MEASUREMENT AND ANALYSIS OF THE INTENSITY-DEPENDENT EFFECTS ON THE CSNS MEDIUM ENERGY BEAM TRANSPORT LINE

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Abstract

A power upgrade project (CSNS-II) has been approved in 2021 to increase the beam power to 500 kW for the China Spallation Neutron Source (CSNS), for which the Linac energy will reach 300 MeV and the beam intensity is expected to be 50 mA. In this study, the beam measurement results given by the wire scanners at various current intensities, and the numerical modeling and fitting methods to obtain the evolution of the beam envelope and emittance along the CSNS medium energy beam transfer (MEBT) are given and discussed. Finally, new matching results have been given to control the emittance blowup.

INTRODUCTION

China Spallation Neutron Source (CSNS) Linac has a medium energy beam transfer (MEBT) line between the Radio-frequency Quadrupole (RFQ) accelerator and the drift tube Linac (DTL) to match the beam between the two. An upgrade plan, officially known as CSNS-II, to increase the beam power on target from 100 kW to 500 kW has been approved recently in which the Linac energy will be boosted from 80 MeV to 300 MeV by adding superconducting Linac after existing DTL tanks and the nominal peak current intensity of the beam will be 50 mA, in contrast to the 10 mA beam at present. In order to have more insightful understanding for a new design for the CSNS-II MEBT and also try the potential with present layout before energy upgrade, we are trying to set up the numerical model to represent the beam commissioning results along the present Linac.

The forward method [1] is adopted as follows: 1) obtain the beam size along the MEBT by fitting the results from the four wire scanners; 2) a numerical model with the beam commissioning settings is set up in TraceWin [2] and the beam parameters are obtained through tracking to reproduce the measured results; and 3) emittance evolution along the MEBT is then obtained and new MEBT settings are proposed for the DTL matching.

PARTICLE TRACKING METHOD

The \( \sigma \) matrix, or the beam size, has the following form in terms of the Courant-Snyder parameters and the emittance,

\[
\sigma = \begin{pmatrix} \epsilon \beta & -\epsilon \alpha \\ -\epsilon \alpha & \epsilon \gamma \end{pmatrix} = \begin{pmatrix} \sigma_1^2 & \sigma_{x1} \sigma_{x1}' \\ \sigma_{x1}' & \sigma_2^2 \end{pmatrix}
\]

where \( \epsilon \) is the emittance and \( \sigma_x \) is beam size. Suppose the beam is transported from \( s_1 \) to position \( s_2 \) and the corresponding transfer matrix is \( M \), the \( \sigma \) matrices at \( s_1 \) and \( s_2 \) can be written as:

\[
\sigma_{s2} = M \sigma_{s1} M^T.
\]

Specifically,

\[
(\sigma_1^2)_{s2} = m_{11}^2 (\sigma_1^2)_{s1} + 2m_{11}m_{12} (\sigma_{x1}^2)_{s1} + m_{12}^2 (\sigma_{x1}')^2_{s1}
\]

where the matrix elements are constructed from the actual layout and settings of the magnets and cavities, and the beam size can be obtained by the wire scanners. In principle, with beam size at three different locations, the \( \sigma \) matrix at a chosen starting point can be calculated. In addition, linear space charge can be considered in \( M \). However, if the beam emittance changes along the way due to nonlinear space charge force, such as in the MEBT, the above method does not hold, especially when the beam intensity goes high.

Multi-particle tracking method, instead, can simulate the non-linear space charge and it is adopted in some previous studies [3]. TraceWin is adopted in our design for the CSNS-II Linac and it is also used for the beam commissioning study.

BEAM SIZE MEASUREMENT AT CSNS-MEBT

Figure 1 illustrates a schematic layout [4] of the CSNS-MEBT [5], which contains two bunchers, ten quadrupoles and beam diagnostic devices including: four wire scanners (PR), one emittance monitor (EM), seven beam position monitors (BPM) and two current transformers (CT). In this study, four wire scanners are used to measure the beam size at beam intensity of 7 mA, 15 mA, 25 mA, respectively. In addition in order to test the coupling between the longitudinal and the horizontal direction, the measurements have been done with the bunchers turned ON or OFF. If the beam from upstream is stable enough, the parameters of the beam at the MEBT entrance should be the same regardless of the bunchers’ status.

BEAM PARAMETERS FITTED WITH PARTICLE TRACKING

**Beam Size Fitting**

A common way to obtained the beam size is to do Gaussian fitting to the the beam profile measured by the wire scanner or wire grid. The fitting is simply done by:
Figure 1: Schematic layout of the CSNS Linac MEBT with beam diagnostics.

\[ N(x; \mu, \sigma^2) = \sqrt{\frac{1}{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2}(x - \mu)^2} \]

where \(\sigma\) is the fitted beam size, \(\mu\) is the beam position center.

Typical profile measurement results by the wire scanners at CSNS Linac MEBT are shown in Fig. 2, with Gaussian fitted curve plotted in dashed line. It is obvious that the real beam profile cannot be reflected by such a Gaussian fitting properly, especially when the beam has a relevantly large portion of particles distributed away from the center, as shown in the same figure.

Figure 2: Typical measured results by a wire scanner at the CSNS Linac MEBT.

Another way is to calculate the statistical RMS from the data points,

\[ \sigma_{RMS} = \sqrt{\frac{\sum (x_i - \bar{x})^2 f(x_i)}{\sum f(x_i)}} \]

where \(\sigma\) is the RMS beam size in standard deviation, \(f(x_i)\) is the amplitude at \(x_i\) and \(\bar{x}\) is the weighted average of the position.

The beam size has been measured at 7 mA, 15 mA and 25 mA beam intensities and the results obtained by both methods are shown in Fig. 3, which shows that RMS results from the measured data points are generally larger than the Gaussian fitted. It reveals the fact that the RMS calculation will include the contribution from the "outside" particles while the Gaussian fitting mostly leave them off. Therefore, Gaussian fitted results tend to result in a smaller beam emittance than the real beam. Moreover, the beam size increases apparently with the beam intensity.

**Multi-Particle Tracking Method vs. Envelope**

In the beam dynamics simulation, the initial distribution at the MEBT entrance in transverse direction is assumed as a two-dimensional Gaussian distribution while the exact parameters such as \(\alpha_{x,y}, \beta_{x,y}\) and \(\epsilon_{x,y}\) required to define the phase space are to be fitted with the beam size obtained above. As a result, the Gaussian fitted results are used as the target values for beam size. For the initial longitudinal distribution, we used an assumed Gaussian distribution from the design. In addition, a modified hard-edge model [6] is adopted for the quadrupoles as described in [7]. Besides, TraceWin also provides the linear space charge model which is termed as "envelope" tracking, which is also included here for comparison.

Table 1 shows the beam parameters at the MEBT entrance obtained by the multi-particle tracking method (Model I) and the envelope method (Model II). Though the envelope method produced similar emittance results compared with the multi-particle tracking method, it has an assumption that the beam emittance stays constant along the beam line which is simply not true at such a low energy like in MEBT.

<table>
<thead>
<tr>
<th>(I[\text{mA}])</th>
<th>(\alpha_{x,y})</th>
<th>(\beta_{x,y})</th>
<th>(\epsilon_{x,y})</th>
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<td>7</td>
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<td>0.084, 0.21</td>
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<tr>
<td>15</td>
<td>-1.71, 1.87</td>
<td>0.19, 0.14</td>
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<tr>
<td>25</td>
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<td>0.077, 0.2</td>
<td>0.23, 0.27</td>
</tr>
<tr>
<td>I</td>
<td>-1.98, 1.55</td>
<td>0.25, 0.14</td>
<td>0.21, 0.25</td>
</tr>
</tbody>
</table>

In our measurement under different beam intensities, the upstream before the MEBT is not fine tuned. As a result, the beam emittance from the front-end becomes larger for higher beam intensity as shown in Table 1.
Figure 3: The beam size results at 7, 15, 25 mA obtained from Gaussian fitting (filled circle) and RMS calculation (cross), compared with the simulated results with multi-particle tracking (dashed lines).

Figure 4: Normalized beam emittance evolution along the MEBT and the DTL without lattice matching (solid) and with matching (dashed).

EMITTANCE GROWTH AND MATCHING TO THE DTL

The MEBT settings (quadrupoles and bunchers) stay the same while the beam intensity is being changed in our measurement. After obtaining the beam parameters at the MEBT entrance, the beam parameters from the MEBT to the DTL can be obtained through multi-particle tracking. Figure 4 shows the results for different beam intensities, where the DTL section is added to show how the emittance blowup looks like if MEBT lattices are not matched. The beam emittance increases along the MEBT on both directions, suggesting that multi-particle tracking method with space charge solver is necessary in such studies compared with the envelope method which assumes linear space charge and constant beam emittance.

Based on the obtained results, a lattice matching from the MEBT entrance to the end of the DTL can be applied. The simulation results are as shown in the same figure. This figure suggest that the emittance blowup in the DTL section can be greatly suppressed if proper matching has been done in the MEBT region.

CONCLUSION

In this paper, the whole process from the beam size measurement to the reconstruction with multi-particle tracking has been shown, aiming to study the beam parameters under different current intensities. We have shown how the beam size calculation will affect the results. In addition, considering the intensity effects, multi-particle tracking are crucial to reflect the emittance blowup in the MEBT region, especially for the high beam intensity for the CSNS-II. MEBT lattice matching shold be done for each beam intensity and our initial results show that it can effectively suppress the emittance blowup in the DTL region. The DTL matching experiment will follow this study and the process described in this paper can be applied to study the beam parameters after the DTL.

REFERENCES


