Beam Dynamics in Low Energy Beam Lines with Space Charge Compensation

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Overview

1. Space Charge Compensation Basic Principles
2. Simulation Code
3. Beam Focusing in a LEBT
4. Beam transport in a LEBT
5. Interceptive Diagnostic Simulation
6. Conclusion and Perspectives
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SCC Principles
Simulation Code
Focusing
Transport
Diagnostic
Conclusion
Space Charge Compensation (SCC)

Example

We consider a proton beam propagating through a H\textsubscript{2} residual gas. It induces a production of e\textsuperscript{-}/H\textsuperscript{+}\textsubscript{2} pairs by ionization.

\[ H^+ + H_2 \rightarrow H^+ + e^- + H_2^+ \]
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

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

\[
\eta(r, z, t) = (r, z, t)
\]
Space Charge Compensation Transient Time

The characteristic space charge compensation transient time, $T_{SCC}$, 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: $T_{SCC} = 49 \, \mu s$
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:

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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: \( T_{SCC} = 49 \, \mu s \)

But in a LEBT, electrons can be produced by other physical processes...
Interactions induced by primary beam

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

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: \( H^+ + A \rightarrow H^+ + A^+ + e^- \)
- Charge exchange with gas: \( H^+ + A \rightarrow H + A^+ \)
- Secondary electron emission on a metallic surface: \( H^+ + \text{Metal} \rightarrow e^- \)

#### 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 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 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
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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 of 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**.


*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
Space Charge Compensation 101

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 ($T_{SSC} = 4.9 \mu$s)
- 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 t = 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 – $t=5\mu$s

Proton distribution at $t = 5\mu$s

Electron distribution at $t = 5\mu$s

Electrostatic potential at $t = 5\mu$s
Beam Propagation in a Drift with SCC
Particle Distribution and Potential – $t=10\,\mu$s

Proton distribution at $t = 10\,\mu$s

Electron distribution at $t = 10\,\mu$s

Electrostatic potential at $t = 10\,\mu$s
Beam Propagation in a Drift with SCC
Space Charge Compensation – 0.5 µs

Space charge compensation map at t = 0.5 µs
Space charge compensation map at t = 2.5 $\mu$s
Space charge compensation map at $t = 10 \mu s$
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


*Simulation of space-charge compensation of low-energy proton beam in a drift section.*
Limits of the PIC Codes

Cause of the partial compensation

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


Simulation of space-charge compensation of low-energy proton beam in a drift section.

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

![Graph showing the effect of increasing the number of macro-particles on the compensation efficiency.]

\[ \eta = 96\% \]
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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
- H₂ gas, pressure: $1 \times 10^{-4}$ 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
Solenoid Focusing
Weak Focusing

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
Solenoid Focusing
Weak Focusing

SCC in z0x plane at steady state
\[ \varepsilon_{x,f} = 1.4 \varepsilon_{x,i} \]

SCC in z0y plane at steady state
\[ \varepsilon_{y,f} = 1.2 \varepsilon_{x,i} \]
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.
Beam Focusing in a LEBT

Summary

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.

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).
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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 $t = 2 \mu s$

**Simulation #1**

Beam Density at $t = 2 \mu s$

**Simulation #2**

Beam Density at $t = 2 \mu s$

SCC at $t = 2 \mu s$

SCC at $t = 2 \mu s$
Simulation Results at $t = 5 \mu s$

**Simulation #1**

Beam Density at $t = 5 \mu s$

**Simulation #2**

Beam Density at $t = 5 \mu s$

SCC at $t = 5 \mu s$

SCC at $t = 5 \mu s$
Simulation Results at $t = 10 \, \mu s$

**Simulation #1**

Beam Density at $t = 10 \, \mu s$

**Simulation #2**

Beam Density at $t = 10 \, \mu s$

SCC at $t = 10 \, \mu s$

SCC at $t = 10 \, \mu s$
Simulation Results at $t = 30 \, \mu s$

**Simulation #1**

Beam Density at $t = 30 \, \mu s$

SCC at $t = 30 \, \mu s$

**Simulation #2**

Beam Density at $t = 30 \, \mu s$

SCC at $t = 30 \, \mu s$
Same emittance value at steady state in both case

Shorter SCC transient time for simulation #2 ($T_1 = 30 \mu s - T_2 = 22 \mu s$)

Beam losses by charge exchange: 4%
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Interceptive Diagnostic Simulation

Insertion of an emittance meter

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 $\eta$ 30 $\mu$s
Simulation Results at steady state

**Simulation #1**

**Simulation #2**

Space charge compensation $\eta$ after 30 $\mu$s
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

<table>
<thead>
<tr>
<th>Twiss Parameters</th>
<th>Exp. Data</th>
<th>Simu. #1</th>
<th>Simu. #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{rms}}$ (\text{(\pi).mm.mrad})</td>
<td>0.26 $\pm$ 0.09</td>
<td>0.44</td>
<td>0.35</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-11.9 \pm 4.1$</td>
<td>$-9.9$</td>
<td>$-10.1$</td>
</tr>
<tr>
<td>$\beta$ (mm/mrad)</td>
<td>4.7$\pm$ 1.6</td>
<td>3.2</td>
<td>4.1</td>
</tr>
</tbody>
</table>
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

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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
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

Thank you for your attention!