Comparison of the Beam Dynamic Solutions for Low Energy Beam Transport Systems for a Laser Ion Source at CERN

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I. INTRODUCTION

The low-energy beam transport (LEBT) on the Laser Ion Source (LIS) is a very delicate part of the pre-injector, due to the large space-charge forces and the many charge-states present. Two types of focusing system have been realised and fully tested.

Firstly, a two-solenoid LEBT was built, but this was shown to suffer from non-linear space-charge forces due to the different charge-states present in the beam, which produced an unacceptable growth of emittance[1].

A second LEBT uses gridded electrostatic lenses (GEL)[2] to focus the beam, but suffers from some emittance growth (from measurements) and shows difficulty in holding the high potentials required. This second voltage holding effect has not been understood at this time, as the system has in the past held higher voltages than presently. The higher laser energy and repetition rate, compared to the test source, will increase both the radiation flux and vacuum pressure, which may increase the flashover rate. Furthermore, the test source has shown degradation of the grids, which will be greatly increased at 1 Hz rep-rate.

Hence, a study of six different LEBT configurations was performed from a beam dynamics standpoint. The aim was to narrow the choice down to a few examples of focusing systems that could be built and installed on the CERN LIS. The list includes the GEL and a two-solenoid LEBT so that any future schemes can be properly compared to the previous installations.

The simulations have been performed with three different codes – CPO, KOBRA3 and IGUN. These codes were cross-checked against each other in a separate study and were shown to have good agreement [3]. Furthermore, it was shown that the codes agree to within 8% of transmission for the existing GEL beam line.

INITIAL BEAM FOR SIMULATIONS

The initial beam for all simulations is generated according to measurement 47 mm after the extraction system. For the GEL LEBT this is the plane of the first grid. At this place the current, the emittance and the Twiss parameters have been measured and a set of 15,000 particles has been generated with this parameters. In Figure 1 the real space and in Figure 2 the phase-space (xx') is shown. The average current was 74 mA. For simulations of magnetic LEBTs, the charge-state distribution was taken from measurements of the CERN LIS plasma distribrution of Tantalum, shown in Figure 3. Simulations of electrostatic LEBTs used only Ta^{20+}.

None of the simulations take into account the following effects: i) variation of the ion current and other ion beam parameters during the ion pulse [4], ii) space-charge compensation by electrons.

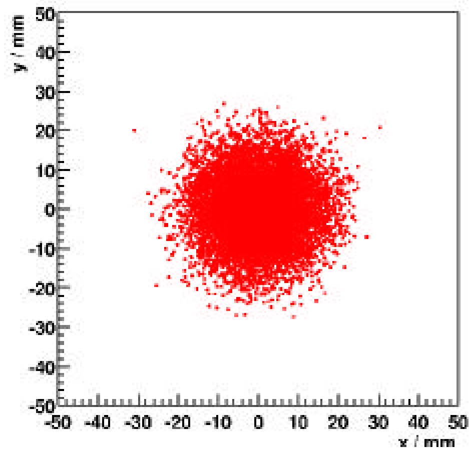

Figure 1 Real space plot of the initial beam distribution.

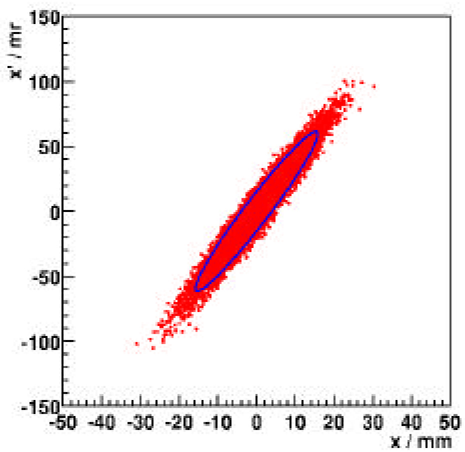

Figure 2 Phase space plot (xx') of the initial beam distribution using the first 11000 rays. The emittance is 240 mm mrad and the Twiss parameters are α = -3.8, β = 1.033 m^{-1}, γ = 15.55 mrad.

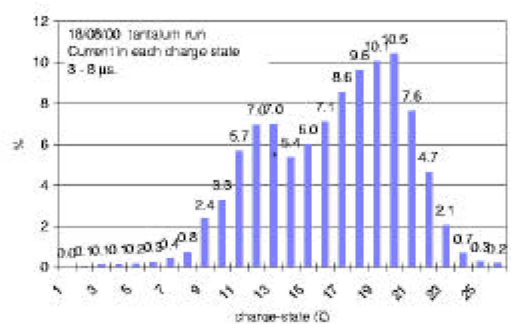

Figure 3 Charge-state distribution used for simulations.

ESQ LEBT – PRELIMINARY RESULTS

An electrostatic quadrupole (ESQ) LEBT has been studied for the CERN laser ion source using KOBRA3 (3.39)[5]. The ESQ LEBT has the advantage of not having grids inserted in the beam line as is the case with the present GEL (gridded electrostatic lens) LEBT. From the beam dynamics point of view, the main difference with respect to the GEL or a solenoid lattice is that an electrostatic quadrupole focuses the beam in one dimension while it is defocusing in the other. Two geometric solutions have been considered: one that is used at LBNL [6] and one that is used at CERN with ISOLDE [7].

LBNL Geometry

As a first example, a geometry described by LBNL [6] was put into KOBRA and run with a typical LIS beam with parameters as measured after the 110 kV extraction. The standard beam input parameters were used with 15,000 macro particles. These preliminary simulations were performed with zero beam current.

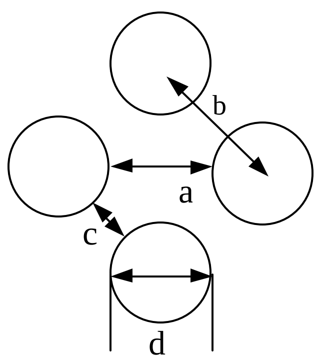

Figure 4. Geometry of the LBNL type ESQ. The geometry used is as follows:

Aperture (a): 6.0 cm
Rod center-to-center distance (b): 9.09 cm
Rod surface-to-surface distance (c) 2.22 cm
Rod diameter (d): 6.88 cm
Rod length: 8.26 cm
V_{max} : 270 kV

It was decided to use three cells of the LBNL geometry which should act as a triplet. Various settings were applied but either the focusing was not satisfactory or the particle loss unacceptable. For the setting ±20 kV, ±40kV, ±20kV (alternating polarity of the lenses), the following transmission was found: at the exit of cell 1, 92% of the particles had survived, at the exit of cell 2 80% and at the exit of cell 3 only 45%. No setting was found which gave both satisfactory transmission and focusing. It should be mentioned that the geometry influences very critically the beam dynamics and we have by no means optimized the dimensions. In a collaborative effort, LBNL are now studying, by simulation, a geometry design (with several quadrupoles of different apertures) better adapted to the CERN LIS.

Rather than optimizing this geometry, we have simulated another set-up which is presently operated at CERN and shows good performance when used with μA beam currents.

ISOLDE Geometry

It was decided to examine a geometry used at ISOLDE. This ESQ LEBT is used to transport μA beam currents. It was designed by the University of Giessen using the code GIOS. It consists of three equal cells with the following dimensions:

rod length: 2.90 cm
rod diameter: 25 mm
rod center-to-center distance: 16.5 cm

With ISOLDE, it is used as a triplet with cell 1 at 1.7 kV, cell 2 at 3.47 kV and cell 3 again at 1.7 kV. The vacuum is 1-2 x 10^{-6} mbar and flashover is not a problem. The emittance growth across the LEBT is not known [7].

In a first simulation, the ISOLDE settings of 1.7/3.47/1.7 kV were applied. The transmission was 100% due to the large aperture of the system, but the beam blow-up was unacceptable. Hence higher potentials were applied, in first approximation with zero beam current. For the setting 4/8/4 kV, the transmission was found to be 100% but no focusing occured. For the setting of 10/20/10 kV, the transmission dropped dramatically (Table 1). Higher potentials, such as 15/30/15 kV, also resulted in unacceptable losses. Higher settings are apparently impossible, as the defocusing effect becomes so strong that losses occur in one plane. The best setting found within this study was 10/20/10 kV. However, simulating this case with 70 mA beam current resulted also in unacceptable losses. All cases with the transmission at the exit of the three cells are summarised in Table 1.

Table 1. Summary of current transmission, as a function of the ESQ settings.

Beam current	0mA	0mA	0mA	70mA	0mA
V1 [kV]	1.7	4	10	10	15
V2 [kV]	3.47	8	20	20	30
V3[kV]	1.7	4	10	10	15
exit cell 1	100	100	99	99	97
exit cell 2	100	100	97	90	91
exit cell 3	100	100	85	47	46

SOLENOIDS

Solenoid LEBT simulations with CPO

The aim was to study a LEBT built from one or both of the existing LIS solenoids with their power supplies. These are limited in the repetition rate and the magnetic field due to heating (0.25 Hz at 1.25 T) [8]. For the study, the magnetic field map of these solenoids has been used assuming linear behaviour of the magnetic field with current, even above the maximum field of 1.5T.

Simulations were done using tantalum beam containing Ta^{20+} ions or using the following charge states:

8,10,12,14,16,18,19,20,21,22,24; with an energy corresponding to 110 kV extraction voltage. With only one charge state 11000 out of the 15000 rays were used. Otherwise for each charge state the first 1000 rays were used for each charge state and the current for each charge-state was set proportional to the measured charge-state distribution. The 4-rms emittance at the entry plane is 240 mm.mrad.

A one and two solenoid LEBT was used on the CERN LIS at extraction voltages of 60-80 kV [9]. These simulations should show whether the same set of solenoids is still usable for the proposed extraction voltage of 110 kV used at the CLIS with the new 100 J CO_2-laser. A possible advantage of the solenoid LEBT could be the better stability compared to the GEL.

Single solenoid LEBT

To get an idea which solenoid current is needed to focus Ta^{20+} ions, only this charge state was used for the first iterations. For magnet currents, which focused this beam, a beam containing multiple charge-states was used. The position of the waist for Ta^{20+} was obtained from the rays at different longitudinal positions. The waist was found either by fitting the Twiss α to a linear function or the Twiss beta to a second order polynomial. Results for different solenoid currents are shown in Figure 6.

To get the current into the aperture of a RFQ, a double square aperture cup was used at different longitudinal positions. The square is 5.9 mm wide and the distance between the two apertures is 44 mm. The cup position is defined as the centre plane between the two apertures. The double aperture cup's longitudinal position was varied around the position of the waist. For each position the current of each charge-state passing through both apertures is plotted in Figure 7. As expected, moving the cup towards the solenoid increases the current of the higher charge states. Increasing the solenoid current above 2760 A moves the waist inside the solenoid and was therefore not further investigated. The highest current for Ta^{20+} ions was 3.5 mA and it was reached for 2760 A in the solenoid.

The 4rms emittance at the position of the waist is, for the 20+ charge-state only, 600 mm mrad at this position corresponding to an emittance blow-up of 2.5. A problem for verification is that only the total emittance of all charge states can be measured, which is simulated to be 2200 mm mrad.

The present solenoids are not capable of a 1 Hz operation with this current. Therefore a new solenoid has to be built with a maximal field on axis of at least B=2 T.

Two solenoid LEBT

In this case the current was varied on both solenoids but limiting it to values far below 2500 A, where only 0.25 Hz are possible. For this cases the distance between the two solenoid was fixed to 37 cm, at which distance the measurements with the 60 kV extraction were performed. The spacing of the two solenoids was not optimised for this simulations. The current in the first solenoid was increased until no 20+ ions were lost on the wall of a r = 5 cm standard vacuum tube. This corresponded to a current of 1800 A. Starting from 1800A / 1800A as currents for the two solenoids their currents were changed in steps of 200 A until the best configuration of 1800 A and 2000 A was found. The Twiss parameters for this case are shown in Figure 8. Figure 9 shows the total current into the double aperture cup and Figure 10 the charge-state distribution.

Conclusions

A LEBT built with one of the existing solenoids is not capable of transporting a beam with the final LIS parameters due to limitations in solenoid cooling. Using a two solenoid LEBT decreases the current into the double aperture cup and the two solenoids are operated near their limits. From the specifications it is not certain if an operation with 2000 A at 1 Hz is possible and should be tested. Otherwise a single solenoid LEBT with one new magnet is the preferable solution.

The emittance increase of a factor 2.3 for only one charge-state is acceptable, but this single charge-state emittance is not accessible by measurements. Due to the separation of different charge-states the total emittance grows much more rapidly.

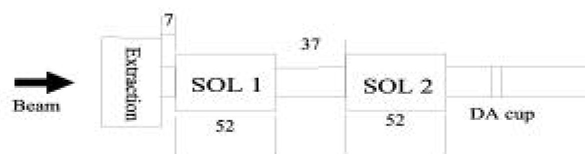

Figure 5: Sketch of solenoid beam line with 1 and 2 solenoids. Distances are given in cm.

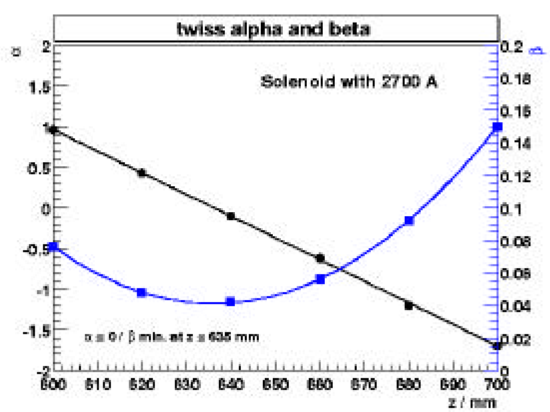

Figure 6 Twiss parameters at different positions after the solenoid which ends at z = 590 mm.

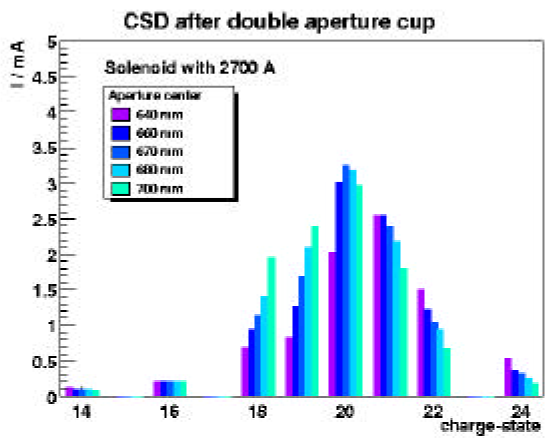

Figure 7 Charge state distribution for the optimal solenoid current in the single-solenoid LEBT.

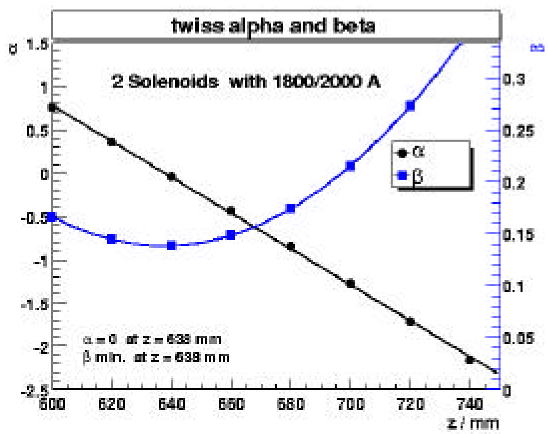

Figure 8 Twiss parameters for the optimal solution found for a two-solenoid LEBT.

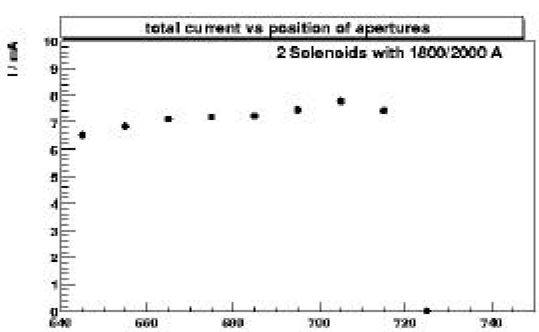

Figure 9 Total current through the double aperture cup for the optimal current settings.

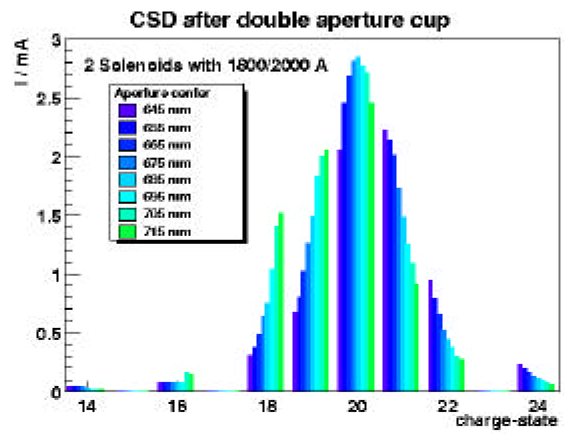

Figure 10 Charge state distribution after the double aperture cup for a optimised two solenoid LEBT.

EINZEL LENSES

The Einzel lens is a very effective and simple way to focus a charged particle beam. In its simplest form, it consists of a vacuum tube held at ground potential, with an isolated ring on which a potential is applied.

However, this type of lens is known to suffer greatly from spherical aberrations, primarily as the energy of the beam is changed as the particles approach the polarized ring. Furthermore, the Einzel lens inherently consists of a focusing and defocusing area, which act like a FD lattice to focus the beam. This gives a rather weak focusing and it may be difficult to overcome the space-charge forces of the LIS ion beam.

Results

Simulations were performed in IGUN, modeling a beam of Ta20+ accelerated through the 110kV. It was not possible to converge to a solution that allowed reasonable focusing of the LIS beam. Shown in Figure 11 below is an example of a simulation result with three consecutive Einzel lenses, each at a potential of 70kV. The small spacing between the high and ground voltage pieces leads to high fields which would already be very difficult to achieve in practice. It is clearly seen from the figure that the beam has not been brought to a small waist, while the beam phase space is highly aberrated.

Reversing the polarity of the rings reduces the aberration as well as the focusing strength, and therefore does not lead to an overall improvement. The aperture of the Einzel lens cannot be increased in order to reduce aberrations, as this would place an impossible demand on the voltage holding of this system.

The solution to increase the focusing strength and reduce the aberration is to add grids between the cells. Added to all the electrodes leads to the situation of the GEL. A solution that may be interpreted as a half-cell GEL, was designed and built for a LIS at GSI [10]. A version of this type of LEBT was realised and the authors reported satisfactory performance. This idea can be adapted to the LIS, and a simulation of such a design in shown in Figure 12, where a 90kV electrode is required. However, this approach does not have a significant advantage over the GEL (except for reduced number of grids), and hence further studies were not continued.

Conclusion

The use of Einzel lenses does not appear to apply to the high current beam of the LIS, as the focusing strength cannot be increased sufficiently to overcome the high space-charge forces. The transmission is assumed to be so low that a figure is not given. There is still some interest in the "half-cell" GEL focusing system, but it does not appear to have any advantages over the presently existing GEL.

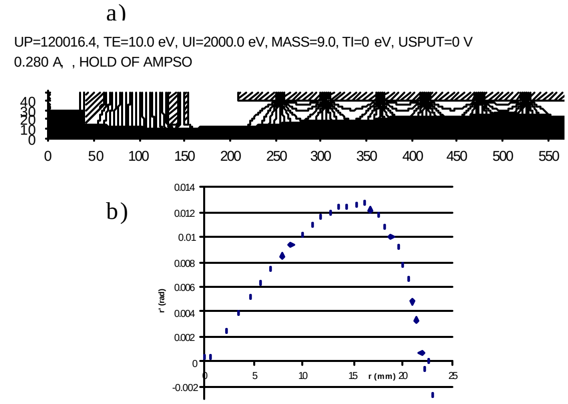

Figure 11. a) Transverse profile of ray tracing and b) r-r' phase plot for the beam at the output of a threeeinzel lens system.

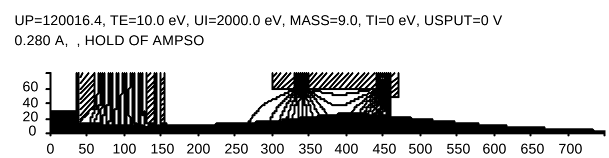

Figure 12. A "half-cell" GEL focusing system.

DISPERSIVE LEBT

In order to use magnetic elements and reduce the total current density of unwanted charge-states, a LEBT incorporating charge-state selecting bending magnets has been studied. The form of this LEBT is similar to that presently installed on Linac 3. The study of such a LEBT for a LIS has previously been proposed and studied in a preliminary form by A Lombardi [11].

The simulation results are considered to be only preliminary for the study of this type of LEBT. The magnetic elements consist of the idealised elements found in PATH/TRAVEL, and the optimisation of the line has not been completed. Several more approximations were also made, in response to problems and bugs with the code, which are detailed in the following sections.

Results

The standard LIS input beam was used, and charge-states were assigned to the macro-particles in order to arrive at the LIS charge-state distribution [12]. A layout of the transport line is given in Figure 13, and consists of two solenoids, two 45 degree bending magnets and four quadrupoles.

The charge-states are separated at two sets of horizontal slits.

The charge-state distribution traversing the second set of slits is give in Figure 14. At this point the reference beam (Ta^{20+}) was off-axis, which would have a grave effect on the beam quality when focused in the solenoid. The reason for this off-axis shift could not be quickly identified, and hence the reference beam was re-centred in x-x'-y-y' and simulation the continued with only this reference charge-state.

The beam was finally focused by a solenoid and the transmission through a double aperture (5.9x44mm) was found. Some optimisation of the solenoid setting and aperture position was performed in order to achieve good transmission. It was found advantageous to use a short solenoid with a high magnetic field.

In total, 3.6mA of Ta^{20+} was transmitted from an input of 7.0 mA, hence a transmission of 51%. The total input current was 60 mA. The phase space and intensity distributions for the horizontal and vertical planes are given in Figure 15.

Remarks about the Simulation

For completeness, the limitations of the simulation are again repeated, so that the present results can be put into context.

1. Idealised magnetic fields are used for the quadrupoles, solenoids and bending magnets.
2. The beam was not correctly steered at the exit of the second bending. The beam was centered at the input of the simulation, and was still on axis at the input to the first bending magnet. The particles were recentered at the second slits.
3. Only Ta^{20+} was simulated after the second slits, mostly because of the difficulty in deciding how to recentre beams other than the reference charge-state, as they should clearly be off-axis.
4. The radially symmetric space-charge model of TRAVEL was used.
5. The beam had no energy spread.

With some effort, all the above limitation can be resolved to allow more accurate future simulations.

Conclusion

The results are sufficiently encouraging to suggest that further studies of this type of LEBT should be undertaken before any final LIS LEBT is built.

The disadvantages of this LEBT are the reduction in transmission of some charge-states close to Pb^{25+}, and the cost of the line.

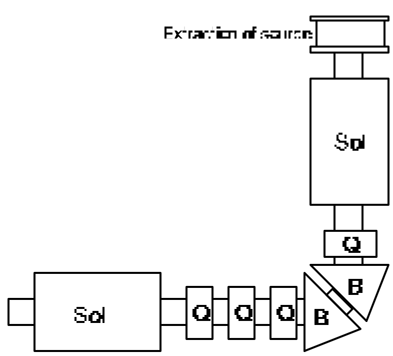

Figure 13. Scheme of the dispersive LEBT. Sol=Solenoid, Q=Quadrupole, B=Bending magnet.

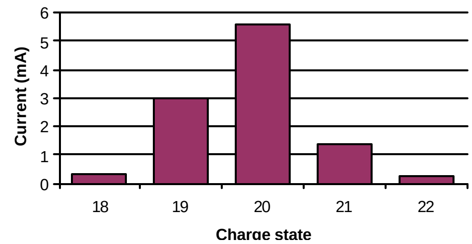

Figure 14. Current traversing the second slit as a function of charge-state.

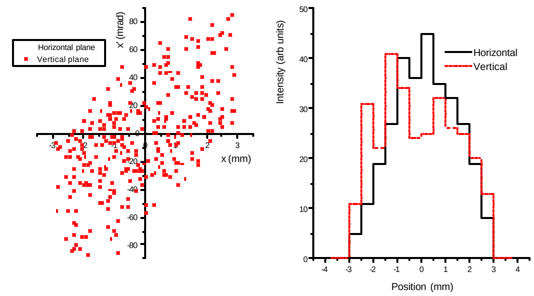

Figure 15. Transverse phase space (left) and intensity (right) plots after the double apertures.

GRIDDED ELECTROSTATIC LENSES (GEL)

The GEL has been simulated with CPO, IGUN and KOBRA[3]. Due to the difficulties of understanding fully the implications of transforming from 2D to 3D for the IGUN code, only the results of CPO and KOBRA are given.

Both codes used the 74 mA beam of Ta^{20+} ions at an energy of 110 keV/charge, with an emittance of 240 mm.mrad. Simulating the transport through the GEL with 20, 40 and 35 kV on the three electrodes respectively, yields a current of 33.5 mA into the standard double aperture cup (when losses of the beam on the grids are taken into account). This can be compared to the average of 25 mA found in experiments. Assuming an 11% proportion of Ta^{20+} in the real beam, results in a transmission of 3.7 mA for comparison with the other codes.

SUMMARY

The results of simulations for 5 different schemes of LEBT have been performed and reported in this note. Where applicable, the simulations have been performed using the same input parameters, and the final currents in a double aperture cup (requiring both beam transport and matching) have been performed. The cup's dimensions of 5.9 mm apertures spaced by 44 mm correspond to a non normlised acceptance of 250 π.mm.mrad (independent of the beam energy).

The results show that the GEL provides the best transport and matching system from a beam dynamics standpoint. However there is a difference of 30% between simulations and experiment, in the ion current transported into the double aperture cup.

In the case that the GEL's technical problems (i.e. sparking) cannot be satisfactorily resolved, a LEBT consisting of two solenoids is an acceptable substitute if a reduction in transmission of 25% can be allowed. However, this reduction in transmission can be limited to 5% if a single solenoid solution can be engineered.

The single-solenoid LEBT and the GEL both have three parameters available for tuning the matching to the RFQ, whereas the two solenoid LEBT has five.

A dispersive LEBT (including bending magnets) still requires more simulation. It's only advantage is the further reduction in the number of unwanted charge-states transported to the RFQ. However, measurements of the present RFQ with beam, have not demonstrated reduction in performance due to a high current of unwanted charge-states. We conclude that this option warrants continued investigation in the case that a new LEBT is constructed (e.g. a new single solenoid). The fact that the LEBT contains two solenoids, two bending magnets and four quadrupoles, would probably lead to an unacceptably high cost.

Table 2. Summary of the simulation results.

GEL	3.7 mA in DA cup
ESQ	N/A
1 Solenoid	3.5mA in DA cup
2 Solenoid	2.8mA in DA cup
Einzel	N/A
Dispersive	3.6mA in DA cup

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