Simulations and Measurements in High Intensity LEBT with Space Charge Compensation

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Outline

1 **Space charge compensation**

2 **Beam Dynamics Simulation Codes**

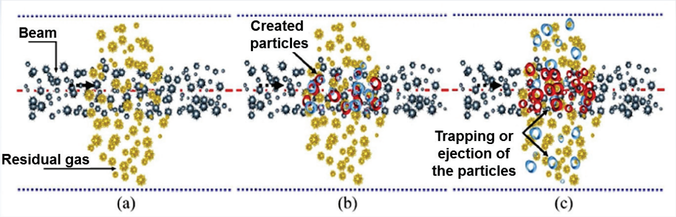
3 **IFMIF LEBT simulation with space charge compensation**

IFMIF injector preliminary experimental results

5 **Conclusion and perspectives**

Outline

The space charge compensation (SCC) principle



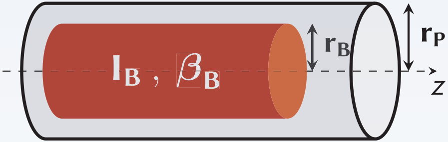
Example

We consider a proton beam propagating through a H_2 residual gas. It induces a production of pairs e^-/H_2^+ by ionization.

$$p + H_2 \rightarrow p + e^- + H_2^+$$

We assume that $n_{gas}/n_{beam} \ll 1$, with n_{gas} and n_{beam} the gas and beam density.

Space charge compensation degree



The potential well (i.e. potential on the beam axis, $r = 0$) created by a uniform beam, without space charge compensation, is given by:

$$\boxed{\phi_0 = \frac{I_B}{4\pi\varepsilon_0\beta_B c}\left(1 + 2\ln\left(\frac{r_P}{r_B}\right)\right)} \qquad (1)$$

where I_B and β_B are respectively the intensity and the reduced speed of the beam.

Space charge compensation degree

If ϕ_c and ϕ_0 are respectively the potential wells (i.e. potential on the beam axis) of the compensated and uncompensated beam, the **space charge compensation degree** is then given by:

$$\boxed{\eta = 1 - \frac{\phi_c}{\phi_0}} \tag{2}$$

Space charge compensation degree

If ϕ_c and ϕ_0 are respectively the potential wells (i.e. potential on the beam axis) of the compensated and uncompensated beam, the **space charge compensation degree** is then given by:

$$\boxed{\eta = 1 - \frac{\phi_c}{\phi_0}} \tag{2}$$

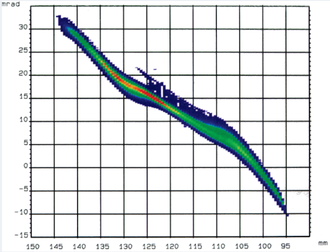
The space charge compensation degree for the 75 keV – 130 mA proton beam of the LEDA has been measured [Ferdinand et al., 1997]:

$$\boxed{95\% < \eta < 99\%}$$

Ferdinand, R., Sherman, J., Stevens Jr., R. R., and Zaugg, T. (1997).
Space-charge neutralization measurement of a 75-kev, 130-ma hydrogen-ion beam.
In *Proceedings of PAC'97*, Vancouver, Canada.

Space charge compensation – Measurements

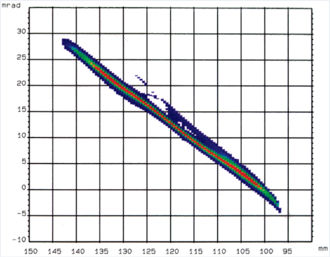
SILHI beam of 75 mA @ 95 keV. [Gobin et al., 1999]



Without ^{84}Kr injection

Pressure: 2.4×10^{-5} hPa.

ϵ_{RMS} = 0.335 π mm.mrad



With ^{84}Kr injection

Pressure: 4.6×10^{-5} hPa.

ϵ_{RMS} = 0.116 π mm.mrad

Gobin, R., Beauvais, P., Ferdinand, R., Leroy, P., Celona, L., Ciavola, G., and Gammino, S. (1999).
Improvement of beam emittance of the CEA high intensity proton source SILHI.
Review of Scientific Instruments, 70(6):2652–2654.

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Space charge compensation

Beam Dynamics Simulation Codes

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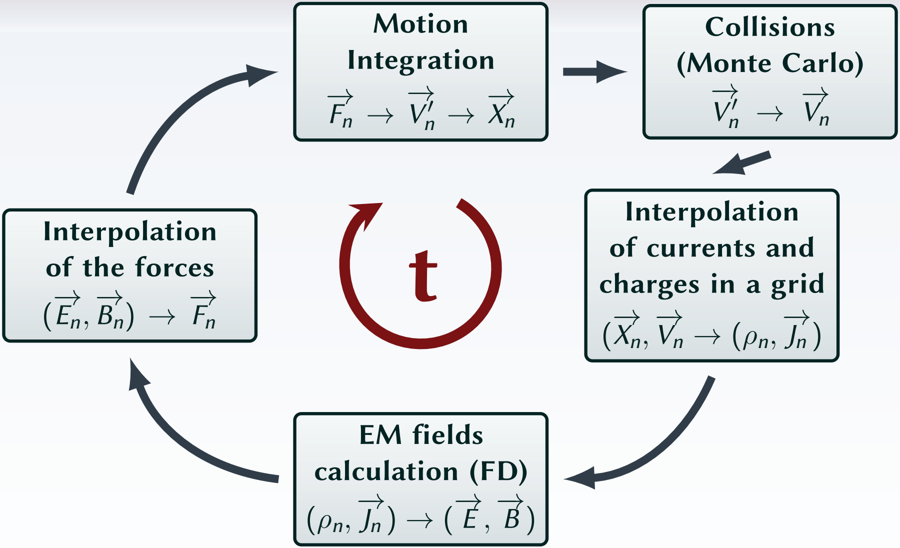
Transport with space charge compensation

- Tracking particle codes (Tracks, Parmilla, Trace3D, TraceWin ...) are used with a **constant space charge compensation degree** along the beam line.
- For more realistic beam transport simulations of high intensity ion beams at low energy, it is necessary to take into account **the space charge compensation of the beam on the residual gas**.
- For that, it is necessary to use a **self-consistent** code that simulate the beam interactions with the gas (ionization, neutralization, scattering) and the beam line elements (secondary emission). The dynamics of main beam is calculated **as well as the dynamics of the secondary particles**. Example of such codes: WARP [Grote et al., 2005]or SOLMAXP (developed by R. Duperrier at CEA-Saclay).

Grote, D. P., Friedman, A., Vay, J.-L., and Haber, I. (2005).
The warp code: Modeling high intensity ion beams.
AIP Conference Proceedings, 749(1):55–58.

SOLMAXP: basic algorithm



SOLMAXP, a PIC code for SCC simulations

SOLMAXP inputs

- Ion source output distributions (ex: H^+, H_2^+, H_3^+).
- Beam line external fields maps (solenoids, source extraction, RFQ cone injection trap...).
- Pressure and gas species in the beam line.

SOLMAXP outputs

- Particle distributions in the beam line (gas, electron, ions).
- Space charge potential map $\Rightarrow$ compute the space charge electric field map.

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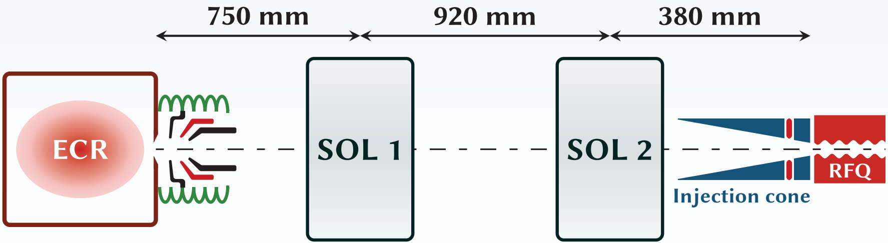
The IFMIF injector

Main parameters

- D^+ beam.
- Energy : 100 keV.
- Intensity : 140 mA.
- Final emittance : $\leqslant 0.25\ \pi$ mm.mrad

IFMIF injector

- SILHI-like source.
- 4 electrodes extraction system.
- LEBT with 2 solenoids.
- Kr injection in the LEBT for space charge compensation.



Total length: 2.05 m

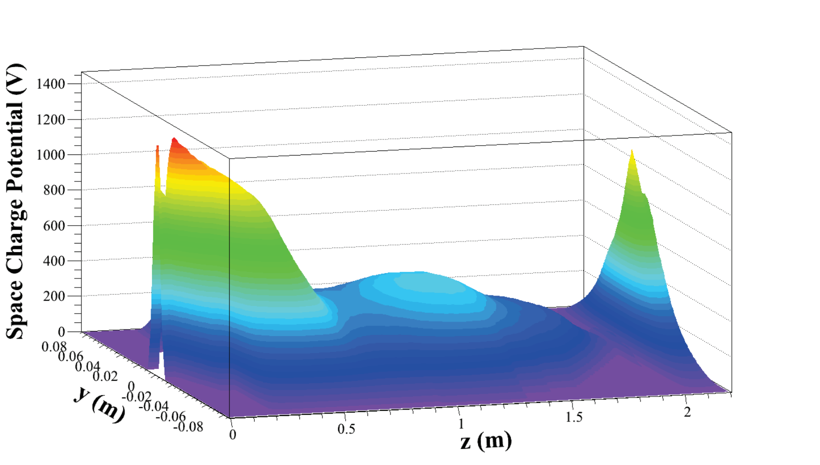
Simulation conditions

- D^+, D_2^+, D_3^+ are transported.
- Residual pressure of D_2 gas (10^{-5} hPa) coming from the source & Kr gas injection (4×10^{-5} hPa).
- Homogeneous pressure in the beam line.
- Ionisation of gas by incoming beams.

  $\Rightarrow\ D^+ + D_2 \to D^+ + e^- + D_2^+$
  $\Rightarrow\ D_2^+ + D_2 \to D_2^+ + e^- + D_2^+$
  $\Rightarrow\ D_3^+ + D_2 \to D_3^+ + e^- + D_2^+$
- Ionisation of gas by created electrons

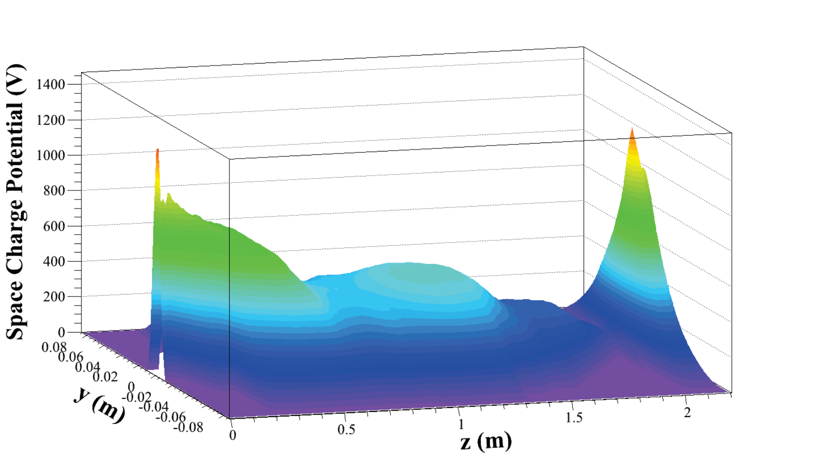
  $\Rightarrow\ e^- + D_2 \to 2e^- + D_2^+$
- No secondary electron created by ion impact on beam pipe.
- No beams beam scattering on gas.

Space charge potential evolution



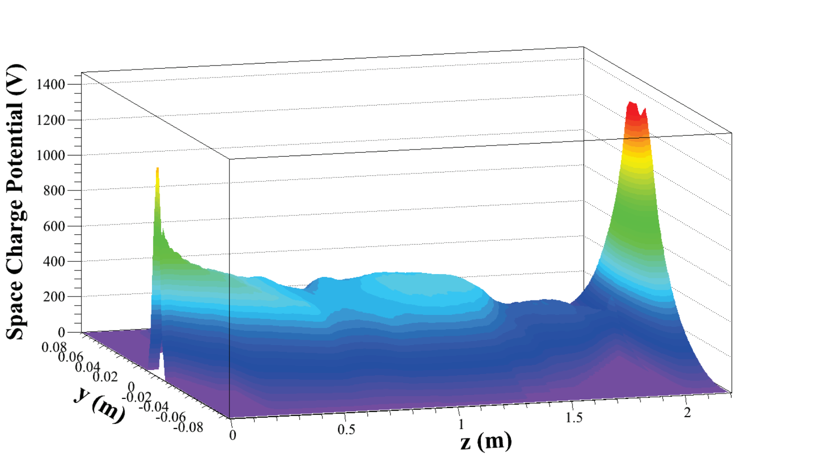
t = 2 μs

Space charge potential evolution



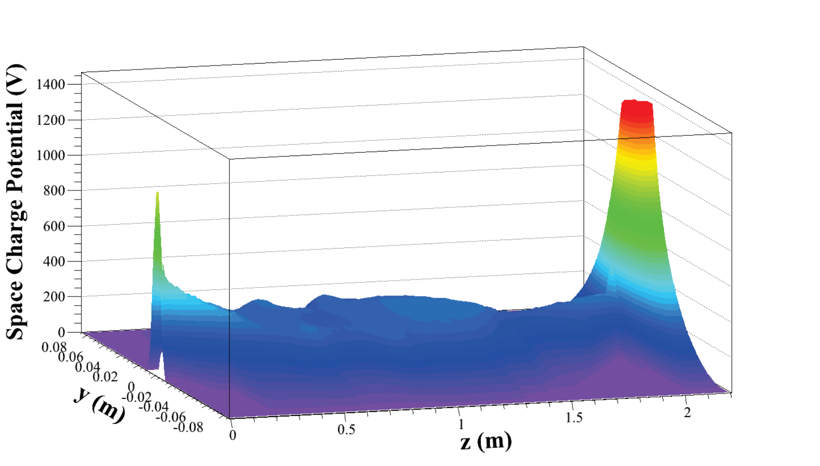
$\boxed{t = 4\ \mu s}$

Space charge potential evolution



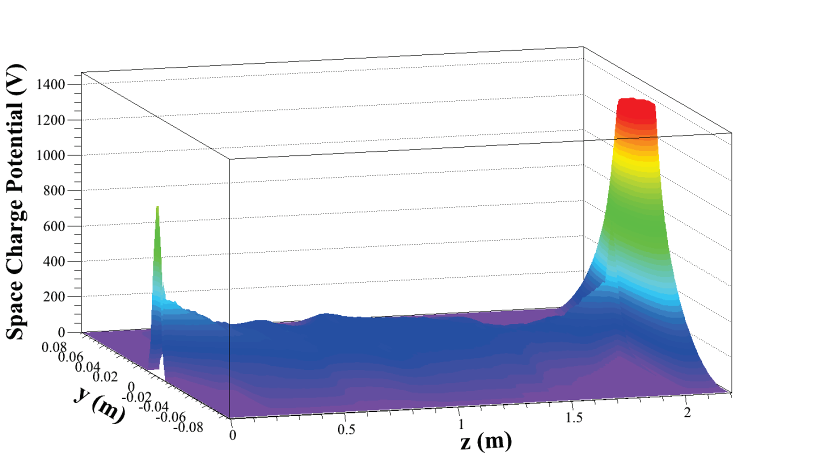
$\boxed{t = 6\ \mu s}$

Space charge potential evolution



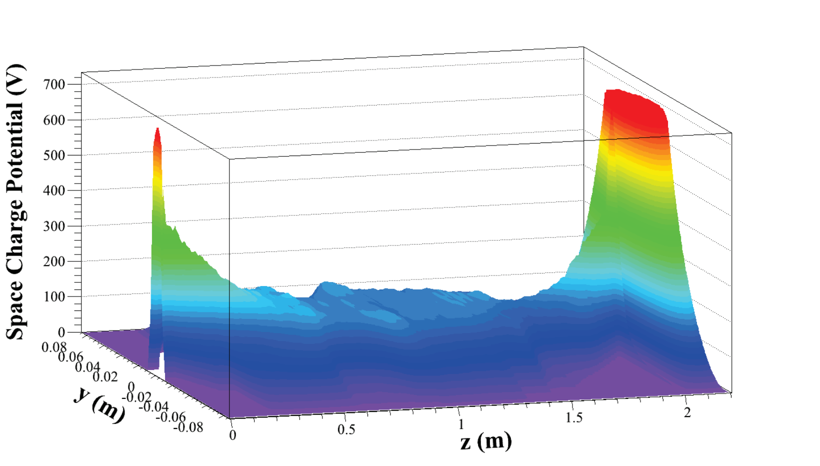
t = 8 μs

Space charge potential evolution



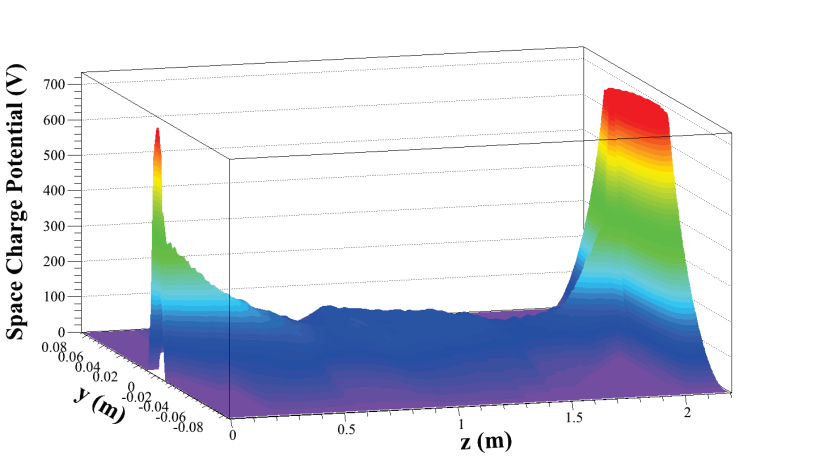
$t = 10\ \mu s$

Space charge potential evolution



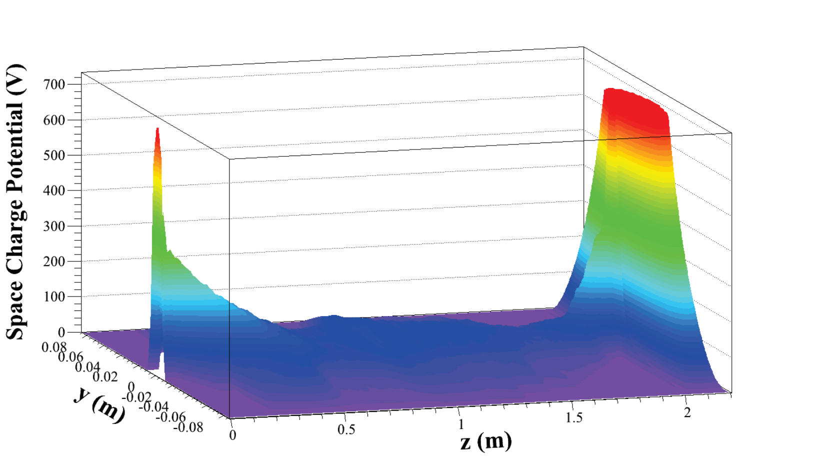
t = 10 μs – ! Cut at 700 V !

Space charge potential evolution



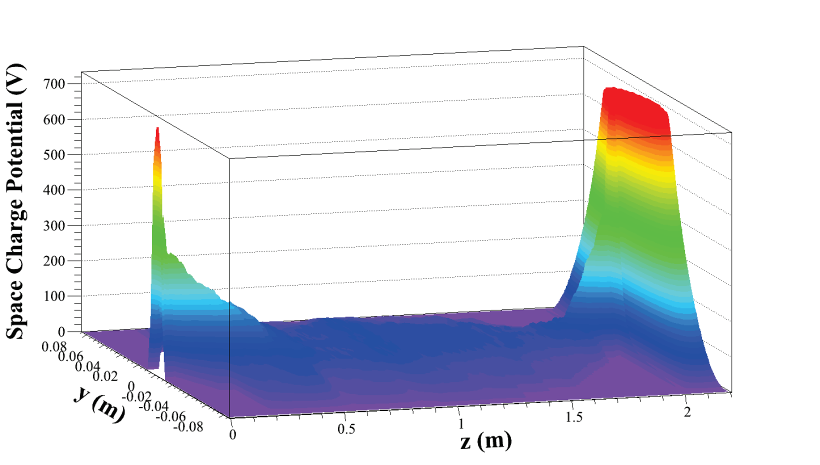
t = 12 μs

Space charge potential evolution



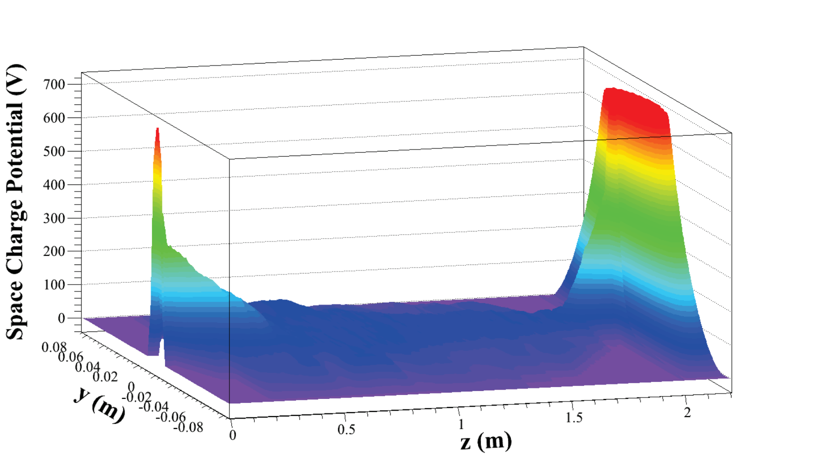
$t = 14\ \mu s$

Space charge potential evolution



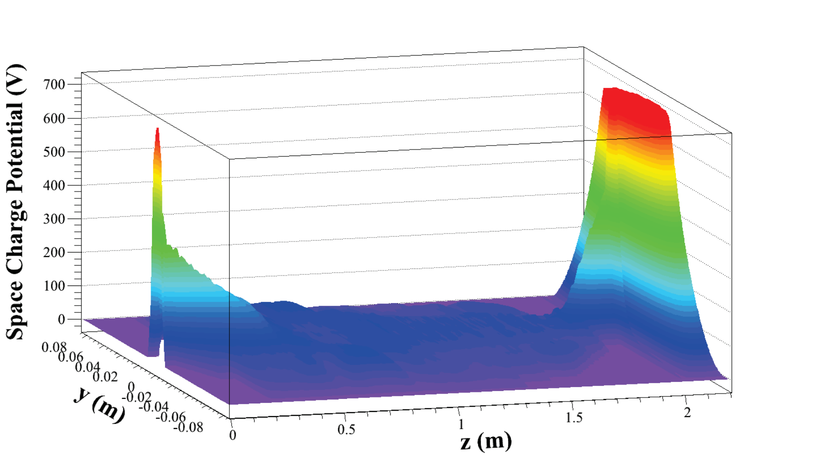
t = 16 μs

Space charge potential evolution



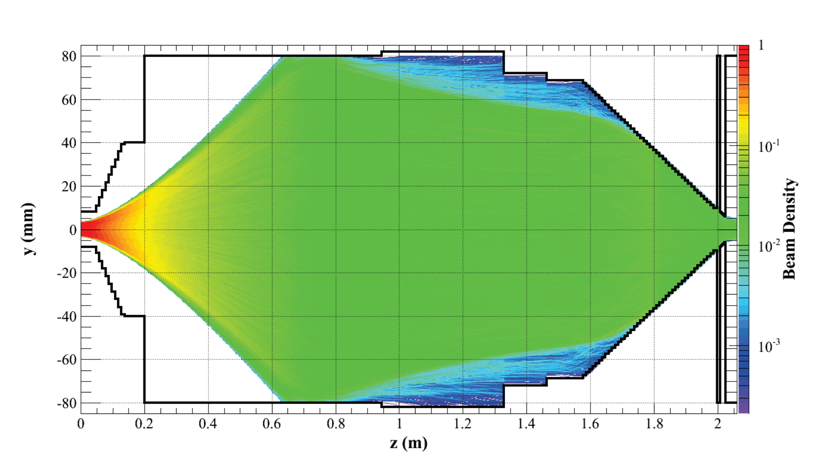
$\boxed{t = 18\ \mu s}$

Space charge potential evolution



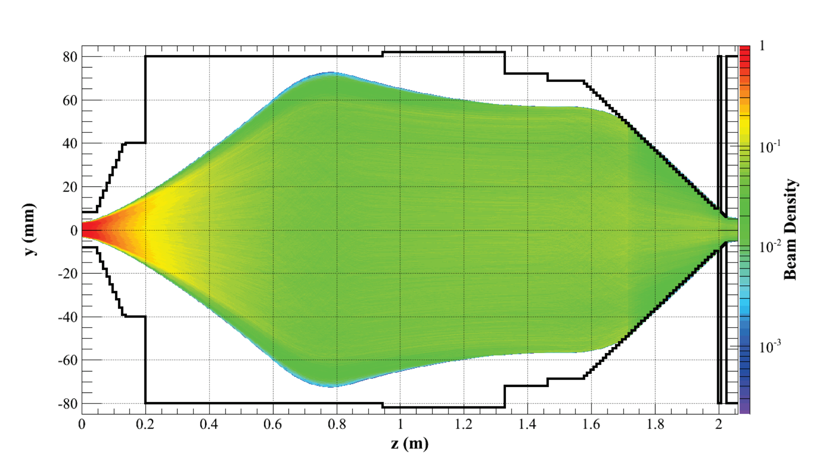
$\boxed{t = 20\ \mu s}$

Beam evolution



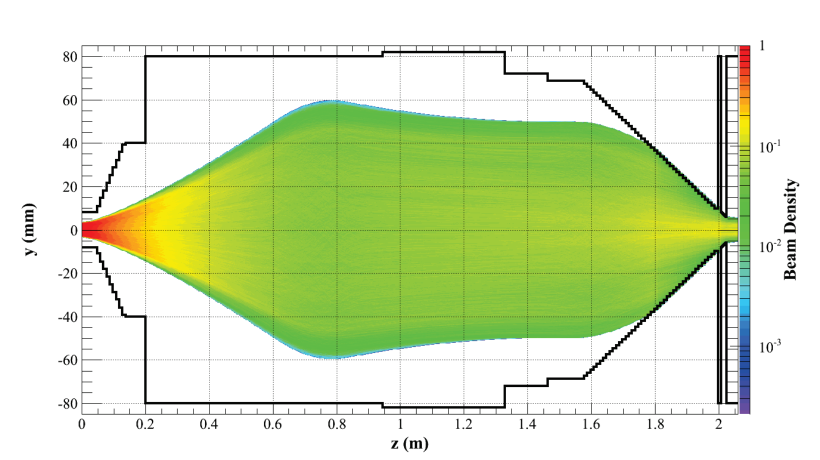
$\boxed{t = 2\ \mu s}$

Beam evolution



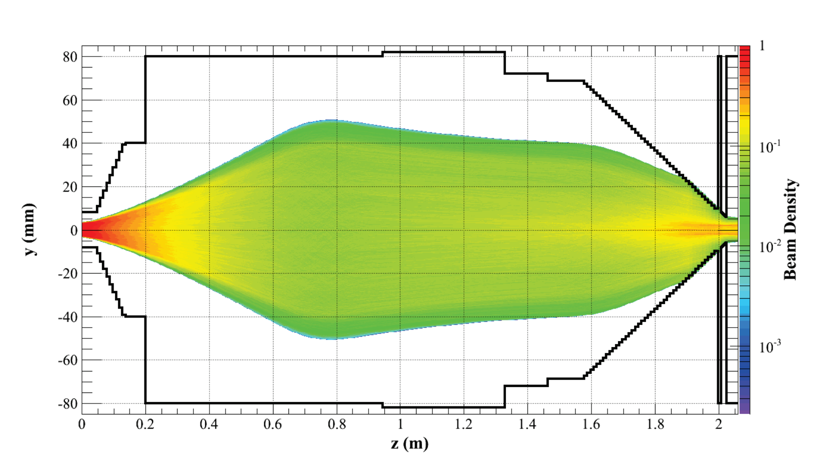
$\boxed{t = 4\ \mu s}$

Beam evolution



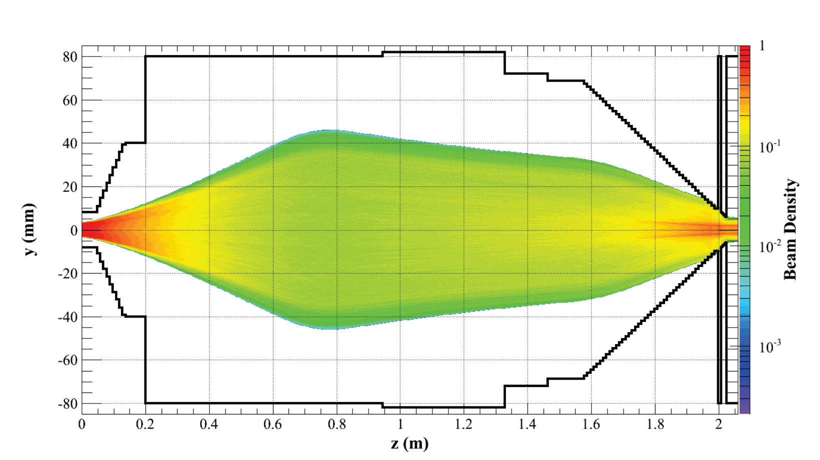
$\boxed{t = 6\ \mu s}$

Beam evolution



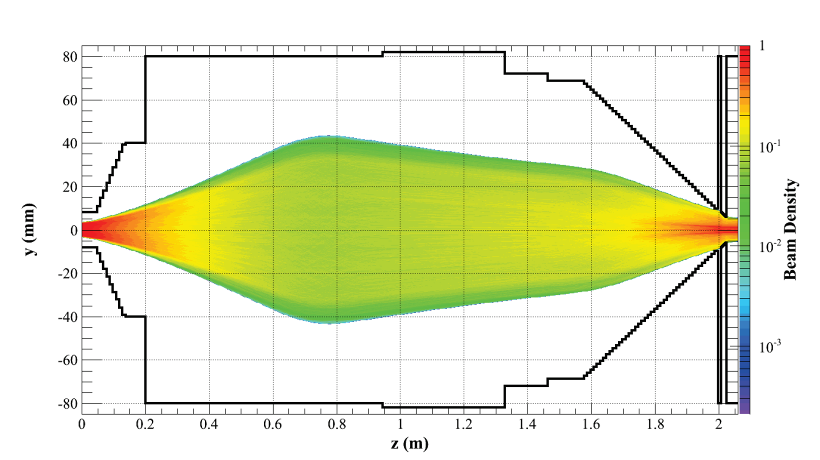
t = 8 μs

Beam evolution



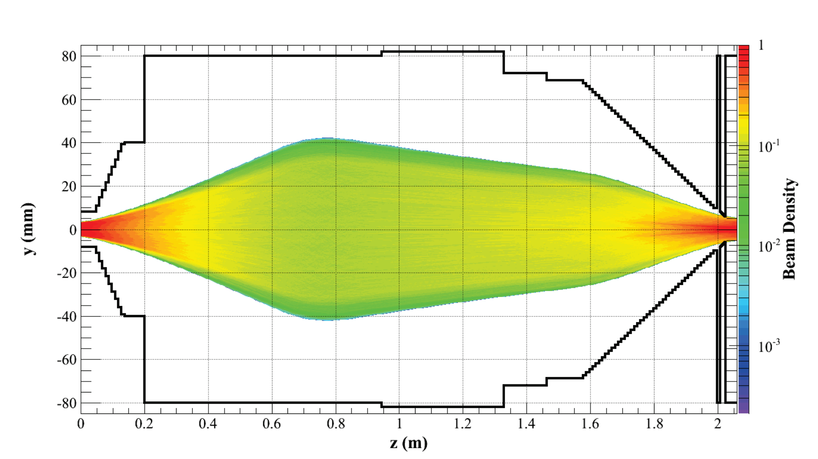
t = 10 μs

Beam evolution



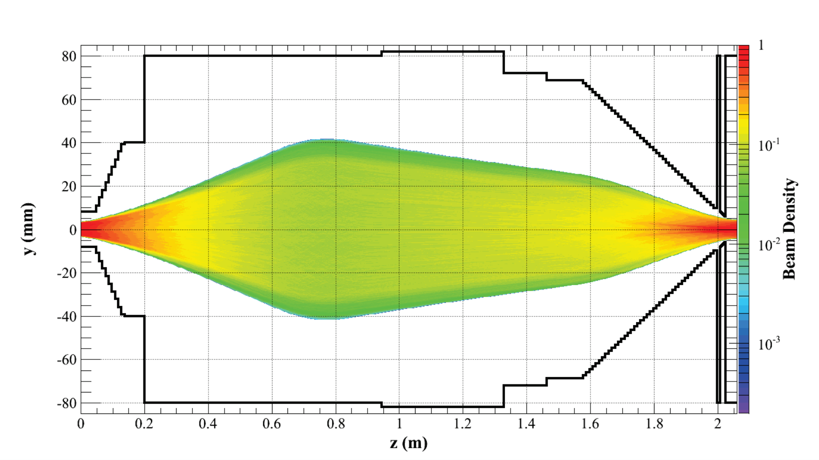
$t = 12\ \mu s$

Beam evolution



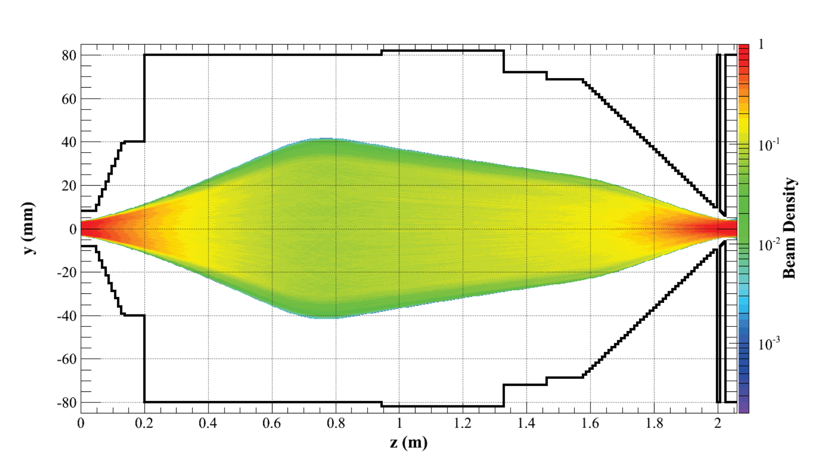
t = 14 μs

Beam evolution



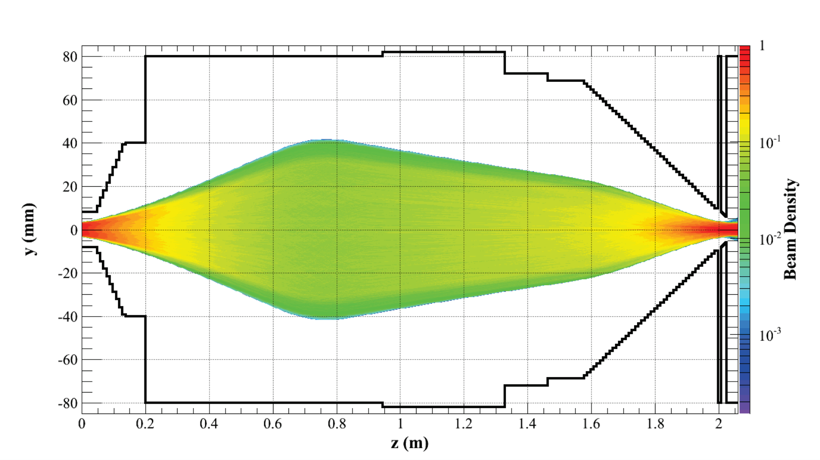
$t = 16\ \mu s$

Beam evolution



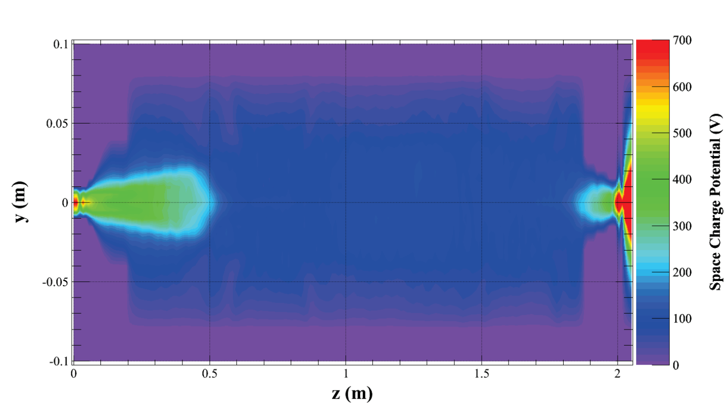
t = 18 μs

Beam evolution



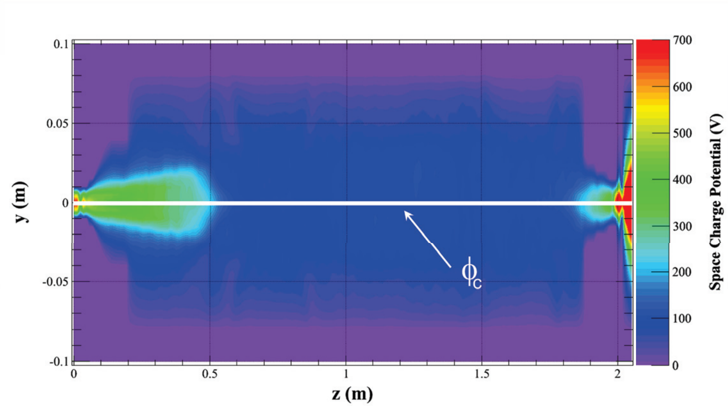
t = 20 μs

SCC degree



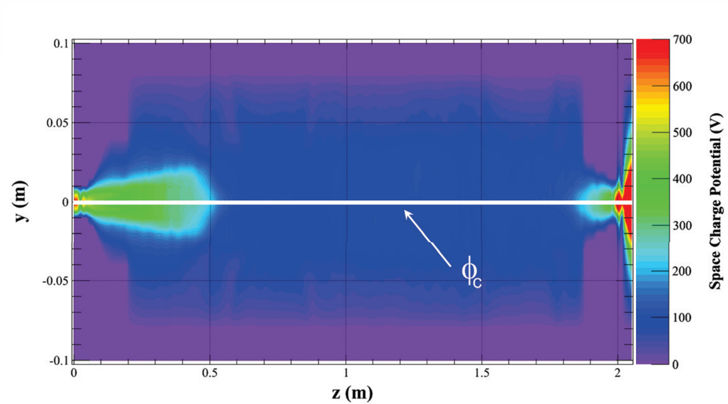
Two dimensions cut in the (z0y) plane of a space charge potential map

SCC degree



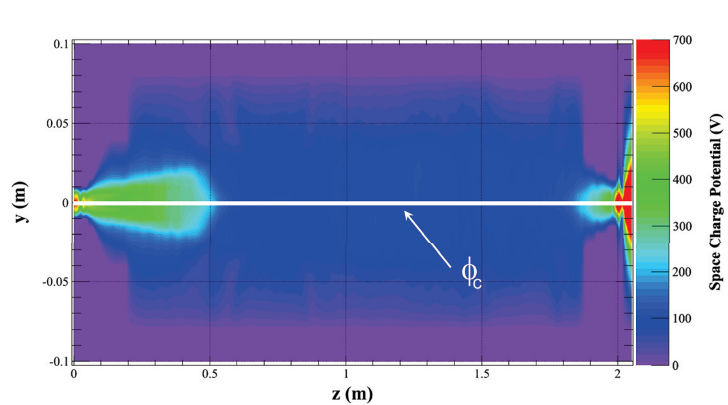
ϕ_c is the **potential on axis** of the **compensated** beam

SCC degree



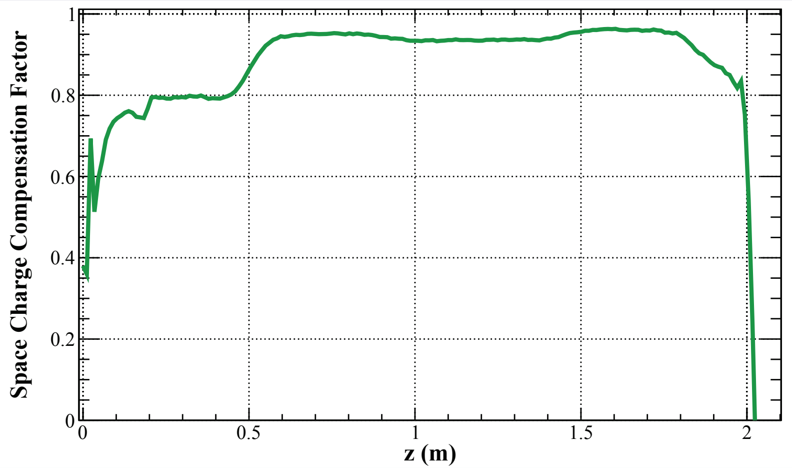
$\phi_0 = \frac{I_B}{4\pi\varepsilon_0\beta_B c}\left(1 + 2\ln\left(\frac{r_P}{r_B}\right)\right)$ is the is the **potential on axis** of the **uncompensated** beam

SCC degree



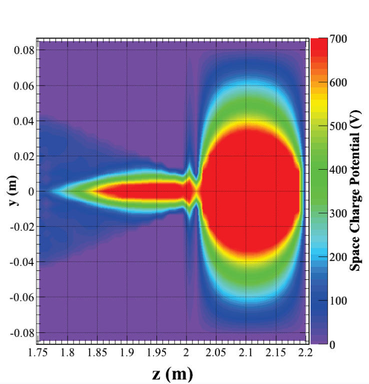
with $\eta = 1 - \frac{\phi_c}{\phi_0}$, we can compute the **space charge compensation degree** along the beam line.

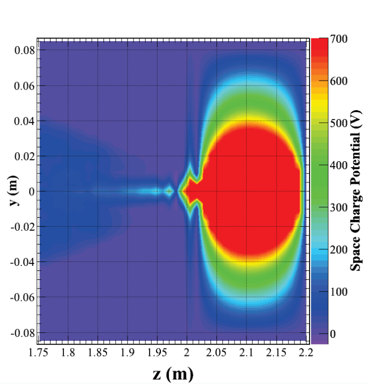
SCC degree



Space charge compensation degree in the IFMIF LEBT

Role of the e⁻ repeller

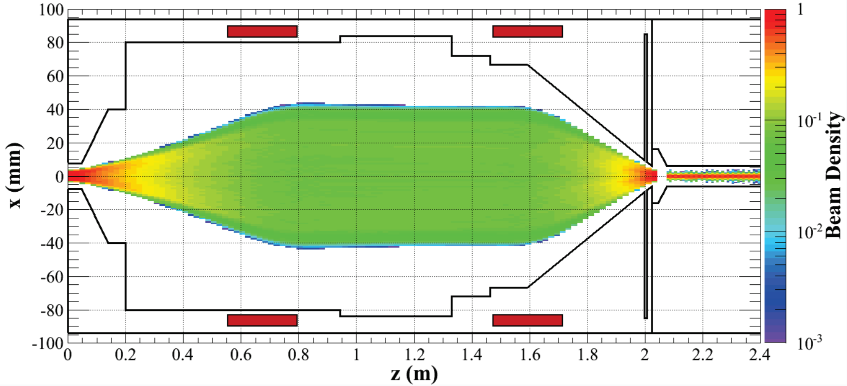




Without electron repeller

With electron repeller

Beam dynamics results



LEBT Output: ϵ_{RMS} = 0.16 π mm.mrad

IFMIF RFQ transmission : 96 %

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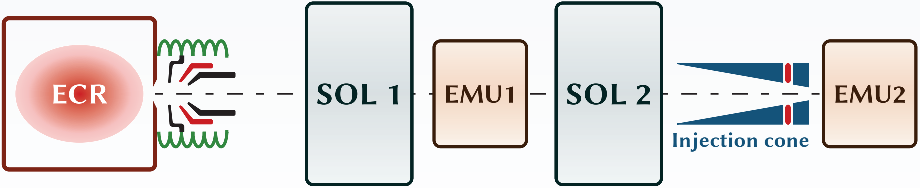
Experimental Conditions

IFMIF Injector Commissioning

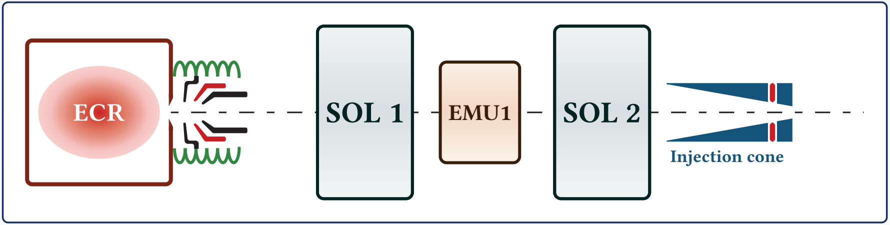
- Commissioning performed with H^+ beam to avoid activation.
- A 80 mA total beam at 50 keV is produced by the ECR source.

$$K = \frac{qI}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3} \quad (3)$$

- Emittance and beam proportion measurements.



Emittance measurement between the two solenoids



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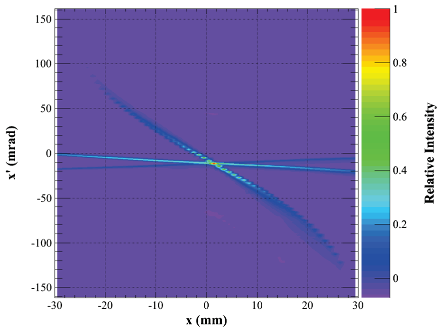
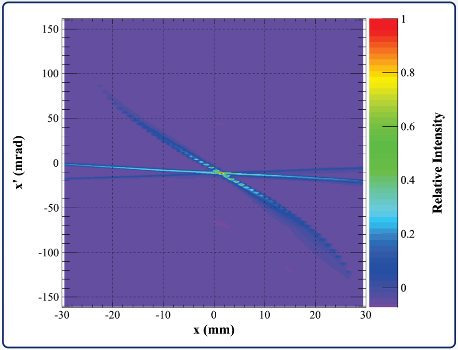
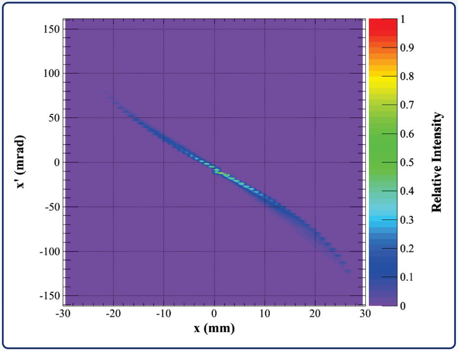


All the species from the source

Emittance measurement between the two solenoids

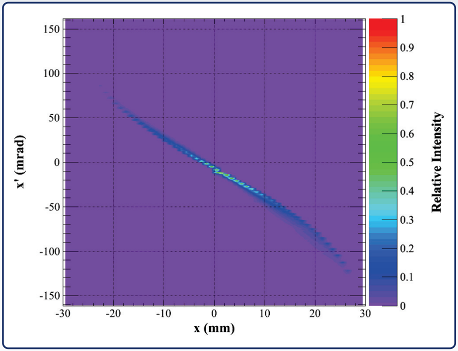




All the species from the source

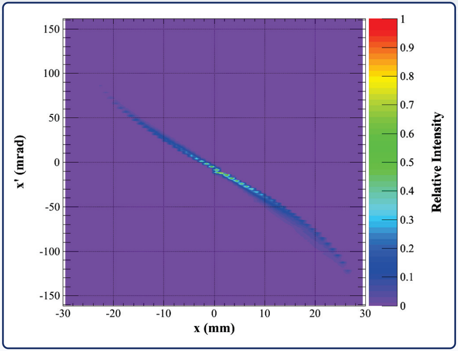
After numerical separation of H^+

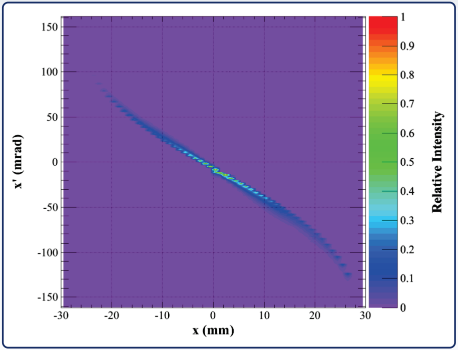
Kr injection in the LEBT



- Without Krypton
- $\epsilon_{RMS} = 0.50 \pm 0.10\ \pi.mm.mrad$

Kr injection in the LEBT

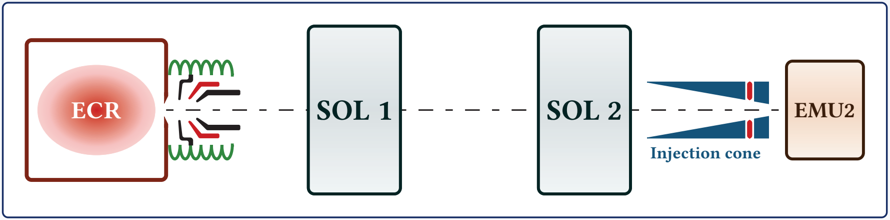




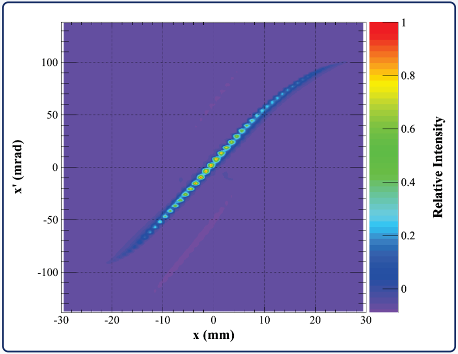
- Without Krypton
- $\epsilon_{RMS} = 0.50 \pm 0.10\ \pi.mm.mrad$

- Injection Krypton
- $\epsilon_{RMS} = 0.51 \pm 0.10\ \pi.mm.mrad$

Emittance measurement after the second solenoid



Emittance measurement after the second solenoid

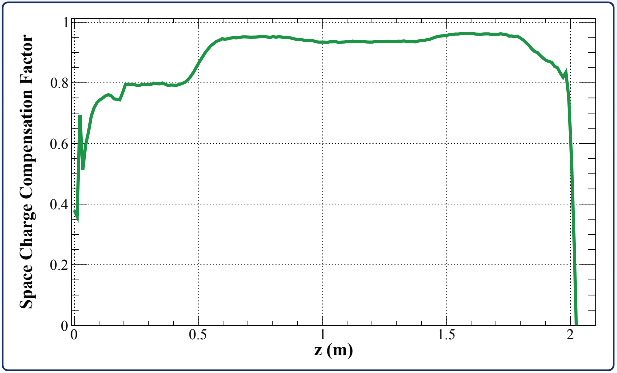


After the second solenoid and the injection cone)

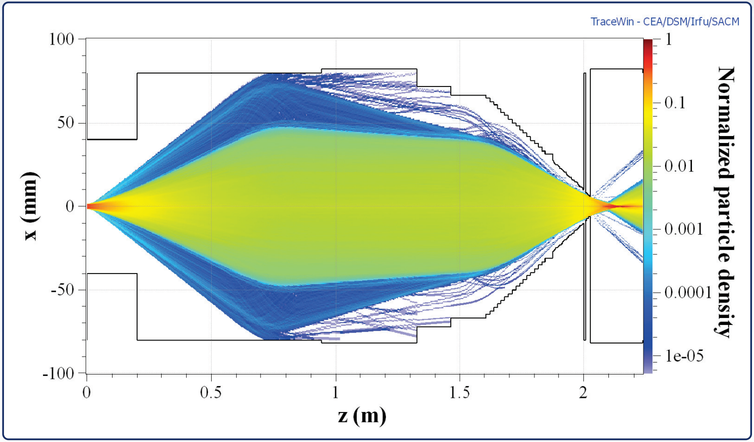
- Only protons.
- Beam intensity after the cone: 50 mA (≈80 mA extracted from the source)
- $\epsilon_{RMS} = 0.29 \pm 0.08\ \pi.mm.mrad$

Comparaison with the simulations

Simulations have been done with TraceWin, **entering a space charge Compensation profile dependent of z** ($\eta(z)$), but **constant on r**.

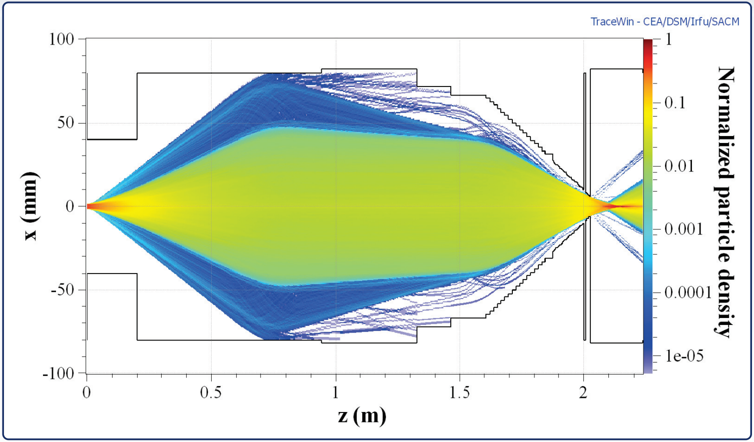


IFMIF injector simulations



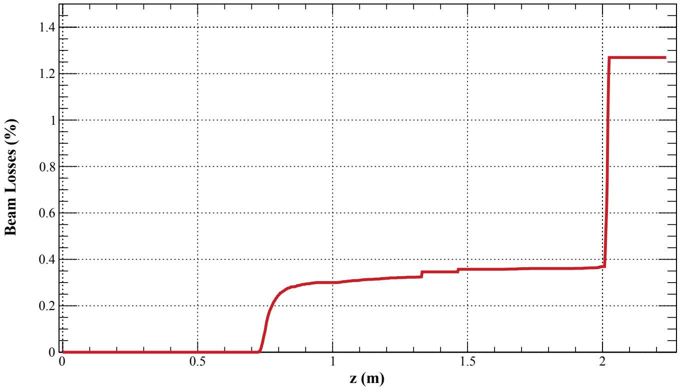
H^+ beam at 50 keV – Intensity: 50 mA

IFMIF injector simulations



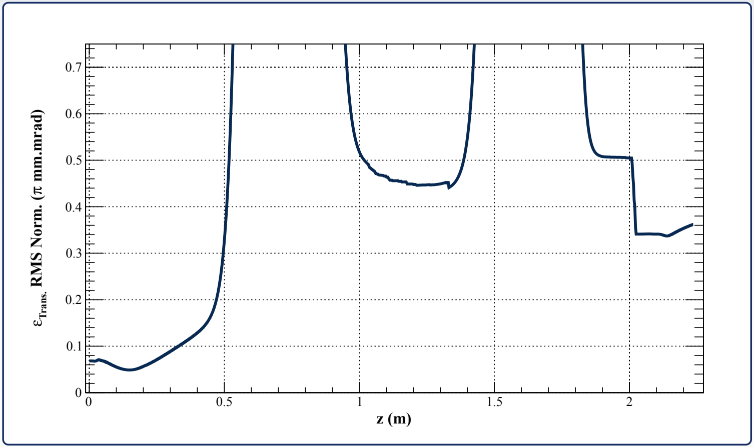
H^+ beam at 50 keV – Intensity: 50 mA

IFMIF injector simulations



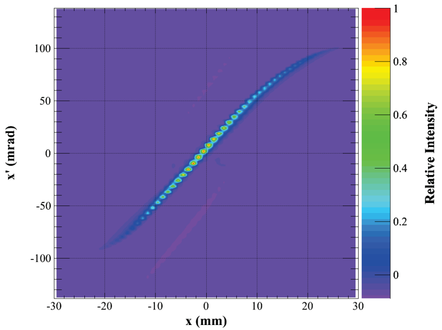
Beam losses in the LEBT

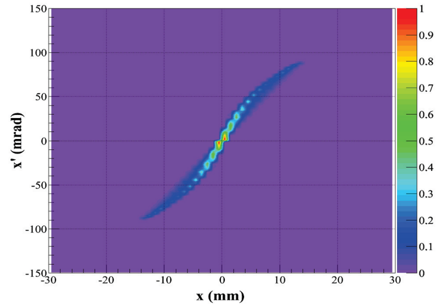
IFMIF injector simulations



Transverse emittance evolution in the LEBT

IFMIF injector measurements





Experiment

$0.29 \pm 0.08\ \pi$ mm.mrad

Simulation

$0.36\ \pi$ mm.mrad

Outline

Space charge compensation

Beam Dynamics Simulation Codes

IFMIF LEBT simulation with space charge compensation

IFMIF injector preliminary experimental results

Conclusion and perspectives

Conclusions and Perspectives

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- A PIC code (with SCC) has been used to design high intensity injectors.
- Simulations are compatibles with preliminary experimental results.
- Emittance at the end of the IFMIF injector are in the specifications.
- Nominal beam current in pulsed mode (20% duty cycle max.).

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Perspectives

- Integration of more physical phenomena (secondary emission, elastic scattering...) in SOLMAXP.
- IFMIF injector has to reach the nominal beam intensity in cw.
- Experiments and measurements with D^+ beam.
- Injector commissioning in Rokkasho !

Thank you for your attention!