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
4. Conclusion and perspectives
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Conclusion and perspectives
The space charge compensation (SCC) principle

Example

We consider a proton beam propagating through a H₂ residual gas. It induces a production of pairs e⁻/H₂⁺ by ionization.

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

We assume that \( \frac{n_{\text{gas}}}{n_{\text{beam}}} \ll 1 \), with \( n_{\text{gas}} \) and \( n_{\text{beam}} \) 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:

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

(1)

where \( I_B \) and \( \beta_B \) are respectively the intensity and the reduced speed of the beam.
Space charge compensation degree

If $\phi_c$ and $\phi_0$ 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:

$$\eta = 1 - \frac{\phi_c}{\phi_0}$$

(2)
Space charge compensation degree

If $\phi_c$ and $\phi_0$ 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:

$$\eta = 1 - \frac{\phi_c}{\phi_0}$$  (2)

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

$95\% < \eta < 99\%$

Space charge compensation – Measurements

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

**Without $^{84}$Kr injection**
Pressure: $2.4 \times 10^{-5}$ hPa.
$\epsilon_{RMS} = 0.335 \, \pi \, \text{mm.mrad}$

**With $^{84}$Kr injection**
Pressure: $4.6 \times 10^{-5}$ hPa.
$\epsilon_{RMS} = 0.116 \, \pi \, \text{mm.mrad}$

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Improvement of beam emittance of the CEA high intensity proton source SILHI.
Outline

Space charge compensation

Beam Dynamics Simulation Codes

IFMIF LEBT simulation with space charge compensation

IFMIF injector preliminary experimental results

Conclusion and perspectives
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).

The warp code: Modeling high intensity ion beams.
_AIP Conference Proceedings, 749_(1):55–58._
SOLMAXP: basic algorithm

- **Motion Integration**
  \[ \vec{F}_n \rightarrow \vec{V}'_n \rightarrow \vec{X}_n \]

- **Collisions (Monte Carlo)**
  \[ \vec{V}'_n \rightarrow \vec{V}_n \]

- **Interpolation of the forces**
  \( (\vec{E}_n, \vec{B}_n) \rightarrow \vec{F}_n \)

- **Interpolation of currents and charges in a grid**
  \( (\vec{X}_n, \vec{V}_n) \rightarrow (\rho_n, \vec{J}_n) \)

- **EM fields calculation (FD)**
  \( (\rho_n, \vec{J}_n) \rightarrow (\vec{E}, \vec{B}) \)
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: $\leq 0.25\,\pi$ mm.mrad

IFMIF injector
- SILH1-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 ($4 \times 10^{-5}$ hPa).
- Homogeneous pressure in the beam line.
- Ionisation of gas by incoming beams.
  $$D^+ + D_2 \rightarrow D^+ + e^- + D_2^+$$
  $$D_2^+ + D_2 \rightarrow D_2^+ + e^- + D_2^+$$
  $$D_3^+ + D_2 \rightarrow D_3^+ + e^- + D_2^+$$
- Ionisation of gas by created electrons
  $$e^- + D_2 \rightarrow 2e^- + D_2^+$$
- No secondary electron created by ion impact on beam pipe.
- No beams beam scattering on gas.
Space charge potential evolution

\[ t = 2 \, \mu s \]
Space charge potential evolution

\[ t = 4 \mu s \]
Space charge potential evolution

$t = 6 \mu s$
Space charge potential evolution

\[ t = 8 \, \mu s \]
Space charge potential evolution

$t = 10 \mu s$
Space charge potential evolution

$\text{t} = 10 \, \mu\text{s} \quad \text{– Cut at 700 V} !
Space charge potential evolution

$t = 12 \, \mu s$
Space charge potential evolution

\[ t = 14 \, \mu s \]
Space charge potential evolution
Space charge potential evolution

\[ t = 18 \, \mu s \]
Space charge potential evolution

$t = 20 \, \mu s$
Beam evolution

$t = 2 \mu s$
Beam evolution

$t = 4 \mu s$
Beam evolution

$t = 6 \, \mu s$
Beam evolution

$t = 8 \mu s$
Beam evolution

$t = 10 \, \mu s$
Beam evolution

$t = 12 \mu s$
Beam evolution

$t = 14 \mu s$
Beam evolution

$t = 16 \, \mu s$
Beam evolution

\[ t = 18 \mu s \]
Beam evolution

\[ t = 20 \, \mu s \]
Two dimensions cut in the (z0y) plane of a space charge potential map
SCC degree

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

\[ \phi \] is the SCC degree.
SCC degree

with $\eta = 1 - \frac{\phi_c}{\phi_0}$, we can compute the **space charge compensation degree** along the beam line.
Space charge compensation degree in the IFMIF LEBT
Role of the $e^{-}$ repeller

Without electron repeller

With electron repeller
Beam dynamics results

LEBT Output: $\epsilon_{RMS} = 0.16 \pi \text{ mm.mrad}$

IFMIF RFQ transmission: 96%
Outline

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Conclusion and perspectives
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.

\[
K = \frac{ql}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3}
\]  
(3)

- Emittance and beam proportion measurements.
Emittance measurement between the two solenoids
Emittance measurement between the two solenoids

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
- $\epsilon_{RMS} = 0.50 \pm 0.10 \pi \text{ mm.mrad}$
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)
- $\epsilon_{RMS} = 0.29 \pm 0.08 \, \mu m.mrad$
Comparaison with the simulations

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

<table>
<thead>
<tr>
<th>$z$ (m)</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Charge Compensation Factor</td>
<td>0</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

![Graph showing space charge compensation factor vs. z](image-url)
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 ± 0.08 \( \pi \) mm.mrad

Simulation
0.36 \( \pi \) mm.mrad
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Conclusions and Perspectives

Conclusions

- A PIC code (with SCC) has been used to design high intensity injectors.
- Simulations are compatible 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.).
Conclusions and Perspectives

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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!