Beam Dynamics in Low Energy Beam Lines with Space Charge Compensation

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N. Chauvin*, F. Gérardin, A. Chancé, N. Pichoff, D. Uriot

*Nicolas.Chauvin@cea.fr

CEA, IRFU, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France.

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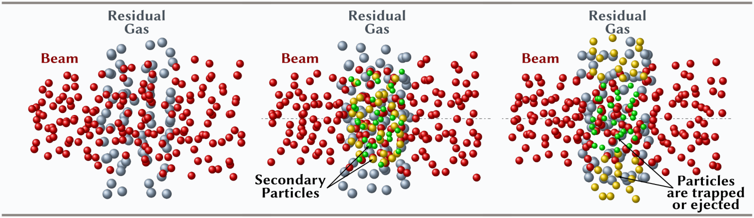
Overview

Overview

Space Charge Compensation (SCC)



Beam propagation through residual gas | Ionisation of residual gas | Secondary particles attracted or repelled

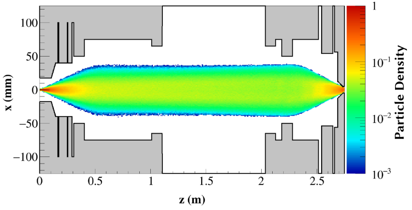
Example

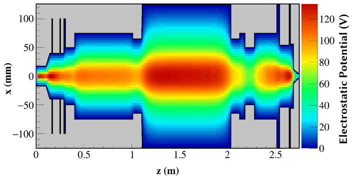
We consider a proton beam propagating through a H_2 residual gas. It induces a production of e^-/H_2^+ pairs by ionization.

$$H^+ + H_2 \to H^+ + e^- + H_2^+$$

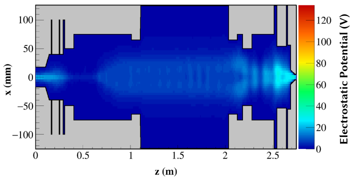
Space Charge Compensation Degree

$$\eta(r,z,t) = 1 - \frac{\phi_c(r,z,t)}{\phi_0(r,z,t)}$$



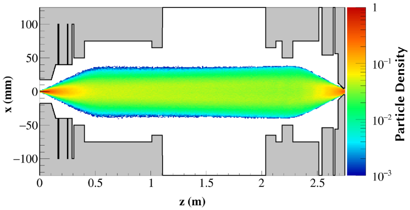


$\phi_0(r,z,t)$

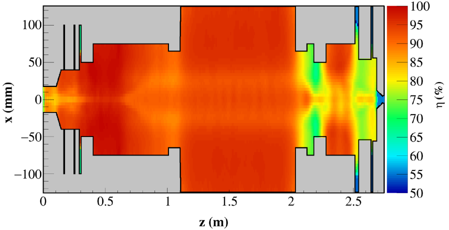


$\phi_c(r,z,t)$

Space Charge Compensation Degree



$$\eta(r, z, t) = 1 - \frac{\phi_c(r, z, t)}{\phi_0(r, z, t)}$$



$$\eta = (r, z, t)$$

Space Charge Compensation Transient Time

The characteristic **space charge compensation transient time**, T_{SSC}, can be approached by considering the time it takes for a particle of the beam to produce a neutralizing particle on the residual gas.It can be approached by:

$$T_{SCC} = \frac{1}{\sigma_i(E) n_g v_f}$$

with

$\sigma_i(E)$	ionisation cross section of gas
v_B	beam velocity
n_g	gas density

Example

100 keV H^+ beam with H_2 gas of 10^{-5} mbar: $T_{SCC} = 49\ \mu s$

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- v_B beam velocity
- n_g gas density

Example

100 keV H^+ beam with H_2 gas of 10^{-5} mbar: $T_{SCC} = 49\ \mu s$

But in a LEBT, electrons can be produced by other physical processes...

Interactions in a LEBT

Non-Exhaustive List

Interactions induced by primary beam

- Ionisation of gas: $H^+ + A \rightarrow H^+ + A^+ + e^-$
- Charge exchange with gas: $H^+ + A \rightarrow H + A^+$
- Secondary electron emission on a metallic surface: $H^+ + \textit{Metal} \rightarrow e^-$

Interactions in a LEBT
Non-Exhaustive List

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Interactions induced by electrons

- Ionisation of gas: $e^- + A \rightarrow A^+ + 2e^-$
- Dissociation reaction: $e^- + A_2 \rightarrow A^+ + A + 2e^-$

Interactions in a LEBT

Non-Exhaustive List

Interactions induced by primary beam

- Ionisation of gas: $H^+ + A \rightarrow H^+ + A^+ + e^-$
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Interactions induced by electrons

- Ionisation of gas: $e^- + A \rightarrow A^+ + 2e^-$
- Dissociation reaction: $e^- + A_2 \rightarrow A^+ + A + 2e^-$

Interactions induced by secondary ions

- Ionisation of gas: $A^+ + A \rightarrow 2A^+ e^-$
- Charge exchange with gas: $A^+ + A \rightarrow A + A^+$

Interactions to be neglected

- Interactions with too low cross section
- Interactions that have no effect on SCC (ex: charge exchange of secondary ions)

Interactions in a LEBT
Summary

Interactions to be neglected

- Interactions with too low cross section
- Interactions that have no effect on SCC (ex: charge exchange of secondary ions)

Interactions to be considered in the simulations

- Gas ionisation by primary beam
- Secondary electron emission
- Charge exchange of primary beam
- Gas ionisation by electrons

Overview

Transport with SCC

- Tracking particle codes (Tracks, Parmilla, Trace3D, TraceWin ...) are used with a **constant space charge compensation degree** along the beam line (or empirically dependant of z).
- High intensity ion beams at low energy: a correct description **the space charge compensation** is necessary.
- Use of a **self-consistent** code that simulate the beam interactions with the gas (ionization, neutralization ...) 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**.

J.-L. Vay, D. P. Grote, R. H. Cohen, and A. Friedman.
Novel methods in the Particle-In-Cell accelerator Code-Framework Warp.
Computational Science & Discovery 5, 2012.

WARP, a PIC code for SCC simulations

Code Inputs

- Beam distributions
- Pressure and gas species in the beam line
- Beam line geometry
- External fields maps (solenoids, source extraction, RFQ cone injection trap...)
- Boundary conditions

Code Outputs

- 6D coordinates of all particle in the beam line (gas, electron, ions)
- Space charge potential map $\rightarrow$ compute the space charge electric field map and $\eta(r, z, t)$

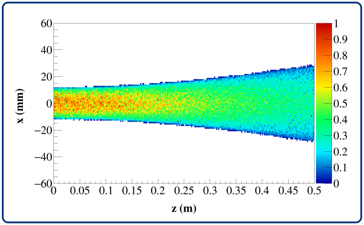
A Basic Example: Beam Propagation in a Drift with SCC

Let's consider

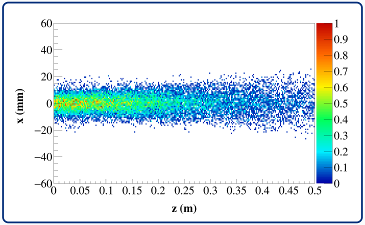
- Proton beam
- Beam intensity: 100 mA
- Uniform input beam distribution
- A drift space of 500 mm length
- Beam pipe of 60 mm radius
- Gas pressure (H_2) of 10^{-4} mbar (T_{SSC} = 4.9 µs)
- Only gas ionisation by the beam

Beam Propagation in a Drift with SCC

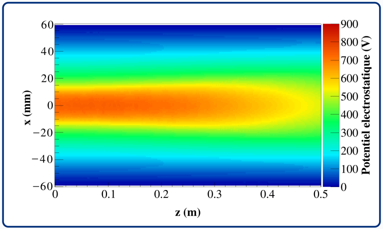
Particle Distribution and Potential – t=0.5 μs



Proton distribution at t = 0.5 μs

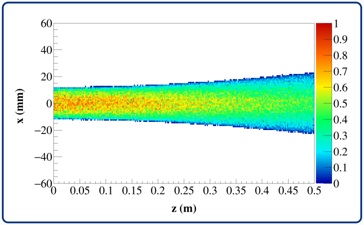


Electron distribution at = 0.5 μs

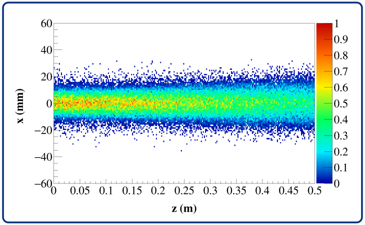


Electrostatic potential at t = 0.5 μs

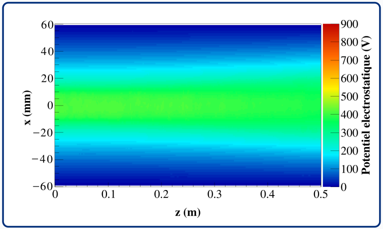
Beam Propagation in a Drift with SCC
Particle Distribution and Potential – t=2.5 µs



Proton distribution at t = 2.5 µs



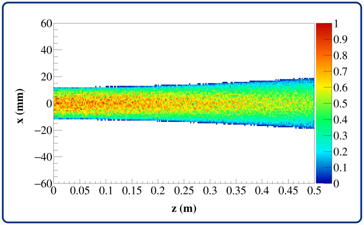
Electron distribution at = 2.5 µs



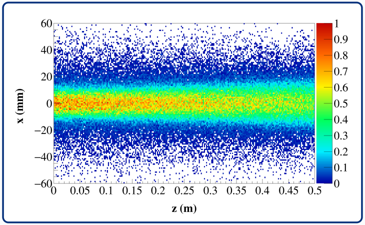
Electrostatic potential at t = 2.5 µs

Beam Propagation in a Drift with SCC

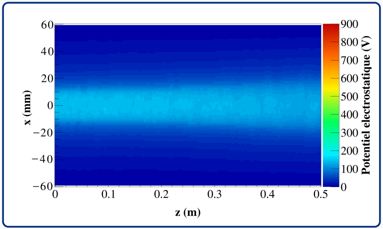
Particle Distribution and Potential – t=5 µs



Proton distribution at t = 5 µs



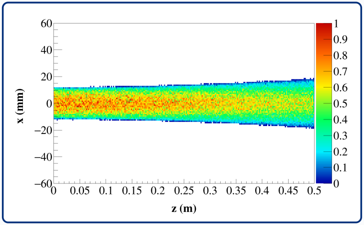
Electron distribution at = 5 µs



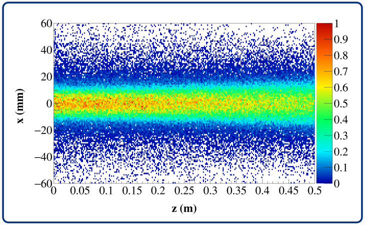
Electrostatic potential at t = 5 µs

Beam Propagation in a Drift with SCC

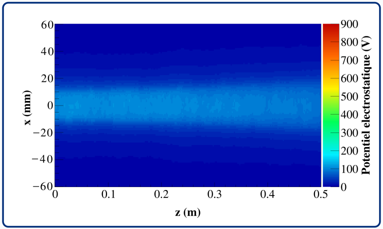
Particle Distribution and Potential – t=10 µs



Proton distribution at t = 10 µs



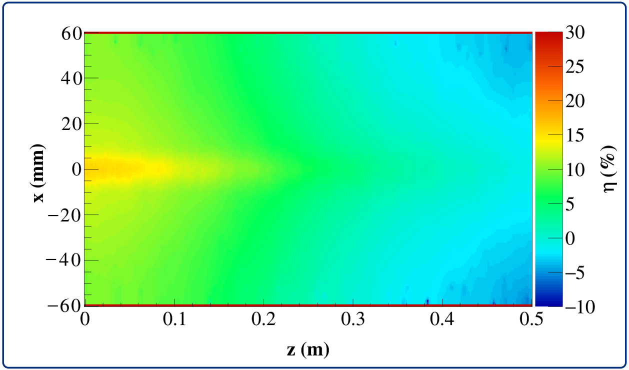
Electron distribution at = 10 µs



Electrostatic potential at t = 10 µs

Beam Propagation in a Drift with SCC

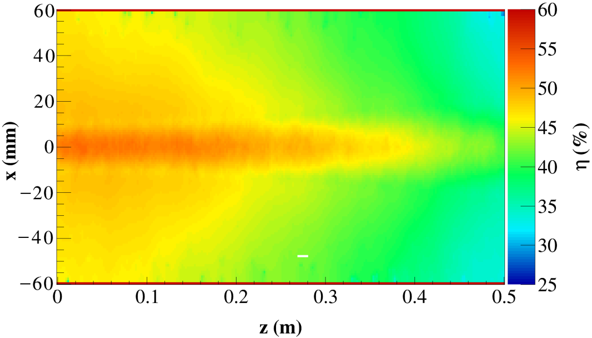
Space Charge Compensation – 0.5 µs



Space charge compensation map at t = 0.5 µs

Beam Propagation in a Drift with SCC

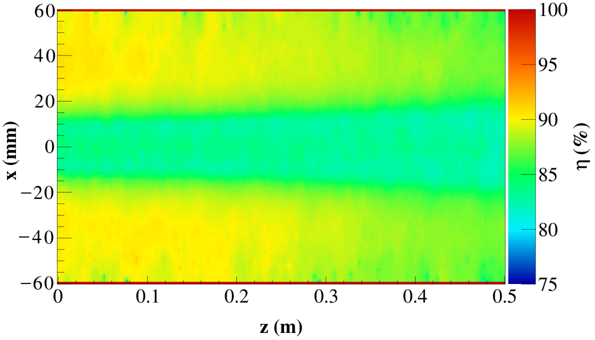
Space Charge Compensation – 2.5 µs



Space charge compensation map at t = 2.5 µs

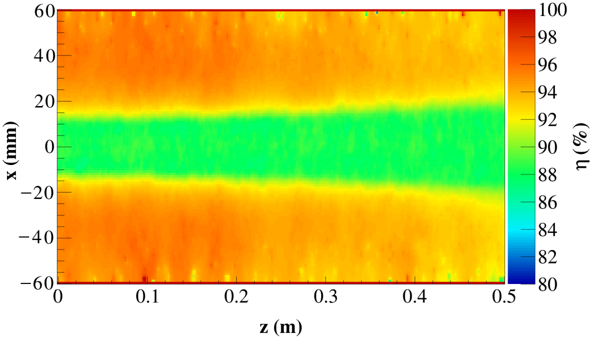
Beam Propagation in a Drift with SCC

Space Charge Compensation – 5 µs



Space charge compensation map at t = 5 µs

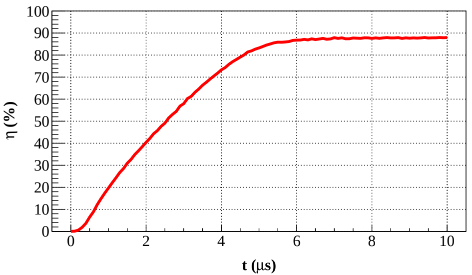
Beam Propagation in a Drift with SCC
Space Charge Compensation – 10 µs



Space charge compensation map at t = 10 µs

Beam Propagation in a Drift with SCC

Determining *eta* and transient time



One gets for the SCC transient time

$$T = 5.2\,\mu s > T_{SCC}$$

An the space charge compensation degree

$$\eta = 88\%$$

Quite low space charge compensation !?!

Limits of the PIC Codes

Cause of the partial compensation

- "Numerical heating" of the electrons
- Electrons are leaving the beam

D. Noll, M. Droba, O. Meusel, U. Ratzinger and K. Schulte.
Simulation of space-charge compensation of low-energy proton beam in a drift section.
Proceedings of HB 2016, Malm, Sweden, WEPM8Y01, 2016.

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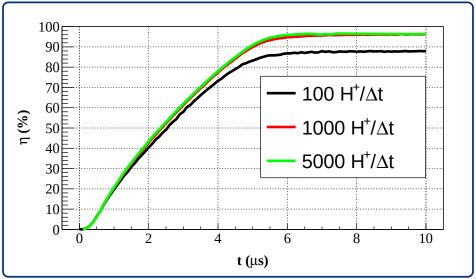
To mitigate this bias: increase the number of macro-particle in the simulation domain (and $\Delta x \approx \lambda_D$).



$\eta = 96\%$

Overview

Beam Focusing in a LEBT

Purposes of a LEBT

- Transport the beam from the ion source to the RFQ
- Match the beam to optimize its injection into the RFQ
- Minimize emittance growth and beam losses

Beam Focusing

- Magnetic or electrostatic focusing
- Cylindrical symmetry or quadripolar focusing
- ”Weak” or ”strong” focusing

→ **Beam transport simulations with different focusing elements under space charge compensation regime**

Simulation Conditions

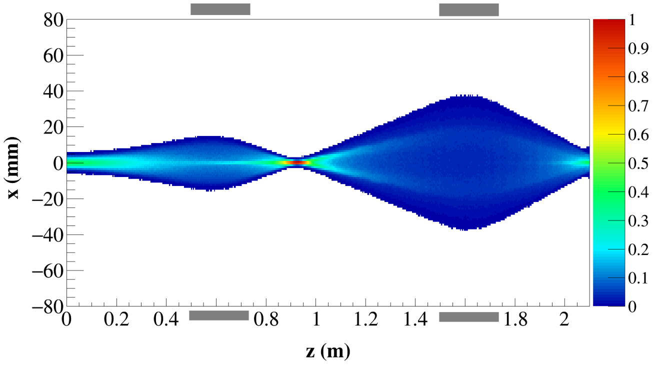
Focusing Elements in the Simulated Beam Line

1. 2 Solenoids
2. 2 Quadrupole doublets
3. 2 Einzel Lenses

Common Simulation Parameters

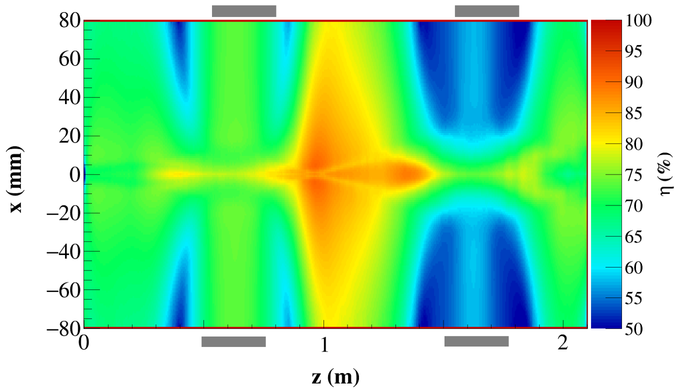
- Proton beam @ 100 keV
- Beam intensity: 50 mA
- Beam distribution: Gaussian, cylindrical symmetry
- Beam line length: 2.1 m
- H_2 gas, pressure: 1×10^{-4} mbar
- Considered reaction: $H^+ + H_2 \rightarrow H^+ + H_2^+ + e^-$

"Strong Focusing": beam waist between the two solenoids



Beam density through the LEBT at SCC steady state

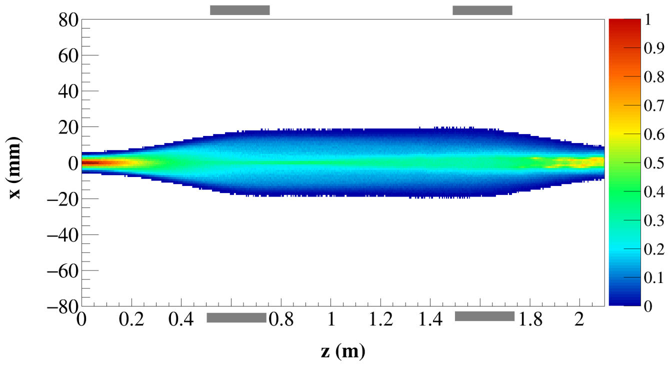
Solenoid Focusing
Strong Focusing



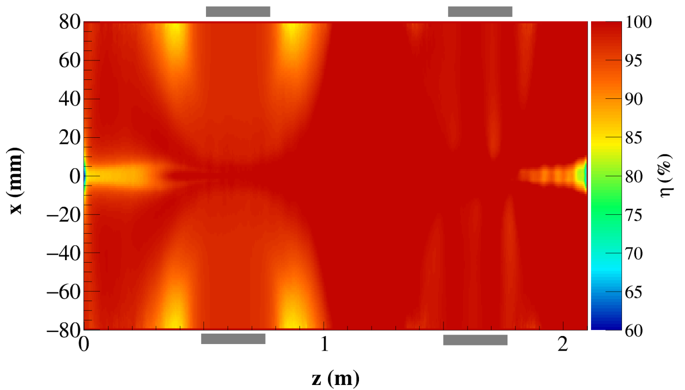
SCC in z0x plane at steady state

$$\varepsilon_{x,f} = 6\ \varepsilon_{x,i}$$

"Weak focusing": no beam waist between the two solenoids



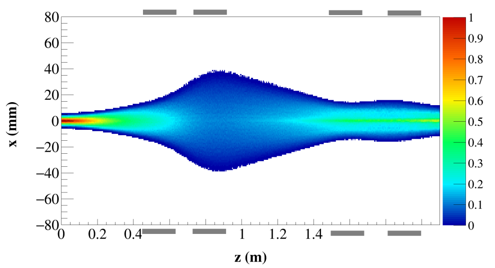
Beam density through the LEBT at SCC steady state



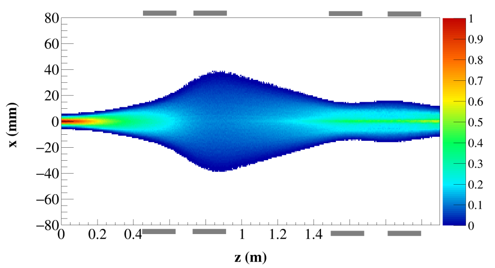
SCC in z0x plane at steady state

$$\varepsilon_{x,f} = 1.3\ \varepsilon_{x,i}$$

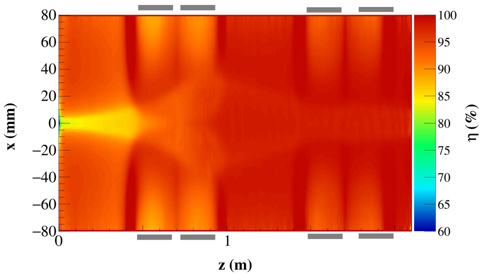
Quadrupole Doublet Focusing



Beam density in the X plane at SCC steady state

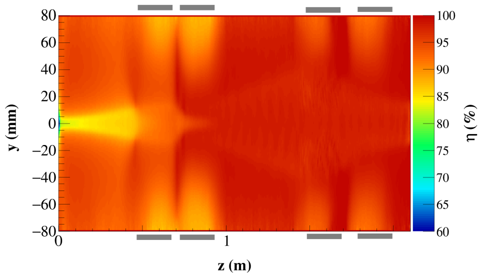


Beam density in the Y plane at SCC steady state



SCC in z0x plane at steady state

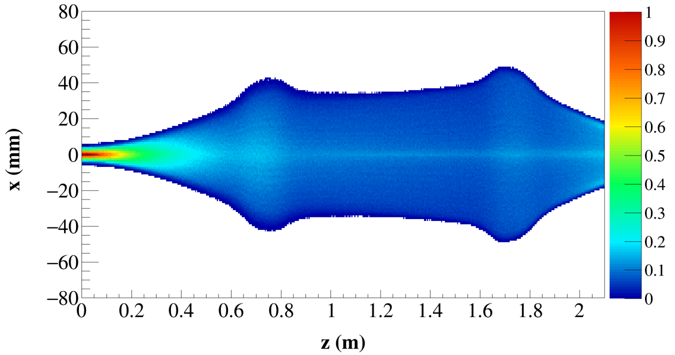
$$\varepsilon_{x,f} = 1.4\ \varepsilon_{x,i}$$



SCC in z0y plane at steady state

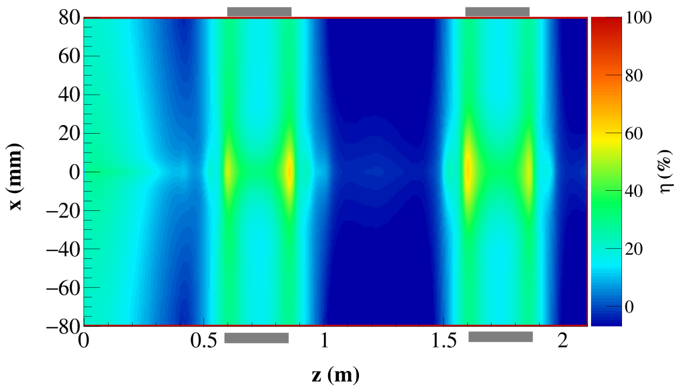
$$\varepsilon_{y,f} = 1.2\ \varepsilon_{x,i}$$

Einzel Lens Focusing



Beam density through the LEBT at SCC steady state

Einzel Lens Focusing



SCC in z0x plane at steady state

$$\varepsilon_{x,f} = 7.6\ \varepsilon_{x,i}$$

Favourable Focusing

- Weak magnetic focusing with solenoid is well adapted to LEBT with SCC (like ESS, IFMIF, MYRRHA...).
- Quadrupole focusing is satisfactory.
- Quadrupole doublet may be an promising alternative to solenoids in LEBT and may be useful to finely adapt the beam injection into the RFQ.

Favourable Focusing

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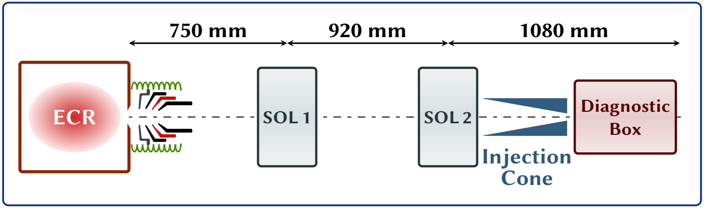
- Quadrupole doublet may be an promising alternative to solenoids in LEBT and may be useful to finely adapt the beam injection into the RFQ.

Unfavourable focusing

- Strong focusing with solenoid induces a high beam density at the waist location ➜ emittance growth.
- With Einzel lens, weak compensation because of a lack of electrons (secondary ions may be focused locally).

Overview

Beam Transport Simulation in a LEBT



Simulation Conditions (IFMIF/LIPAc LEBT)

- Deuteron beam @ 100 keV
- Beam intensity: 135 mA
- Input beam distribution: ion source extraction system simulated with Axcel
- Pressure profile in the beam line (D_2 and Kr)

GOAL: Study the effects of the different interactions on the beam transport

Simulation #1: only gas ionisation by the beam

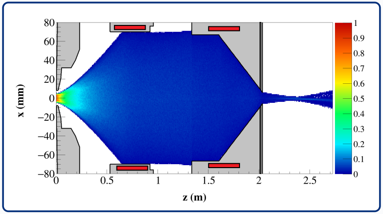
- $D^+ + D_2 \rightarrow D^+ + D_2^+ + e^-$
- $D^+ + Kr \rightarrow D^+ + Kr^+ + e^-$

Simulation #2: other collisions are considered

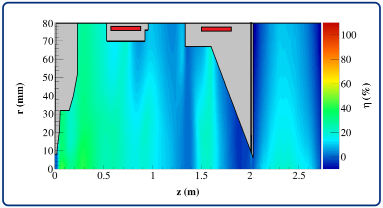
- $D^+ + D_2 \rightarrow D^+ + D_2^+ + e^-$
- $D^+ + Kr \rightarrow D^+ + Kr^+ + e^-$
- $D^+ + Metal \rightarrow e^-$
- $e^- + D_2 \rightarrow e^- + D_2^+ + e^-$
- $e^- + Kr \rightarrow e^- + Kr^+ + e^-$
- $D^+ + D_2 \rightarrow D + D_2^+$
- $D^+ + Kr \rightarrow D + Kr^+$

Simulation Results at t = 2 µs

Simulation #1

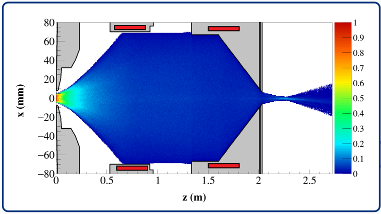


Beam Density at t = 2 µs

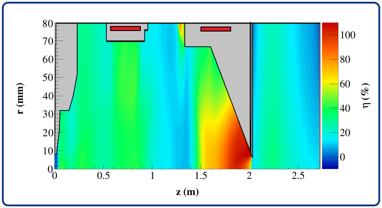


SCC at t = 2 µs

Simulation #2



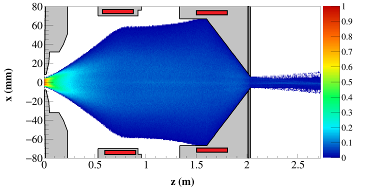
Beam Density at t = 2 µs



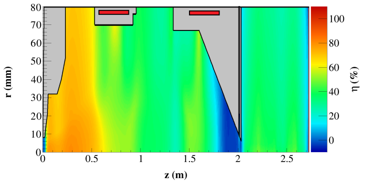
SCC at t = 2 µs

Simulation Results at t = 5 μs

Simulation #1

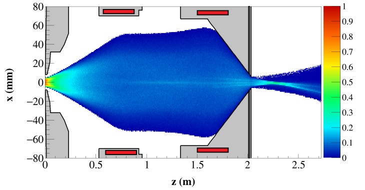


Beam Density at t = 5 μs

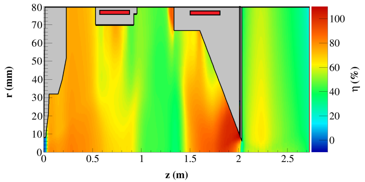


SCC at t = 5 μs

Simulation #2



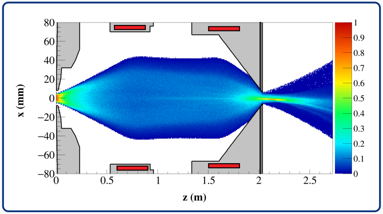
Beam Density at t = 5 μs



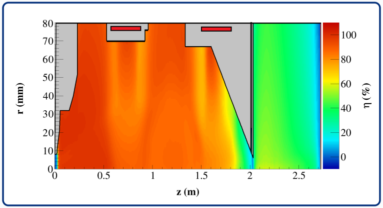
SCC at t = 5 μs

Simulation Results at t = 10 μs

Simulation #1

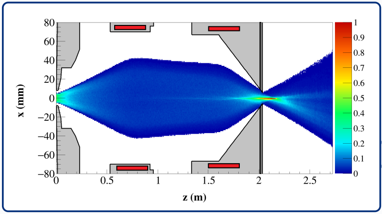


Beam Density at t = 10 μs

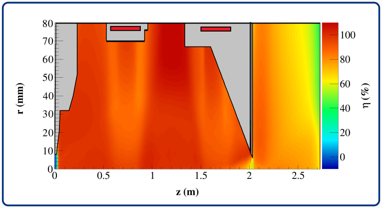


SCC at t = 10 μs

Simulation #2



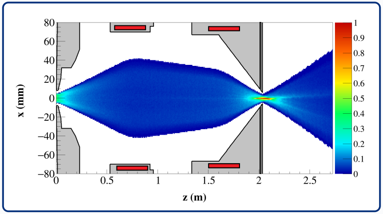
Beam Density at t = 10 μs



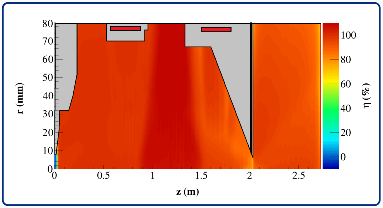
SCC at t = 10 μs

Simulation Results at t = 30 μs

Simulation #1

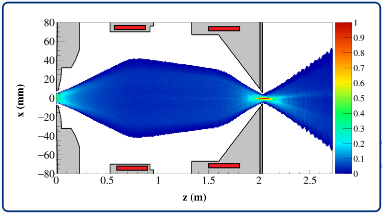


Beam Density at t = 30 μs

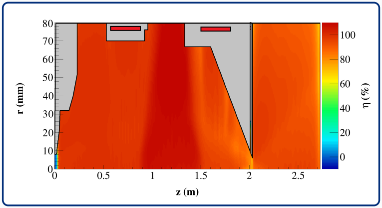


SCC at t = 30 μs

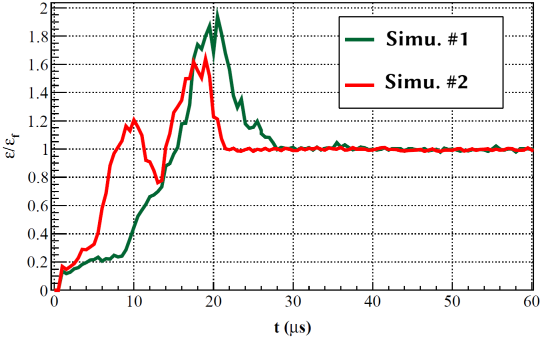
Simulation #2



Beam Density at t = 30 μs

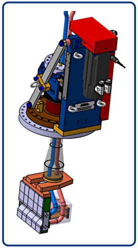


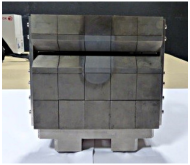
SCC at t = 30 μs



- Same emittance value at steady state in both case
- Shorter SCC transient time for simulation #2 (T_1 = 30 μs – T_2 = 22 μs)
- Beam losses by charge exchange: 4%

Overview



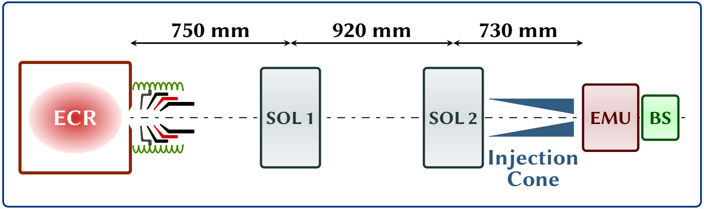


Emittance Measurement Unit (IFMIF/LIPAc LEBT)

- Alisson scanner
- Thermal screen made of W tungsten tiles (brazed on Cu)
- Entrance slit of 0.1 mm that selects a beamlet to analyse
- W screen intercept the beam during the measurement

GOAL: Study the effect of the insertion of such a device on the beam space charge compensation

Interceptive Diagnostic Simulation



Simulation Conditions (IFMIF/LIPAc LEBT)

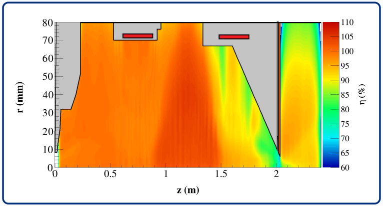
- Deuteron beam @ 100 keV
- Beam intensity: 135 mA
- EMU is simply modelled by a W plate at $z_E = 2.4$ m

Simulation #1 the W plate does not emit secondary electrons

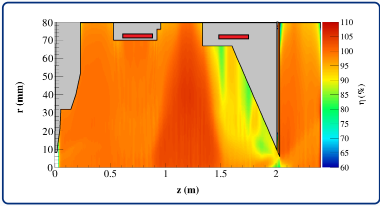
Simulation #2 the W plate does emit secondary electrons

Simulation Results at Steady State

Simulation #1



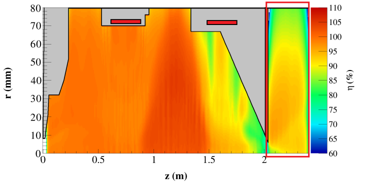
Simulation #2



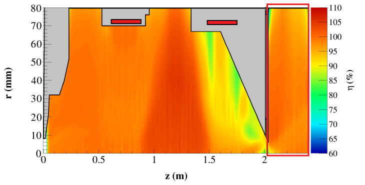
Space charge compensation η 30 µs

Simulation Results at steady state

Simulation #1



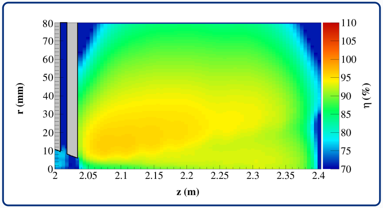
Simulation #2



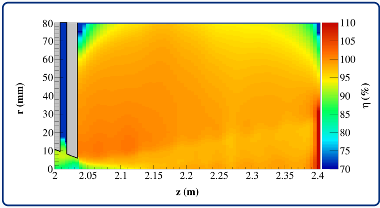
Space charge compensation η atfter 30 µs

Simulation Results at steady state

Simulation #1



Simulation #2

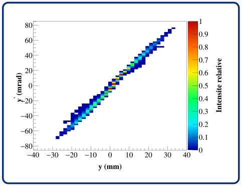


The presence of the EMU modifies space charge compensation

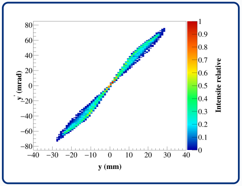
- Simulation #1: $\eta \sim 90$ % close to z_E
- Simulation #2: $\eta > 100$ % close to z_E

Emittance Measurement: Experimental Data vs Simulations

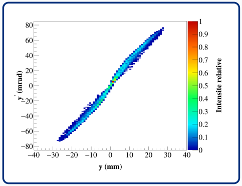
Experiment



Simulation #1



Simulation #2



Twiss Parameters	Exp. Data	Simu. #1	Simu. #2
ε_{rms} (π.mm.mrad)	0.26 ± 0.09	0.44	0.35
α	-11.9 ± 4.1	-9.9	-10.1
β (mm/mrad)	4.7 ± 1.6	3.2	4.1

Overview

Conclusions and Perspectives

Conclusion

- Simulation of beam transport in a LEBT
- More physics in the models
- Codes like Warp are precious tools to reach a better understanding of the beam dynamics in LEBTs
- It is mandatory to simulated the interceptive diagnostics used in LEBTs

Conclusions and Perspectives

Conclusion

- Simulation of beam transport in a LEBT
- More physics in the models
- Codes like Warp are precious tools to reach a better understanding of the beam dynamics in LEBTs
- It is mandatory to simulated the interceptive diagnostics used in LEBTs

Perspectives

- Perform better simulations (and understanding) of the ion source extraction system
- Collect more robust experimental data from different LEBTs
- A lot of work ahead to obtain results that are quantitatively reliable

Conclusions and Perspectives

Conclusion

- Simulation of beam transport in a LEBT
- More physics in the models
- Codes like Warp are precious tools to reach a better understanding of the beam dynamics in LEBTs
- It is mandatory to simulated the interceptive diagnostics used in LEBTs

F. Gérardin.
Étude de la compensation de la charge d'espace dans les lignes basse énergie des accélérateurs d'ions légers de haute intensité.
PhD Dissertation, Université Paris-Saclay, 2018.

Thank you for your attention !