Measurements and Simulations of the Beam Extraction from the ESS Proton Source

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Abstract
A proton source with a Low Energy Beam Transport (LEBT) will be delivered to ESS in January 2018 by INFN-LNS. In order to prepare for the commissioning of this system at ESS, understanding the beam dynamics of the Beam extraction and transport at low energy is important. The ion source and LEBT were commissioned at INFN-LNS in 2016-17 with measurements of the beam current, fractions of different ion species (H\textsuperscript{+}, H\textsubscript{2}\textsuperscript{+}, and H\textsubscript{3}\textsuperscript{+}), and emittance. In this paper we compare IBSimu simulations with these measured data. The goal is to reproduce different beam distributions at the exit of the ion source, which will help to optimize the beam optics and transmission to match the RFQ acceptance.

LEBT beam measurement
- Extracted beam current: 100 mA.
- Ion species: 80\% protons, 15\% H\textsubscript{2}\textsuperscript{+}, 5\% H\textsubscript{3}\textsuperscript{+}.
- Faraday cup current: 72 mA.
- Emittance in commissioning tank:
  \( \varepsilon = -3.5 \) mm mrad
  \( \beta = 0.78 \) m
- Solenoid settings:
  Solenoid 1: 300 A, 0.25 T
  Solenoid 2: 200 A, 0.17 T
- Gas pressure:
  Pumping box: 3.6 \times 10^{-5} \text{ mbar}
  Permanent tank: 1.6 \times 10^{-6} \text{ mbar}
  Commissioning tank: 0.55 \times 10^{-3} \text{ mbar}

Simulation of beam extraction and transport with IBSimu
- Two-stage simulation of beam extraction from microwave discharge ion source with a cylindrical symmetry, and beam transport through the LEBT:
  1. Beam extraction from a plasma with 0.4 mm mesh size
  2. Beam transport with 2 mm mesh size
- Input plasma parameters:
  Plasma potential: 20 V
  Transverse ion temperature: 1 eV
  Electron temperature: 10 eV
  Initial ion energy: 10 eV
- Ion species: 80\% protons, 15\% H\textsubscript{2}\textsuperscript{+}, 5\% H\textsubscript{3}\textsuperscript{+}
- 80,000 trajectories

Qualitative comparison of measurements and simulations
- Measured and simulated values of Faraday cup current [mA], normalized rms emittance (\( \varepsilon \)) [mm mrad], and Twiss \( \alpha \) and \( \beta \) [m] as a function of solenoid 2 current [A].

<table>
<thead>
<tr>
<th>Solenoid 2 current</th>
<th>Permanent tank</th>
<th>Commissioning tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>Faraday cup current</td>
<td>( \alpha )</td>
</tr>
<tr>
<td>55 65 72 72</td>
<td>0.22 9.6 9.2</td>
<td>0.24 3.5 0.78</td>
</tr>
<tr>
<td>Simulation</td>
<td>58 72 77 77</td>
<td>0.38 5.9 4.9</td>
</tr>
</tbody>
</table>

Simulation of transmitted current through the LEBT as a function of the current on solenoid 1 and 2
- Simulations with three different levels of space charge compensation: 87\%, 90\%, and 94\%.
- The black circles indicate the settings of the measurements.
- The results for 87\% SCC shows signatures of the sensitivity against the solenoid 1 setting as well as a moderate current reduction along with the solenoid 2 reduction.
- The results for the 90\% and 94\% SCC are consistent with our observation of reduced current for N\textsubscript{2} injection with no solenoids adjustment.
- The contours in the figures indicate the regions where the beam is matched to the RFQ acceptance.
- \( M \) is the mismatch parameter, which takes into account both Twiss parameters \( \alpha \) and \( \beta \).

\[
M = \sqrt{1 + \Delta M (\Delta M + 4/3)^{1/2}} - 1,
\]
where \( \Delta M = (\Delta \alpha)^2 - \Delta \beta^2 \Delta \gamma \).
- For the calculation of \( M \), we used the anticipated values of \( \alpha \): 1.02, and \( \beta \): 0.11 m, at the RFQ entrance.

Comparison of phase space plots
- Solenoid 1: 300 A, solenoid 2: 200 A.

CONCLUSION
- The simulations of the ion source and LEBT show that the beam transport and quality is sensitive to the level of space charge compensation.
- The beam is also sensitive to the settings of the solenoids, especially solenoid 1.
- Further beam studies will be done by scanning the full parameter space of solenoid current settings for different levels of injected N\textsubscript{2} gas for space charge compensation.
- Additional tests are being made at INFN-LNS with different extraction system electrode shapes to reduce the divergence of the extracted beam.

 simulation of beam extraction from a plasma, and beam transport through the LEBT.

Figure 1: Layout of the ion source and LEBT.

Figure 2: IBSimu simulation of beam extraction from a plasma, and beam transport through the LEBT.

Figure 3: Simulations of transmitted current as a function of the B-field on solenoid 1 and solenoid 2.

Figure 4: Phase space plots from emittance measurements in the permanent tank and commissioning tank.