DE LA RECHERCHE À L'INDUSTRIE

CEA - Saclay

Model of an IPM: investigation on space charge perturbation to the profile measurement

CEA-ESS-DIA-RP-0018 v0.1
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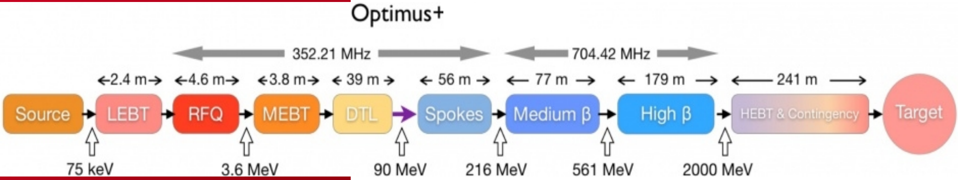

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31st January 2017, Lund

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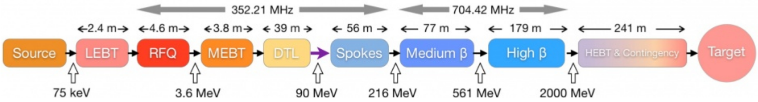
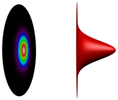
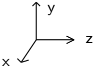
Non-interceptive Profile Monitors: why?







MOTIVATIONS:

Provide a transverse profile measurement to

- support the tuning of high power beam
- maximize protons on target

⇓

REQUIREMENTS:

- stand high proton beam intensity
- have minimum impact on proton beam
- provide enough statistics

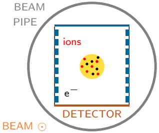
⇓

IONIZATION PROFILE MONITORS
(1 in Spokes, 3 in Medium β, 1 in High β)

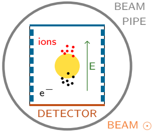
IPM : Ionization Profile Monitor

PRINCIPLE OF OPERATION

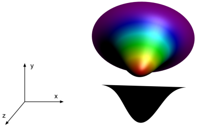
- proton beam ionizes residual gas



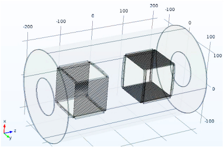
- $\vec{E}$ separates e^-/ions



- charge collection on read-out

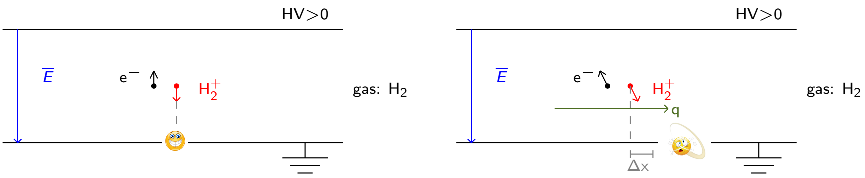


2 cages for 2D beam profile measurement



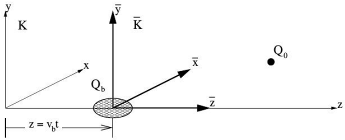
Space charge effect

REMINDER:



POSSIBLE CORRECTION METHODS

- Add magnetic field ✗
- High electric field ✓ ✗
- Software correction ✓



SOFTWARE CORRECTION

R. Wanzenberg, Nonlinear Motion of a Point Charge in the 3D Space Charge Field of a Gaussian Bunch.

A Gaussian bunch with total charge $\mathbf{Q}_b$ is moving with the velocity $\mathbf{v}_b$ along the z-axis of the laboratory frame K.
The electric field of the bunch is calculated in the comoving frame and transformed into an electric and magnetic field in the laboratory frame K where the Lorentz-Force on a point charge $\mathbf{Q}_0$ is calculated.

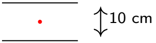
Correction code

CODES:

- MATLAB (**C. Thomas**)
- C++ (translation of the MATLAB code)

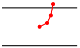
SIMULATION STEPS:

- **a single electron (or ion)** is created in the center of the IPM: x= Gaus(0,σ_x)
  y= Gaus(0,σ_y)
  z = Unif(-2.5 mm, 2.5 mm)



- in a first moment it is assumed that at creation time the electron (or ion) is **at rest**
- a proton bunch of total charge Q = 1.7 e^{-10} C and kinetic energy E_p is considered
- a time step *dt* is chosen by the program
- the displacement $d\bar{x}$ of the electron (or ion) is calculated by solving the motion equation (adaptive Runge Kutta Fehlberg method)

- another time step *dt* is chosen by the program
- the displacement $d\bar{x}$ of the electron (or ion) is calculated by solving the motion equation (adaptive Runge Kutta Fehlberg method)



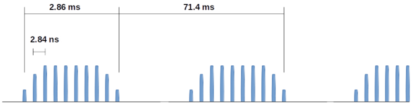
- time ... displacement ... time ... displacement ...
- when the y position of the electron (or ion) y$\geq y_{collection\ plate}$, the simulation stops
- at every *dt* passed, the following variable values were saved: t, x, y, z, v_x, v_y, v_z, a_x, a_y, a_z, fields info (lab and comoving frame)
- t and y are plotted and fitted with a spline to find the time $\mathbf{t}_{stop}$ when the electrode was reached
- t and x are plotted and fitted with a spline. x(t_{stop}) is extracted
- the procedure is iterated N times, to reach a statistical uncertainty of (100 $\frac{\sqrt{N}}{N}$) %

Demo

ESS code parameters

ESS PROTON BEAM PARAMETERS:

- Energy : [90,2000] MeV
- Current peak: 62.5 mA $= 0.0625 \times 6.242 \times 10^{18}$ p/s
- Pulse length: 2.86 ms
- Pulse frequency: 14 Hz (duty cycle 4%)
- Bunch frequency: 352.21 MHz

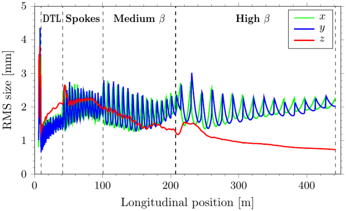


IPM GAS PARAMETERS:

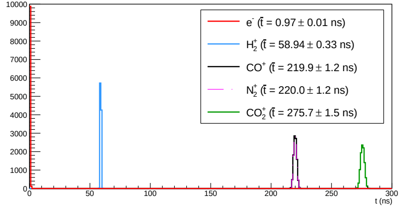
- Composition : H_2 (79%), CO (10%), CO_2 (10%), N_2 (1%) [source: ESS vacuum group]
- Pressure: 10^{-9} mbar

CHOSEN CODE PARAMETERS:

- Proton energies: **90 MeV, 200 MeV, 1 GeV**
- Proton bunch intensity: 62.5 mA/ 352.21 MHz = **1.1 10^{+9} p/bunch**
- σ_x = **0.5 mm, 1.4 mm, 2.3 mm, 3.2 mm, 4.1 mm, 5 mm, 10 mm**
- σ_y = **0.5 mm, 1.4 mm, 2.3 mm, 3.2 mm, 4.1 mm, 5 mm, 10 mm**
- σ_z = **0.75 mm, 2.0 mm, 10 mm**
- Ionization products: **e^-, H_2^+**, N_2^+, CO^+, CO_2^+
- $\overline{E}$: **50 kV/m, 100 kV/m, 200 kV/m, 600 kV/m, 1000 kV/m**



[600 kV/m, 90 MeV, $\sigma_x = \sigma_y = 0.5$ mm, $\sigma_z = 0.75$ mm]

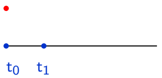


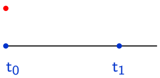
THE HEAVIER THE TEST PARTICLE:

- the more time it spends in the field
  - → more time subjected to the elm field (+)
  - → equal contributions from bunches before and after the particle coordinates (-)
- the more resistance it opposes to the elm field (-)

THE HIGHER THE PROTON ENERGY:

- the higher the elm field (+)
- the less time a bunch affects the trajectory of a test particle (-)





THE HIGHER THE ELECTRIC FIELD:

- the fastest a test particle reaches the electrode (-)

The various parameters contribute in different way, sometimes increasing and sometimes decreasing the space charge effects felt by the test particles (focusing and defocusing effect). Therefore, it is impossible to foresee a priori (withouth calculations) the behaviour of the created ions in the field obtained by the sum of the external electric field and elm field.

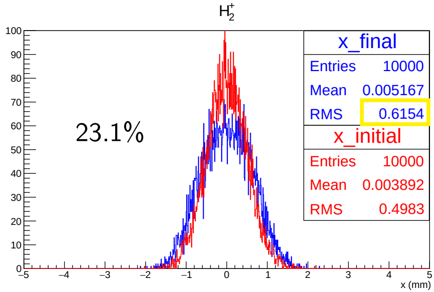
Results: heavier ion comparison

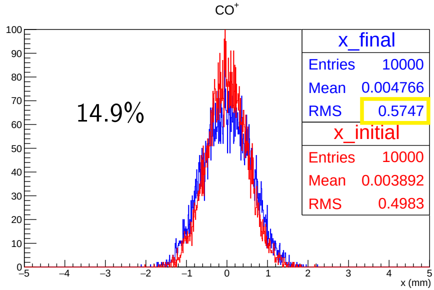
- Initial conditions:

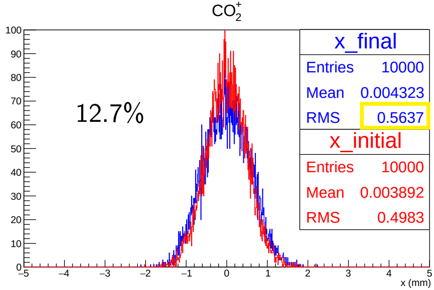
$$\overline{E} = 600 \text{ kV/m}$$
$$E_p = 90 \text{ MeV}$$
$$\sigma_{x_i} = \sigma_{y_i} = 0.5 \text{ mm}$$
$$\sigma_{z_i} = 0.75 \text{ mm}$$

- Remarks:

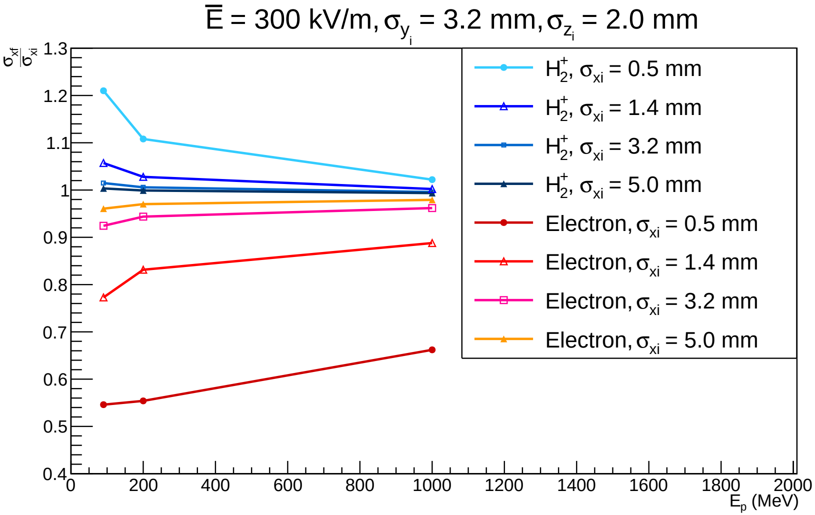
$$m_{N_2} \approx m_{CO}$$
$$\text{heavier particle} = \text{smaller } \Delta x$$





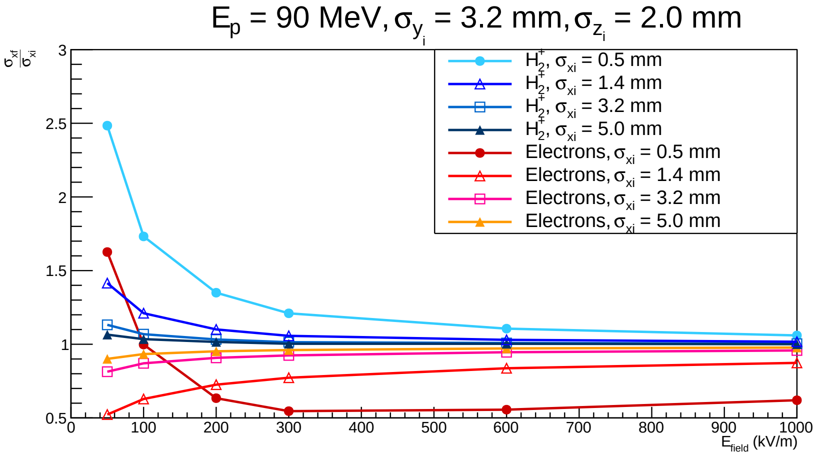


Results: $f(E_p)$

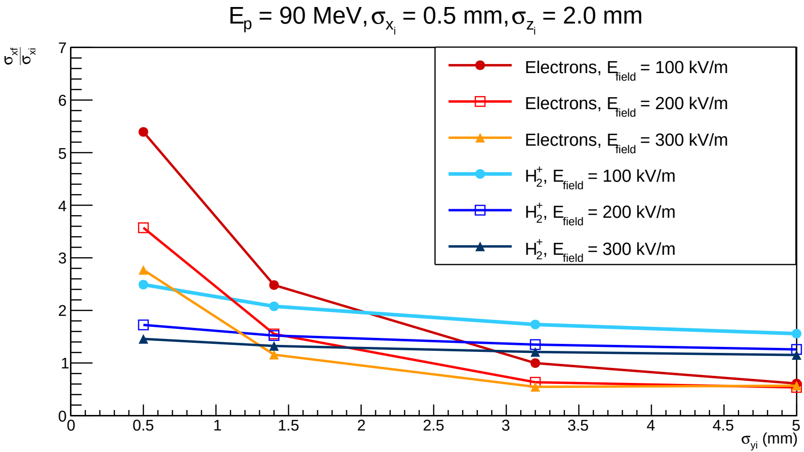


$\bar{E} = 300$ kV/m, $\sigma_{y_i} = 3.2$ mm, $\sigma_{z_i} = 2.0$ mm
$\frac{\sigma_{xf}}{\sigma_{xi}}$
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
200
400
600
800
1000
1200
1400
1600
1800
2000
E_p (MeV)
H_2^+, σ_{xi} = 0.5 mm
H_2^+, σ_{xi} = 1.4 mm
H_2^+, σ_{xi} = 3.2 mm
H_2^+, σ_{xi} = 5.0 mm
Electron, σ_{xi} = 0.5 mm
Electron, σ_{xi} = 1.4 mm
Electron, σ_{xi} = 3.2 mm
Electron, σ_{xi} = 5.0 mm

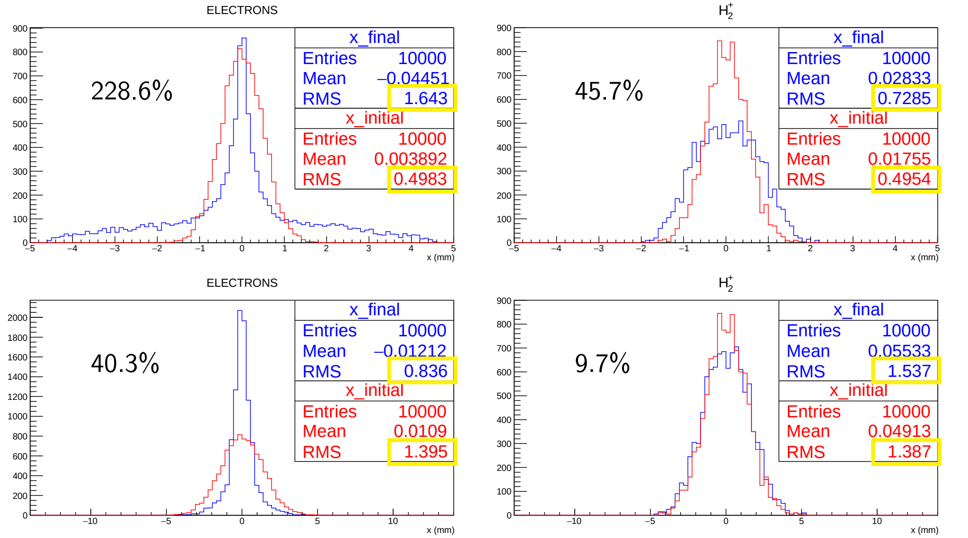
Results: $f(\overline{E})$

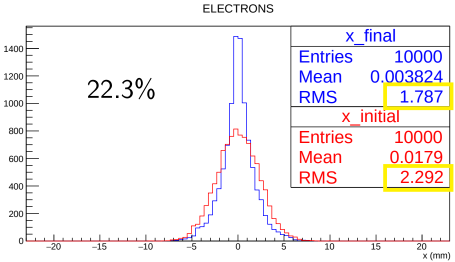


Results: $f(\sigma_{y_i})$

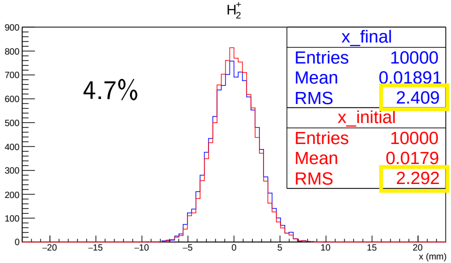


Results: minimim σ_{y_i} & σ_{z_i}, $\overline{E} = 300$ kV/m, $E_p = 90$ MeV

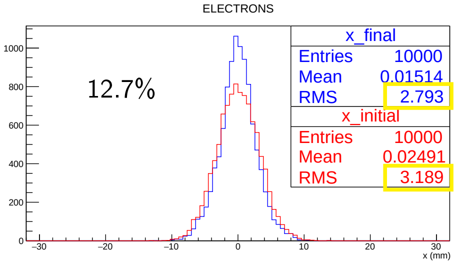




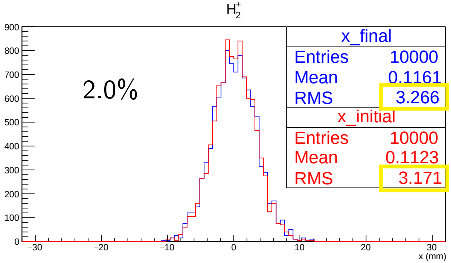
ELECTRONS
22.3%
x_final
Entries 10000
Mean 0.003824
RMS 1.787
x_initial
Entries 10000
Mean 0.0179
RMS 2.292
x (mm)



H_2^+
4.7%
x_final
Entries 10000
Mean 0.01891
RMS 2.409
x_initial
Entries 10000
Mean 0.0179
RMS 2.292
x (mm)



ELECTRONS
12.7%
x_final
Entries 10000
Mean 0.01514
RMS 2.793
x_initial
Entries 10000
Mean 0.02491
RMS 3.189
x (mm)

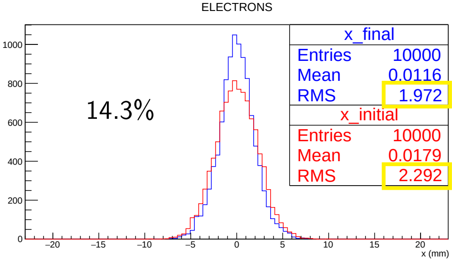


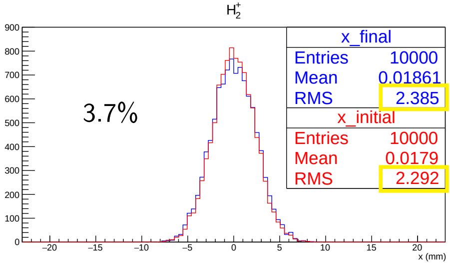
H_2^+
2.0%
x_final
Entries 10000
Mean 0.1161
RMS 3.266
x_initial
Entries 10000
Mean 0.1123
RMS 3.171
x (mm)

Results: nominal conditions

Nominal ESS beam parameters and IPM setting:

- σ_x = 2mm - 3 mm
- σ_y = 2mm - 3 mm
- σ_z = 2mm
- I = 62.5 mA
- $\overline{E}$ = 30 kV/m



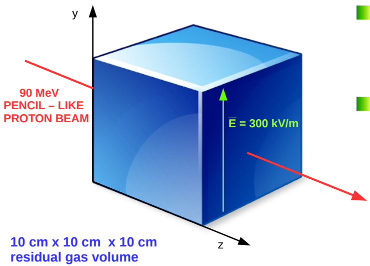


Assumption review: speed

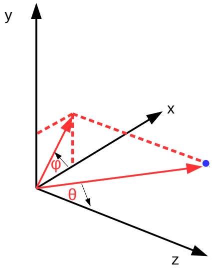
SIMULATION STEPS (Slide 9):

- ...
- in a first moment it is assumed that at creation time the electron (or ion) is **at rest**
- ....

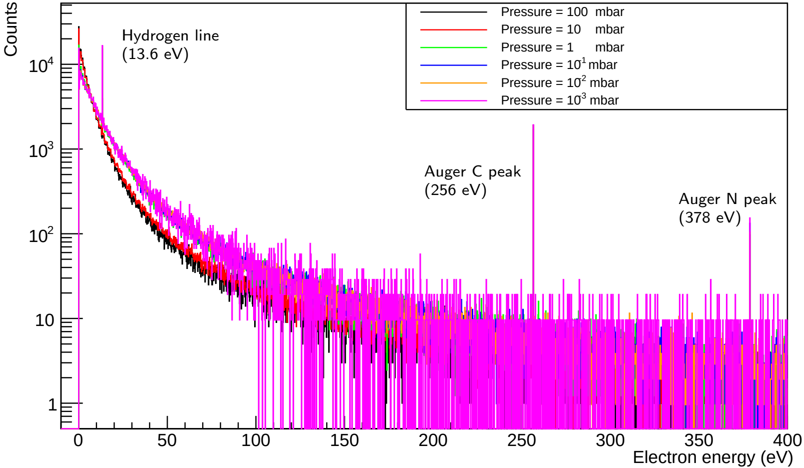
Check assumption validity with Garfield++ (toolkit for simulations of particle detectors with gas and semi-conductors as sensitive medium)



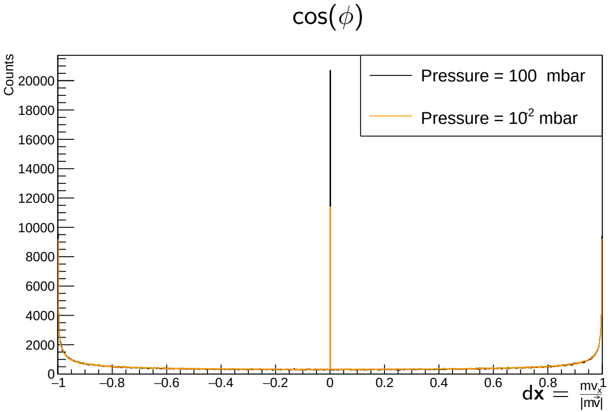
- Different gas densities tested to gain time & statistics
- As for primaries, only electron info can be retrieved



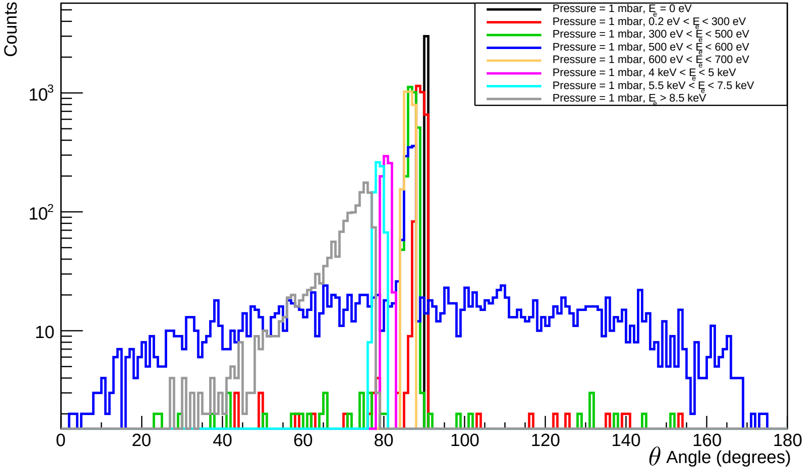
Assumption review: speed



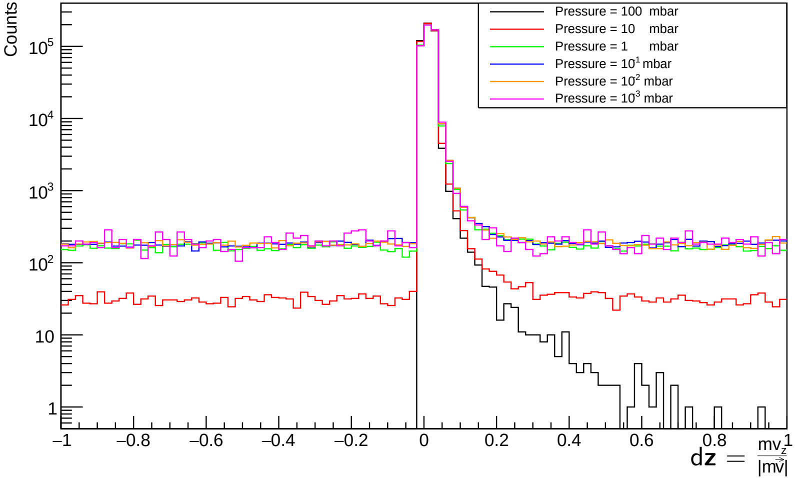
- In GARFIELD++ the ϕ (azimuthal) angle is uniformly sampled in $[0,2\pi)$ $\Rightarrow$ same distribution for $\cos(\phi)$ & $\sin(\phi)$.
- At higher gas pressures more electrons are emitted with lower speed



Assumption review: angular distribution



Assumption review: angular distribution



Assumption review: simulations

✓ GARFIELD++ provides different momenta distribution of the primary electrons for different incident proton beam energies and electric fields ($\mathbf{v}_e$, θ_e, ϕ_e).

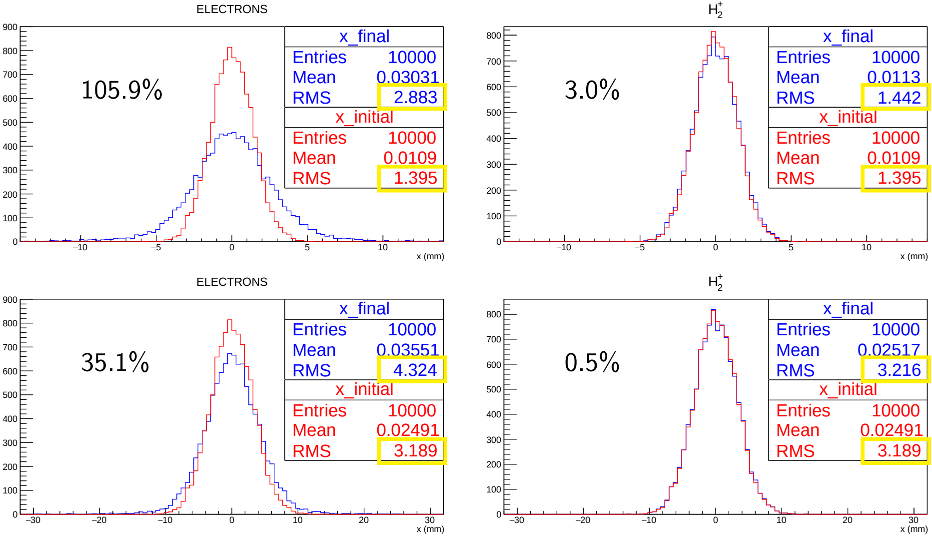
ELECTRONS:

- $E_p = 90$ MeV
- $\overline{E} = 300$ kV/m
- $x_{i_{el}} = f(\sigma_{x_{i_{el}}}), y_{i_{el}} = f(\sigma_{y_{i_{el}}})$
- $z_{i_{el}}$ uniformly $\in$ [-5 cm, 5 cm]
- $\sigma_{x_{i_{el}}} = \sigma_{y_{i_{el}}} =$ 0.5 mm, 1.4 mm, 3.2 mm, 4.1 mm, 5.0 mm, 10.0 mm
- $\sigma_{z_{i_{el}}} =$ 0.75 mm, 2.0 mm, 10.0 mm
- $\mathbf{v}_{i_{el}}$ from GARFIELD++
- (θ, ϕ) from GARFIELD++

IONIZED MOLECULES:

- $E_p = 90$ MeV
- $\overline{E} = 300$ kV/m
- $x_{i_{ion}} = f(\sigma_{x_{i_{ion}}}), y_{i_{ion}} = f(\sigma_{y_{i_{ion}}})$
- $z_{i_{ion}}$ uniformly $\in$ [-5 cm, 5 cm]
- $\sigma_{x_{i_{ion}}} = \sigma_{y_{i_{ion}}} =$ 0.5 mm, 1.4 mm, 3.2 mm, 4.1 mm, 5.0 mm, 10.0 mm
- $\sigma_{z_{i_{ion}}} =$ 0.75 mm, 2.0 mm, 10.0 mm
- $\mathbf{v}_{i_{ion}}$ assuming $\mathbf{v}_{i_{electron}} \cdot m_{electron} = \mathbf{v}_{i_{ion}} \cdot m_{ion}$
- (θ, ϕ) from GARFIELD++

Assumption review: $\sigma_x = \sigma_y$, $\sigma_z = 2$ mm



First conclusions

The results from the IPM simulation code with the above initial conditions show:

- the space charge effect is lower for higher proton energies
- ionized molecules are less affected by space charge effects than electrons
- the initial momentum with which particles are created can be neglected for ionized molecules, but not for electrons
- if electrons are detected and the beam sizes are $\sigma_{x_i} = \sigma_{x_i}$ 3.2 mm and $\sigma_{z_i} = 2.0$ mm an error of about 35% is obtained (requirements not met)
- if electrons are detected and the beam size is smaller than 2 mm, the errror on the beam width is higher than 35% (requirements not met)
- if ionized molecules are detected, in nominal conditions, not more than 4% error on the beam width is obtained
- as for ionized molecules here above H_2^+ was meant. If the totality of the ionized molecules is considered with the appropriate weight, the previously given error improve by few %.