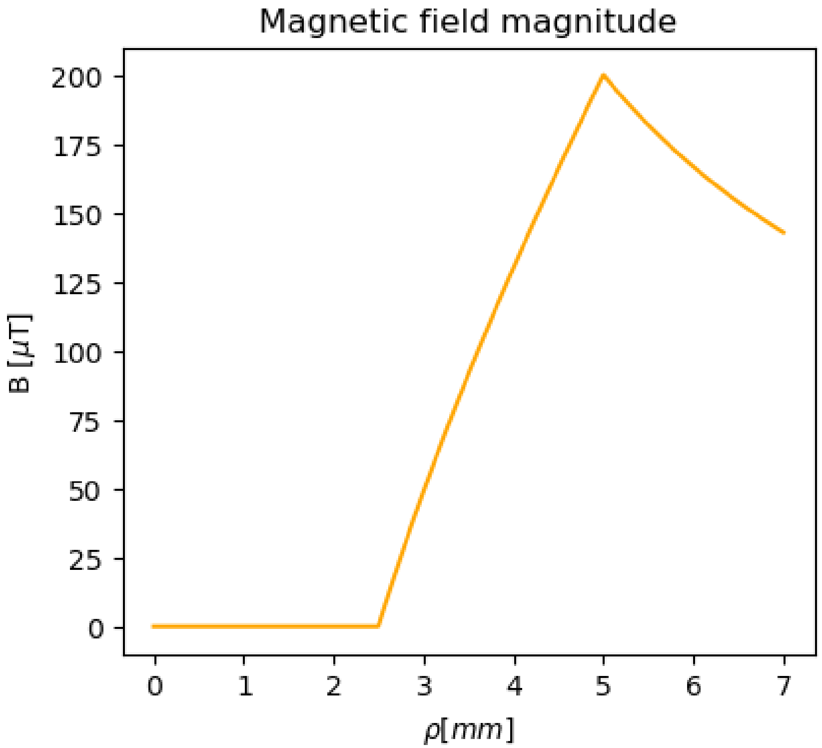
Electric & magnetic fields of electron beam

- Simplified as the field of the hollow cylinder infinite in z-direction.
- Do not depend on the z coordinate
- To be updated.





$$E(r) = \begin{cases} 0, & \text{if } r < r_0 \\ \rho\frac{r^2 - r_0^2}{2r\varepsilon_0}, & \text{if } r_0 < r < R \\ \rho\frac{R^2 - r_0^2}{2r\varepsilon_0}, & \text{if } r > R \end{cases}$$

$$B(r) = \begin{cases} 0, & \text{if } r < r_0 \\ \mu_0 j\frac{r^2 - r_0^2}{2r}, & \text{if } r_0 < r < R \\ \mu_0\frac{I}{2\pi r}, & \text{if } r > R \end{cases}$$

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Proton bunch field in rest frame

- The equation for the electric field:

$$\vec{E}' = \frac{\vec{r}'}{R}\frac{\sigma'}{\sigma'_z}\frac{Q}{(2\pi)^{3/2}R^2\varepsilon_0}\left(\sqrt{\frac{\pi}{2}}Erf\left(\frac{R}{\sqrt{2}\sigma'}\right) - \frac{R}{\sigma'}e^{-\frac{R^2}{2\sigma^2}}\right) + \vec{E}_c$$

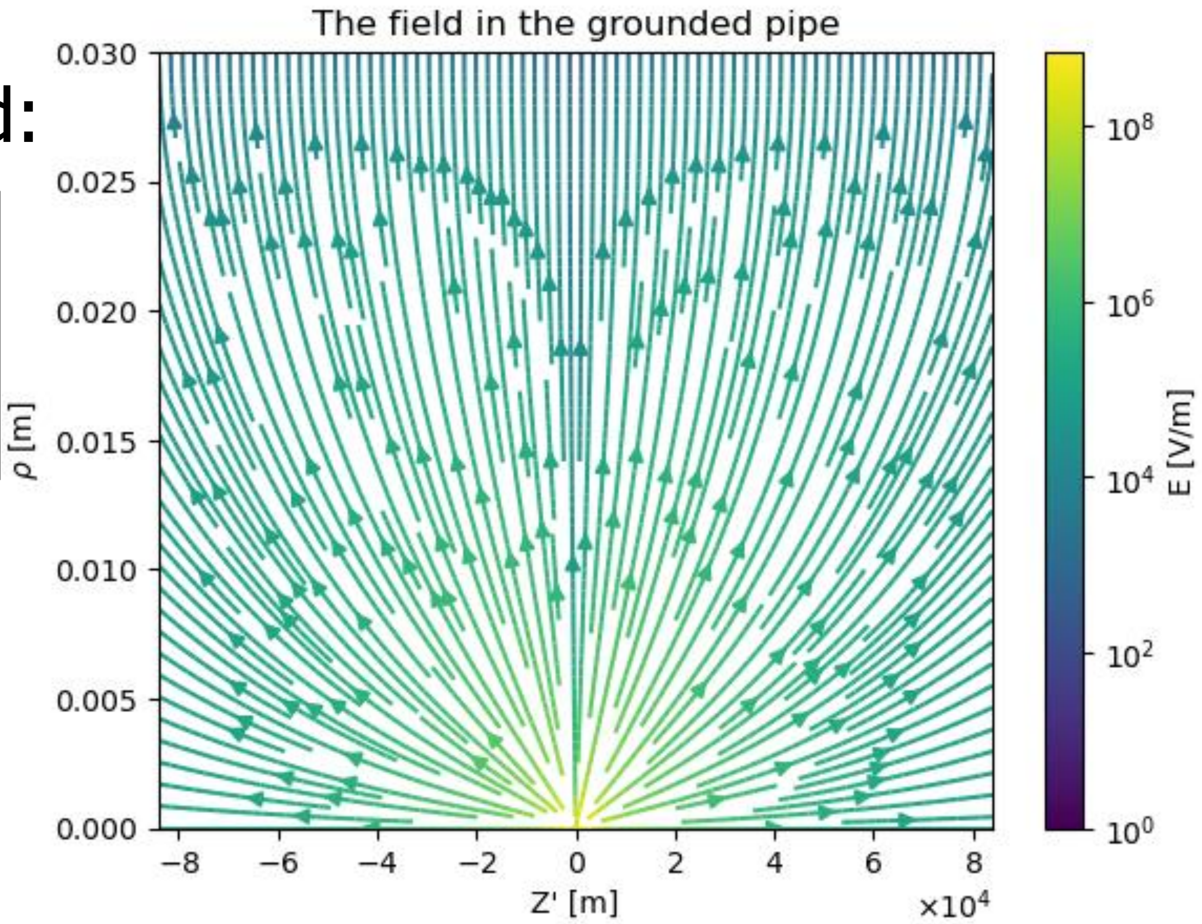
Here $Erf(\cdot)$ is an error fucntion, $R = \sqrt{x'^2 + y'^2 + (\frac{\sigma'}{\sigma'_z}z')^2}$

$\vec{E}_c$ is the correctional field due to the beam pipe grounding.

$$\rho'(x', y', z') = \frac{Q}{(2\pi)^{3/2}\sigma'^2\sigma'_z}e^{-\frac{x'^2+y'^2}{2\sigma'^2}-\frac{z'^2}{2\sigma'^2_z}}$$

$$\begin{cases} x' = x \\ y' = y \\ z' = \gamma\left(z - v(t - t_0)\right) \end{cases}$$

$$\begin{cases} \sigma' = \sigma = \sigma_x \\ \sigma' = \sigma = \sigma_y \\ \sigma_z{}' = \gamma\sigma_z \end{cases}$$



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Proton bunch field in LHC frame

- The fields at the LHC frame come from the Lorentz transformation.

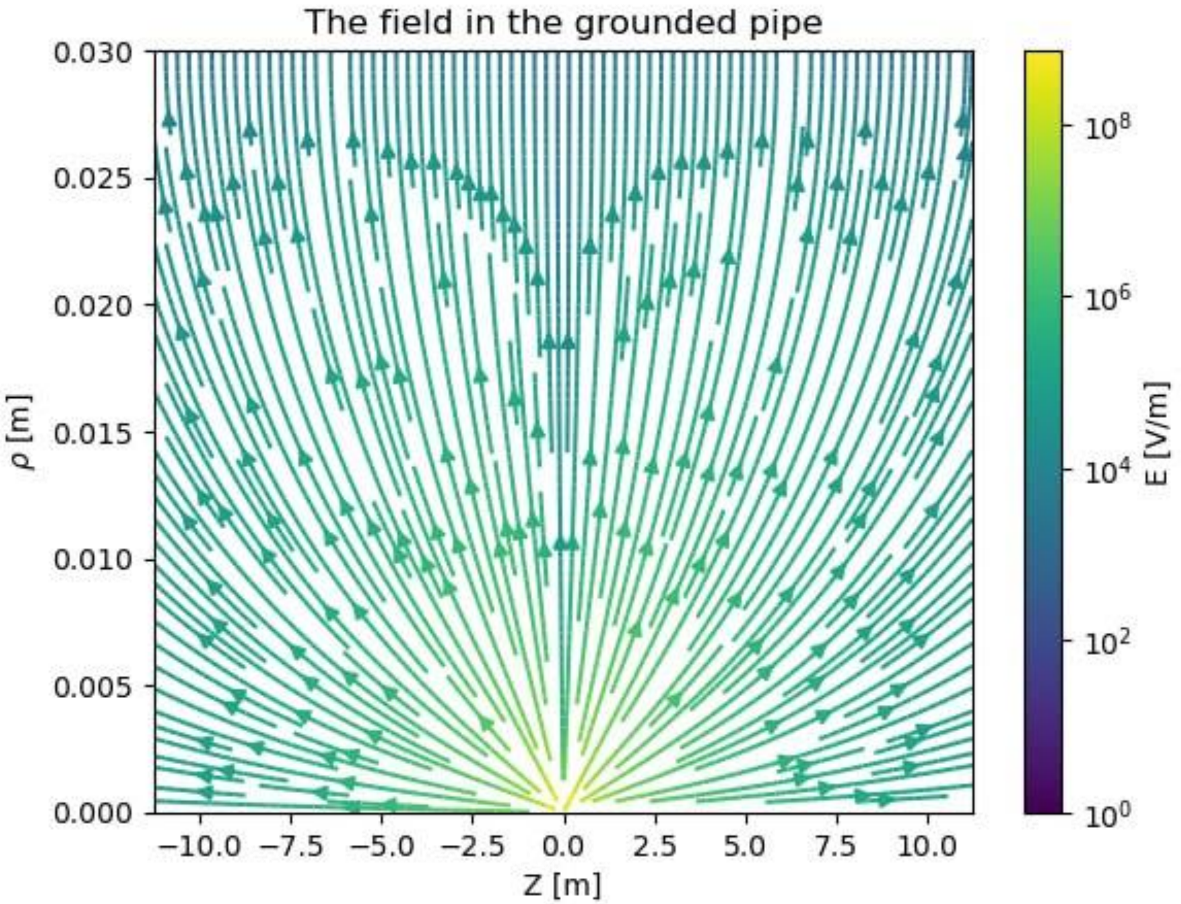
$$\begin{cases} \vec{E}_{\parallel} = \vec{E}'_{\parallel}, & \vec{B}_{\parallel} = \vec{B}'_{\parallel} \\ \vec{E}_{\perp} = \gamma(\vec{E}'_{\perp} - [\vec{v} \times \vec{B}']), & \vec{B}_{\perp} = \gamma(\vec{B}'_{\perp} + \frac{1}{c^2}[\vec{v} \times \vec{E}']) \end{cases}$$

$$\vec{B}' = \vec{0}$$

$$\gamma \approx 7460.3$$

For 7 TeV protons

$$\begin{cases} E_{\rho} = \gamma E'_{\rho} \\ E_{\varphi} = 0 \\ E_z = E'_z \end{cases} \quad \begin{cases} B_{\rho} = 0 \\ B_{\varphi} = \gamma \frac{v}{c^2} E'_{\rho} \\ B_z = 0 \end{cases}$$



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Proton bunch field in LHC frame, crosscheck

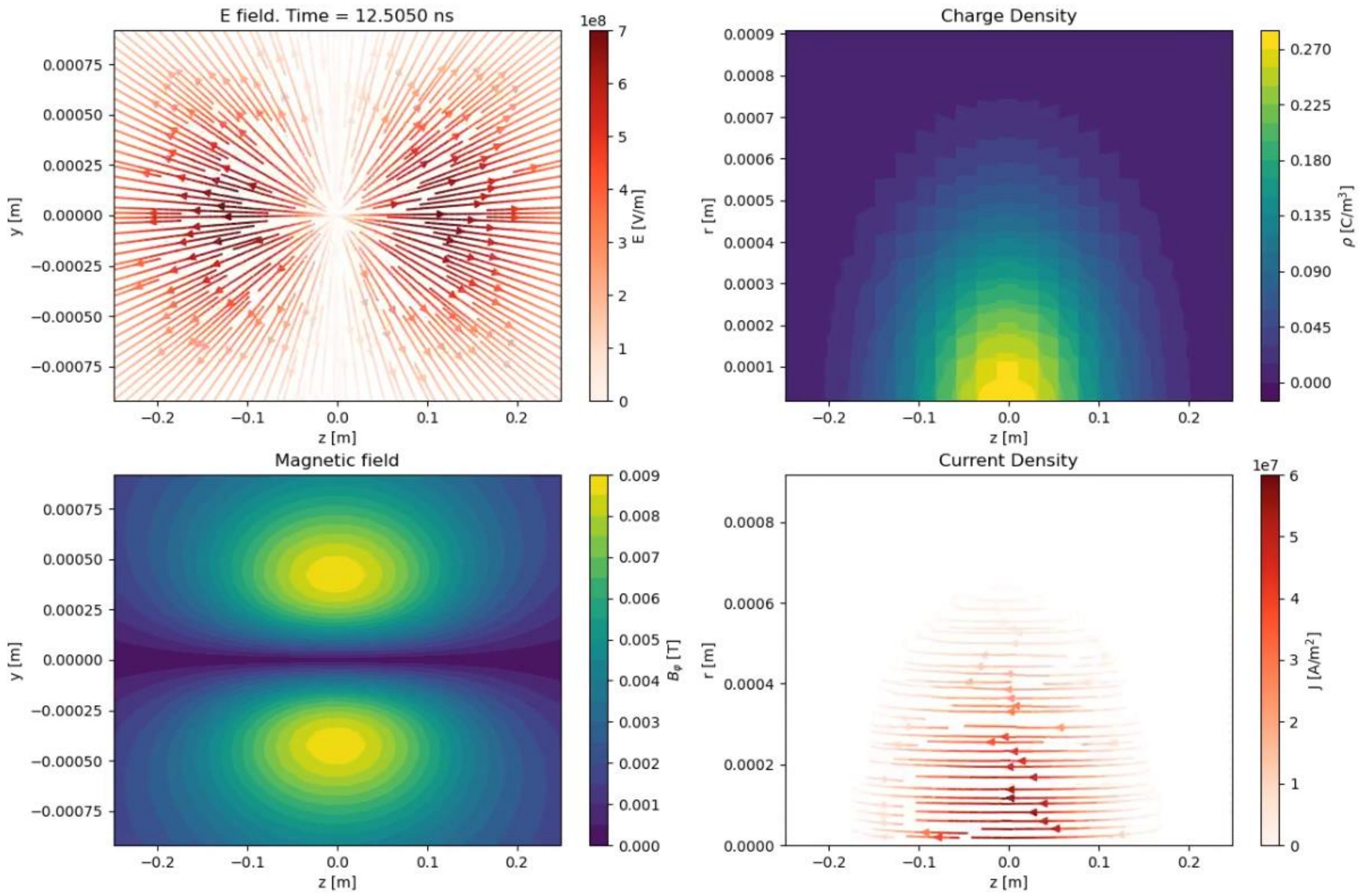
$$\begin{cases} \frac{rot(\vec{B})}{\mu_0} = \vec{j} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \\ div(\vec{E}) = \frac{\rho}{\varepsilon_0} \end{cases}$$

$$\Downarrow$$

$$\begin{cases} \vec{j} = \frac{rot(\vec{B})}{\mu_0} - \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \\ \rho = div(\vec{E})\varepsilon_0 \end{cases}$$

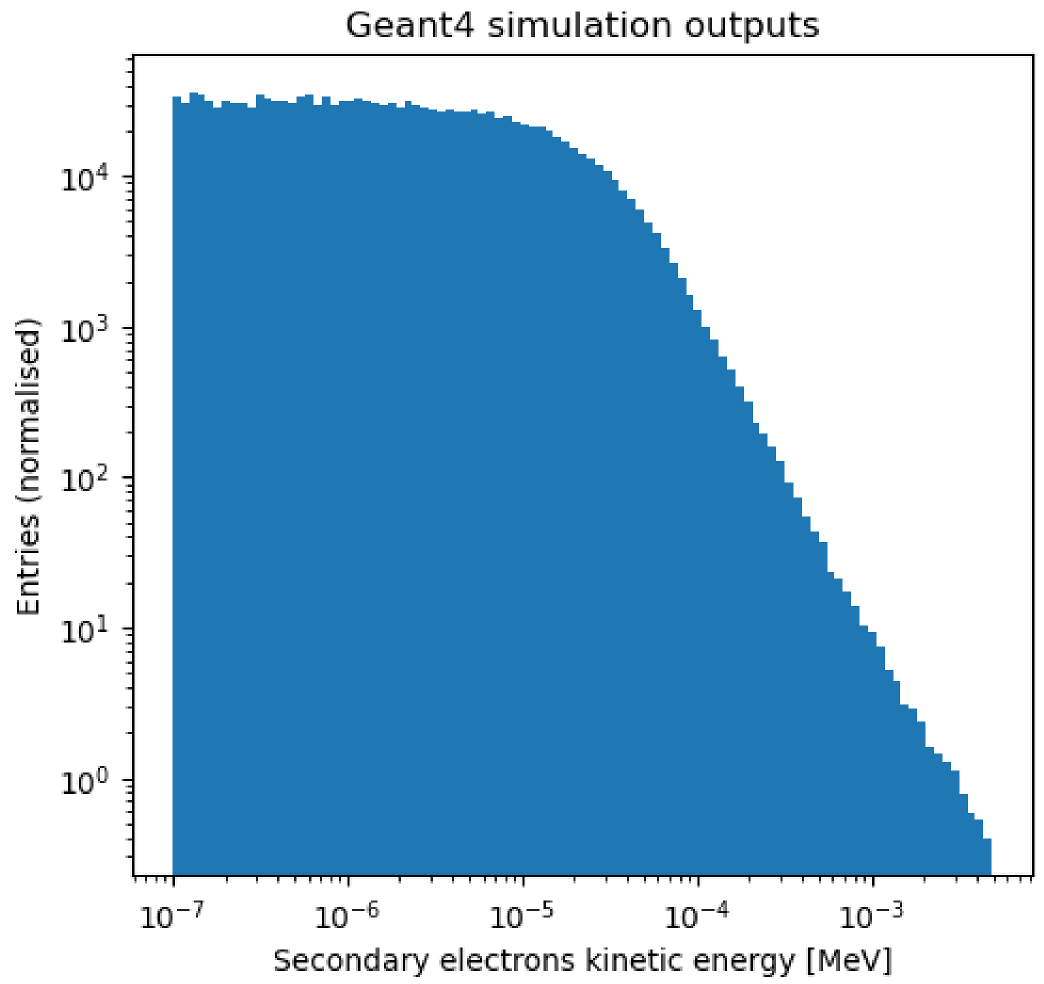
ρ is with Gaussian distribution.

$$\boxed{\vec{j} = \rho \vec{v}}$$

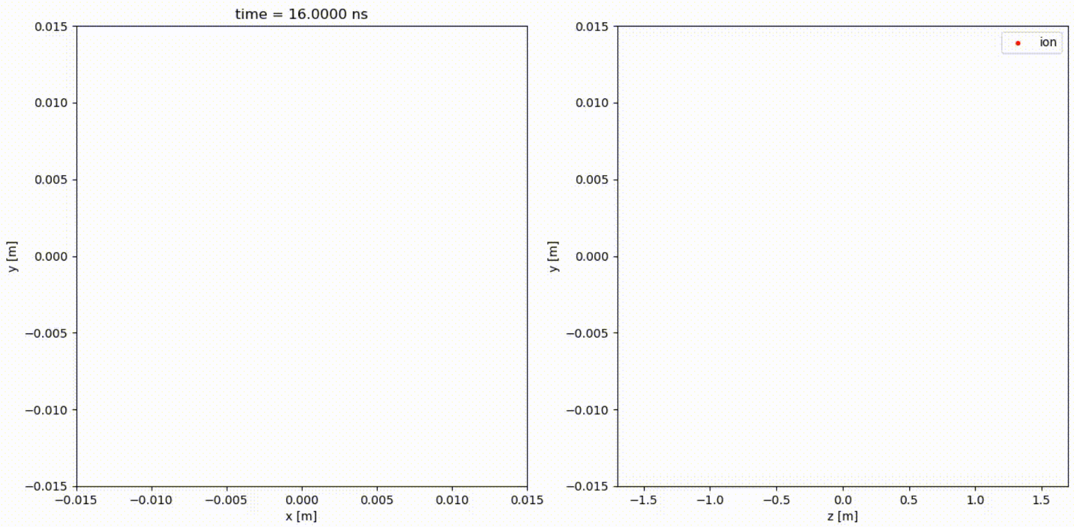


Initial parameters $(\vec{r}, \vec{v})$ of ionised particles

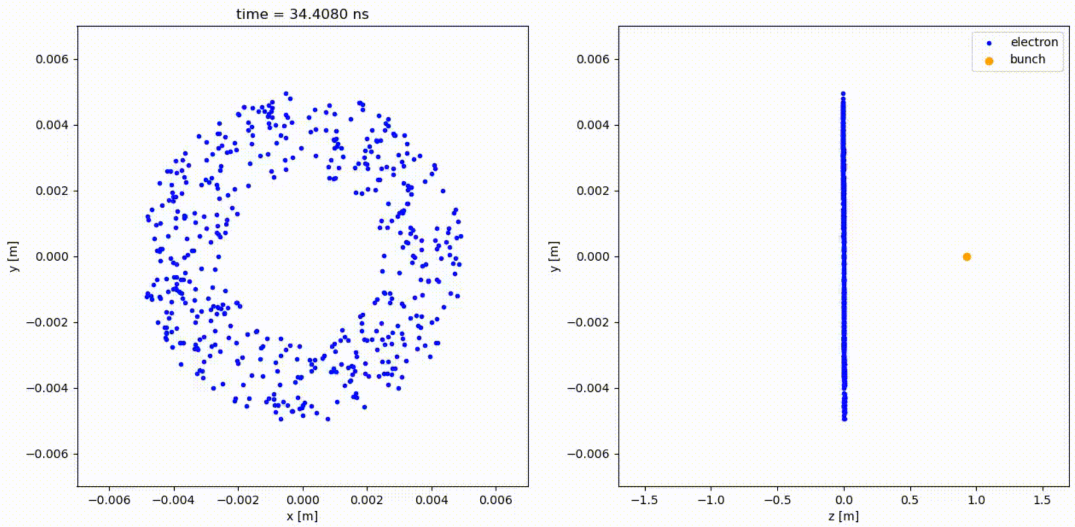
- Parameters of e^- taken from Geant4 simulation with low-energy physics.
- The initial $\vec{v}$ of the protons were "artificially" set to the same as neon atoms.
- The ionization rate of electron beam is about $5{,}39 \cdot 10^{12}\ s^{-1}$
- Ionisation by proton beam is 870 times smaller (neglected).



Ionised particles motion



Ions movement



Electrons movement

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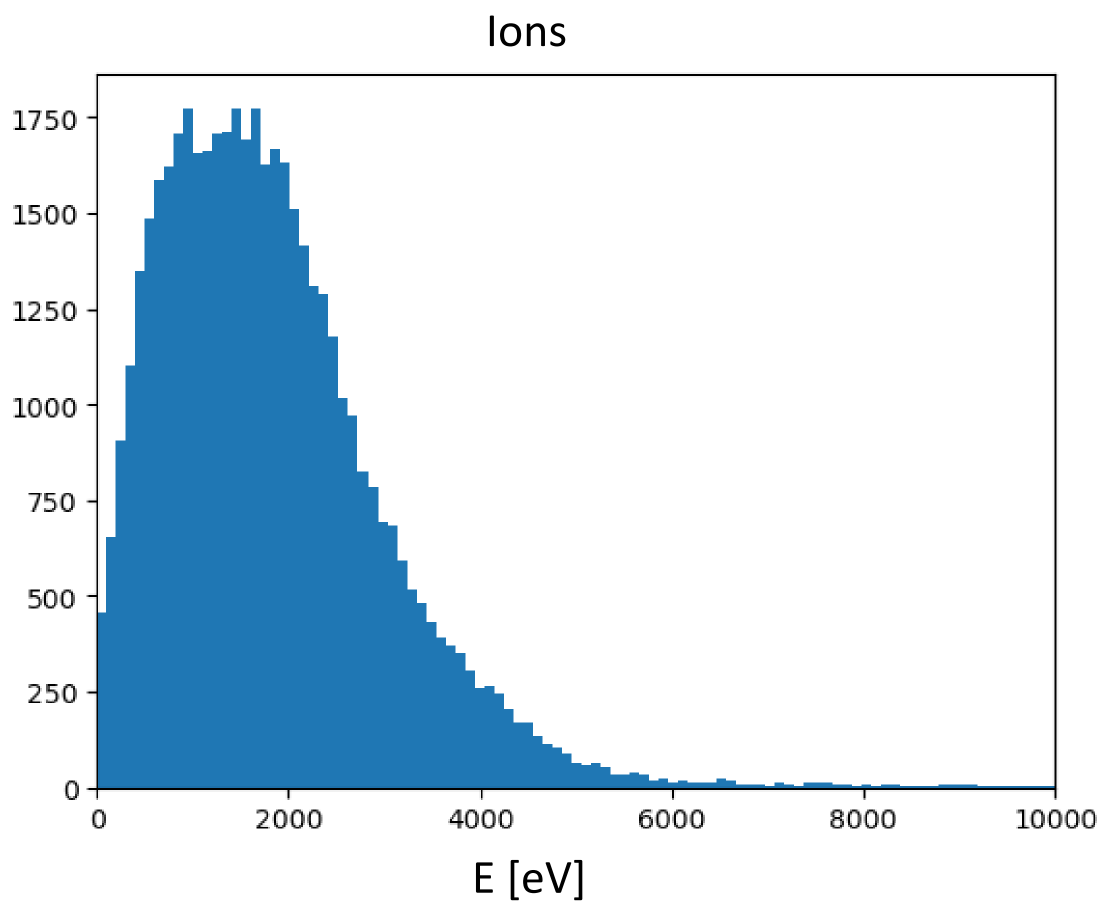
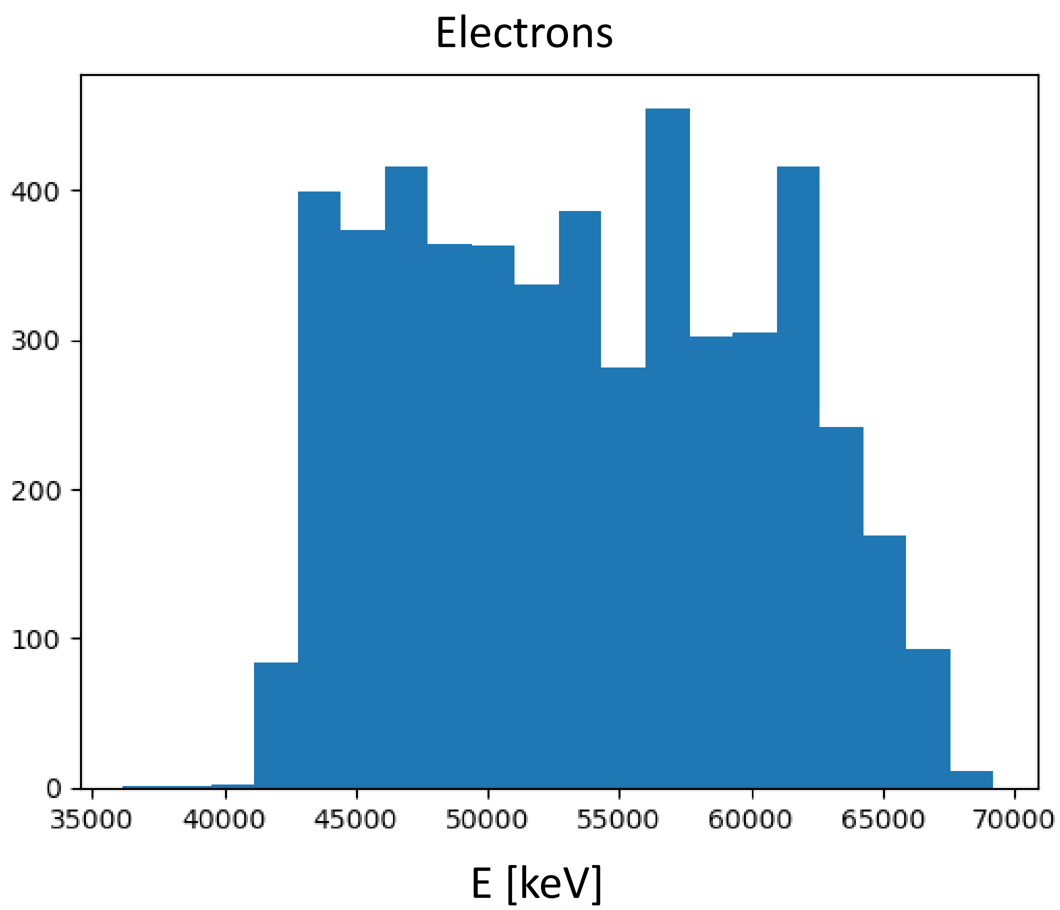
Final energy of the ionised particles

- The ionised particle energies at the edge of the simulated volume.





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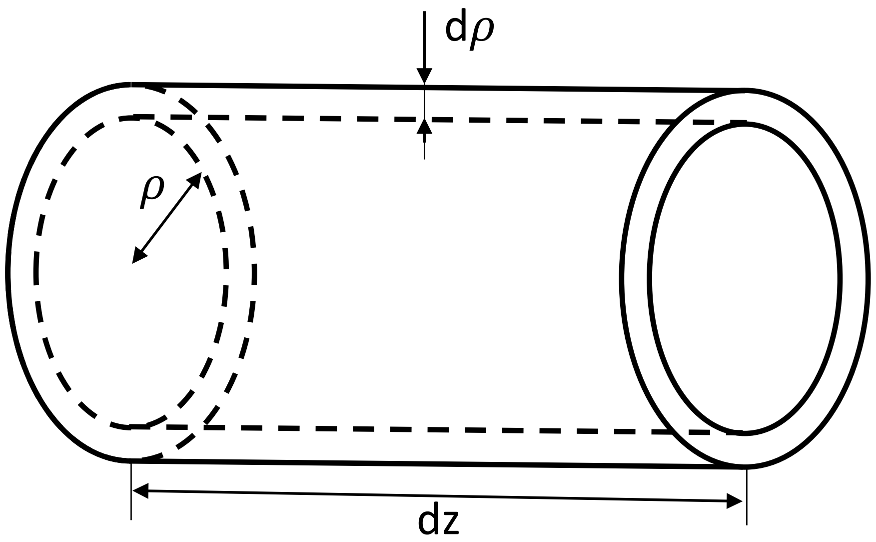
Ion density mesh

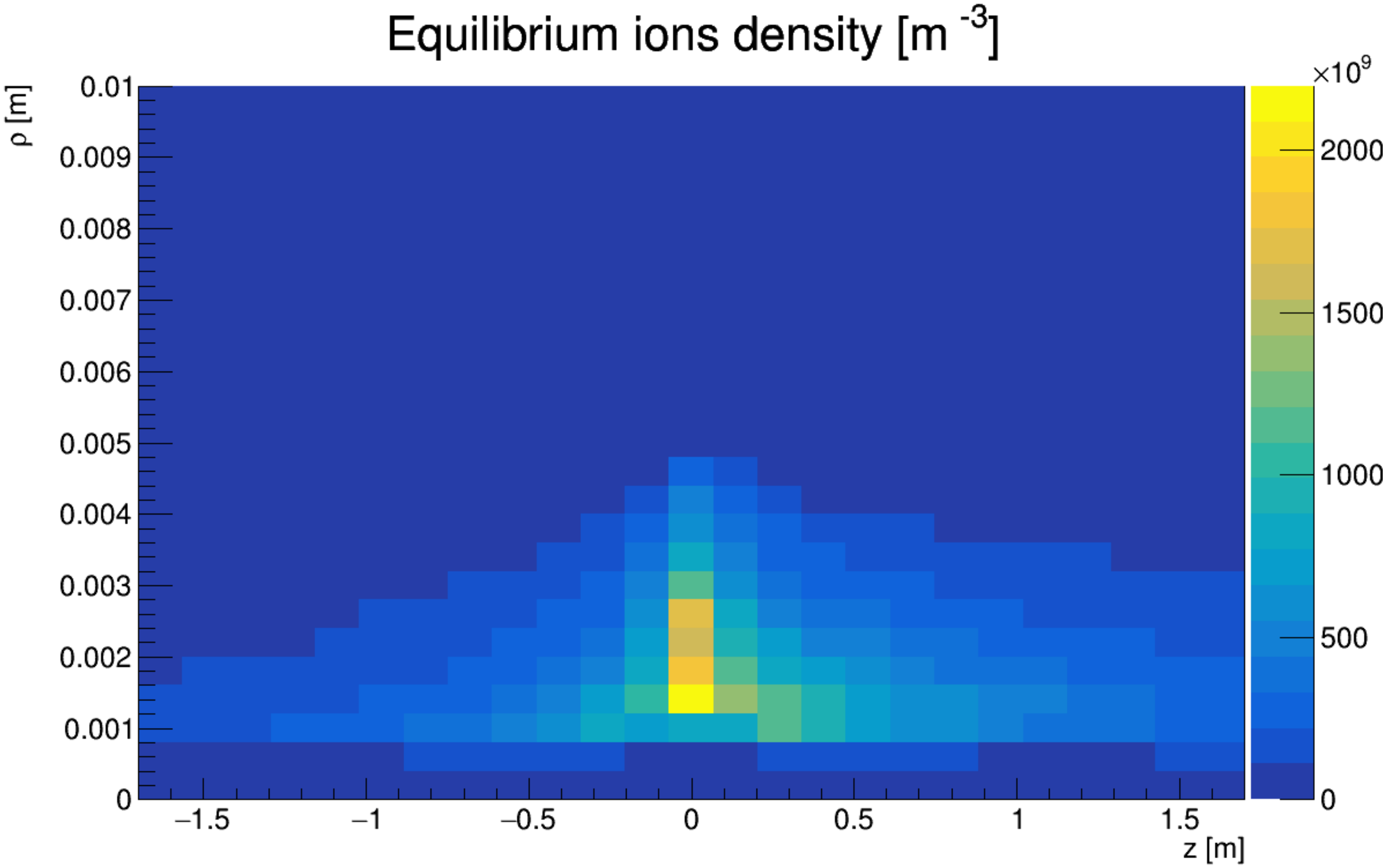
- The mesh contains the cylindrical layers.
- $dV = 2\pi \, dz \, \rho d\rho$.
- dN - number of particles inside the mesh layer.
- $n(\rho, z) = \frac{dN}{dV}$ - ions density.



Equilibrium ions density

- The peak value of the ion's density is 7 orders lower than the electron's density in a hollow beam.

- The electric field created by ions is negligibly small.



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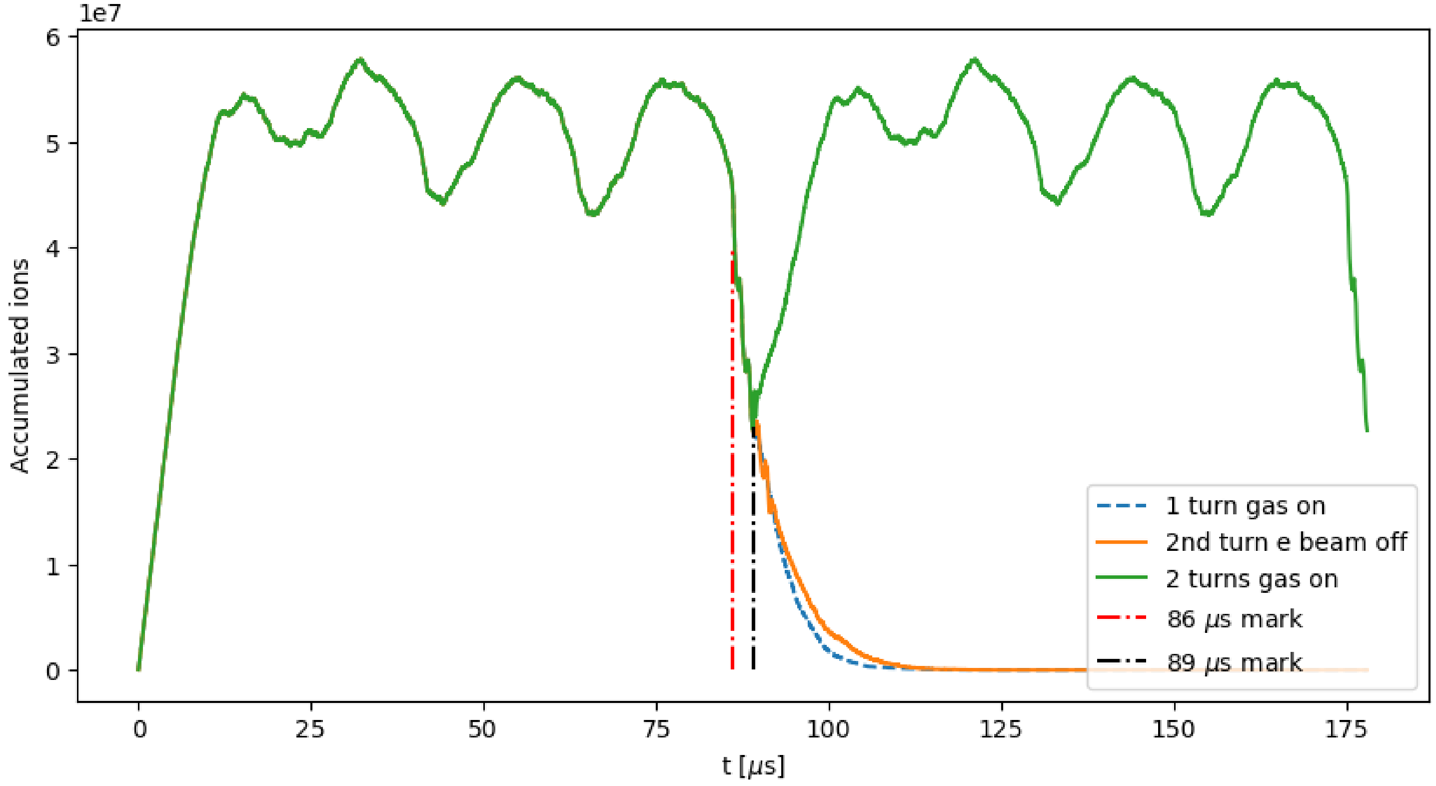
Accumulated ions quantity

Time, μs	1 turn gas on	2 turns gas on	2^{nd} turn e beam off
… - 86	gas e beam p beam	gas e beam p beam	gas e beam p beam
86 – 89	nothing	nothing	nothing
89 - …	e beam p beam	gas e beam p beam	gas p beam



Conclusion

The results of the simulations show the following:

- Ionised electrons are escaping fast, drawn by proton beam;
- Ions are also escaping but drifting slowly;
- Ionised particles are not trapped inside the magnetic “bottle”;
- The number of ions decreases fast if there is no ionisation, it tells us that the clearing electrodes might not be necessary.

To be continued

- Improve the electric field of the electron beam;
- Tracking of the ionised particles in the entire volume, including electron collector and gun;
- Study influence of the proton beam on the electron beam and the changing of the beam's field;
- Improving the simulation of the gas ionisation.
- Wrapping developed code to the user oriented toolbox.

Thank you for your attention

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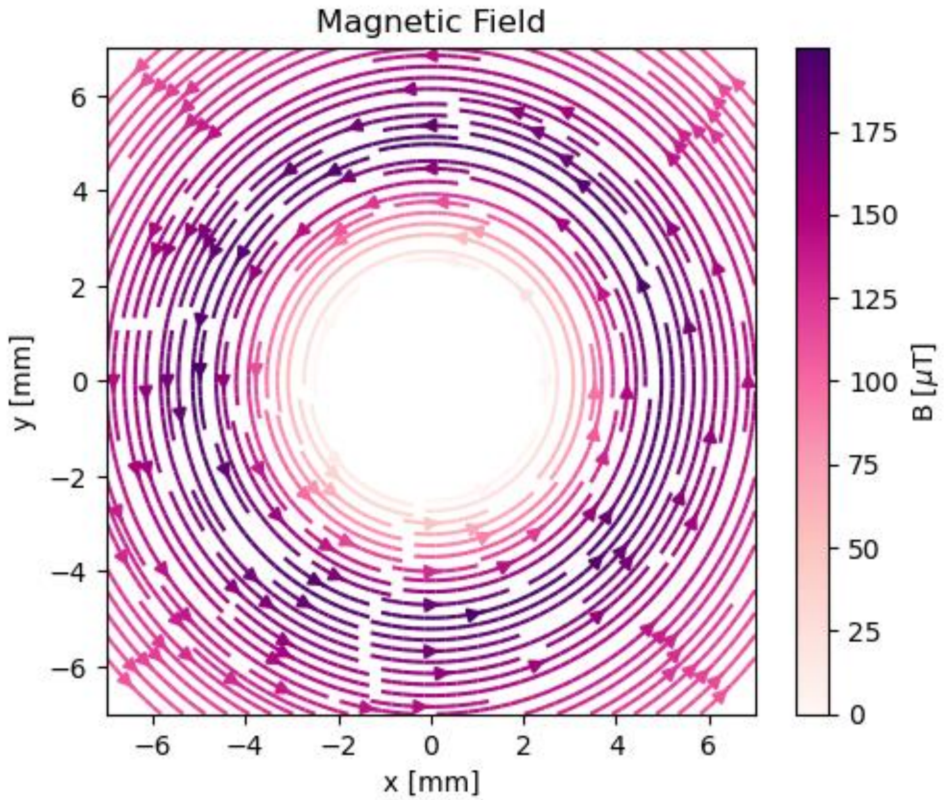
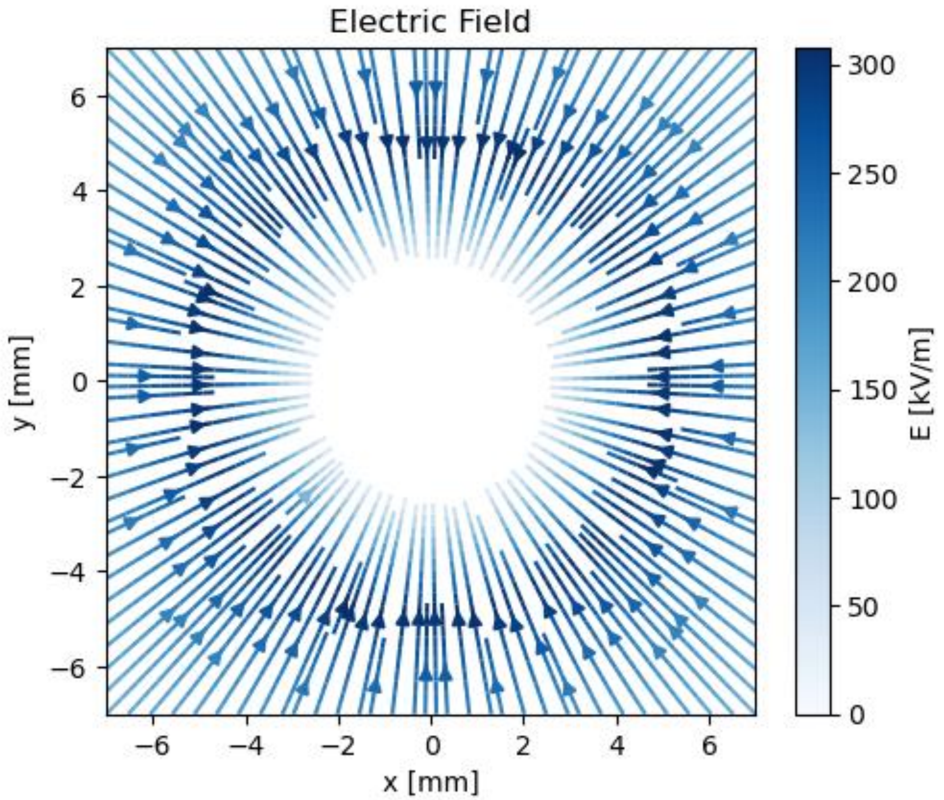
Any questions?

Backup slides

Electric & magnetic fields of electron beam





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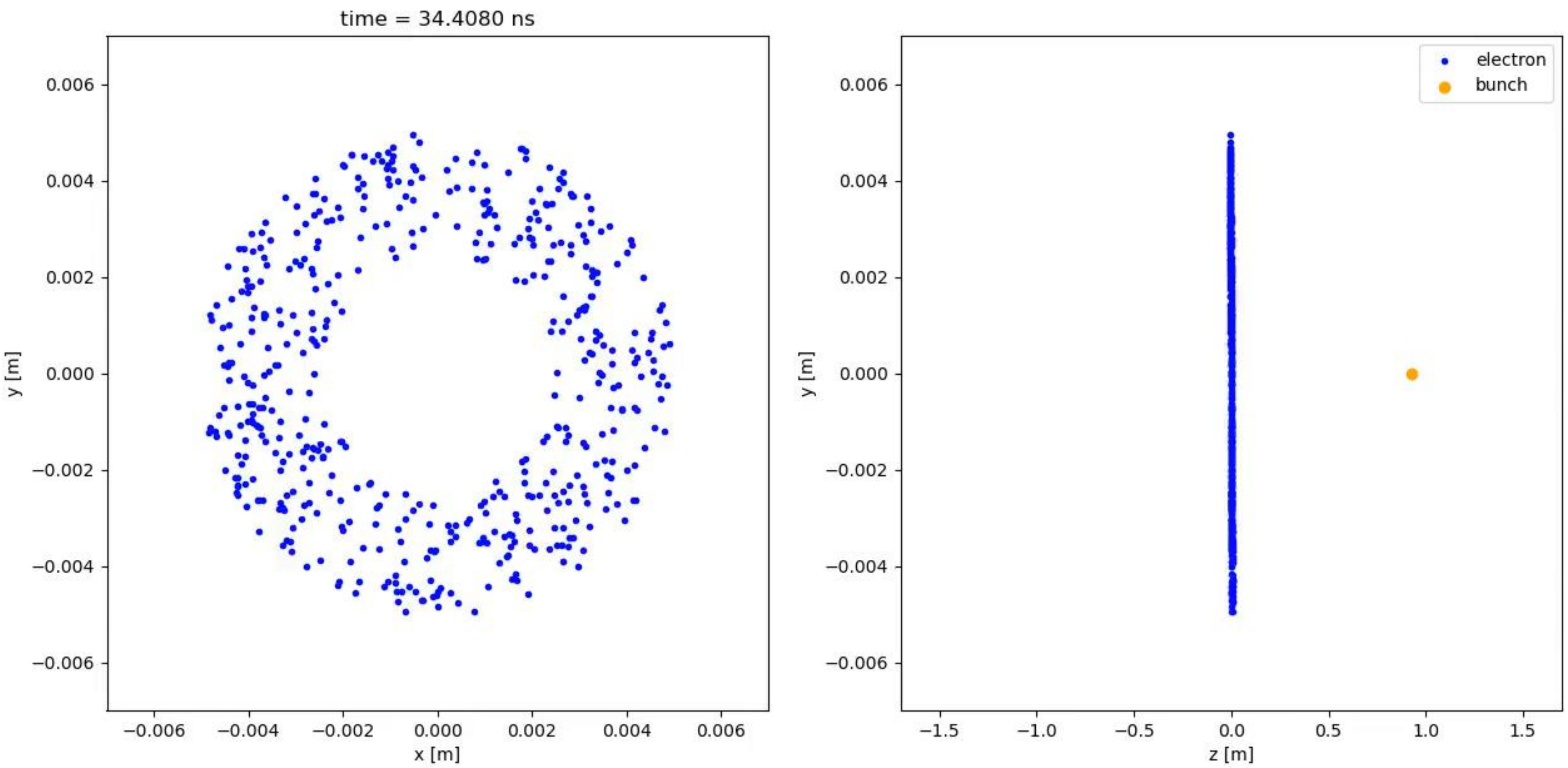
Reasoning to develop a custom code

- Computation time
- Flexibility to implement electromagnetic field
- Flexibility to implement beams' time and space parameters
- Flexibility to define simulation outputs
- Flexibility to define simulation volume

Benchmarks of the developed code.

- The code was checked with module tests.
- The code was checked to have the same tracking output as the Virtual-IPM
- The calculation speed was compared with the Virtual-IPM in the same simulation and was 11.2 times faster in single-thread mode. (23 sec on our program, 4 min 15 sec on Virtual-IPM)
- The developed code is highly parallel. Reduces computing time by a factor of parallel threads number.

Electrons are escaping very fast



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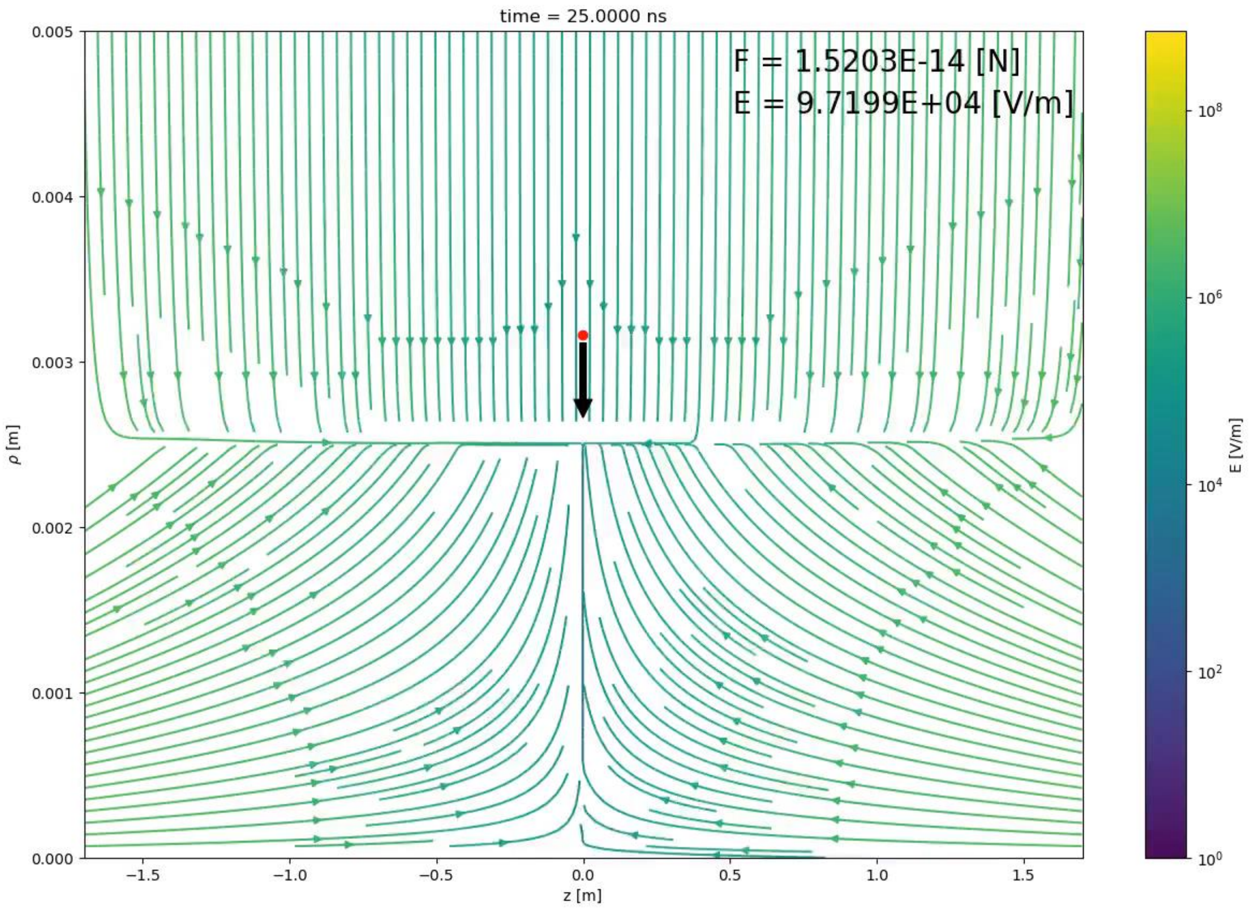
Ions are moving much slower



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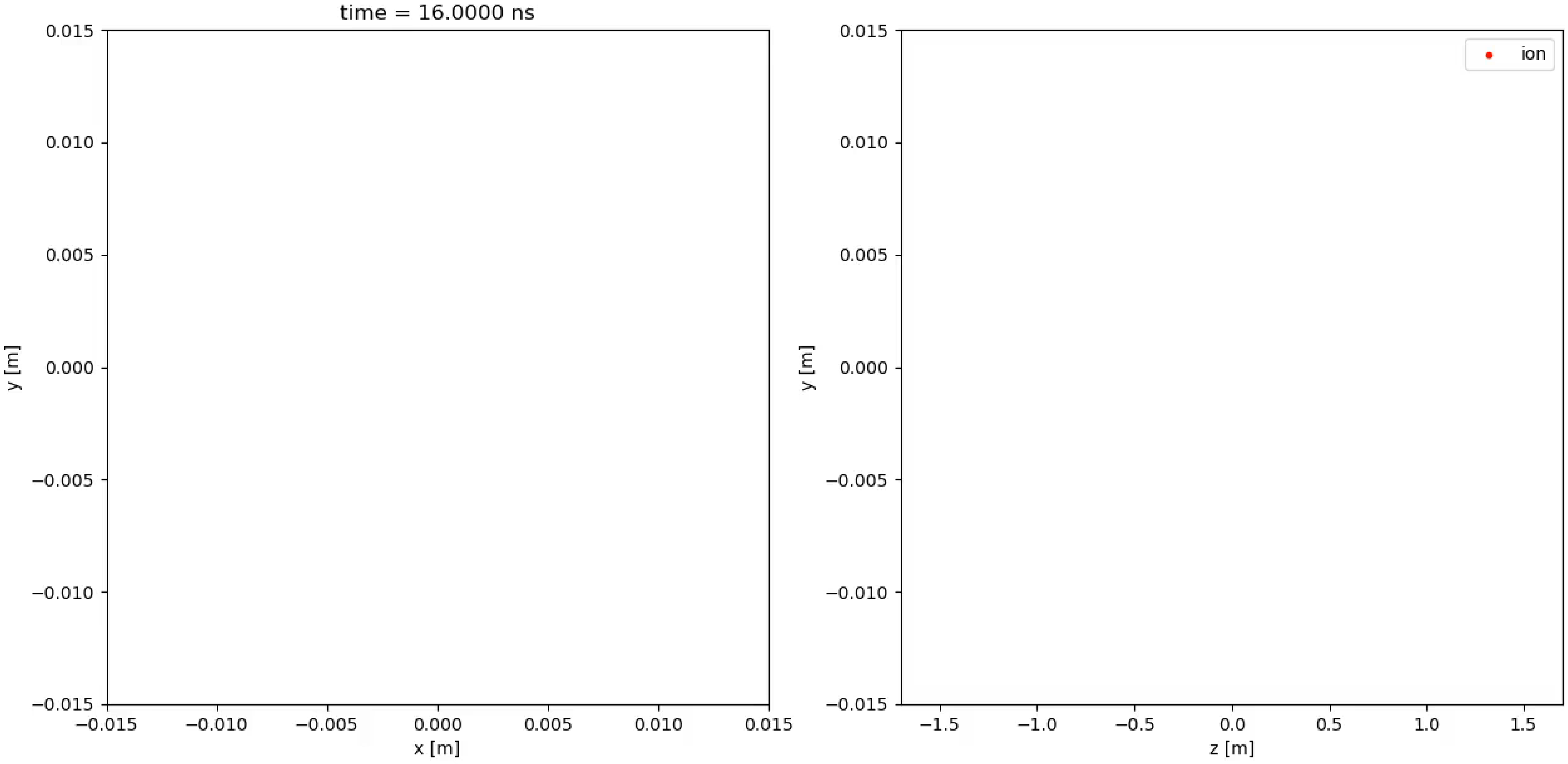
Ion movement



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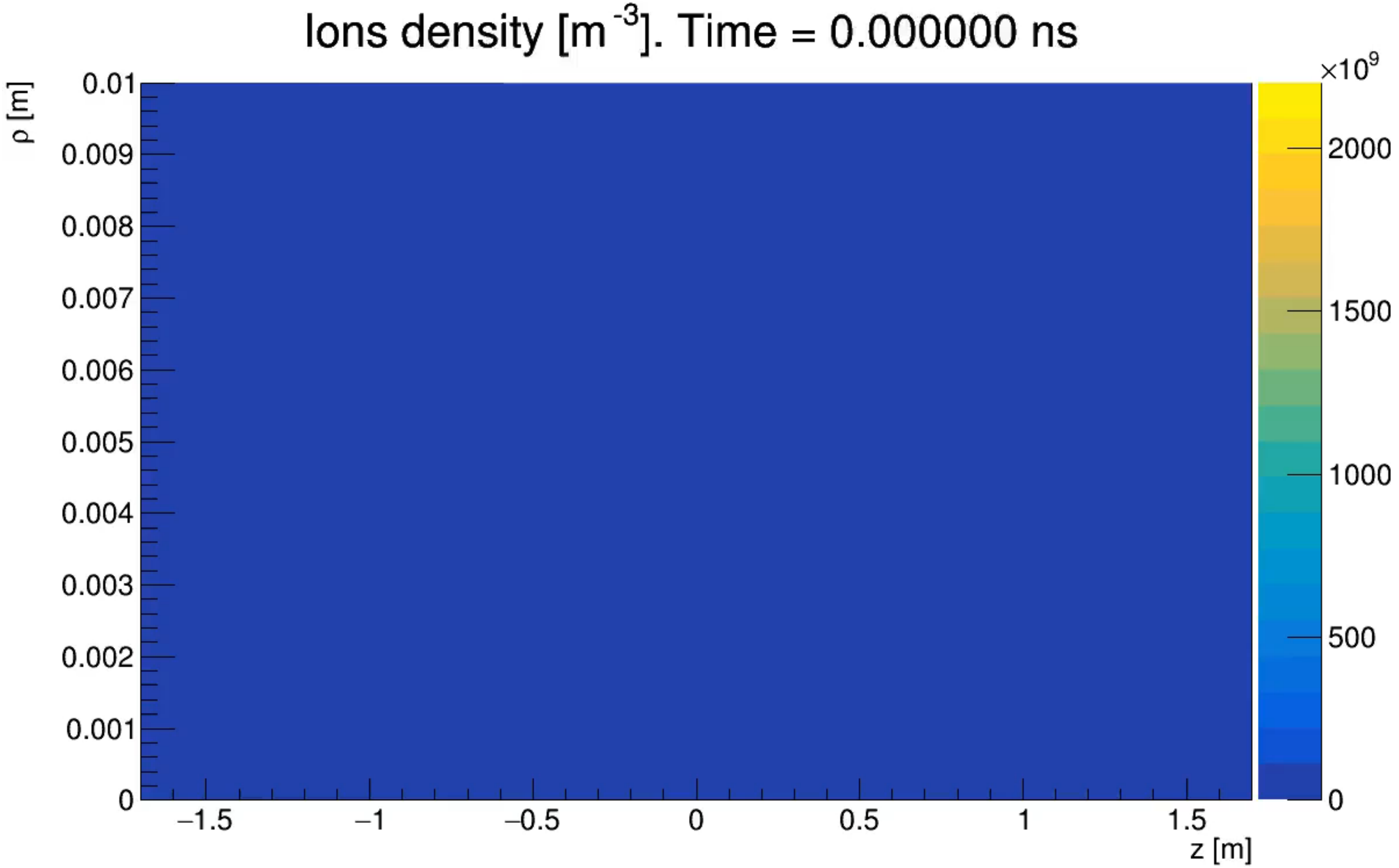
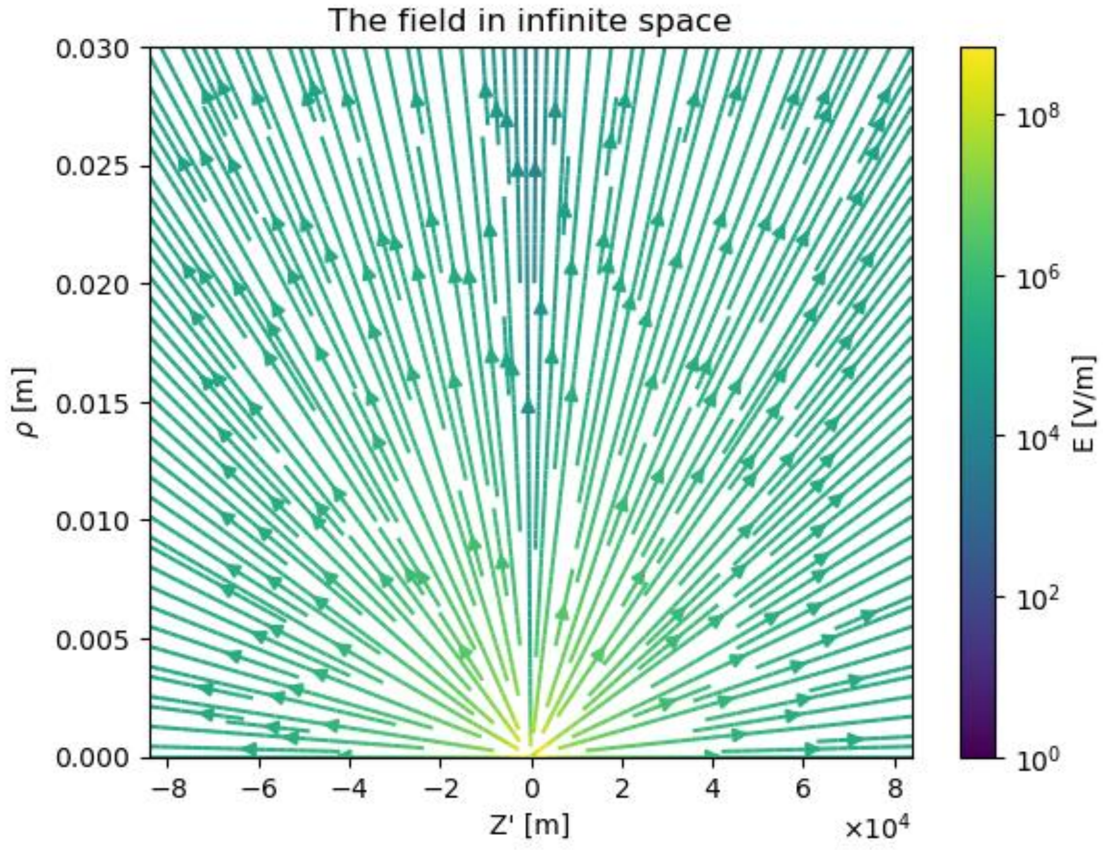
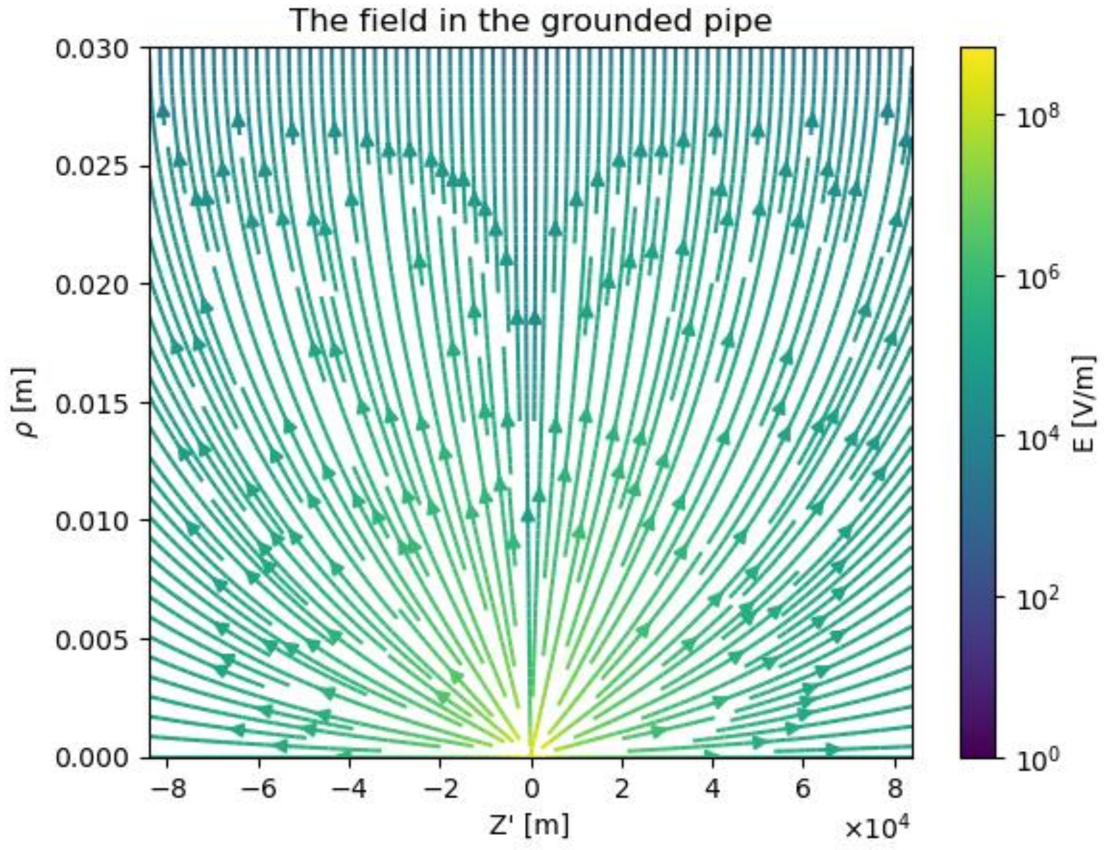
Accumulation of ions



Web link

Correction field (due to beam pipe grounding)





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Correction field (due to beam pipe grounding)

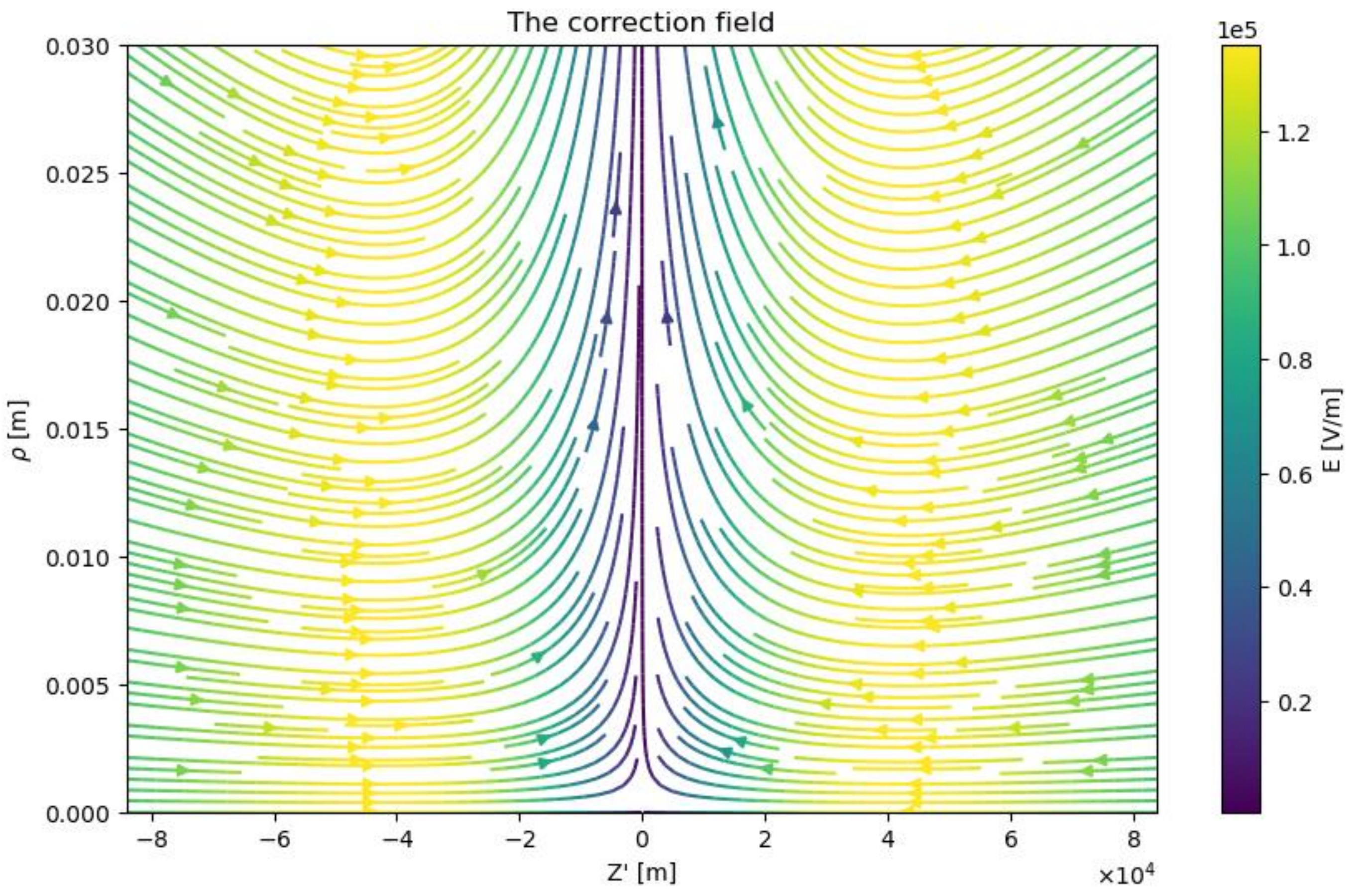
$$\begin{cases} \Delta\varphi(z,\rho) = 0 \\ -\frac{\partial\varphi(z,\rho=R)}{\partial z} = E_z^b(z,R) \end{cases}$$

$$\varphi(z,\rho) = \int_{-\infty}^{\infty} e^{ikz} f(k) I_0(k\rho) dz$$

$$E_z^b(k,R) = \frac{2}{\sqrt{2\pi}} \int_0^{\infty} sin(kz) E_z^b(z,R) dz$$

$$E_z(z,\rho) = \frac{2}{\sqrt{2\pi}} \int_0^{\infty} sin(kz) E_z^b(k,R) \frac{I_0(k\rho)}{I_0(kR)} dk$$

$$E_\rho(z,\rho) = \frac{-2}{\sqrt{2\pi}} \int_0^{\infty} cos(kz) E_z^b(k,R) \frac{I_1(k\rho)}{I_0(kR)} dk$$



e^- vs p^+ beam ionisation ratio

$$\frac{R_e}{R_p} = \frac{\sigma_e I_e}{\sigma_p I_p} \approx 870$$

$$I_p = \frac{Q}{\tau} = \frac{3{,}25 \cdot 10^{-8} C}{25 \cdot 10^{-9} s} = 1{,}3A$$

Bethe-Bloch: $\sigma_p = 2\pi r_e^2 Z_{Ne} m_e c^2 \left\langle \frac{1}{I} \right\rangle$

$$\left\langle \frac{1}{I} \right\rangle = 12{,}17 \cdot 10^{-3} eV^{-3} \qquad \sigma_p = 3{,}1 \cdot 10^4\ barn$$

- R_e is much higher compared to R_p.
- The estimate is consistent with the Geant4 simulation.

Evaluated Electron Data Library