

Simulation of electron transport within Hollow Electron Lens using Warp

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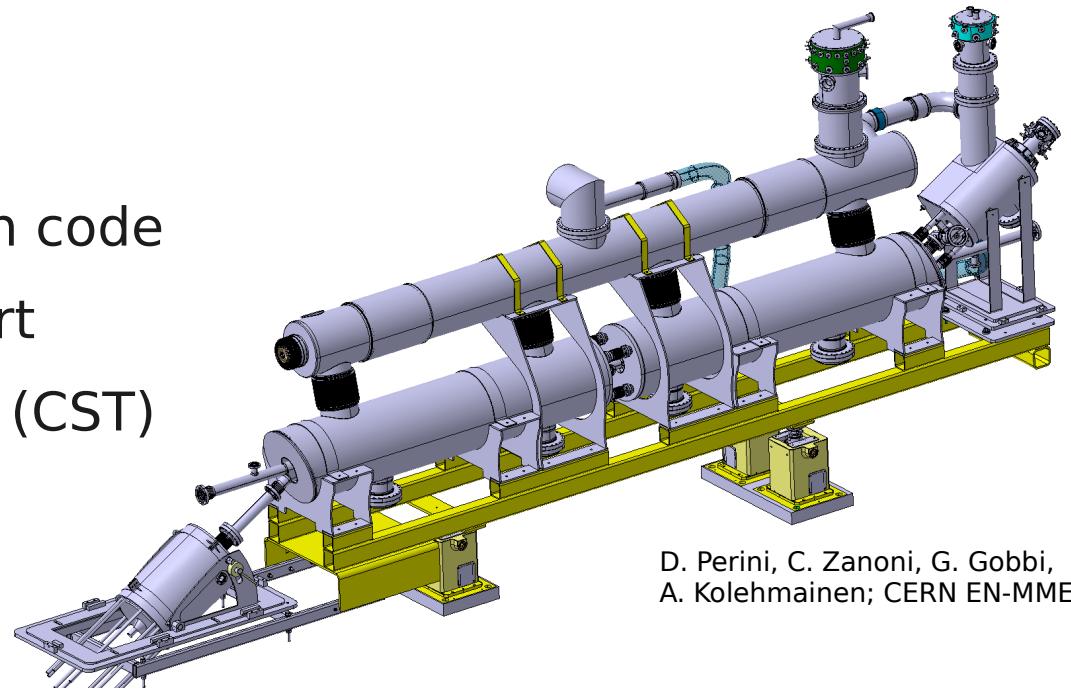
Supervisor: Adriana Rossi

Date: 08.07.2020

Scope of the work

Simulate electron plasma transport in electron lens and/or electron cooler, including the bend, with open source code Warp

- Understand details of transport especially in bends
- Offer an alternative method to "follow" the bend, and reduce computational load
- Work done
 - Construction of the simulation code
 - Analysis of the beam transport
 - Comparison with other codes (CST)



D. Perini, C. Zanoni, G. Gobbi,
A. Kolehmainen; CERN EN-MME

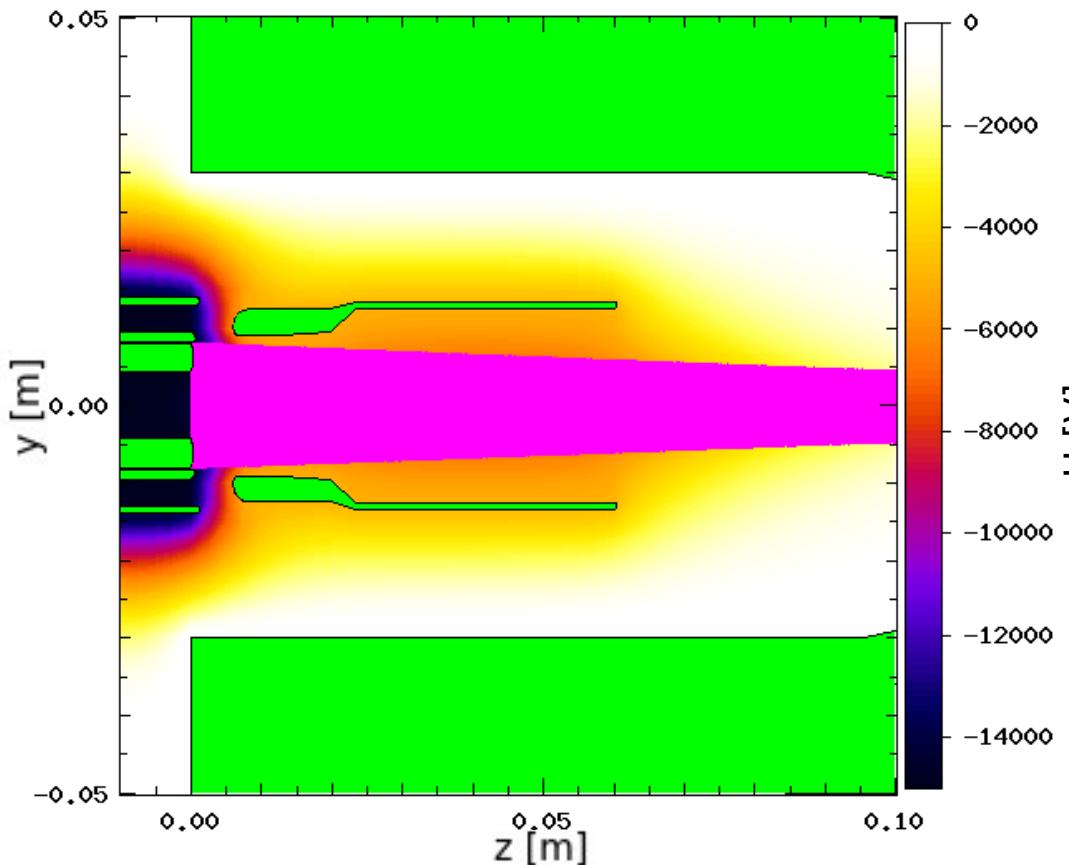
Beam parameters and Warp simulation

Beam:

I	5.2 A
r_i	4.05/1.10 mm
r_o	8.10/2.20 mm

Magnetic field: Flat top

Gun	0.37 T
Main	5.00 T



- 3D Electrostatic particle in cell simulations

$$\nabla^2 \phi = -\rho$$

- Poisson equation → Electrostatic field and self-field
 - Space-charge
 - Conductors
- Magnetic self-field is neglected
- External magnetic field imported
- Space-charge limited emission
→ realistic beam

Warp timestep algorithm

- 3D Electrostatic particle in cell simulations
 - Simulation of beam evolution

C. A. Gonzalez, et al., DOI:
[10.1088/1742-6596/370/1/012033](https://doi.org/10.1088/1742-6596/370/1/012033)

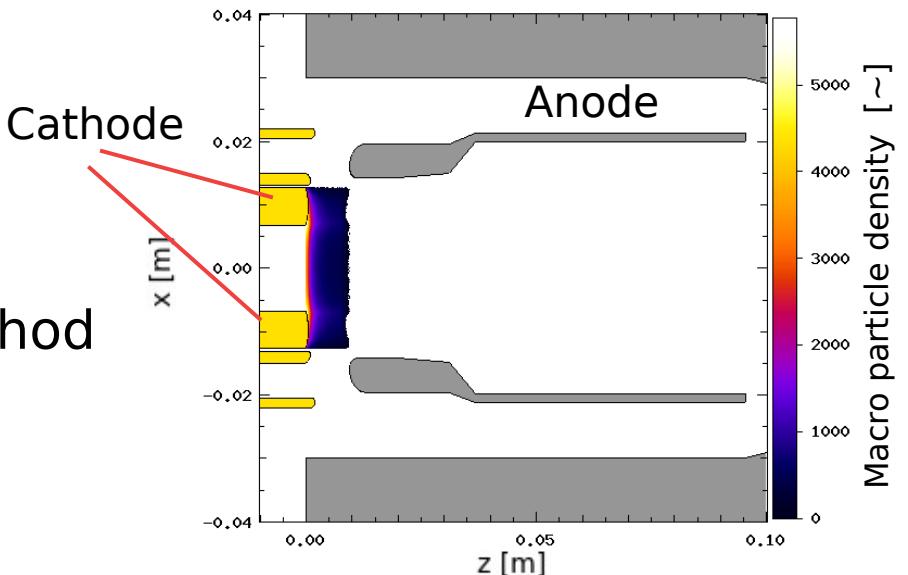
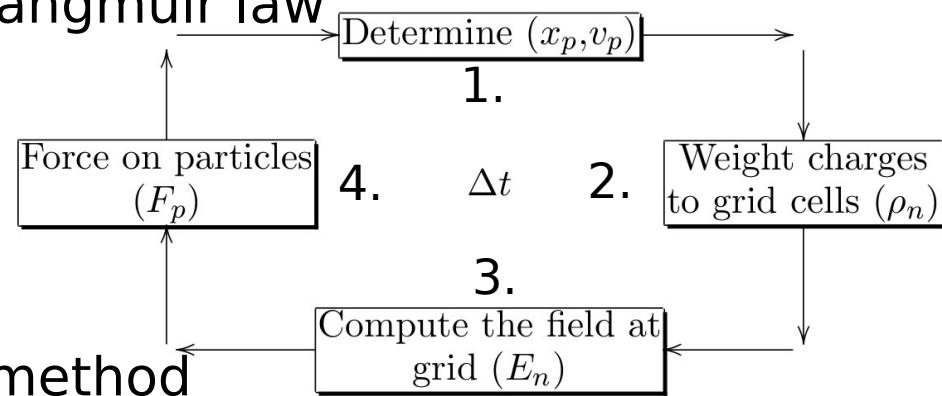
1. Particle injection according to Child-Langmuir law

2. Linear charge interpolation

3. Poisson equation solved by iterative method

4. Linear force interpolation

5. Particle advanced by “leap-frog” method



Warp timestep algorithm

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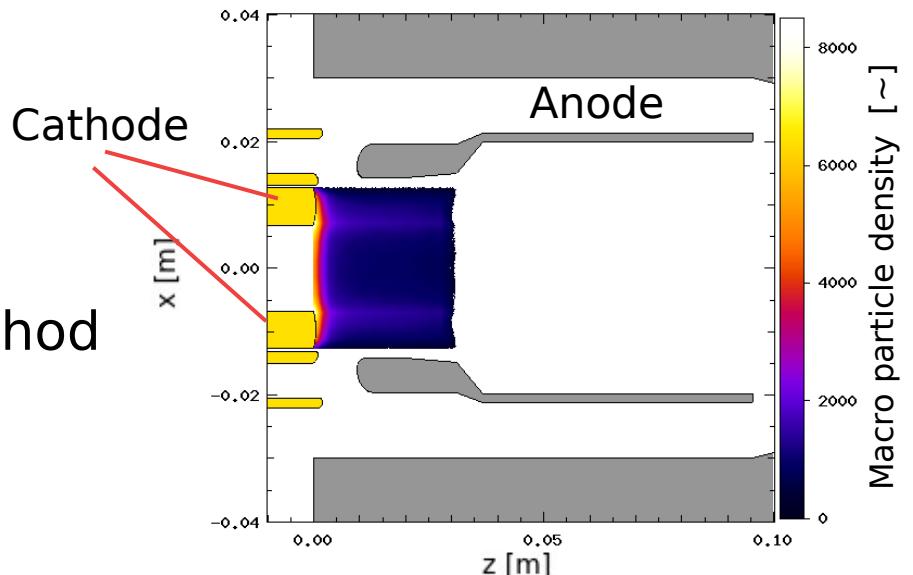
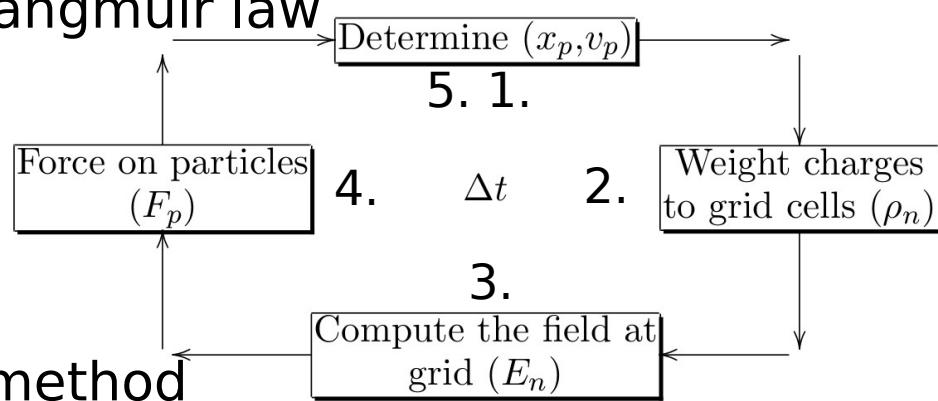
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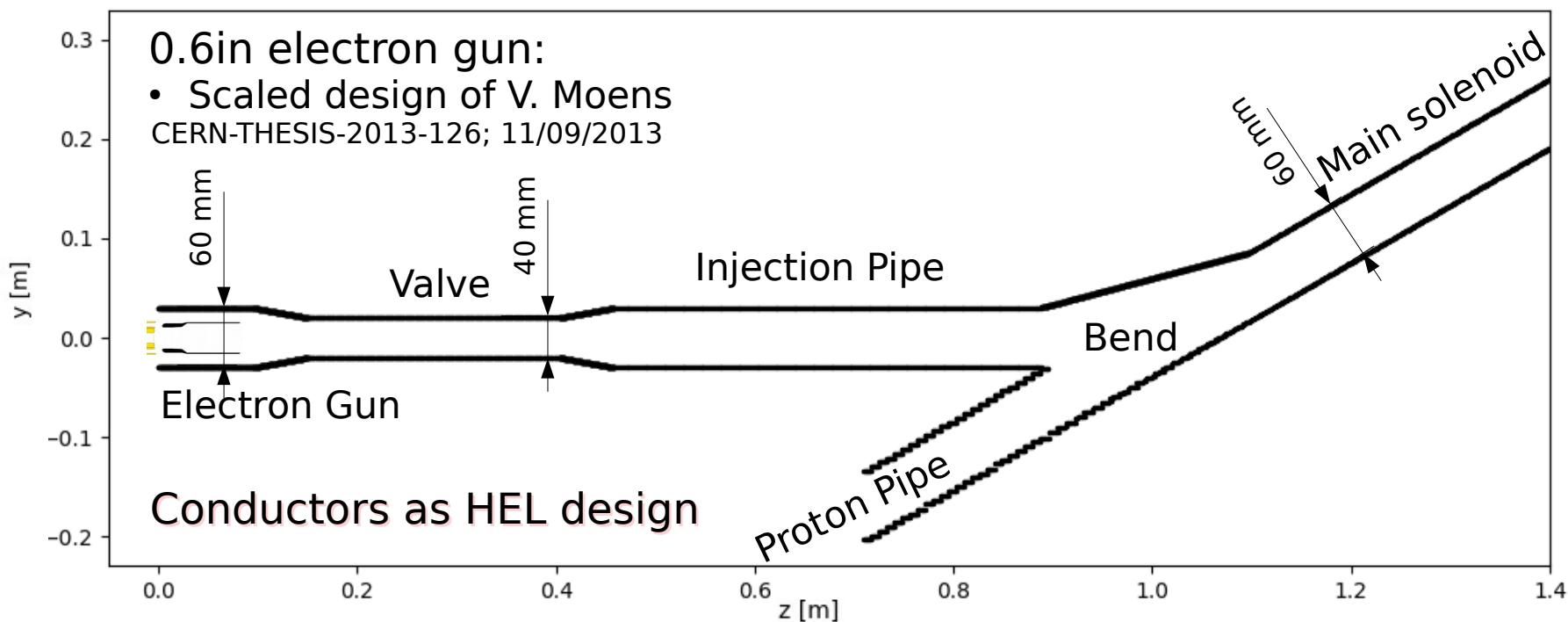


Pipe

Pipe

Bent mesh

Results



Bent mesh

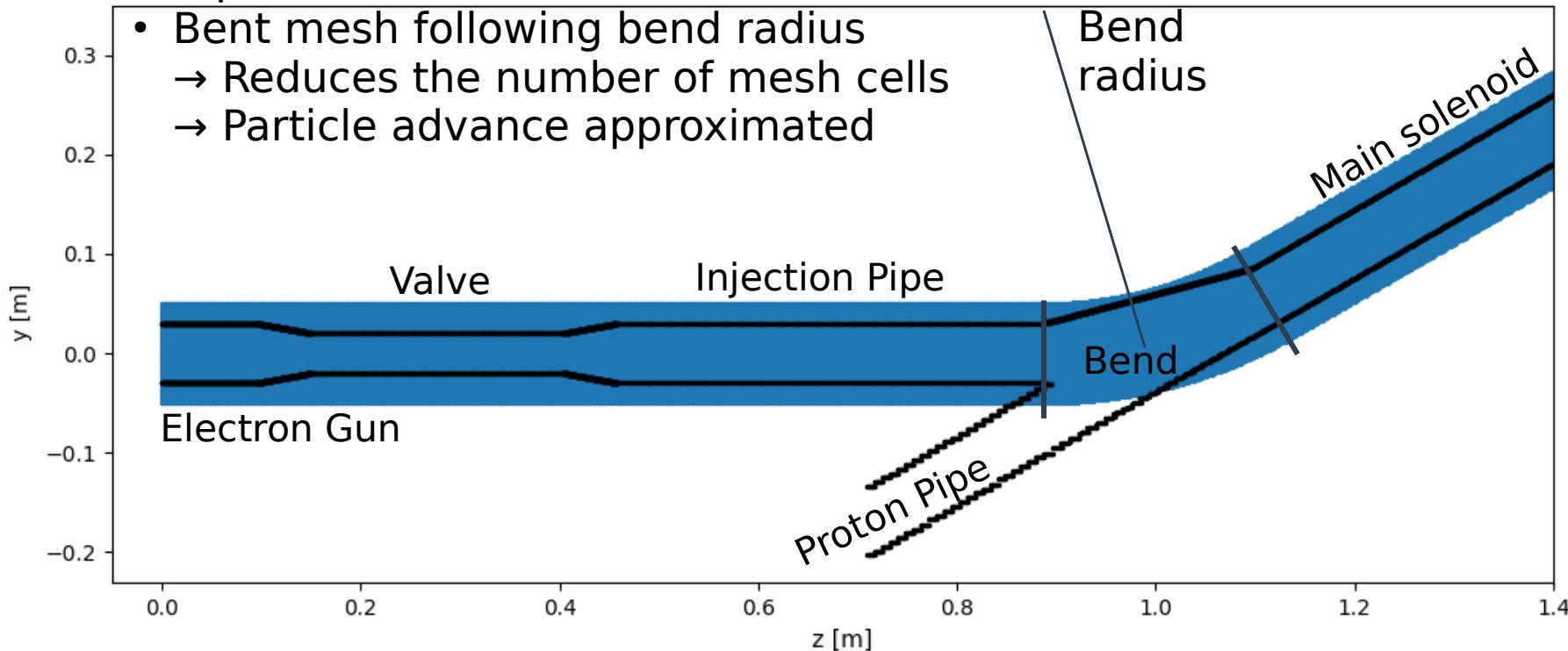
Pipe

Bent mesh

Results

Warped (Cartesian Fernet-Serret) coordinates

- Bent mesh following bend radius
 - Reduces the number of mesh cells
 - Particle advance approximated



Simulation:

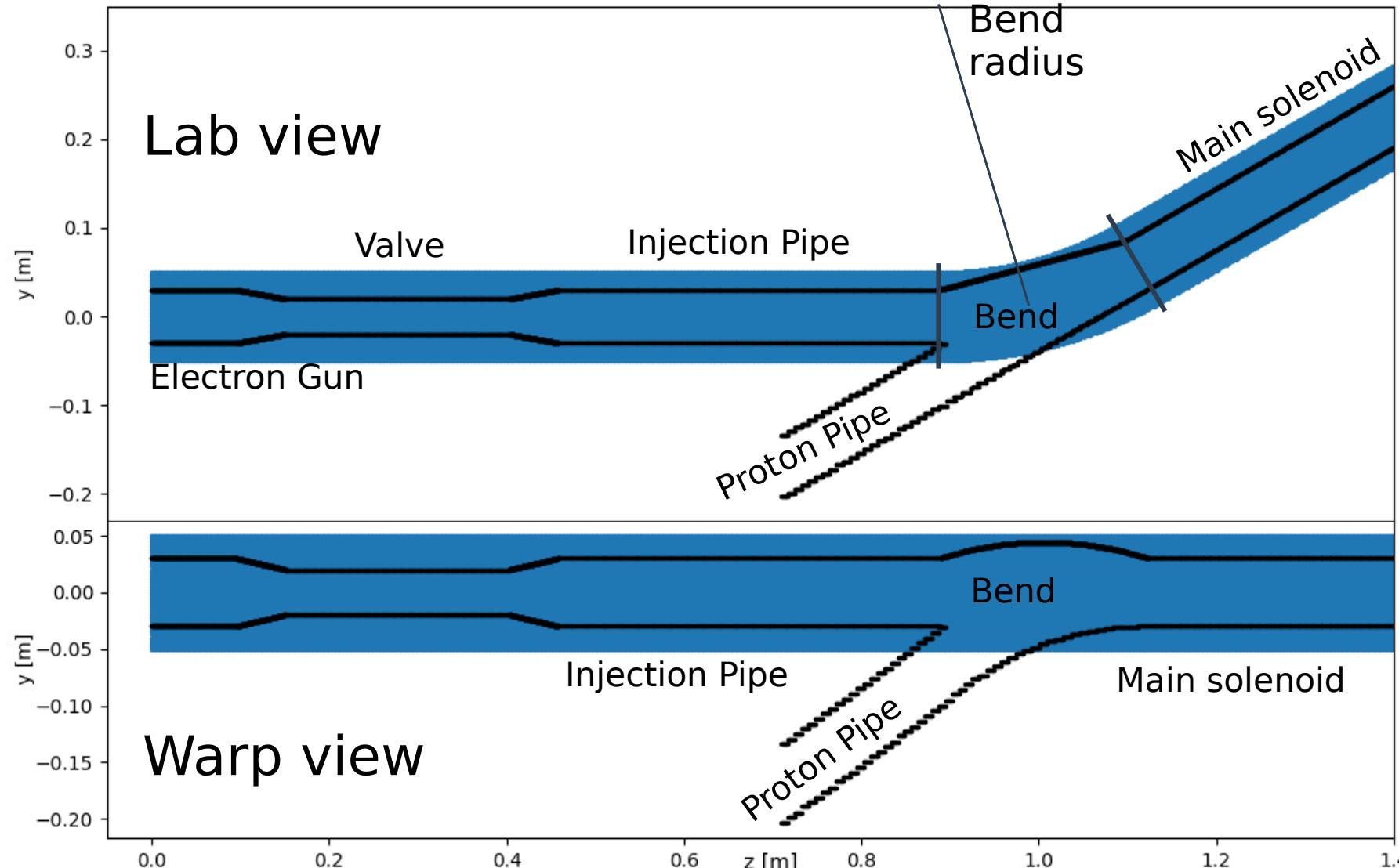
mesh cell size	Δx	1.25 mm
time-step	Δt	1.75 ps
macro particle	weight	$2 \cdot 10^4$

Bent mesh

Pipe

Bent mesh

Results



Results

Virtual Cathode

Beam trajectory

Beam offset vs I

Simulation tests

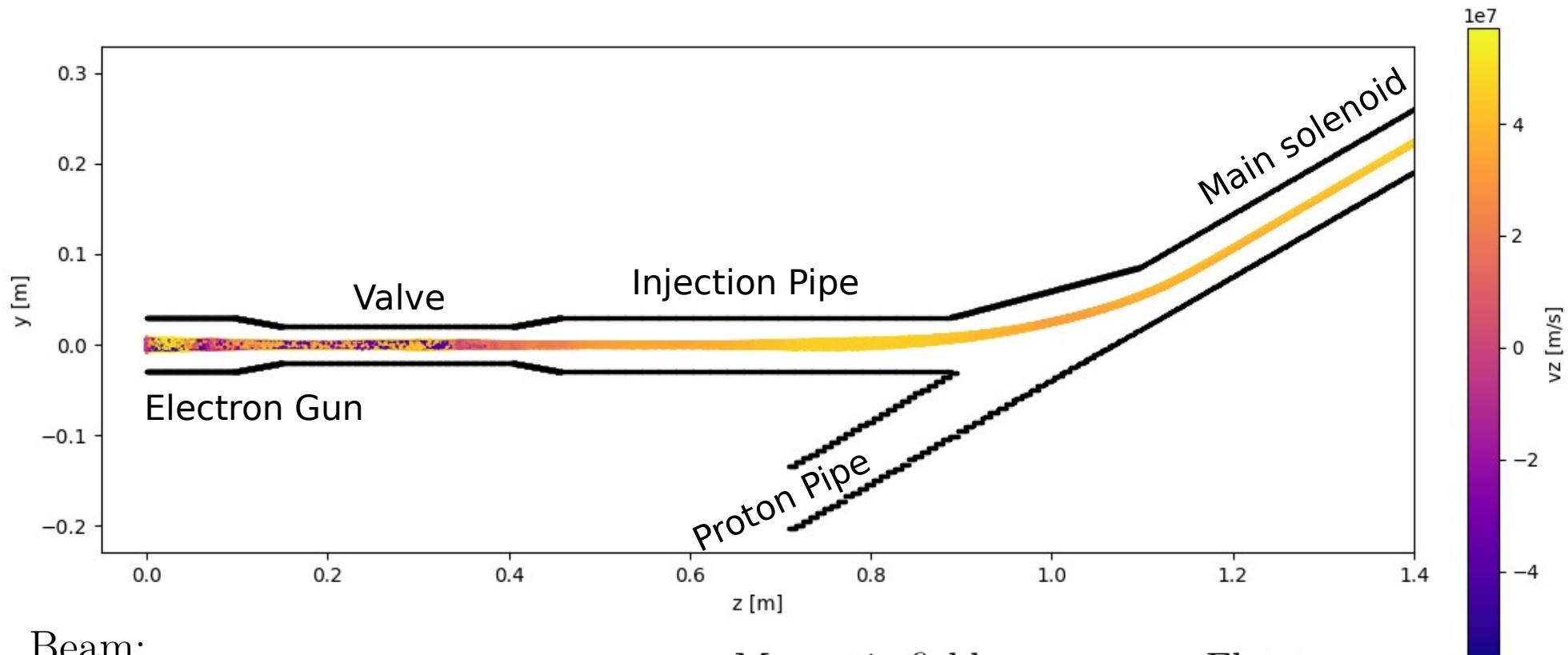
Virtual cathode

Virtual Cathode

Beam trajectory

Beam offset vs I

Simulation tests



Beam:

$U_{cathode}$ -10 kV

U_{anode} 0 kV

Magnetic field:

Flat top

Gun 0.37 T

Main 5.00 T

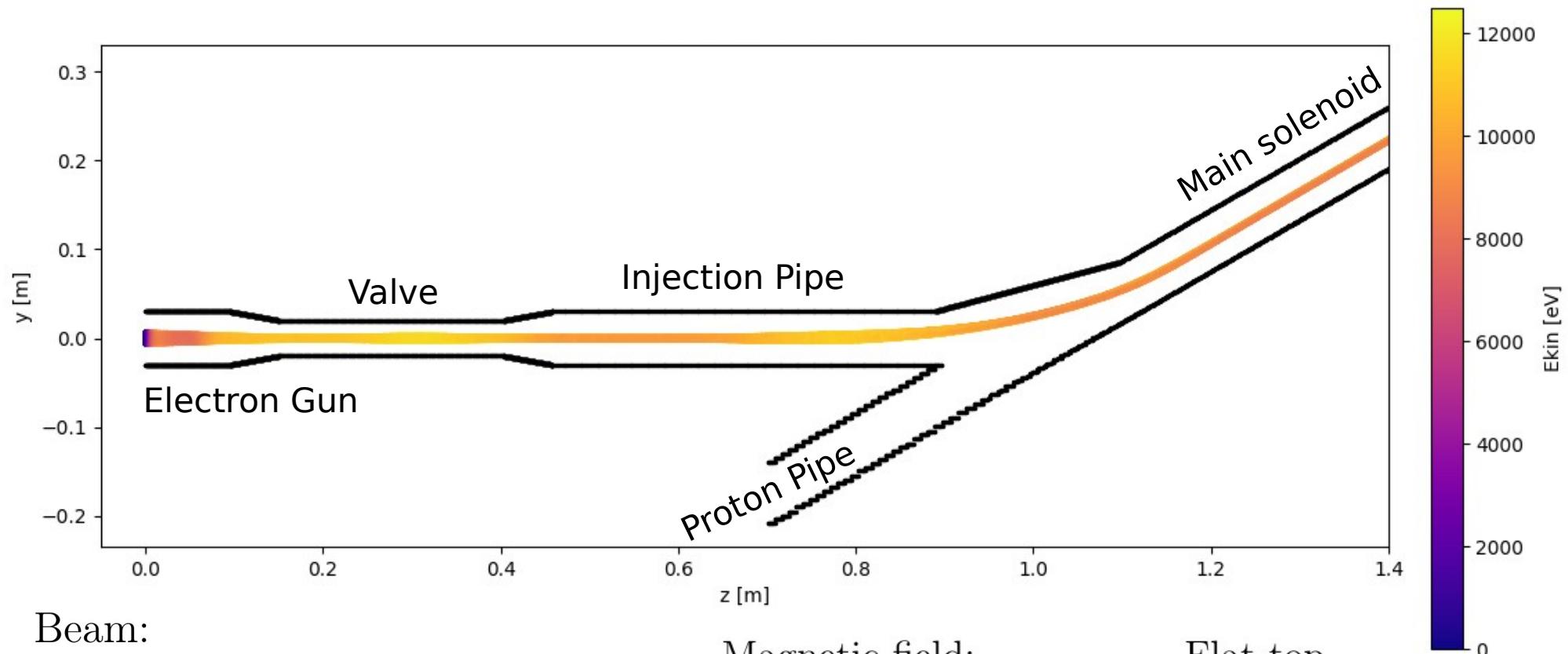
Beam trajectory

Virtual Cathode

Beam trajectory

Beam offset vs I

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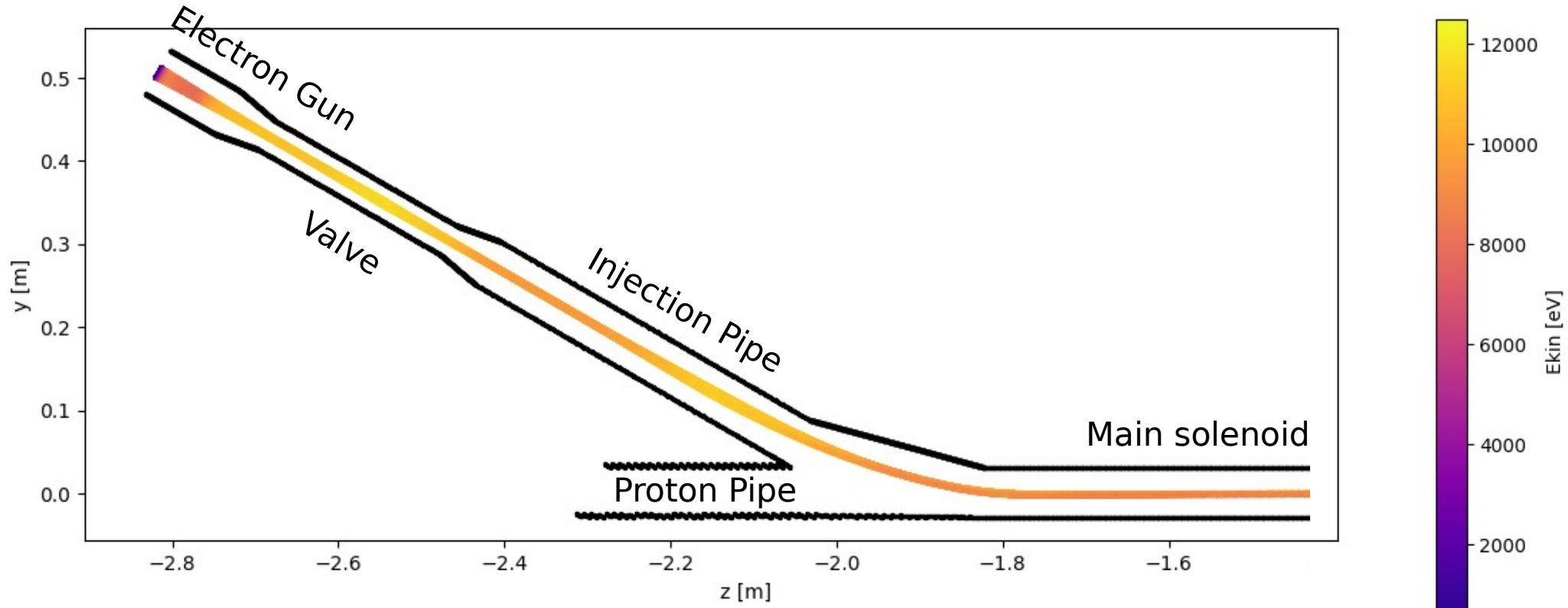
Beam trajectory

Virtual Cathode

Beam trajectory

Beam offset vs I

Simulation tests



Beam:

$U_{cathode}$ -15 kV

U_{anode} -5 kV

Magnetic field:

Flat top

Gun 0.37 T

Main 5.00 T

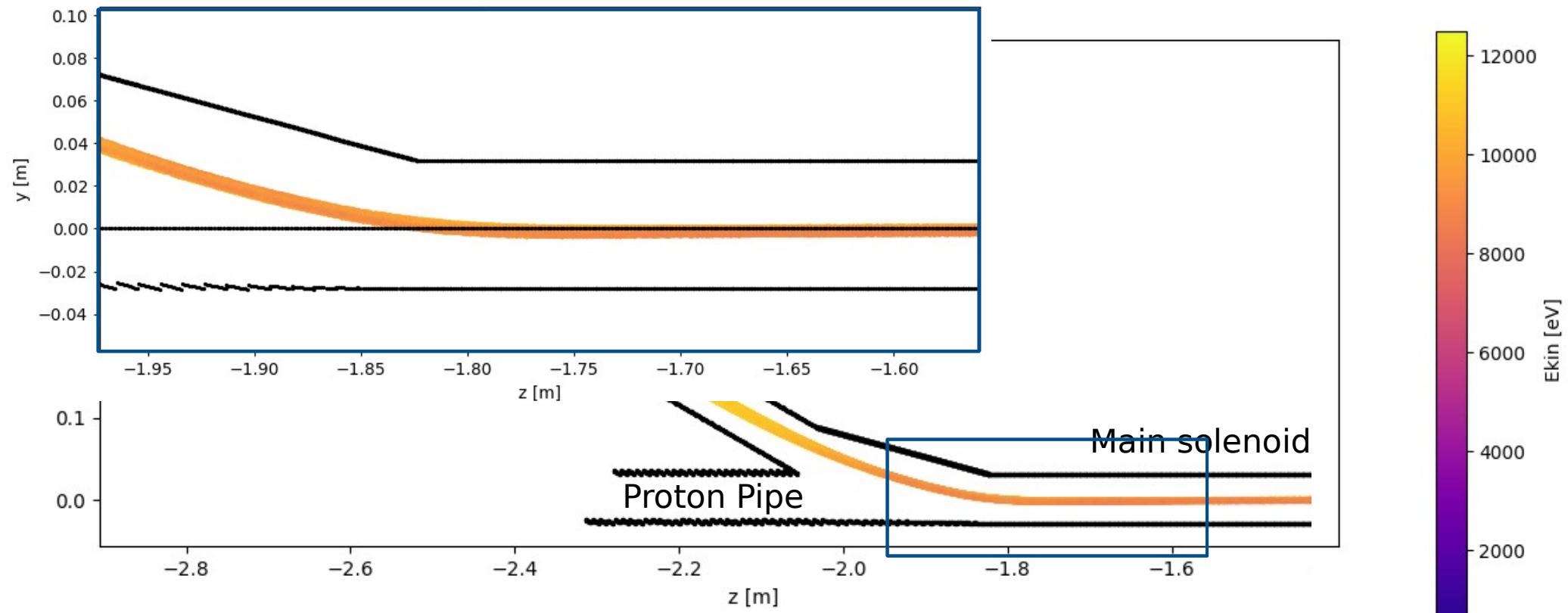
Beam trajectory

Virtual Cathode

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Beam offset vs I

Simulation tests



Beam:

$U_{cathode}$ -15 kV

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Magnetic field:

Flat top

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Beam offset vs current

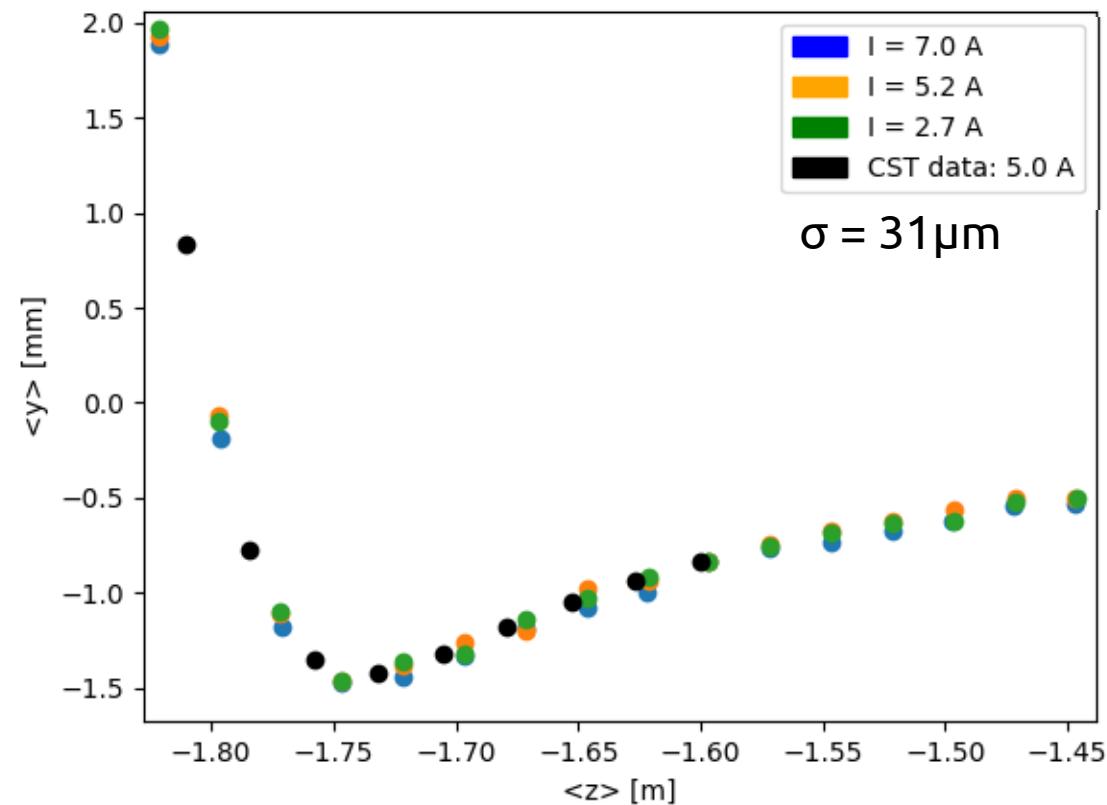
Virtual Cathode

Beam trajectory

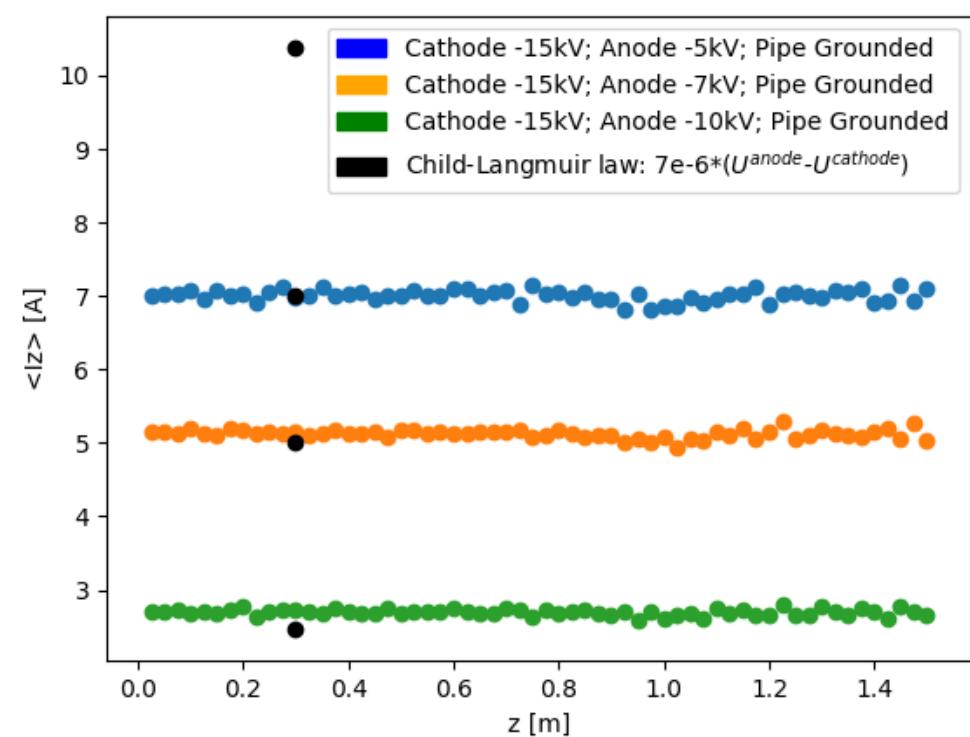
Beam offset vs I

Simulation tests

Vertical beam offset



Current



Simulation verification

Compression

Magnetic selfield

Mesh bend study

Summary

Simulation verification - Compression

Compression

Magnetic selfield

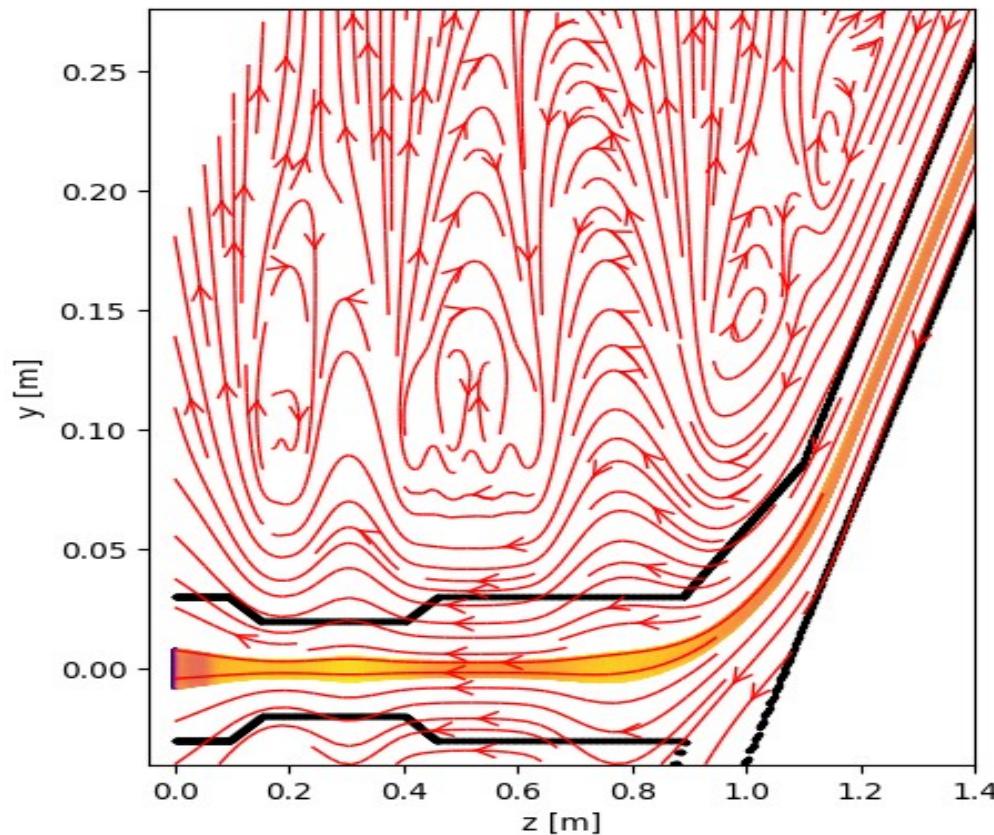
Mesh bend study

Summary

Flat top magnetic field

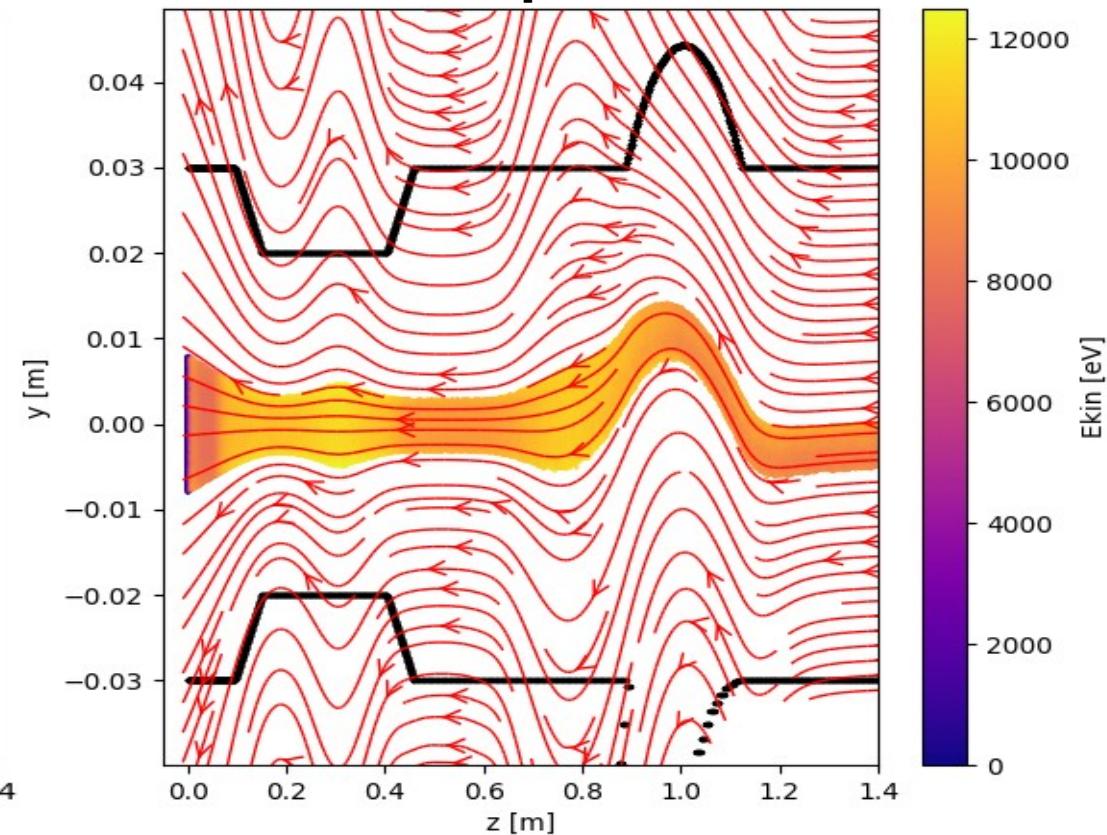
- Beam follows magnetic field-lines
- Compression as expected

Lab view



$$\frac{r_1}{r_2} = \sqrt{\frac{B_2}{B_1}} = 3.54$$

Warp view



Simulation verification - Magnetic self-field

Compression

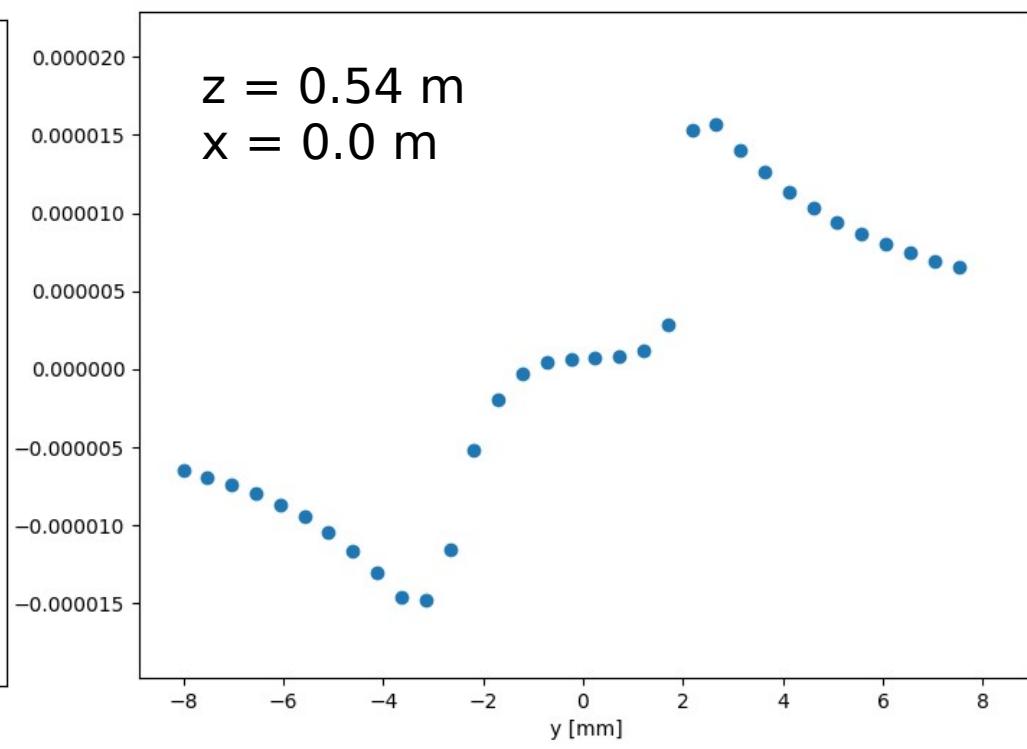
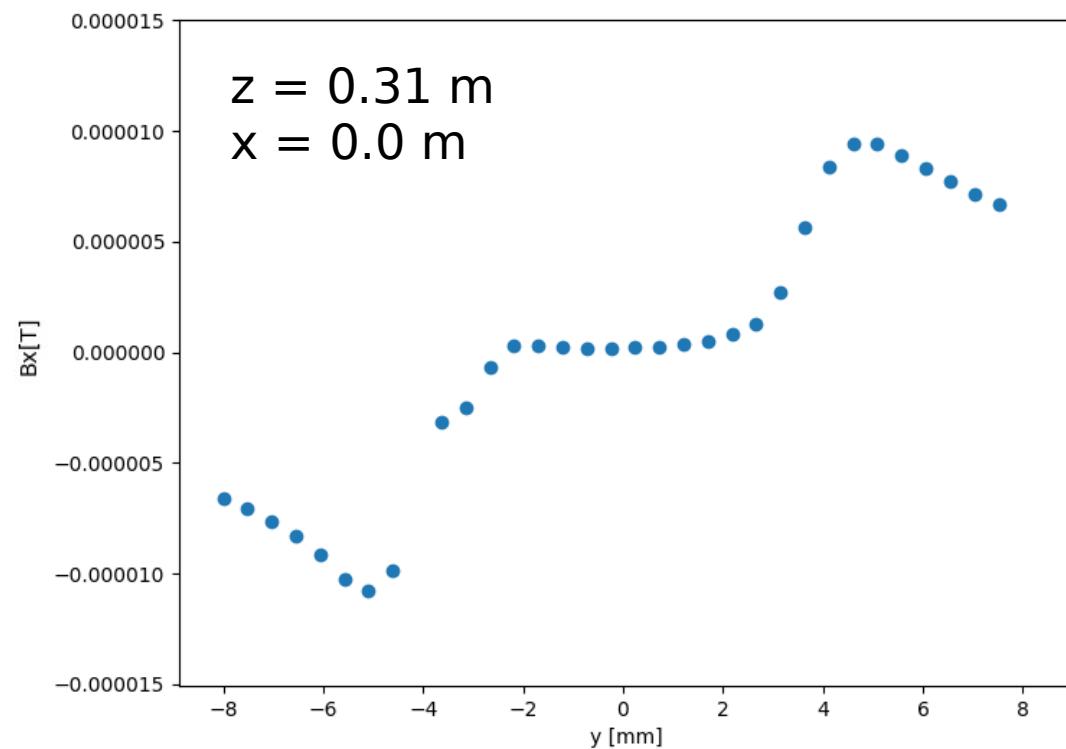
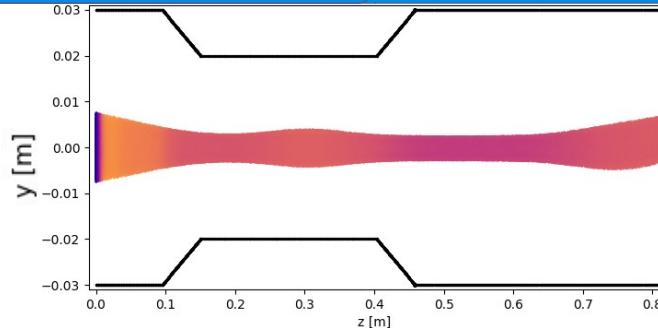
Magnetic selffield

Mesh bend study

Summary

External Magnetic field $\sim 5\text{T}$

→ Magnetic self-field neglected in the simulation seems justified



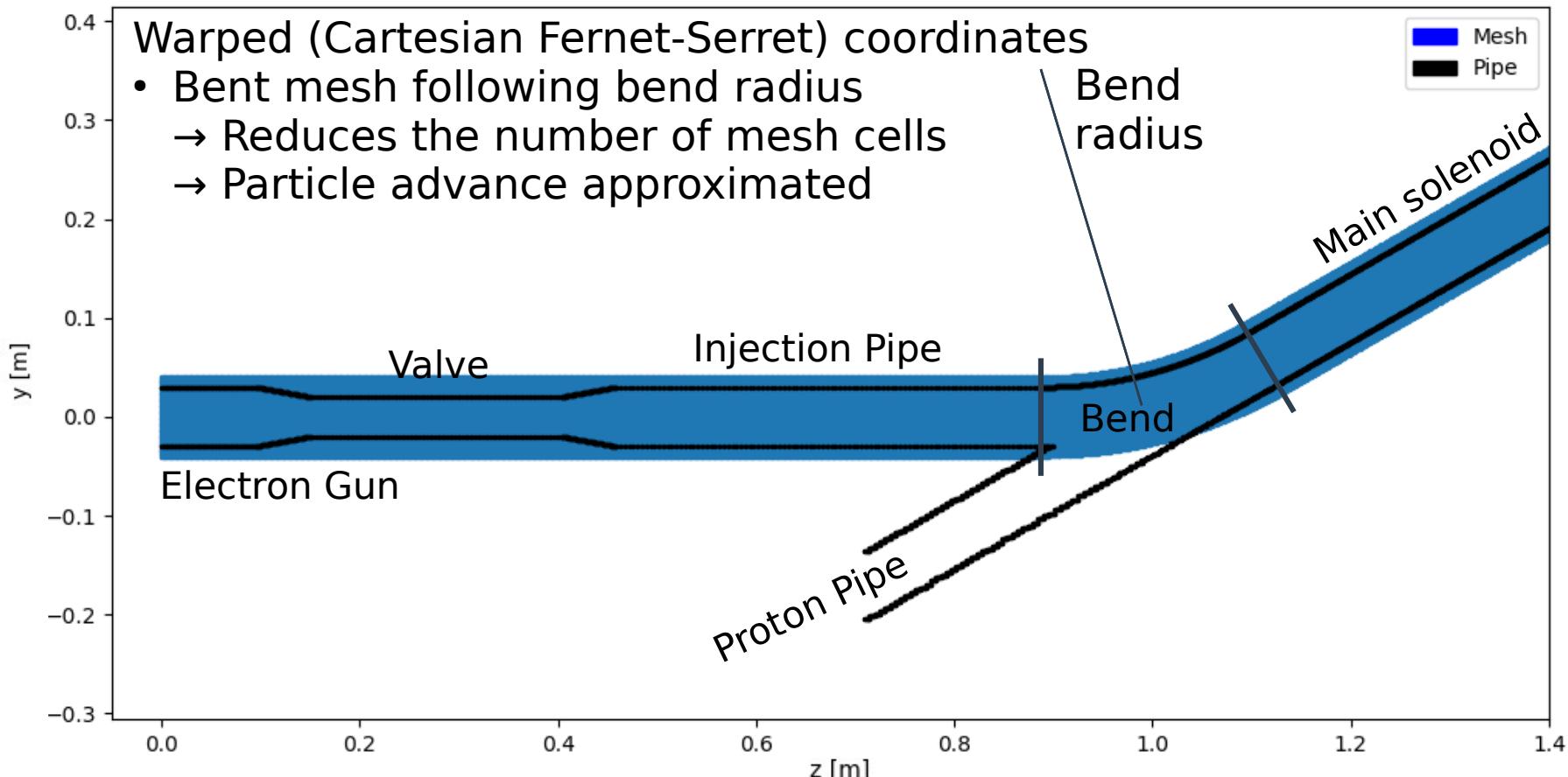
Simulation verification - Mesh bend study

Compression

Magnetic selfield

Mesh bend study

Summary



- Study the bend mesh effects
 - Varying the bend radius

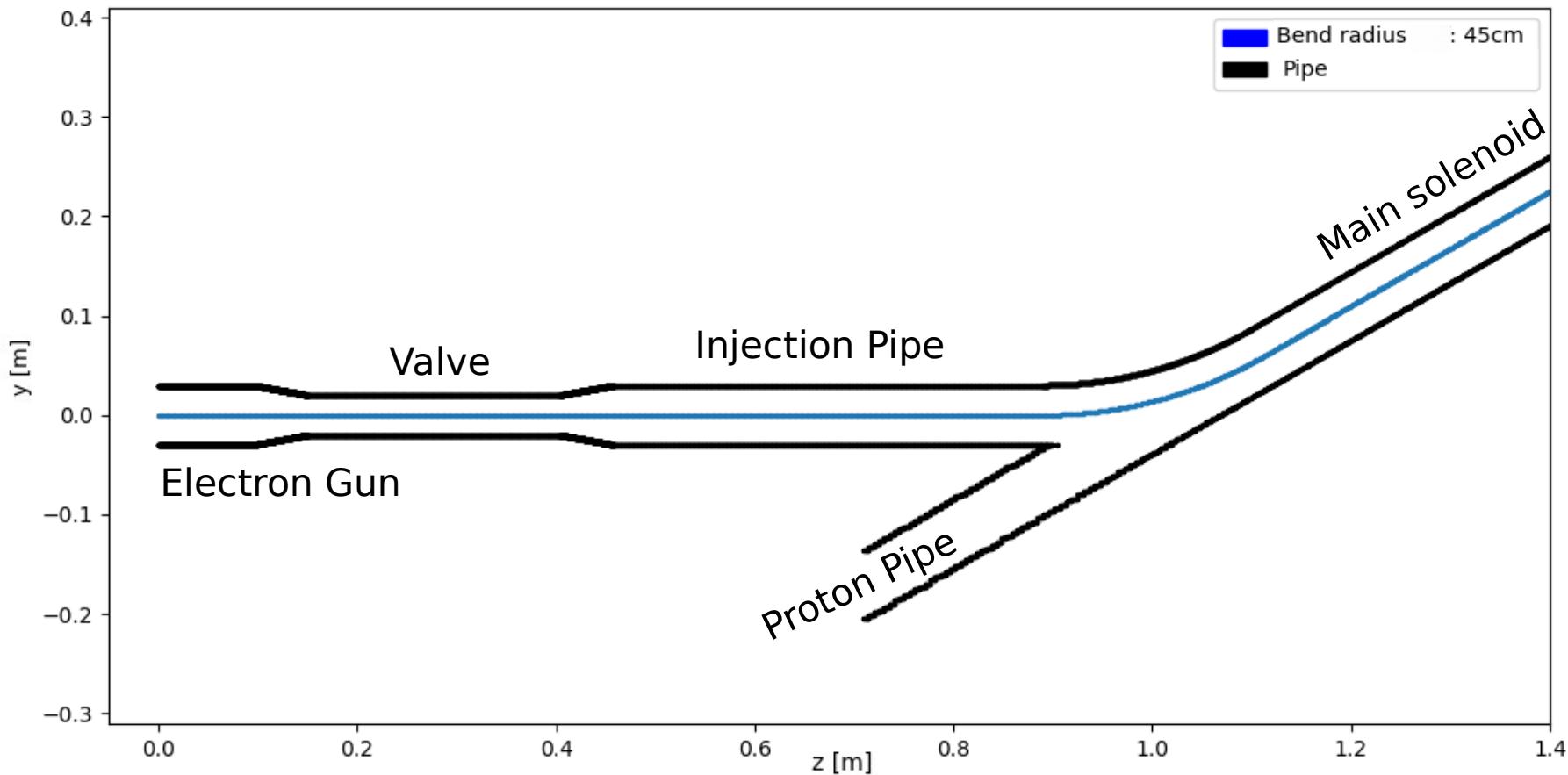
Mesh bend study - Different meshes used

Compression

Magnetic selfield

Mesh bend study

Summary



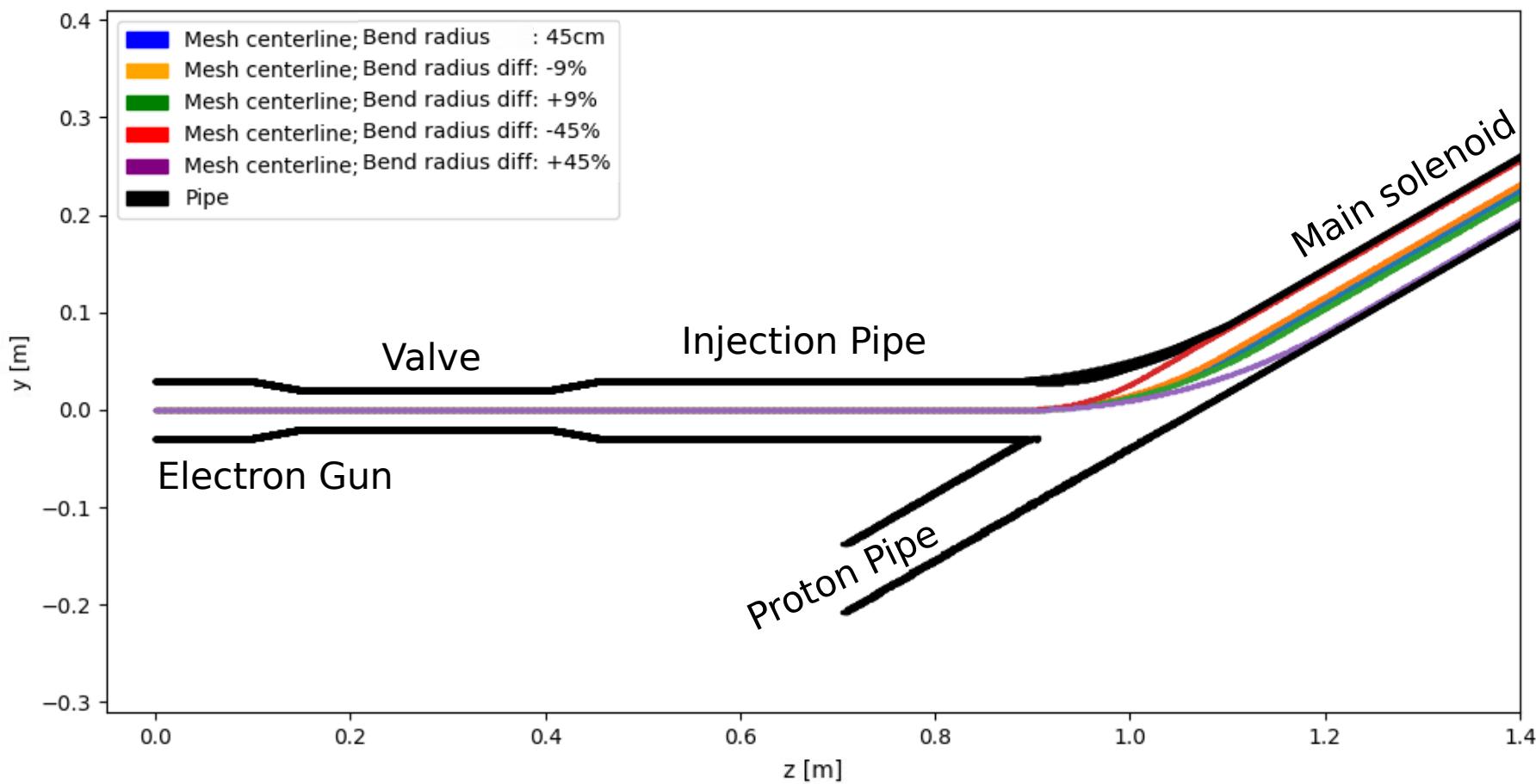
Mesh bend study - Different meshes used

Compression

Magnetic selfield

Mesh bend study

Summary



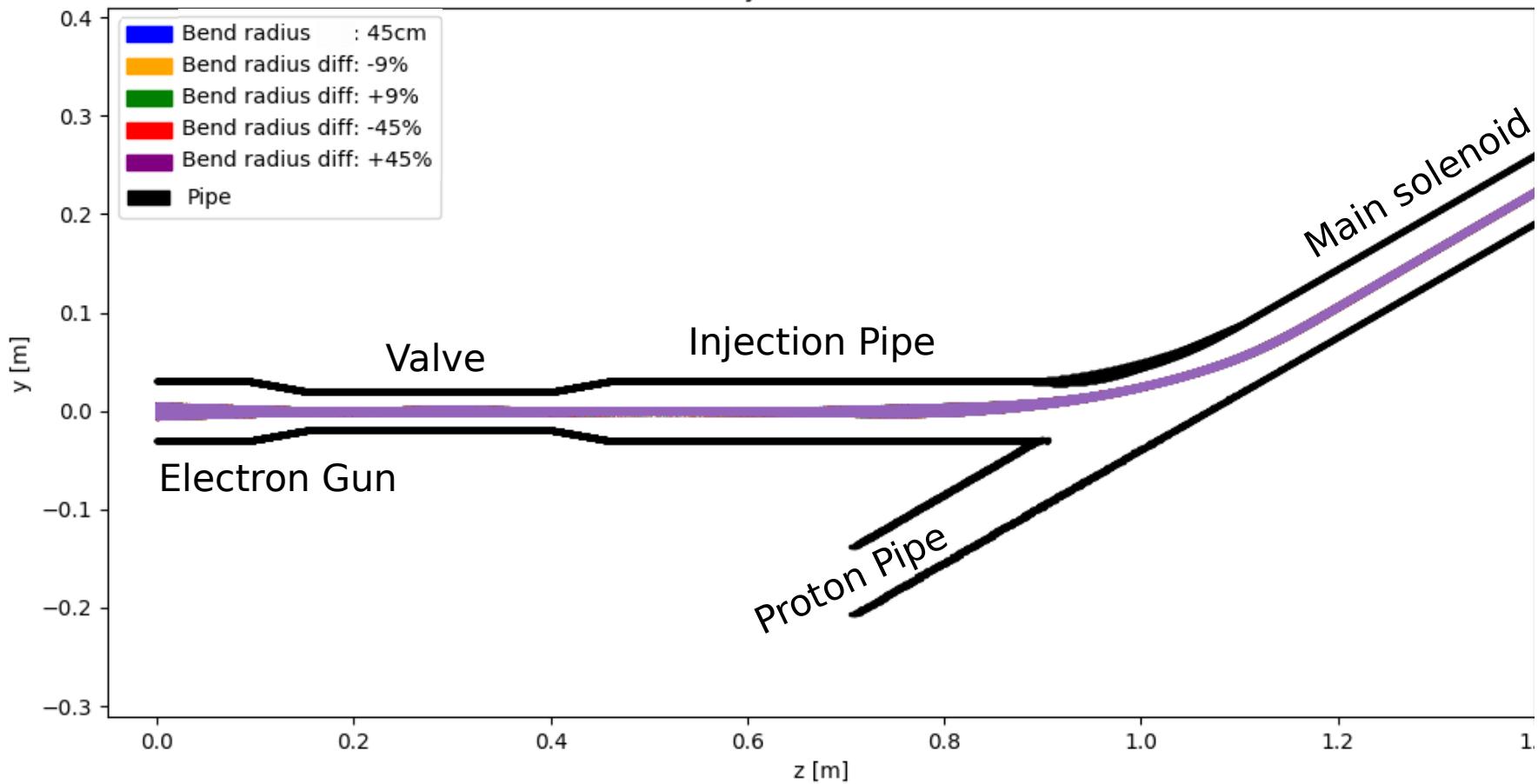
Mesh bend study - Beam trajectory

Compression

Magnetic selfield

Mesh bend study

Summary



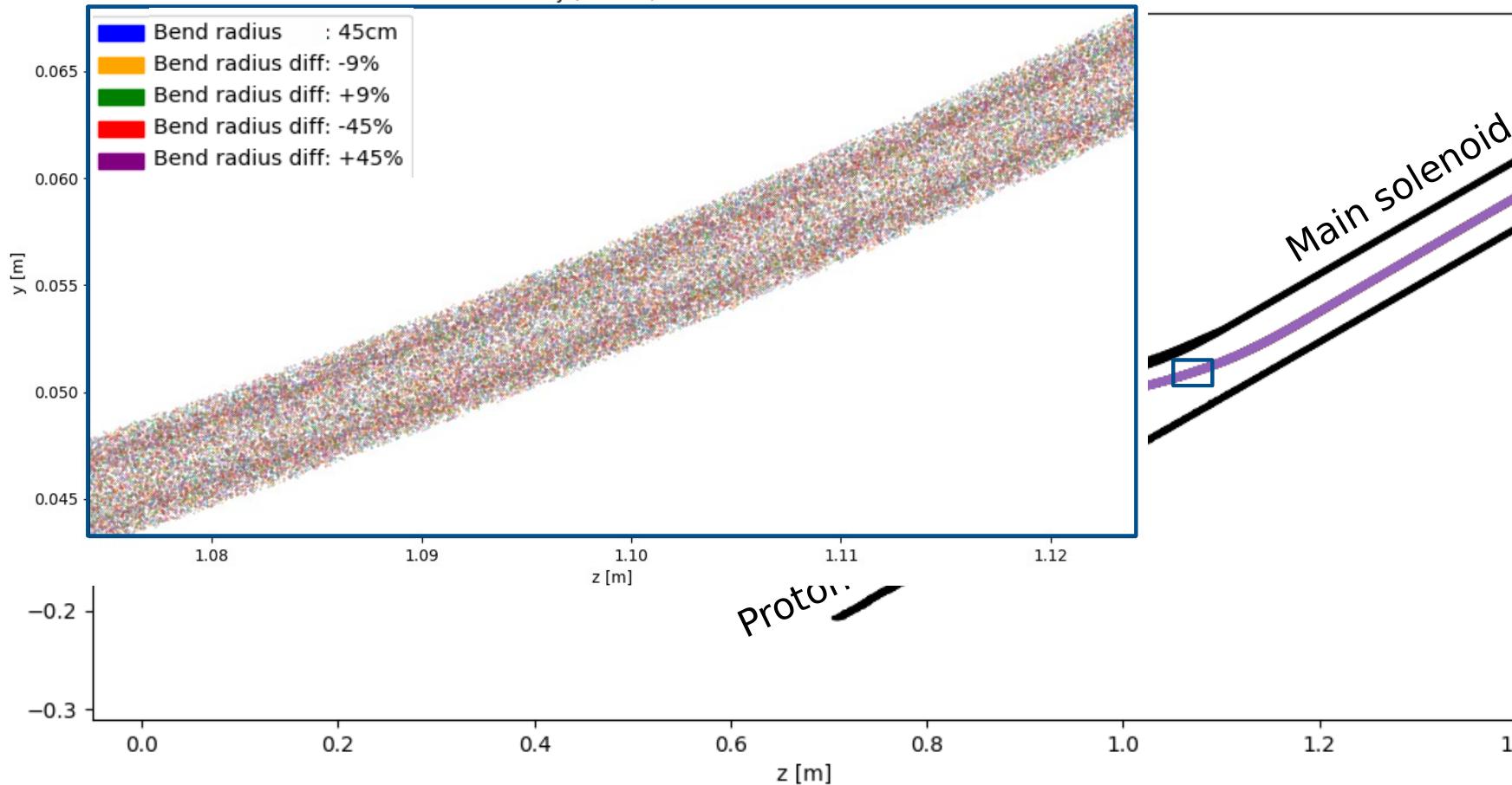
Mesh bend study - Beam trajectory

Compression

Magnetic selfield

Mesh bend study

Summary



Mesh bend study - Beam offset

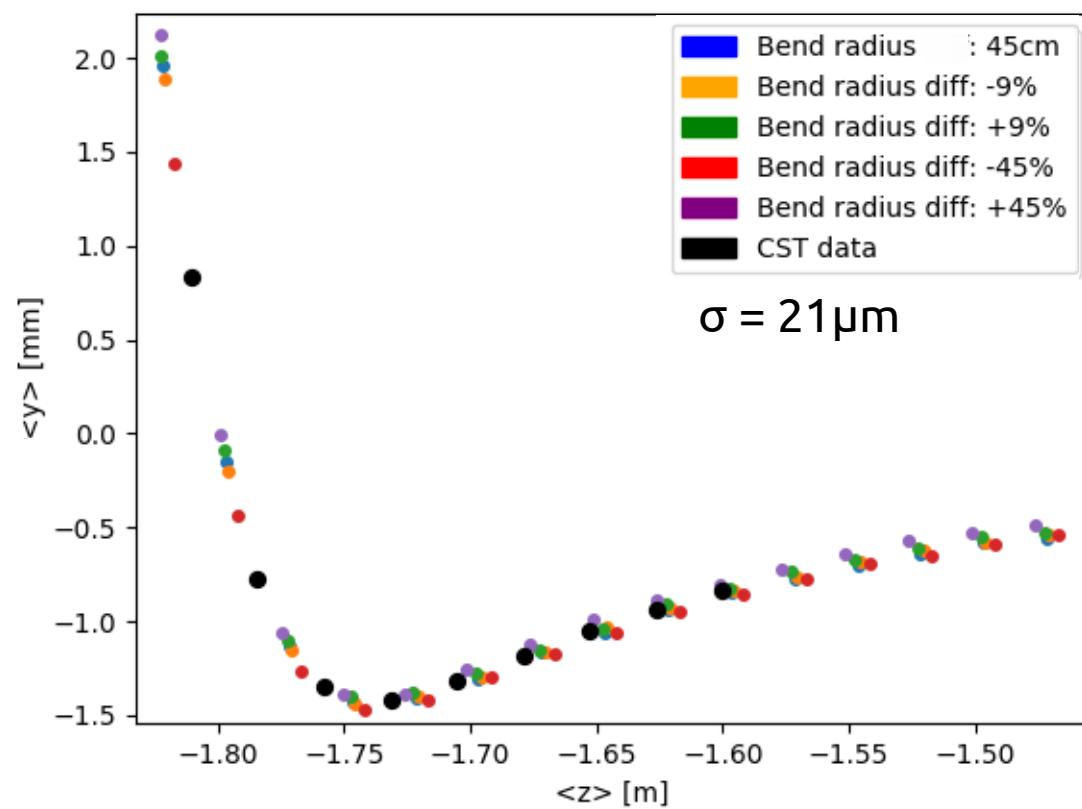
Compression

Magnetic selfield

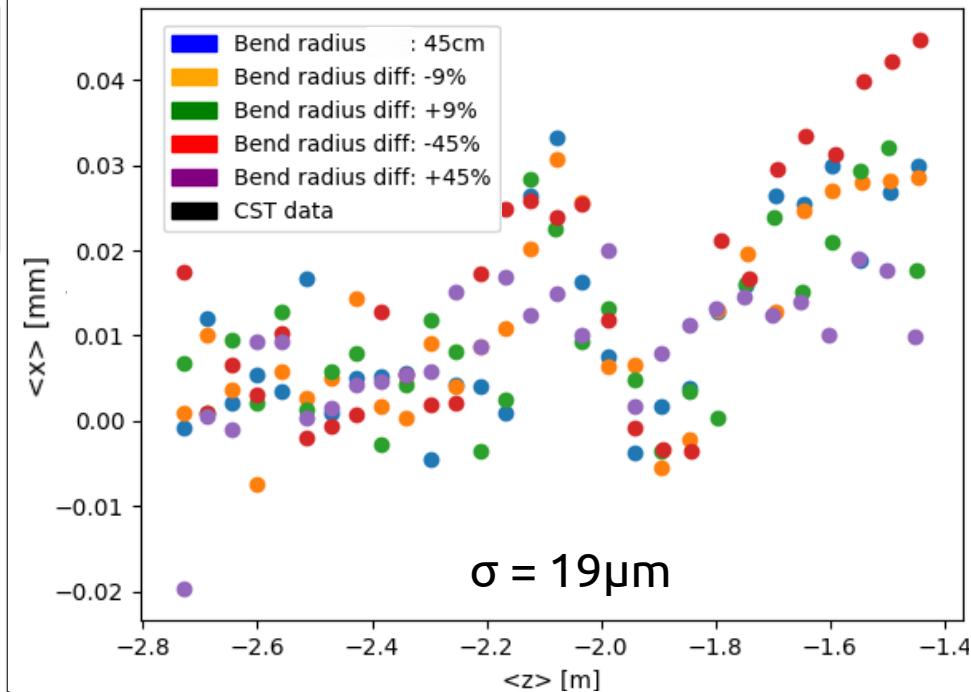
Mesh bend study

Summary

Vertical beam offset

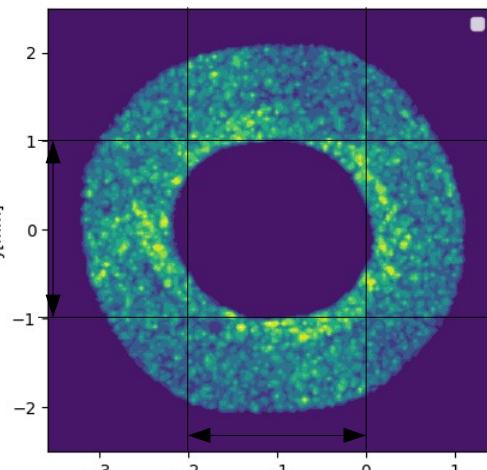


Horizontal beam offset

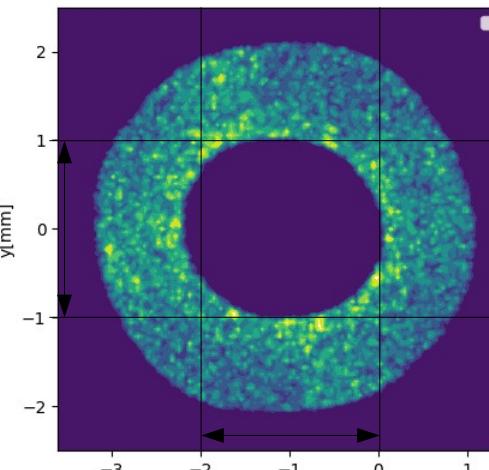


Mesh bend study - Beam profile

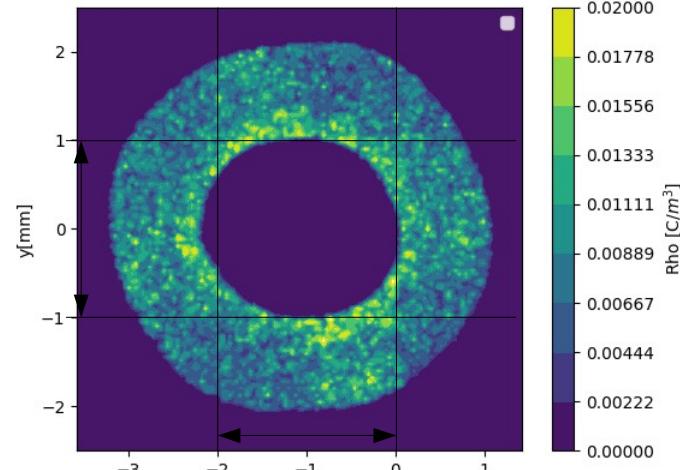
Compression



Magnetic selffield

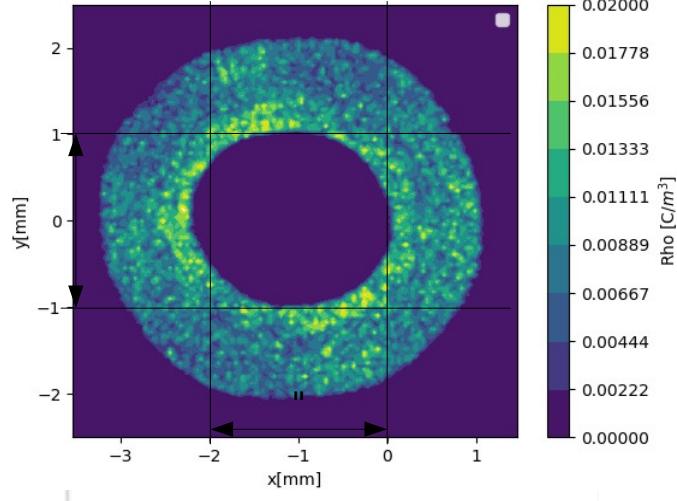
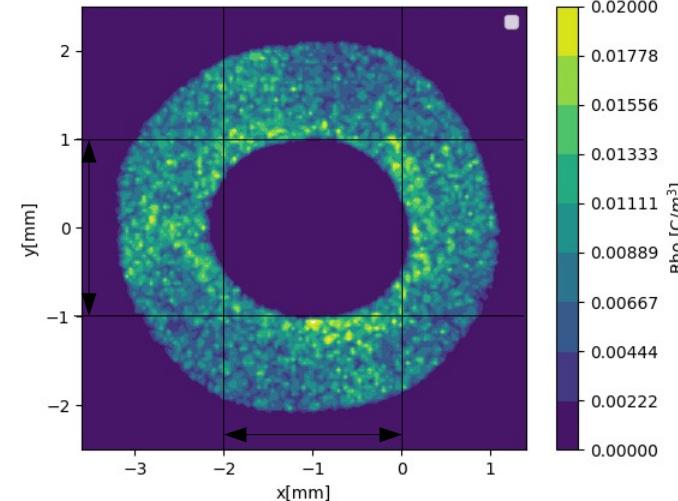


Mesh bend study



Summary

$Z = -1.655 \text{ m}$



Warp Simulation of electron transport

Summary

- Warp simulation constructed with usage of “Bent mesh”
- Pipe and junction according to HEL design; (E-gun (scaled design of V. Moens))
- Simulations tested:
 - Beam is magnetized and follows the magnetic field lines
 - Magnetic self-field neglecting in simulation seem justified.
 - Study of effect of mesh bending by varying the bending radius by up to 45% does not affect significantly the trajectory calculations or beam cross section profile
 - Beam offset unchanged with $\sigma = 21\mu\text{m}$
 - No obvious bend radius dependent artifacts in beam profile
- Beam offset
 - Seems independent off beam current with currents of 7, 5.2, 2.9 A producing $\sigma = 31\mu\text{m}$
 - In good agreement with CST

Future steps

- Comparison of particle and energy distribution to CST
- Simulating without bent mesh to provide robust test of the mesh bending effect

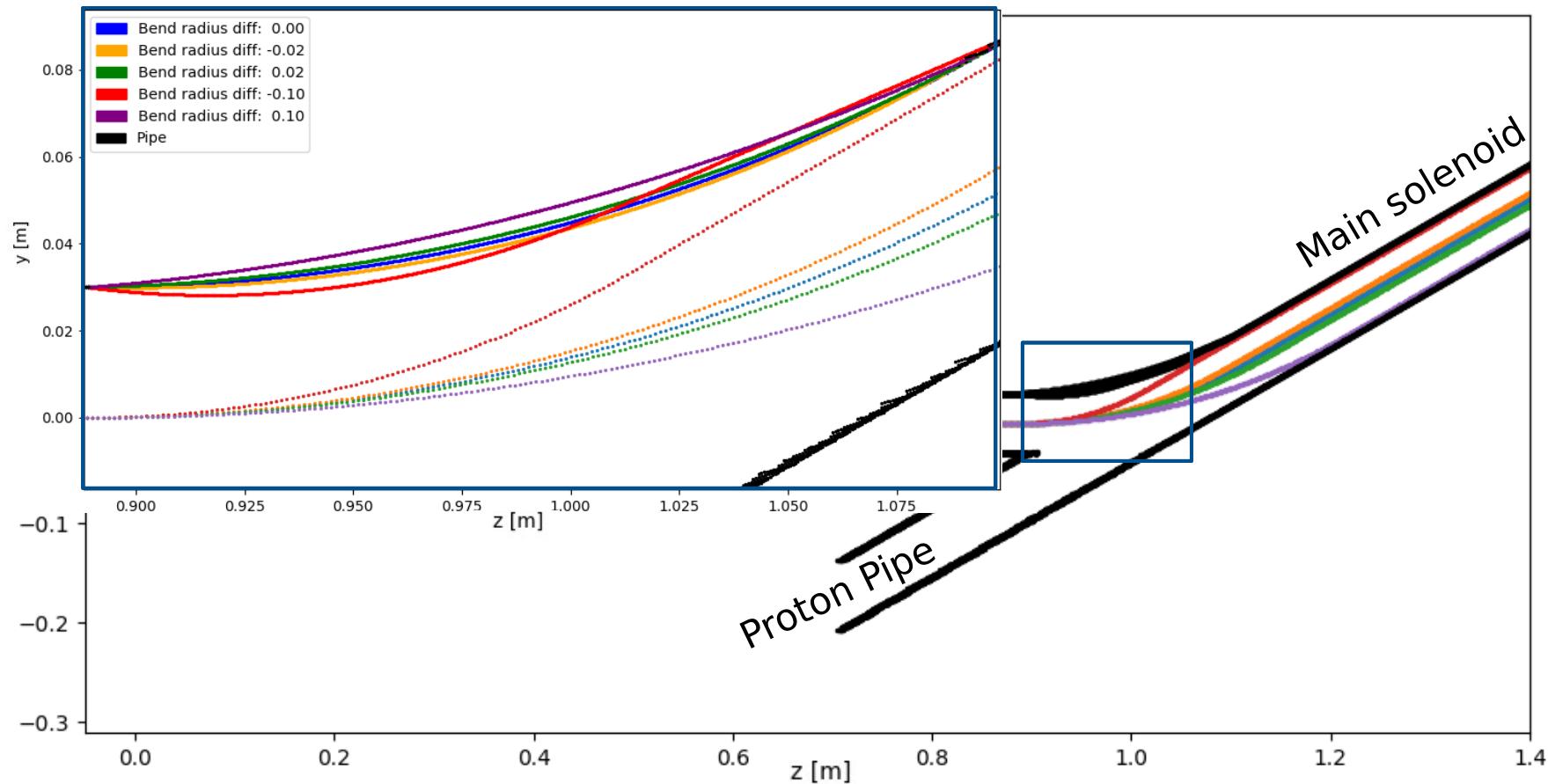
Different meshes used

Compression

Magnetic selffield

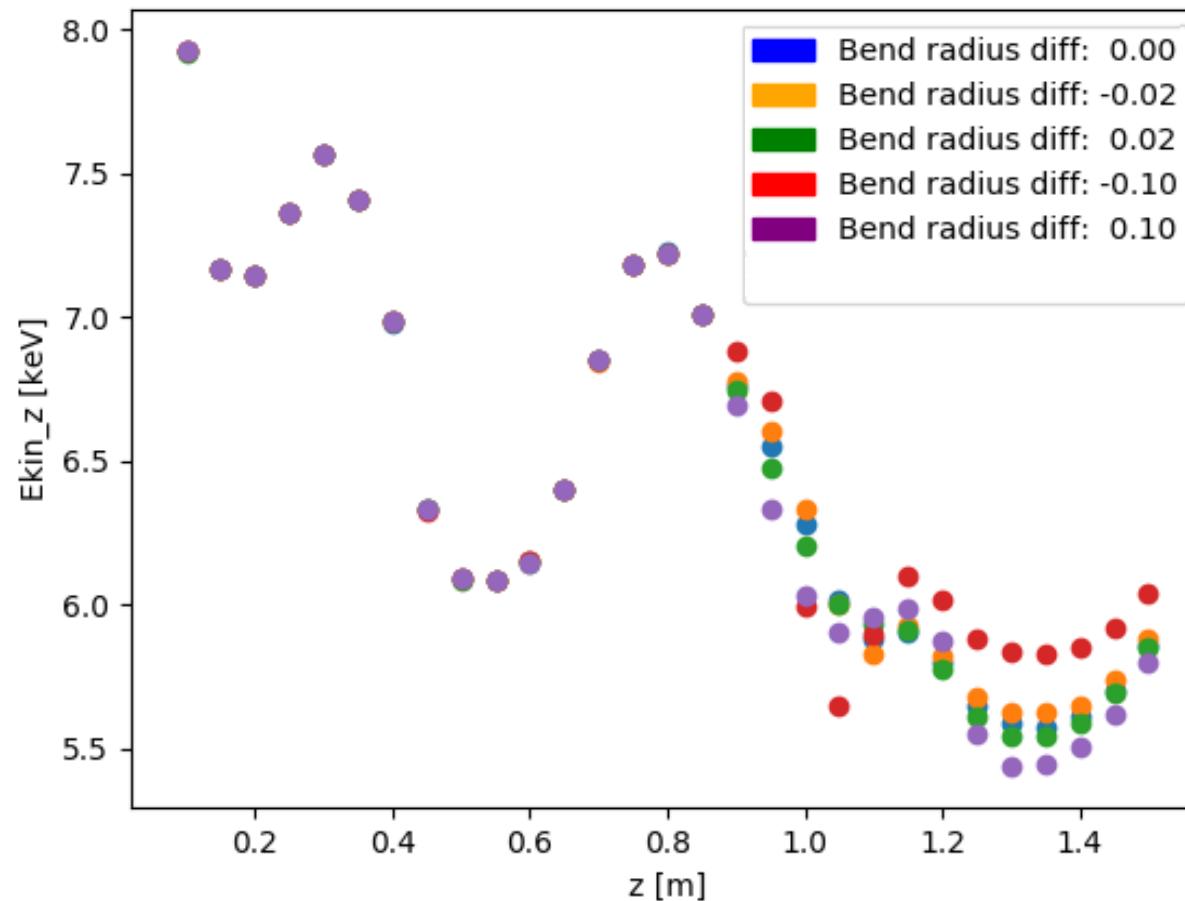
Mesh bend study

Summary

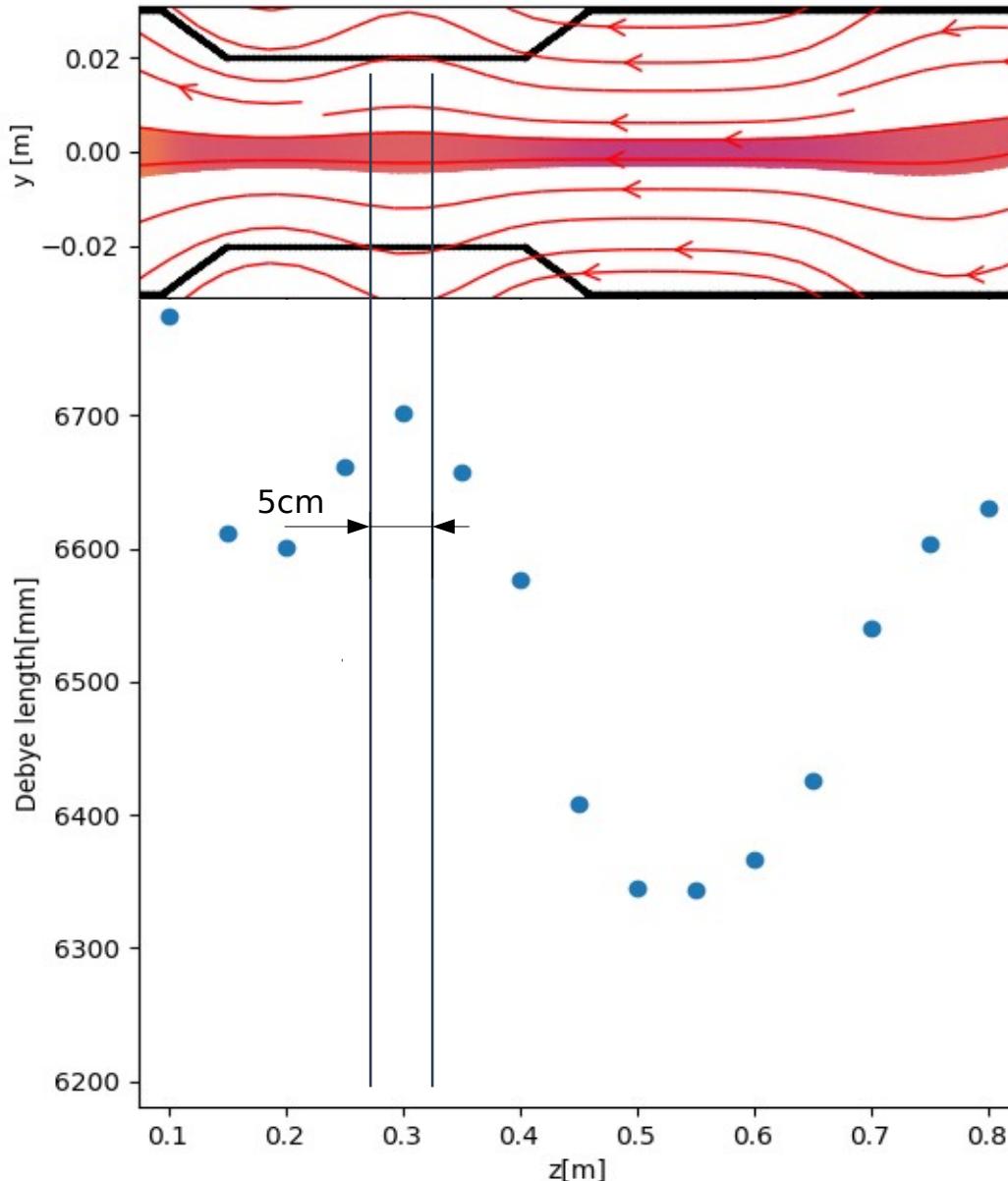


Kinetic energy

Longitudinal kinetic energy



Beam analysis - Transverse Debye length



$T = 900 \text{ }^{\circ}\text{C}$ (Cathode temperature)

- Approximation of constant temperature in transverse plane

$$\lambda_D^{\text{Transverse}} = \sqrt{\frac{T k}{4 \pi n e^2}}$$