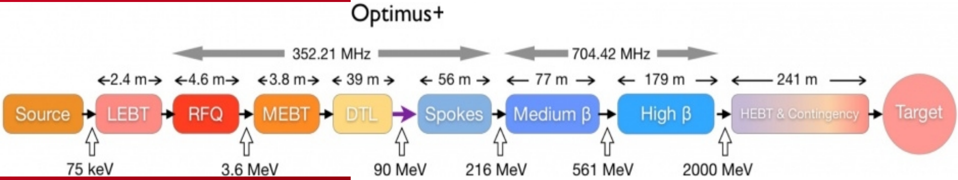
DE LA RECHERCHE À L'INDUSTRIE

Space charge studies for the ESS Ionization Profile Monitor



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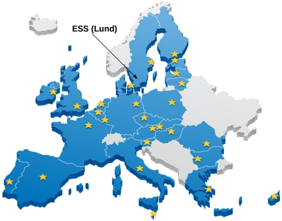
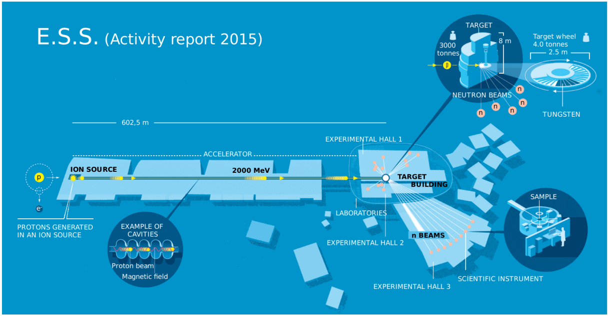
European Spallation Source

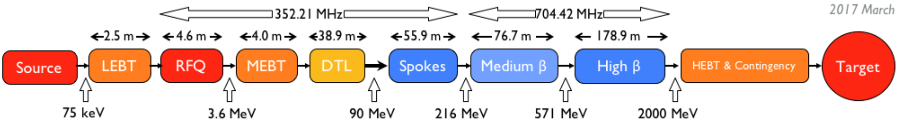




Facility	Protons/s	Target
n_TOF (CERN, Europe)	$2\cdot 10^{12}$	Pb
JSNS (JPARC, Japan)	$2\cdot 10^{14}$	W
LANSCE (Los Alamos, USA	$3.2\cdot 10^{14}$	W
SNS (Oak Ridge, USA)	$2.5\cdot 10^{17}$	Hg
ESS (Lund, Europe)	$3.9\cdot 10^{17}$	W

- Life science (Macromelecules, for instance proteins, study)
- Material science
- Imaging (archeology)
- Fundamental particle physics

NPM/IPM



Transverse profile measurement to support the tuning of high power beam.

REQUIREMENTS for the BEAM TRANSVERSE PROFILER:

- stand high proton beam intensity ($I_{peak} = 65$ mA, $Power_{peak} = 125$ MW)
- have minimum impact on proton beam (avoid proton scattering and proton induced nuclear reactions)
- provide enough statistics (capability of measuring the profile per pulse at nominal beam & vaccum conditions)

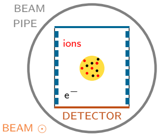
NPM/IPM

- no cooling forseen
- 1 detector in Spokes, 3 in Medium β, 1 in High β
- total measurement error in the RMS extension of the beam of less than $\pm$ 10% (**L4 requirement**)

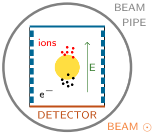
IPM : Ionization Profile Monitor

PRINCIPLE OF OPERATION

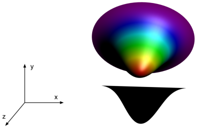
- proton beam ionizes residual gas



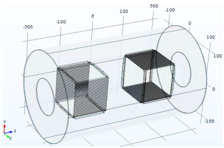
- $\vec{E}$ separates e$^-$/ions



- charge collection on read-out

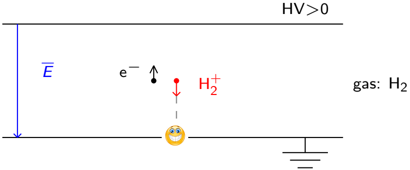


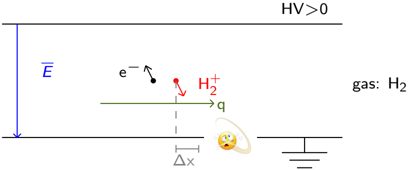
2 cages for 2D beam profile measurement



Space charge effect

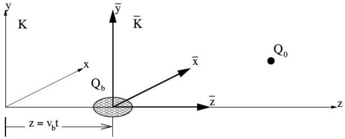
REMINDER:





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.

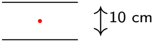
Correction code

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 $d\overline{x}$ of the electron (or ion) is calculated by solving the motion equation (adaptive Runge Kutta Fehlberg method)

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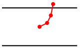


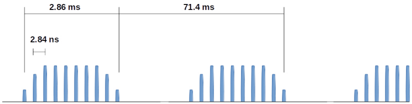
- time ... displacement ... time ... displacement ...
- when the y position of the electron (or ion) y$\geq y_{collection\ plate}$, the simulation stops
- at every *dt* passed, the following variable values were saved: t, x, y, z, v_x, v_y, v_z, a_x, a_y, a_z, fields info (lab and comoving frame)
- t 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

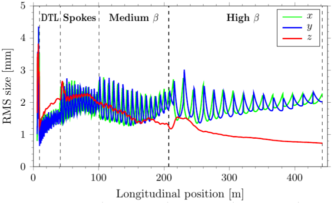


IPM GAS PARAMETERS:

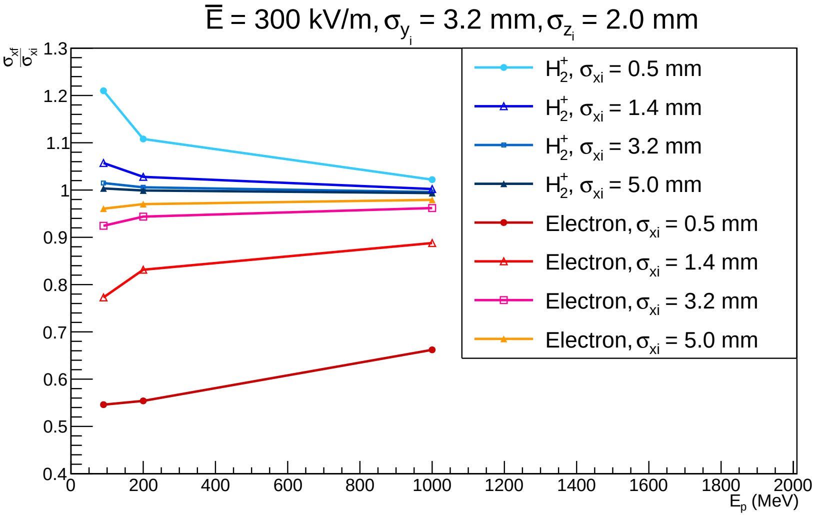
- Composition : H_2 (79%), CO (10%), CO_2 (10%), N_2 (1%) [source: ESS vacuum group]
- Pressure: 10^{-9} mbar

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, 300 kV/m, 600 kV/m, 1000 kV/m**

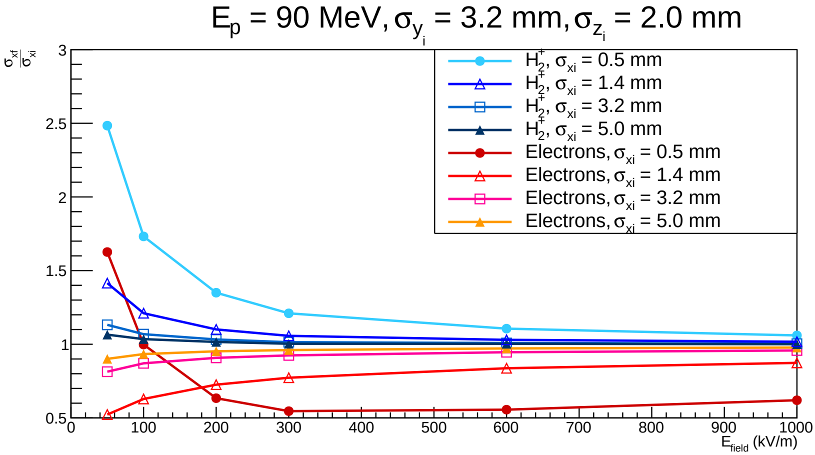


Results: $f(E_p)$

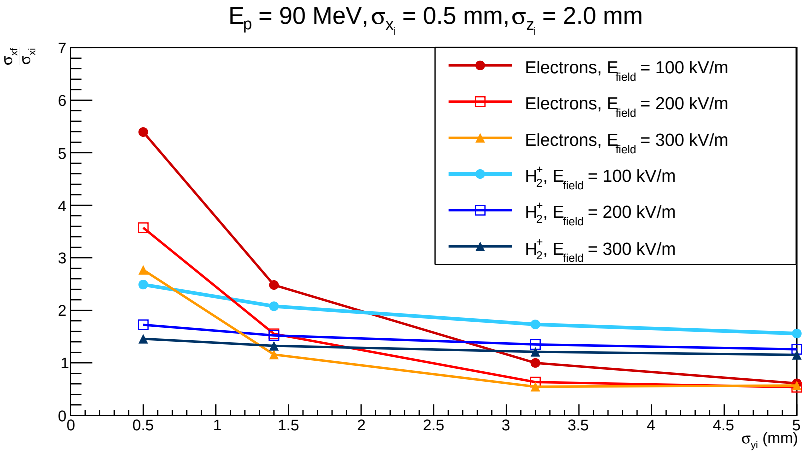


$\bar{E}$ = 300 kV/m, σ_{y_i} = 3.2 mm, σ_{z_i} = 2.0 mm
$\frac{\sigma_{xf}}{\sigma_{xi}}$
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
200
400
600
800
1000
1200
1400
1600
1800
2000
E_p (MeV)
H_2^+, σ_{xi} = 0.5 mm
H_2^+, σ_{xi} = 1.4 mm
H_2^+, σ_{xi} = 3.2 mm
H_2^+, σ_{xi} = 5.0 mm
Electron, σ_{xi} = 0.5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

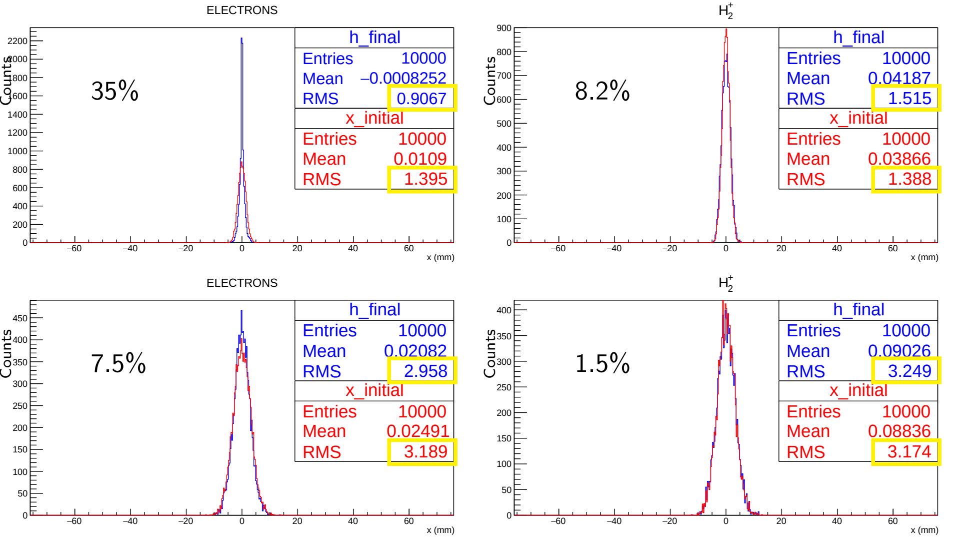
Results: $f(\overline{E})$



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



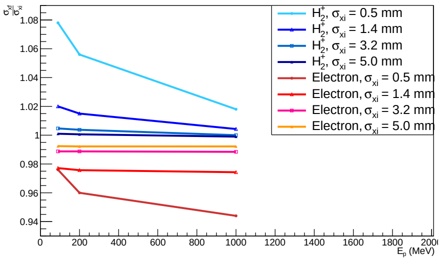
Results: $\sigma_{x_i} = \sigma_{y_i}$ & $\sigma_{z_i} = 2$ mm, $\overline{E} = 300$ kV/m, $E_p = 90$ MeV

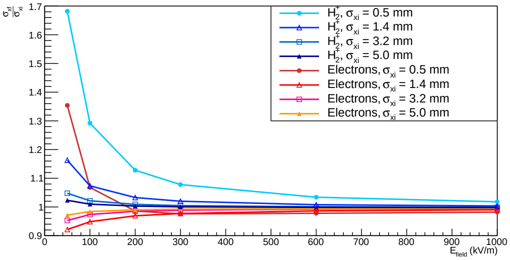


1^{st} assumption review: sampling along z

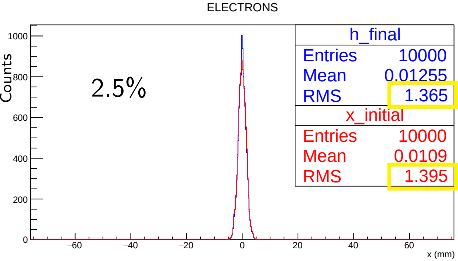
SIMULATION STEPS (Slide 9):

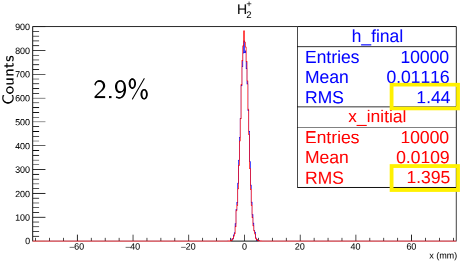
- ...
- **a single electron (or ion)** is created in the center of the IPM:
  x= Gaus(0,σ_x)
  y= Gaus(0,σ_y)
  z = Unif(-2.5 mm, 2.5 mm) $\rightarrow$ z = Unif(-5 cm, 5 cm)
- ....

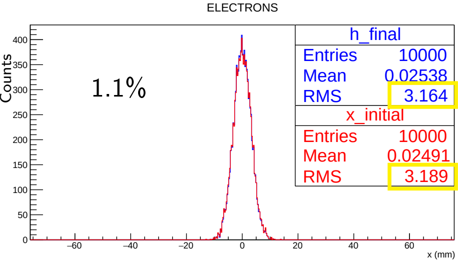


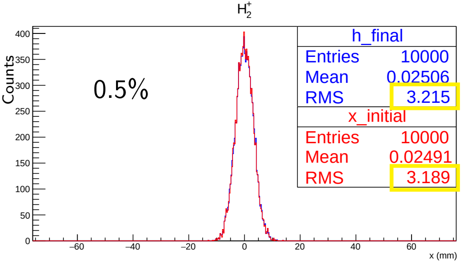


Results: $\sigma_{x_i} = \sigma_{y_i}$ & $\sigma_{z_i} = 2$ mm, $\overline{E} = 300$ kV/m, $E_p = 90$ MeV







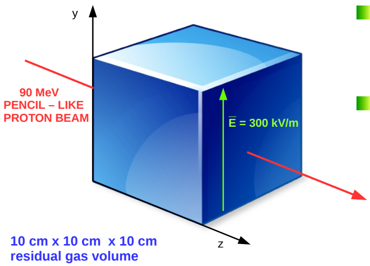


2^{nd} assumption review: speed

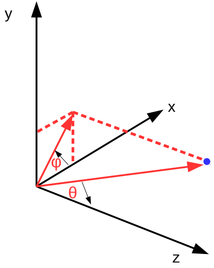
SIMULATION STEPS (Slide 9):

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

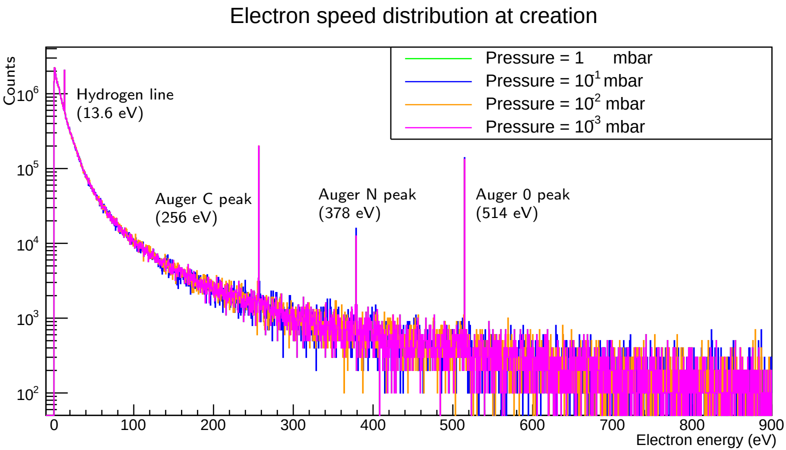
Check assumption validity with Garfield++ (toolkit for simulations of particle detectors with gas and semi-conductors as sensitive medium)



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



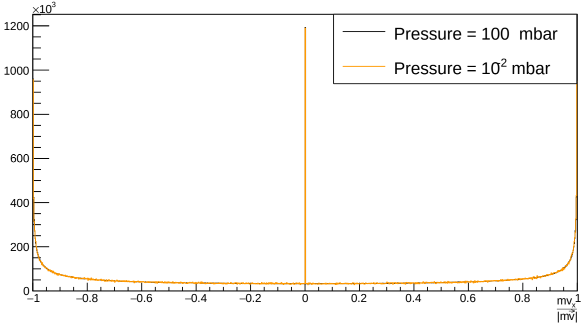
2^{nd} assumption review: speed



Assumption review: angular distribution

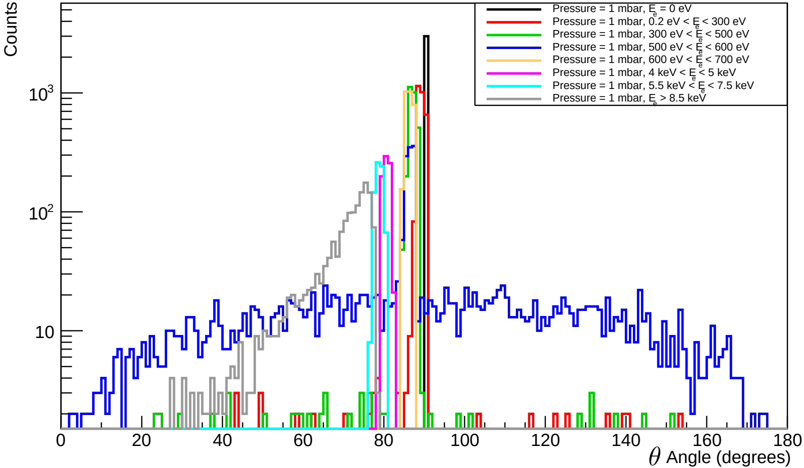
- In GARFIELD++ the ϕ (azimuthal) angle is uniformly sampled in $[0,2\pi)$ $\Rightarrow$ same distribution for $\cos(\phi)$ & $\sin(\phi)$.
- At higher gas pressures more electrons are emitted with lower speed

$\cos(\phi)$

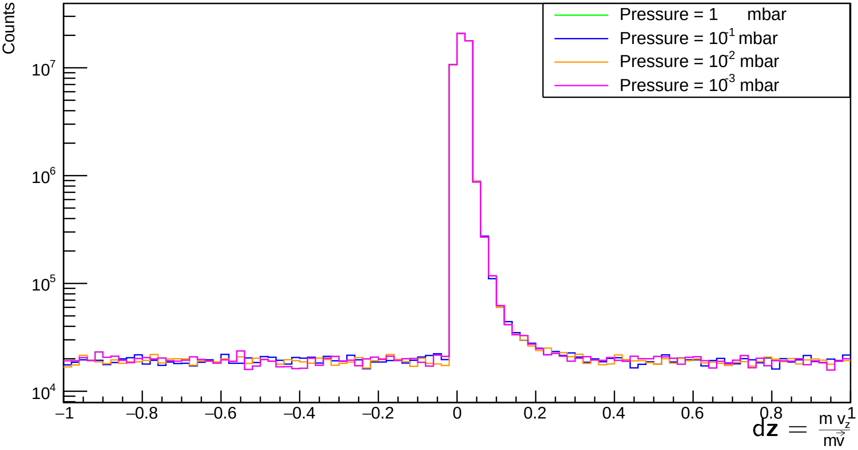


dx =

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).

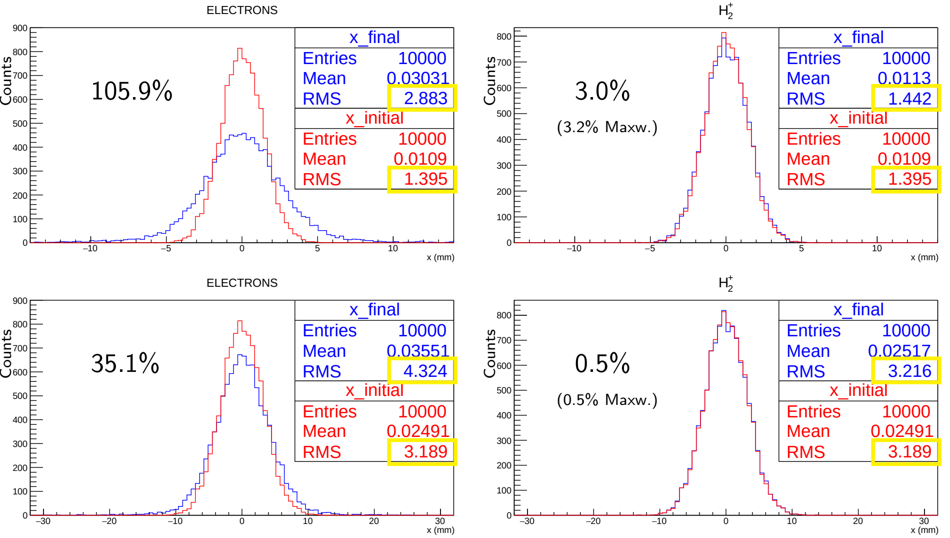
ELECTRONS:

- $E_p = 90$ 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
  a) $\mathbf{v}_{i_{electron}} \cdot m_{electron} = \mathbf{v}_{i_{ion}} \cdot m_{ion}$
  b)Maxwellian energy distribution
- (θ, ϕ) from GARFIELD++

Results: $\sigma_{x_i} = \sigma_{y_i}$ & $\sigma_{z_i} = 2$ mm, $\overline{E} = 300$ kV/m, $E_p = 90$ MeV



Conclusions (FILTER 10% L4 constraint)

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

- the space charge effect is lower for higher proton energies
- the space charge effect is higher for lower beam sizes (smaller than nominal conditions)
- 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 the L4 requirements are not met
- if ionized molecules are detected, the L4 requirements are not met
- 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 %.

Thanks

BACKUP SLIDES

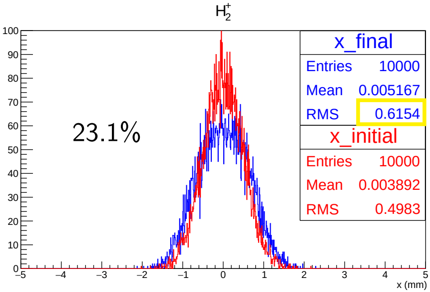
Results: heavier ion comparison

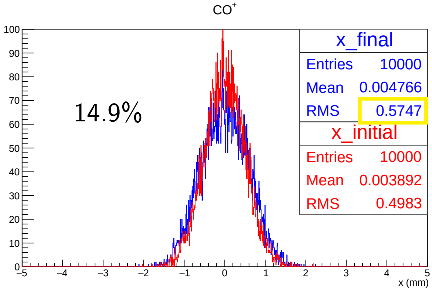
- Initial conditions:

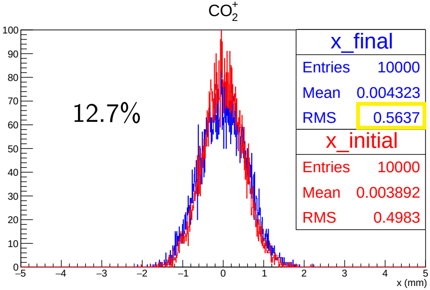
  $\overline{E} = 600$ kV/m
  $E_p = 90$ MeV
  $\sigma_{x_i} = \sigma_{y_i} = 0.5$ mm
  $\sigma_{z_i} = 0.75$ mm
  $z_i \in$ [-2.5 mm, 2.5 mm]

- Remarks:

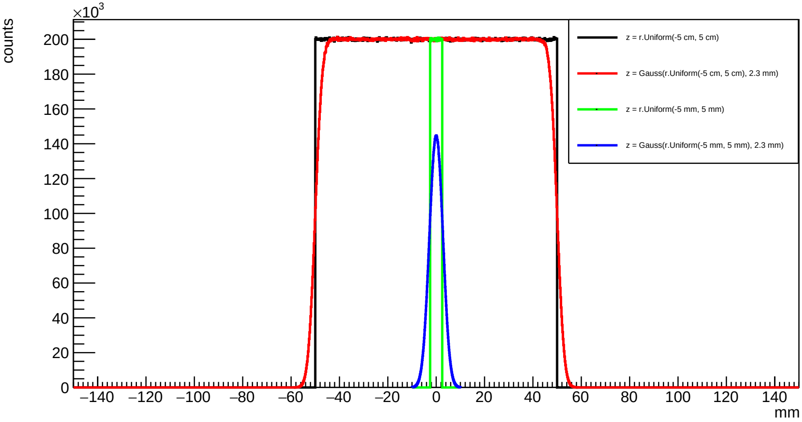
  $m_{N_2} \approx m_{CO}$
  heavier particle = smaller Δx







Choice of the sampling along the z axis



Assumption review: simulations