IN-DEPTH ANALYSIS AND OPTIMIZATION OF THE EUROPEAN SPALLATION SOURCE FRONT END LATTICE

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Abstract

The European Spallation Source front end will deliver a 62.5 mA of DC beam current of 2.86 ms duration flattop to the downstream linac, which in turn will produce a 5 MW proton beam onto the target. Such unprecedented beam power requires a high quality beam with accurate and stable beam parameters in order to assure low beam losses and safe transport through the linac. In this paper we present advanced tuning methods for the low energy beam transport and the radio frequency quadrupole.

INTRODUCTION

The ion source and Low Energy Beam Transport (LEBT) for the European Spallation Source (ESS) are already under commissioning at the in-kind partner INFN/LNS in Catania, Italy. The beam properties that this front end can provide sets the beam dynamics performance for the rest of the machine, making it essential to understand properly how we can optimise and tune its performance. The plasma physics of the ion source is a complicated challenge which we will not discuss further in this paper. More details about the ESS ion source can be found in [1, 2].

The main elements of the LEBT are the two focusing solenoids, the chopper, and the instrumentation to measure the beam properties. The beam at the ion source exit has an energy of 75 keV, so the space charge forces are naturally quite high, and a good space charge compensation is required in order to keep the beam emittance at a reasonable level. For the current LEBT lattice we are assuming 95 % space charge compensation.

LEBT LATTICE

The LEBT lattice used in these studies can be found in [3], also shown in Fig. 1. The total length of the LEBT is 2.53 m from the IS-LEBT beam physics interface to the inner wall of the RFQ. The two solenoids are 330 mm long, one placed 405 mm from the interface and the LEBT, while the second is placed 355 mm from the interface between the LEBT and the radio frequency quadrupole (RFQ). Other major components of the LEBT lattice are the iris and the diagnostic box which are placed between the two solenoids, and a collector located just before the RFQ entrance.

The space charge compensation is ensured through proper distribution and combination of the gas in the beam chamber. The beam collides with the residual gas in the chamber, and ions form to compensate for the strong space charge forces in the beam. This process takes about 20 μs to build up [4]. As there are several gas injection points in the LEBT there is a vacuum valve just upstream of the RFQ to protect it in case there is a undesired vacuum breach in the LEBT. It has been discussed if it would make sense to move the vacuum

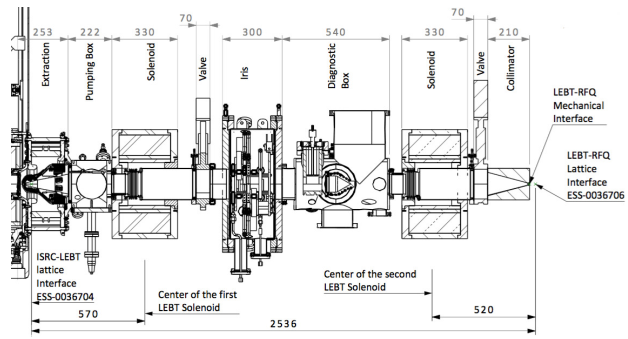


Figure 1: The current LEBT Layout [3].

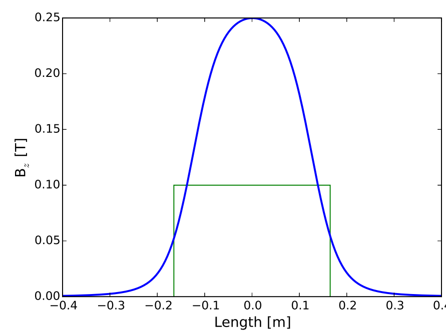


Figure 2: The LEBT 1D field map. The blue line shows the magnetic field along the beam axis. The green box indicates the extent of the solenoid (330 mm).

valve upstream of the second solenoid, i.e. swap the position of the second solenoid. That would require the solenoid to operate with a stronger field (stronger focusing), but would mean that the average beam size is larger in the last part of the LEBT and so reducing the space charge forces.

FIELD MAPS AND INTEGRATED MODEL

The simulations are done using TraceWin [5], which internally uses Partran for tracking in the LEBT and Toutatis [6] for tracking inside the RFQ. TraceWin has an internal solenoid model which is described in the manual. This is a basic solenoid model assuming perfect axial symmetry without fringe fields. We have also developed our own field map model of the solenoid, shown in Fig. 2. Both implementations yielded similar results in the studies presented here.

METHOD

The main method to optimise the beam through the front end is by tuning the solenoid amplitudes in order to optimise the transmission of accelerated particles through the RFQ. Hence, this is also what we have now applied a similar simulation technique which is presented here. The more straightforward matching between the LEBT and the RFQ typically done in simulations, is to match the input Twiss parameters. Such a method can be considered more of an optimisation for the core of the beam, while what presented here is more of an optimisation for the halo of the beam.

For each setting of the two solenoid amplitudes, we track 50 000 macro-particles through the LEBT and RFQ. We then calculate the transmission as the number of particles which are accelerated to at least 85 % of the nominal energy. The majority of the particles have an energy distribution within ± 10 % of the nominal energy (3.62 MeV).

After a full scan is performed, we do a cubic interpolation to find the optimal settings. This final setting is checked with 10 times more particles in the simulation to confirm that there was no bias because of the somewhat low number of particles for the simulation of each setting. The difference between the two is reasonable, mostly related to having better statistics in the halo and loss pattern.

RESULTS

In Fig. 3 we show two examples of results of a parameter scan for two different emittances, 0.12 π.µm·rad and 0.18 π.µm·rad . A typical "banana-shaped" matched region is found. We see that the optimal transmission is more stable when the two solenoid are moved in opposite directions (x = -y) rather than in the same direction (x = y).

The transmission limit of 90 % and 95 % are shown in Fig. 3, as well as the peak location. The size of the transmission limit region gives a good indication of how difficult it will be to obtain this in commissioning. A smaller region will require more accurate commissioning methodology.

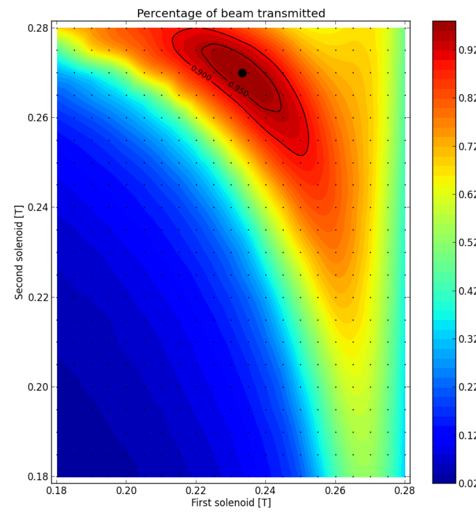
In Fig. 4 the 3 sigma envelope of the matched beam is shown, again for 0.12 π.µm·rad and 0.18 π.µm·rad . We can here note that the beam is slightly more mismatched for the larger emittance, something that indicates that there is a larger difference in this case between matching the core and halo of the beam. The transverse oscillation is in both cases quickly dampened in the RFQ and makes little difference for the output beam.

It is also noticeable that it looks like for the 0.12 π.µm·rad case in particular that the beam is larger in the second solenoid. This is however only present in the halo of the beam. The 1 sigma envelope is equally large through both solenoids.

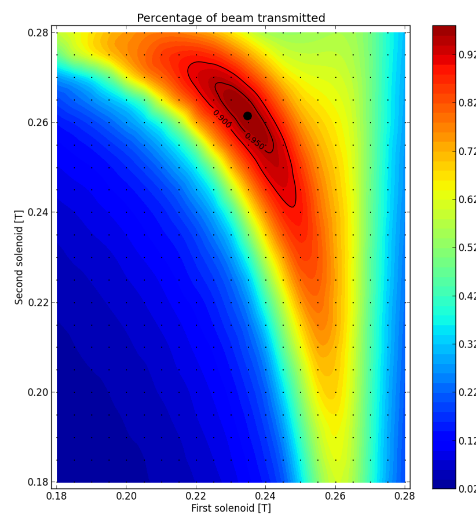
The difference in the relative amount of non-accelerated particles in the beam coming of the RFQ does not vary significantly in the simulations. The minimum fraction of acceleration is around 96 % which means we will have a maximum of around 4 % of non-accelerated beam out of the RFQ. For the optimal transmission we have close to 100 % captured beam, hence maximising the current out of the RFQ seems to coincide with maximising the transmission of accelerated particles out of the RFQ.

VACUUM VALVE POSITION

The main performance limiting factor of the LEBT from a beam dynamics point of view is the space-charge forces which increase the beam emittance. This can be mitigated by having a shorter LEBT, or having high space-charge compensation. Another idea came up to move the last



(a) 0.12 π.µm·rad transverse input emittance



(b) 0.18 π.µm·rad transverse input emittance

Figure 3: The fraction of accelerated and transmitted beam through the RFQ for two different beam emittances coming out of the ion source. Two islands are denoted in the figure, the 95 % transmission limit and the 90 % transmission limit.

vacuum valve which is currently just after the second solenoid, to before the second solenoid. This would mean that the average beam size through the LEBT is increased, at the cost of needing a stronger solenoid field in the second solenoid (stronger focusing). We have studied this solution applying the same simulation techniques.

The width of the valve is 70 mm, and is from a beam dynamics viewpoint a drift space. Hence the modification we have done to the lattice is to move the solenoid 70 mm closer to the RFQ entrance. This can be considered a minimal improvement obtained from this change. In addition to the 70 mm for the valve itself, there will also be the need to move

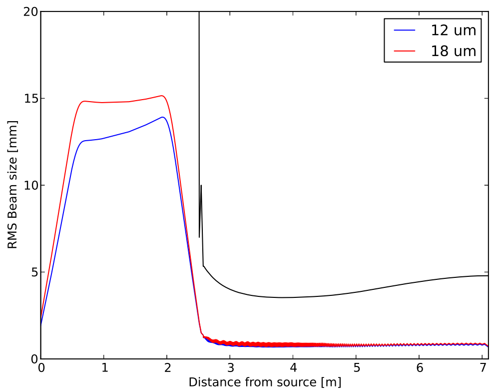


Figure 4: Comparison of transverse beam envelopes for 0.12 π.µm·rad (blue) and 0.18 π.µm·rad (red). The black line shows the aperture in the simulation (50 mm radius in the LEBT). The beam is symmetric and centred in this part of the machine when misalignments are not considered.

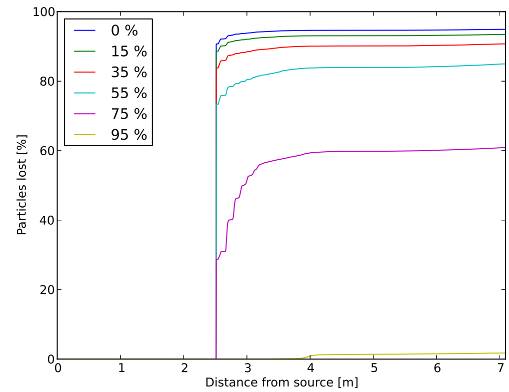


Figure 5: The losses through the LEBT+RFQ when varying the space-charge compensation in the LEBT. The legend denotes the space-charge compensation after the LEBT chopper location, until the RFQ entrance.

some more space to allow for the access to the bolts that fix the flange onto the beam pipe.

HEAD OF PULSE

The ESS pulse will be chopped in two stages. The first chopper is in the LEBT between the two solenoids. The second chopper sits in the MEBT. The reason to have the second chopper is because the space-charge compensation takes about 20 μs to build up in the LEBT [4]. This means that the first 20 μs of the pulse out of the LEBT will be effectively mismatched with respect to the rest of the pulse. Hence the idea is that this part will be chopped off in the MEBT.

To understand the importance of the MEBT chopper, we have performed a study where we looked at varying space-charge compensation downstream of the LEBT chopper. The beam losses for varius compensations are shown in Fig. 5. An example comparison of the beam out of the RFQ can be seen in Fig. 6. We see that with reduced compensation the size of the beam does not increase dramatically. However there is a visible filamentation of the beam that has happened as it goes through the RFQ, and the tails are not anymore as Gaussian as for the full (95 %) space charge compensation.

CONCLUSIONS

We have in this paper discussed several studies which confirm that the current design should be able to deliver within the required specifications. The transmission through the RFQ is well above requirements (62.5 mA), but one has to remember that we have not looked at magnetic/RF/vane machining imperfections, installation tolerances etc. The RFQ tolerances are discussed in [7]. Should the performance of the front-end system as a whole be below the needed performance, then our study show that moving the last vacuum valve upstream of the second solenoid will improve the beam dynamics of the LEBT on the 5 % level. We may decide to make this configuration change when we install the LEBT in the ESS tunnel, if it is not too complicated to do mechanically.

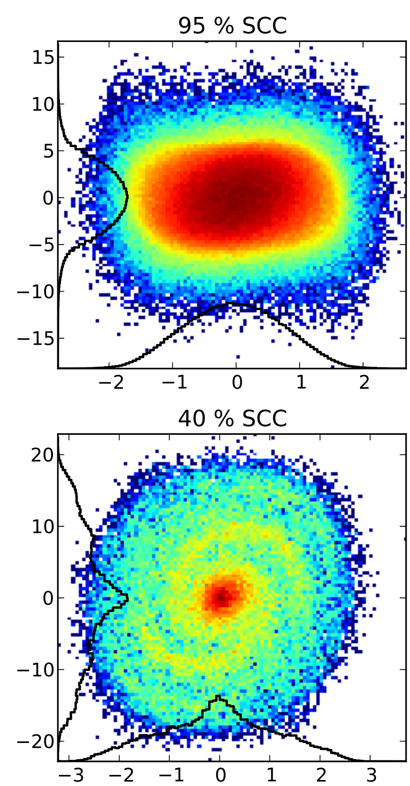


Figure 6: The phase space distribution (X-X') of the beam out of the RFQ for 95 % (top) and 40 % (bottom) space-charge compensation in the LEBT after the chopper.

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