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SIMULATION STUDIES ON THE LOW ENERGY BEAM TRANSFER (LEBT) SYSTEM OF THE ISIS NEUTRON SPALLATION SOURCE

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Abstract

The transmission efficiency and beam dynamic parameters of the low-energy beam transfer (LEBT) section of proton accelerators, serving as a neutron spallation source, have a critical impact on beam loss in subsequent sections of the linear accelerator. Due to variations and mismatches, the beam parameters at the entrance of the radio-frequency quadrupole (RFQ) change, significantly affecting the transmission efficiency of the RFQ and the matching between RFQ and drift tube linac (DTL) structures. Recognizing the importance of this concept, particle-in-cell studies were conducted to optimize the LEBT section of the ISIS accelerator. This study presents the results of simulations.

INTRODUCTION

Nowadays, proton or H- linear accelerators find a wide range of applications, with one of the most significant being neutron spallation sources. The ISIS neutron spallation source stands as a renowned research centre, having provided neutrons to the user community for almost 40 years. Beam parameters are matched between the ion source and RFQ by the LEBT and is planned between the RFQ and DTL by a new MEBT sections [1, 2].

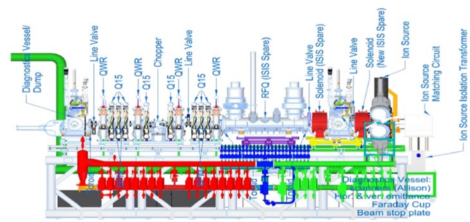
Two types of H- Penning ion sources are currently in use, one on the existing ISIS machine, and one on (Front End Test Stand) FETS. The high output current of these ion sources necessitates use of caesium which limits the lifetime and typically results in replacement every two weeks. Recently, RF ion sources are being developed at ISIS, offering greater reliability and longer lifetimes, albeit with lower current density compared to their predecessors [3].

In the current configuration of the machine, it is desirable to extract higher currents out of the ion source and transport to the end of RFQ, accepting poor transmission into the DTL to obtain 25 mA for injection into the RCS. Following the machine's upgrade with the MEBT section, the required current at the output of RFQ will be 25 mA instead of 35 mA for the current RCS operation. The MEBT design also includes a chopper which will be synchronised to the ring RF system to place beam directly into the RF bucket, removing beam losses associated with RF capture [4, 5].

Figure 1 depicts the LEBT section, while Table 1 reports the simulation beam parameters at the output of the Penning and RF ion sources, along with the matched beam parameters at the entrance of the 665 keV RFQ.

The unnormalized rms beam emittances is $\varepsilon_x = \varepsilon_y = 34.24\,\pi$ mm mrad. The ISIS and FETS ion sources are 35 keV and 65 keV respectively.

In every scenario, it is imperative to achieve complete matching between the ion source and RFQ to attain the maximum possible transmission of the H- ion beam. Besides ensuring the correct settings for solenoid magnets and drift distances, it is crucial to take into account the process of space charge compensation (SCC). For this investigation, we have focused solely on the pure reduction of beam current and conducted simulations using TRACE beam envelope and Parmila PIC codes for the ISIS LEBT section [6,7].



(b)

Figure 1: Drawing of ISIS low energy section including ion Source, LEBT, RFQ and MEBT.

STUDY OF LEBT PARAMETERS

The LEBT section of ion accelerators typically comprises a pumping section, diagnostic box, solenoid magnets, and collimators. The parameters of the LEBT section have been optimized using the TRACE-3D code. The simulation layout and parameters of the LEBT section are illustrated in Fig. 2. The solenoid fields for different beam currents after compensation are presented in Fig. 3. It is noteworthy that the variations in magnetic field strength in both solenoid-1 and solenoid-2 remain linear during the process of matching beam parameters between the ISIS RF ion source and RFQ in LEBT/MEBT arrangement.

When adjusting the solenoids to achieve a complete 90% beam space charge compensation for a 35-mA beam, any deviation in the level of compensation can lead to changes in the beam Twiss parameters and subsequent variations in beam emittance. This variation becomes particularly significant during the transition to 100% compensation. The maximum achievable level of compensation is contingent upon the vacuum conditions and the combination of gases present within the ion source and LEBT section.

To better understand the effects of compensation with solenoid adjustments, a study was conducted for a 3.5 mA (90% beam compensation), exploring different compensation percentages ranging from 85% to 100%. This analysis estimated the Twiss parameters α and β, considering the degree of mismatch. Notably, the change in α was found to be linear, while β exhibited a nonlinear response. These results are presented in Fig. 4. These results pertain to a uniform charge distribution, and it is noted that for other types of charge distributions such as Waterbag and Gaussian, the

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Table 1: Beam Parameters at Output of RF and Penning Ion Sources and Desired Parameters for RFQ Input

Parameters	α_x	β_x (mm/mrad)	α_y	β_y (mm/mrad)	α_z	ε_x-unnorm (π·mm-mrad)	ε_y-unnorm (π·mm-mrad)
RF ion source	-6.068	0.373	-6.068	0.373	0.0	34.24	34.24
Penning ion source	-5.05	1.49	-2.62	1.07	0.0	46	46
Desired beam at RFQ entrance	1.08	0.039	1.08	0.039	-0.127		

outcomes may differ. The mismatch factor is calculated based on Eq. (1):

$$F=\sqrt{\frac{1}{2}\left(R+\sqrt{R^2-4}\right)}-1. \quad (1)$$

In this equation R= $\beta_{RFQ}\Upsilon_{Trace\text{-}3D}+\beta_{Trace\text{-}3D}\Upsilon_{RFQ}-2\times\alpha_{RFQ}\times\alpha_{TRACE\text{-}3D}$ [7]. By application of this mismatch factor, it is possible that the percentage of space charge compensation may be deduced.

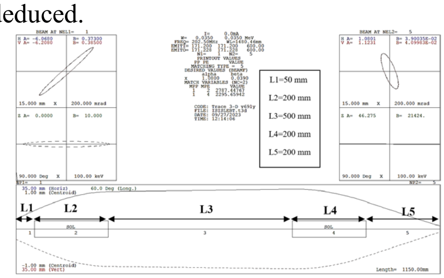


Figure 2: ISIS neutron spallation source LEBT section modelling in Trace beam envelope code.

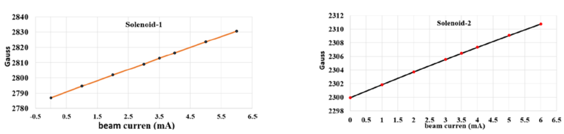
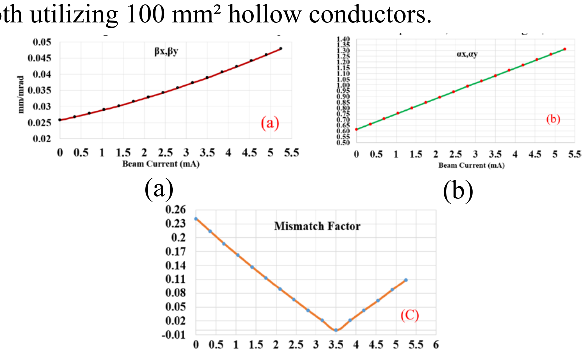


Figure 3: Solenoid magnet adjustments for matching with respect to the percentage of beam current compensation.

SOLENOID MAGNETS

After these preliminary calculations, it is necessary to design the required solenoid magnets. The design of these solenoids was carried out using CST Studio Suite and is presented in Fig. 5 [8]. This design includes 4 pancake coils with 12 windings and 5 pancake coils with 10 windings, both utilizing 100 mm² hollow conductors.



(a) (b)

(c)

Figure 4: The variation in Twiss parameters and mismatch factor in response to different levels of beam space-charge compensation (a) β_x, β_y, (b) α_x, α_y, (c) Mismatch factor.

To simplify calculations in the Parmila code, the magnetic field intensity was adjusted based on the optimal parameters for a 3.5 mA beam after compensation, as shown in Fig. 6.

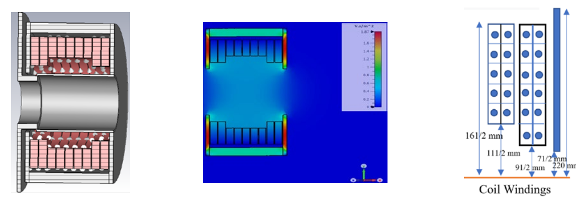


Figure 5: Solenoid magnet design for ISIS LEBT section.

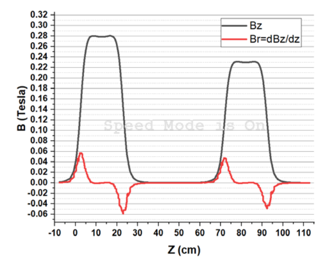
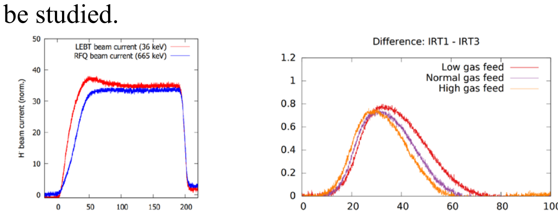


Figure 6: Solenoidal magnetic field distribution in LEBT.

The background pressure in the ISIS ion source and LEBT is on the order of 10^{-5} mbar, which means that the space charge compensation time, measured from the beginning of the beam pulse to reach the final space charge compensation degree, is around 60 – 80 µs. This process was measured in the ISIS LEBT section based on beam current pulse length measurements after the ion source (IRT1) and RFQ (IRT2), as shown in Fig. 7-(a). Also, the effect of pressure on the space charge compensation are presented in the Fig. 7-(b). Therefore, in the beam dynamics calculations with Parmila, we should consider currents of 35 mA before compensation and 3.5 mA after compensation (90% space charge compensation). Any fluctuation in the vacuum level will result in different compensation values. In the next section, the effects on the output beam parameters will be studied.



(a) (b)

Figure 7: Space-charge compensation time (a) experimental measurement (b) Test in different vacuum pressures.

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SIMULATION STUDY OF ISIS LEBT

The studies were done for three different particle distributions: KV, Waterbag and Gaussian beams, as shown in Fig. 8. The beam RMS size and normalized emittance will change for the three different beam distributions according to Figs. 9-a and 9-b.

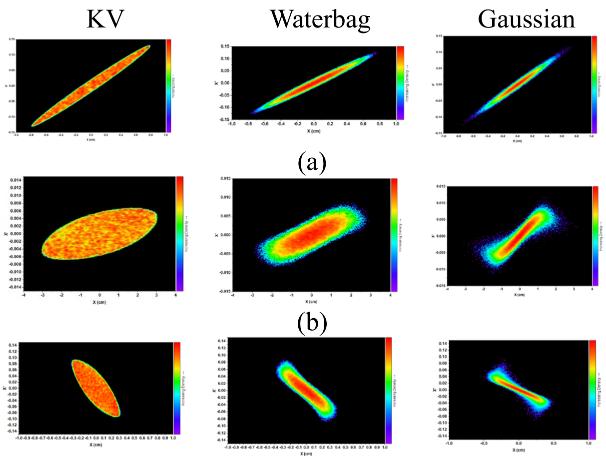

Figure 8: Beam transverse phase space distribution in X-X' at the (a) extraction point of ion source, (b) measurement location, (c) at the entrance to RFQ.

The beam has different parameters in transient and steady state due to SCC with different currents of 35 mA and 3.5 mA (90% SCC). The beam transmission efficiency for 35 mA is 74% (25 mA). But Twiss parameters and emittance will change, resulting in changes to the beam transmission efficiency through the RFQ. The beam shape in the position of the beam diagnostic box for two different beam currents are shown in Fig. 10.

The nonlinearity of space charge is clear in Fig. 10. Additionally, increased beam divergence leads to aberration in the beam distribution. The output beam exhibits additional traces of distributions that significantly impact beam matching, transmission, and have a considerable effect on beam loss and halo formation in the transmission line of the ISIS linac. The parameters for the waterbag distribution, when compared to the uniform distribution (Trace beam envelope code), are presented in Table 2. According to these results, the 35-mA beam is completely mismatched with the RFQ matching section, resulting in drastic losses inside the RFQ and partial halo formation. This leads to further losses downstream in the DTL and High Energy Drift Space (HEDS) of the ISIS linac.

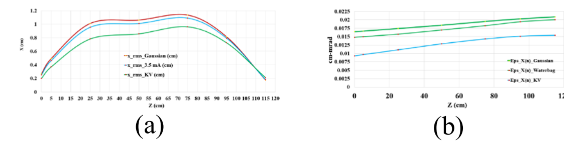

Figure 9: Beam parameters for three different initial beam distributions along the LEBT (a) rms beam size, (b) normalized emittance

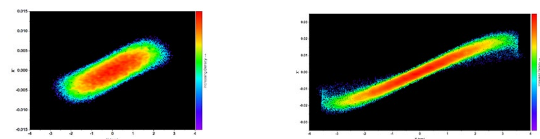

Figure 10: Beam phase space (a) in diagnostic box for 3.5 mA (left) and 35 mA (right)

CONCLUSION

This study was done to estimate the design and optimization of the LEBT section, specifically focusing on achieving 90% space charge neutralization. The solenoid values required for beam matching to RFQ were assessed across a range of SCC levels from 85% to 100%. The study also explored the variation in beam Twiss parameters, revealing a linear variation in α and a nonlinear variation in β. Mismatch factors were evaluated for each scenario and change between 0.01 to 0.23.

Preliminary design and positioning estimates, including solenoidal field requirements, were carried out, leading to the design of solenoids using CST Studio Suite that is 2800 and 2300 Gauss for solenoids 1 and 2, respectively. Subsequently, comprehensive Particle-in-Cell (PIC) simulations of the LEBT section were conducted with Parmila for three distinct beam distributions: KV, waterbag, and gaussian. The study involved plotting beam emittance growth and beam size along the LEBT.

Notably, the study revealed that the main loss and halo formation occurred due to the transient behaviour of the beam, particularly in the transient section of time characterized by completely mismatched Twiss parameters.

ACKNOWLEDGMENT

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Table 2: Comparison of Beam Parameters before and after Transient of SCC at the RFQ Matching Section

Beam current		α_x	β_x (mm/mrad)	ε_x-norm-rms (π-mm-mrad)	Solenoid-1 (Gauss)	Solenoid-2 (Gauss)
3.5 mA-Desired RFQ matching	Uniform	1.08	0.039	0.295	2812.81	2302
3.5 mA	Waterbag	1.0879	0.0474	0.357	2812.81	2302
35mA	uniform	5.208	0.347	0.295	2812.81	2302
35mA	Waterbag	3.69	0.406	0.4436	2812.81	2302

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