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EXPERIMENTAL CHARACTERISATION OF SOLENOID LEBT FOR LIS SOURCE

N. Lisi, C. Meyer, R. Scrivens, F. Varela Rodriguez

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ABSTRACT

This note aims to offer a complete set of experimental results to be compared with simulations. This note does not aim at finding an optimum LEBT for the LIS. A Summary of all the results obtained in the characterisation of a one solenoid LEBT and a two solenoids LEBT is presented. This note includes total current measurements performed with Faraday cups of different apertures. The solenoid alignment has been optimised using both small apertures Faraday cups and a fluorescent screen. The beam diameter at different distances from the solenoid was measured with the fluorescent screen.

INTRODUCTION

In this note the results of the experiments of beam propagation performed in September 98 are reported. The Low Energy Beam Transport (LEBT) relies on the focusing properties of magnetic solenoids [1].
The improvements with respect to the previous configurations and the reason for performing again such measurements are:

1) Ability to vary the plasma drift length in order to match the Plasma current to the ion extraction optics.
2) New extraction geometry
3) Possibility to work with higher extraction voltages (up to 100KV)
4) Ability to move both solenoids independently in both directions transverse to the beam (X and Y)

Possibly a limitation of the present configuration consists of the presence of a long (250mm) drift section in the extraction chamber that limits the minimum distance where to put the first solenoid. This might in the end limit the beam capture by the first solenoid.
In the fist part of this note we present the results for a one solenoid LEBT, while in the second part the results with two solenoids are reported.

ONE or TWO SOLENOIDS

Although the two solenoid configuration could in principle achieve a better matching to the RFQ input acceptance for the LIS beam, several simulations have demonstrated that this geometry can bring to large emittance increase. The reason for the emittance increase, if one neglects the solenoid aberrations, appears to be the non-linear space charge interaction of the different charge states which are separated by the magnetic field for a long distance (>1m), which leads to ring structures in the beam profile.
This is the reason why we decided to compare systematically the one solenoid and the two solenoids configurations studying both the beam profile and the transmission into Faraday cups of different apertures.

ONE SOLENOID

BEAM ALIGNMENT

The magnetic axis position with respect to the physical frame of each solenoid is known from measurements [2]. This allowed in the past to align nominally each solenoid to the LIS beam axis. This method was found not satisfactory and dipoles had to be used in the past in order to drive the beam into small apertures [3]. This implied that the solenoids' misalignment could lead also to a rather large emittance increase due to loss of cylindrical symmetry in the space charge dominated multicharge beam.
The beam axis is defined with respect to the laboratory frame by reference alignment columns and the extraction flange is presently aligned to it.
The alignment procedure that we used during these measurements was the following

c) The vacuum tube and all the flanges are then aligned to be concentric to the reference HeNe beam. The precision achieved is probably around or less than 1mm
d) A phosphor screen with a slit plate in front of it is inserted in the vessel and markings on it allow to define the beam axis.

The reason for having a slit plate in front of the screen is to attenuate the beam. We used slit spacing of 3 and 5mm. The light emitted by the screen is collected by a CCD camera gated during the arrival time interval of the high charge state ions. The scheme for the one solenoid LEBT is in figure 1.

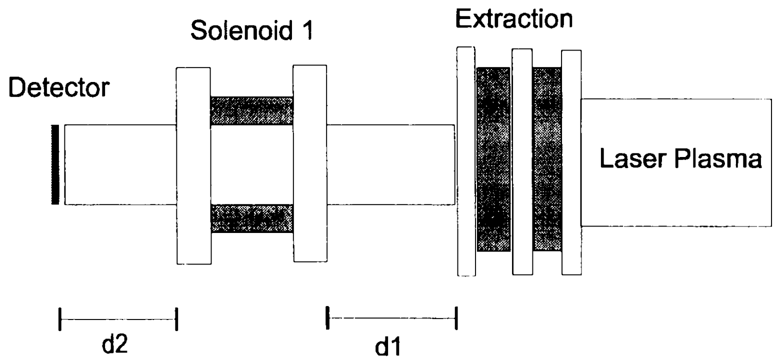


Figure 1. Scheme of one solenoid LEBT The distance d1=82mm, while d2 was varied during the experiments. The ions are separated from the plasma a further 226mm inside the extraction chamber.

We started by placing the screen at d2=1m from the solenoid. As it can be seen from figure 2, initially the beam was found more than 10mm of axis, moreover the beam centre did vary by increasing the solenoid current which indicated that the magnetic axis of the solenoid and the beam axis did not coincide, giving rise to a dipole field component.

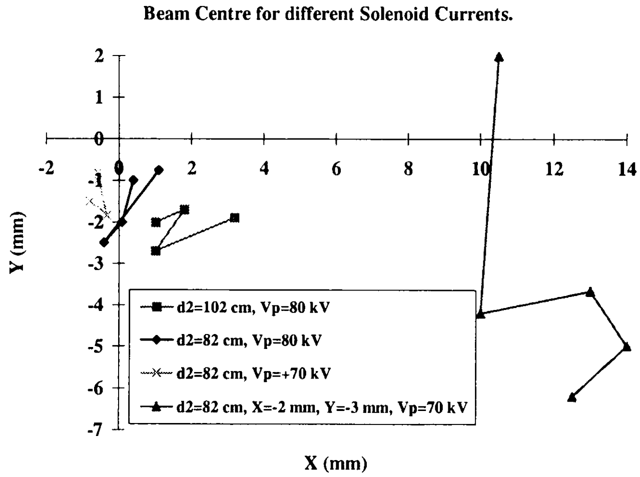


Figure 2. Beam Centre for different solenoid positions and solenoid currents. One solenoid LEBT.

By shifting the solenoid we could move the ion beam until it coincided with the beam axis. Such solenoid position was then referenced as x=0, y=0. At this point, within the measurement error the ion beam centre did not move when we changed the solenoid current (figure 2). In total we shifted the solenoid 3mm vertically (y, up) and 2mm to the left (x).
We moved the screen up to 1.5m from the solenoid and we verified that the beam centre did not move. In this case we are confident that the beam centre is well aligned when compared to experiments performed in 1996 [1].

BEAM DIAMETER

By looking at the CCD images we measured the ion beam diameter (FWHM) for different solenoid currents and at different distances from the solenoid. This data can be compared with results from simulations, although the space charge compensation effects arising from the slit plate in front of the fluorescent screen should be taken into account. In fact beam sizes much smaller than predicted were found.
In figure 3 we show the beam diameter as function of the solenoid current for different solenoid to screen distances.

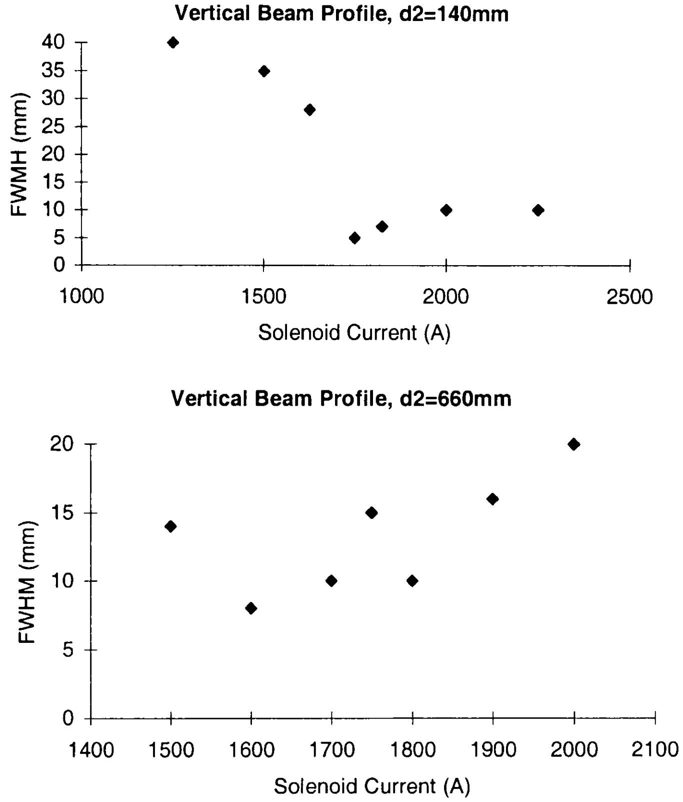


Figure 3 Beam size Vs solenoid current for different distances between fluorescent screen and solenoid. Unbiased slit plate in front of the screen.

We remember that the distances are measured from the edge of the solenoid frame.
Generally we found a circularly symmetric ion beam except when the beam was overfocused and high solenoid currents were used (>2200A) in which case wings appeared. Some kind of astigmatism seemed to affect out solenoid lens, although the beam centre did not change. The reason for such behaviour is not understood but such effect is not affecting us much since the currents at which we routinely run the solenoids are lower than these.

TRANSMISSIONS

We used an insertable Faraday Cup with different input apertures in order to characterise the beam transport in conditions more similar to the final set-up, when the RFQ will be at the end of our LEBT line. The Faraday cup was placed 190mm from the edge of the solenoid frame.
The transmission measurement that we performed are the following:

a) Transmission versus Solenoid Current, in which the solenoid current was varied and the source potential was kept fixed.
b) Transmission versus Extraction Voltage, in which the source potential was changed and the solenoid current was kept constant
c) A similar set of measurements a) and b) was repeated for two extraction distances, 1m and 1.1m. The extraction distance is the distance between target and extraction electrodes. We did this

measurement to check the effect of varying the source current (33% in principle) on the solenoid transmission. We often refer to the source current as to the positive electrode current.

d) Transmission versus horizontal and vertical shift of the solenoid for a Faraday Cup Diameter of 6.5mm. This measurement was performed to confirm the solenoid alignment procedure initially done with the fluorescent screen.

The input apertures that we used were 30mm,15mm and 6.5mm. Moreover we made a small device consisting of two 6.5mm apertures spaced of 65mm in order to simulate a maximum acceptance angle of 100mrad, similar to the RFQ.

EXTRACTION DISTANCE 1m

In figure 4 we show the transmissions for the three apertures both as function of solenoid current and as function of extraction voltage. In a crude approximation the maximum solenoid transmission into the 30mm cup gives an idea on the solenoid “capture efficiency” while the transmission into the 6.5mm cup tells us about the quality of the transmission line. During this experiments d2=150mm
The transmissions are plotted versus the normalised solenoid current, that it the solenoid current in A divided by 1250A.

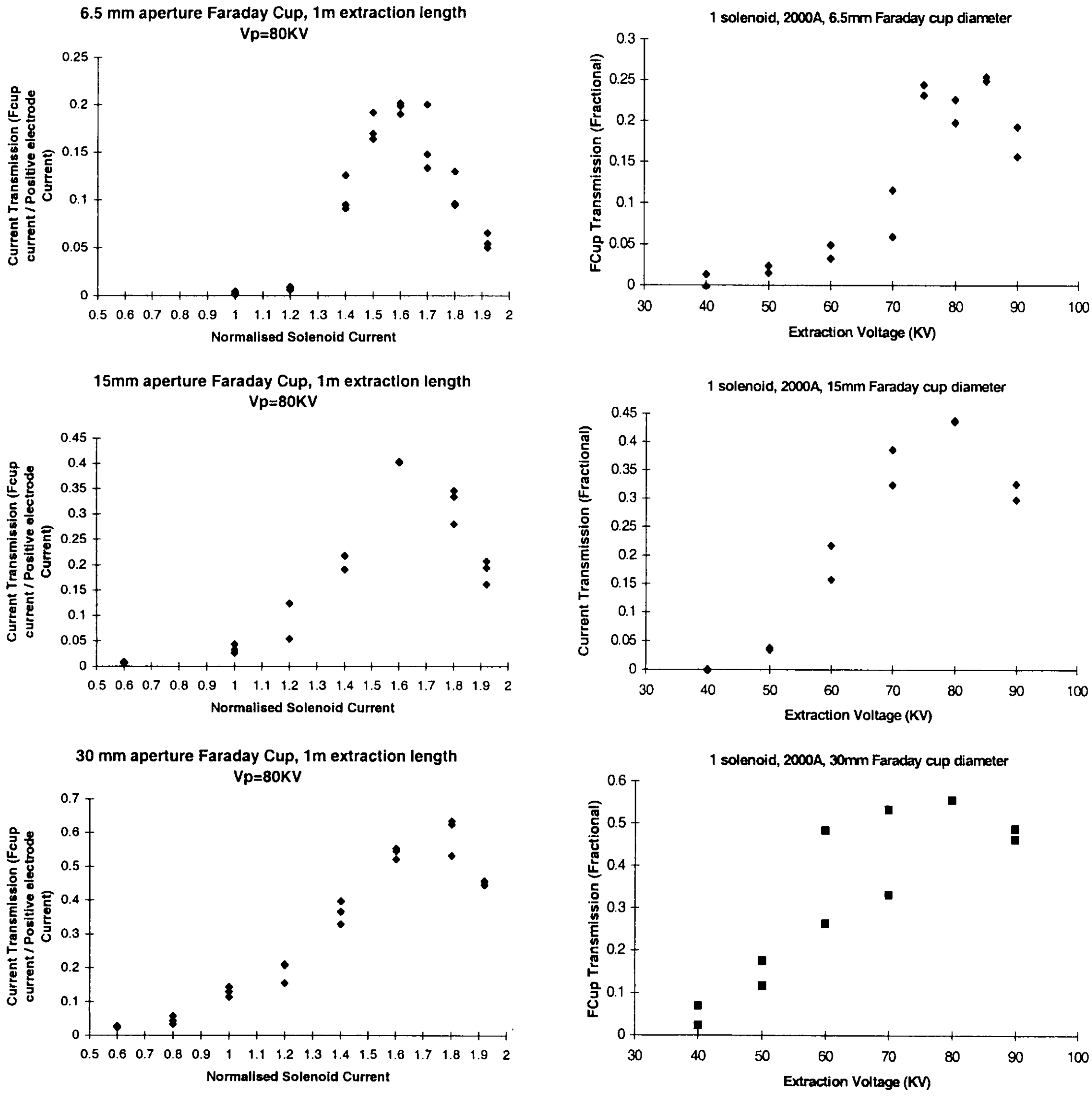


Figure 4 Transmission curves for 6.5mm, 15mm, 30mm diameter Faraday Cup. The cup is sitting 100mm from the edge of the solenoid field. For each case the average transmission between 3 and 8μs is plotted versus the solenoid current (normalised to 1250A) and the extraction voltage.

EXTRACTION DISTANCE 1.1m

At this extraction distance we expect a decrease in source current of 33% (or 1.1^3) due to the 3D expansion of the plasma plume. By repeating a similar set of measurements as at the extraction distance of 1m we expect to investigate the effect of the matching of extraction. In this case we utilised 6.5mm aperture, 30mm aperture and a modified Faraday cup that simulates a maximum acceptance angle of 100mrad and an aperture of 6.5mm. Again d2=160mm.
As it can be seen in figure 5 the transmission curves are similar to those shown in figure 4. We can see from table 1 that as the total source current decreases and the transmission increases the total transmitted current remains more or less on the same level. A similar behaviour was found with two solenoids in previous experiments [1]

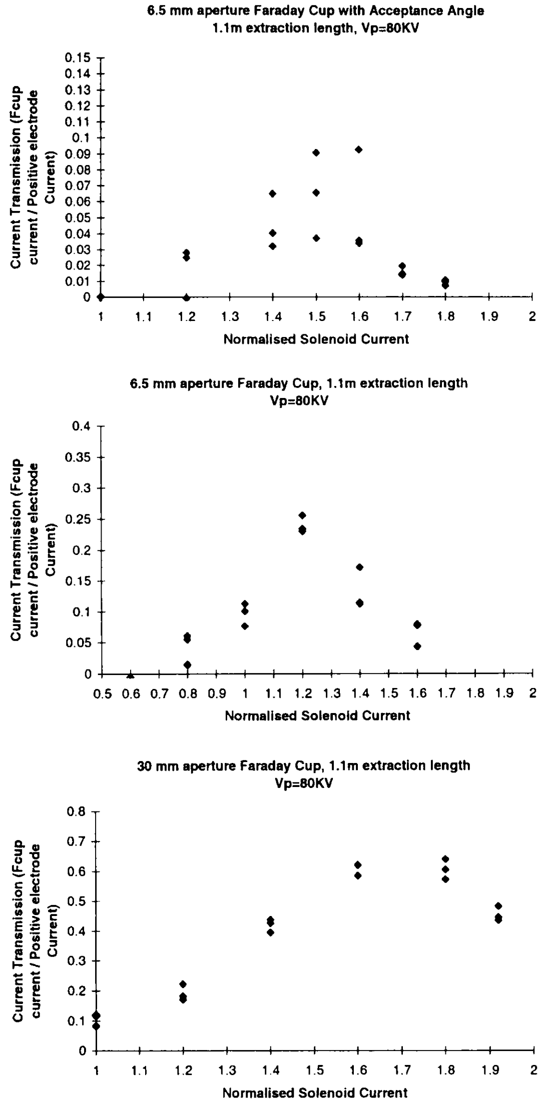


Figure 5. Transmission curves for 6.5mm with acceptance angle (as explained in the text), 6.5mm and 30mm diameter Faraday Cup. The cup is sitting 100mm from the edge of the solenoid field. For each case the average transmission between 3 and 8μs is plotted versus the solenoid current (normalised to 1250A). We do not report the plots versus extraction voltage as they are not substantially different from those shown in figure 4.

Extraction Distance (m)	1	1	1	1.1	1.1	1.1
Faraday Cup Aperture (mm)	6.5	15	30	6.5	30	6.5*100mrad
Source Current (mA)	85	84	77	69	65	80
Cup Current (mA)	16.7	35.8	43.5	16.5	39.5	5.1
Transmission (%)	20	41	60	24	60.7	6.5
Solenoid Current (A)	2000	2000	2250	2000	2000	1875

Table 1. Summary of the results for the one solenoid LEBT. All the values are averaged in (3-8)μs.

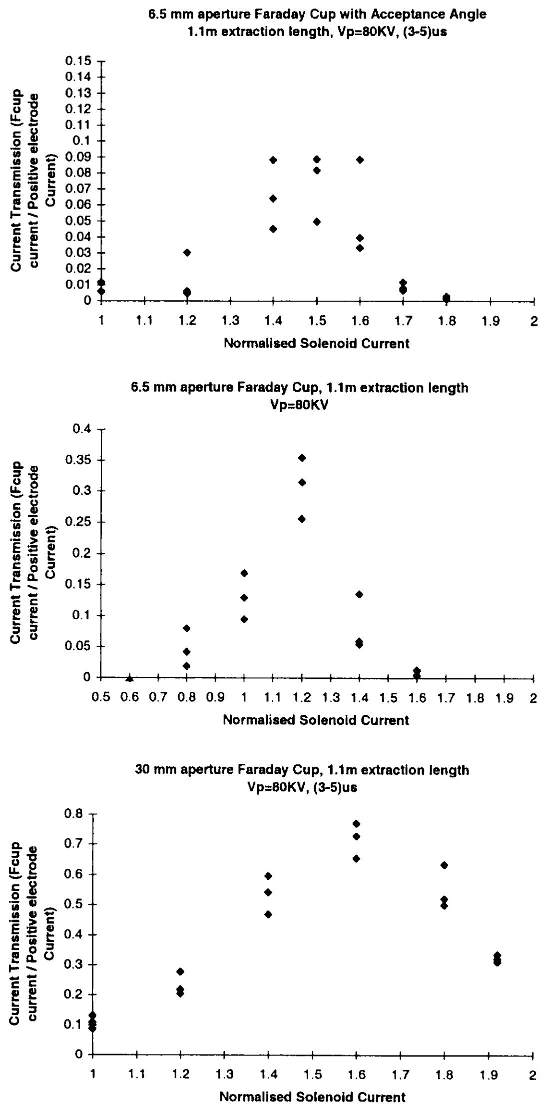
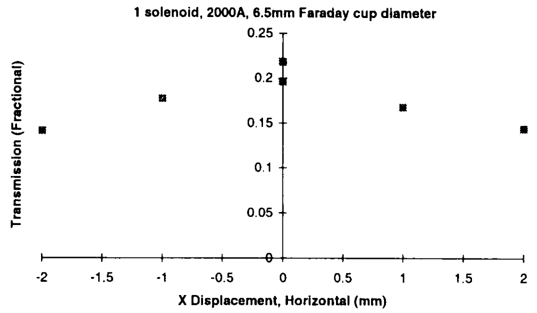


Figure 6. Transmission in the (3-5)μs interval for 6.5mm with acceptance angle, 6.5mm and 30mm diameter Faraday Cup. Same conditions as for figure 5.

If we restrict the current interval over which we calculate the transmissions we obtain a transmission slightly higher. This result seems to indicate that the transmission of high charge states is more efficient, as suggested by simulation results.

Finally some measurements were performed in order to check the solenoid magnetic axis alignment with respect to the beam axis. Here we report the transmissions (averaged between 3 and 8μs) for a horizontal and a vertical shift of +/-2mm. A reproducible decrease in transmission is the effect of moving the solenoid in both directions.



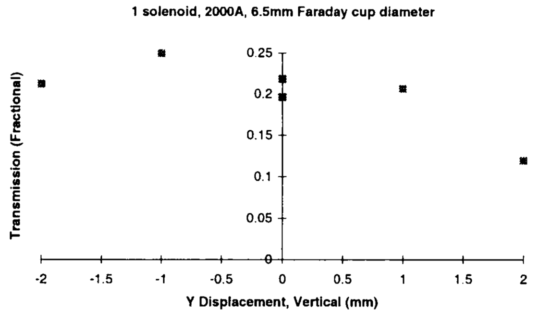


Figure 7 Transmission into 6.5mm cup for one solenoid LEBT. (3-8)μs interval.

ONE SOLENOID: Current stability

We took a series of 27 shots in the conditions of maximum transmission for the 6.5mm aperture Faraday Cup in order to study the stability of the source current transmitted through the solenoid for the case of an extraction distance of 1.1m and a Faraday Cup diameter of 6.5mm.
In figure 7 we report the results of this run. The average transmission was found 24% (as in table 1). The standard deviation of the source current (or positive electrode current) is about 15% while the current in the cup has a standard deviation from shot to shot of 11%.
We can remark two things. First that the source current is more stable than usual. In previous experiments, when the LEBT was not installed the usual deviation is in the range between 20% and 30%. About this topic see the section on the two solenoid LEBT further in this note. Second we notice that the current transmitted through the LEBT is more stable than the total source current.

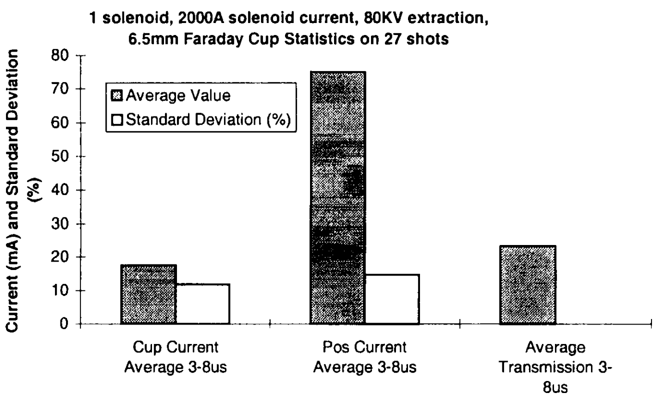


Figure 7 Summary of statistics for 27shots of LIS and one solenoid LEBT. (3-8)μs interval.

It seems that the presence of the magnetic field from the first solenoid stabilises the total current emitted from the source, although the extraction region should be decoupled from the beam transmission optics by a suppression voltage of -10KV. The reason for this effect are not known but we suspect influence on secondary electron mobility by the magnetic field. More recent simulation results show that -10KV are not sufficient to stop electrons, as a consequence we decide to work with lower suppression voltages in the next experiments.

TRANSMISSION Vs TRANSMITTED CURRENT

We can then ask ourselves whether it is more correct to characterise the LEBT by using an adimensional Transmission or the Transmitted current, taking into account that in the end we are interested in the stability of the transmitted current.
It all depends on the relation between the source current and the transmitted current as measured by the Faraday cup. One should talk of transmission only when the source current and the transmitted current are directly proportional to each other, all the other parameters being fixed. The relation between the source current (or positive electrode current) and the transmitted current as measured by the Faraday cup is plotted in figure 8. The graph shows both some statistical fluctuations as some saturation behaviour. The reason for the fluctuations lies in the detailed time history of the current pulse, both regard extraction and beam dynamics. The reason for the saturation behaviour in the heavily non linear beam dynamics due to strong space charge interaction.
By looking at table 2 we find that probably it is still correct (or equivalent) to talk about transmission rather than transmitted current since statistically the transmission has a slightly lower standard deviation than both the source current and the transmitted current.
This condition seems to be unsatisfied for the two solenoid LEBT as shown in the next section of this note.

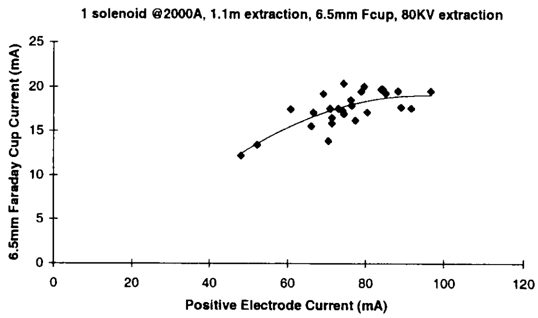


Figure 8. The 6.5mm cup current Vs total source current (or source electrode current) It shows a saturation behaviour and some statistical fluctuations. (3-8)μs interval.

	Average	StDev (%)
6.5mm Cup Current (mA)	17.52403	11.81922
Source Current (mA)	75.1704	14.68792
Transmission (%)	23.52625	10.37556

Table 2 Summary of the statistics for the one solenoid LEBT with 6.5mm cup. The fluctuations for the Transmission are comparable to the fluctuations of both source current and cup current. (3-8)μs interval.

TWO SOLENOID LEBT

BEAM ALIGNMENT

In figure 9 we show the scheme of the two solenoid LEBT. We followed a similar alignment procedure as for one solenoid. A fluorescent screen was placed after the two solenoid and its centre was aligned to lie on the beam axis defined by a HeNe laser, as explained in a previous section.
The solenoid would then be aligned if the ion beam centre was overlapping to the beam axis for various values of the solenoid current. This was found to be true, with the precision of about 1mm, for the initial positioning of the second solenoid. Such position corresponded to the nominal alignment of the magnetic field. In this respect the first and the second solenoid where found to be different as the first one had to be shifted of 3mm vertically and 2mm horizontally.
In figure 10 we report the horizontal beam widths as measured on the fluorescent screen for various values of the second solenoid current. The first solenoid current was kept at 0. The extraction length was of 1.1m.

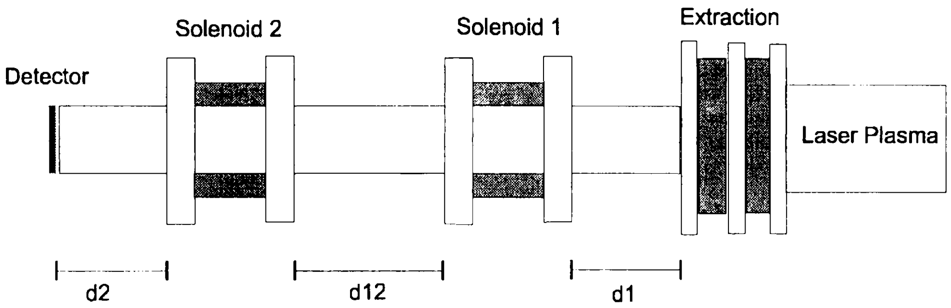
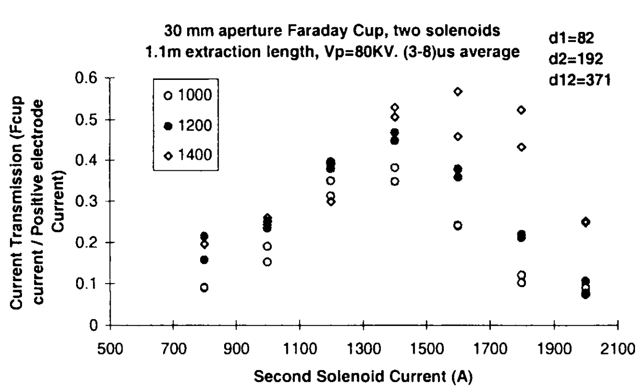
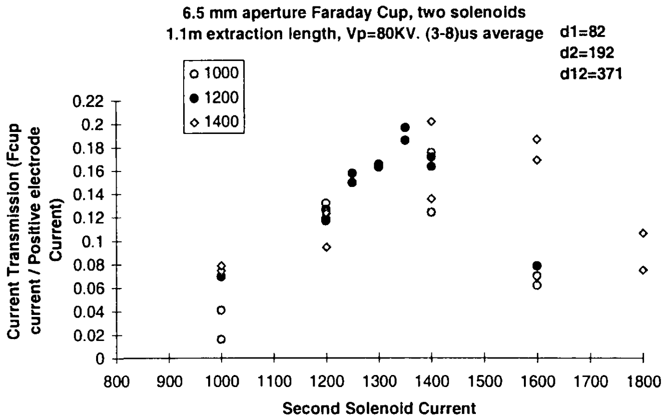


Figure 9 Scheme for the two solenoids LIS LEBT. The distance d1=82mm, while d12 and d2 were varied during the experiments. The ions are separated from the plasma a further 226mm inside the extraction chamber.

TRANSMISSIONS

We utilised the same Faraday cup apertures as we did for the one solenoid LEBT. For the two solenoid case we had to vary both solenoid currents to achieve maximum transmission.
A further degree of freedom is given by the possibility to vary the solenoid distances: d2 and d12. We kept the distance d1 minimum throughout the experiments to have the same value as for the one solenoid LEBT. We utilised two different distances d2. The first one d2=192mm (d12=371mm) and the second one as short as possible d2=84mm (d12=480mm) since according to simulations there could be a significant increase in transmission in the latter case.
At this distances we measured the transmission with the 30mm and the 6.5mm cup varying both solenoid currents. In figure 10 and 11 we show the transmissions for various first solenoid currents for d1=192 and an averaging interval of the current pulse between (3-8)μs and (3-5)μs respectively, while in figure 11 and 12 we show similar results for d2=84mm and similar time windows.





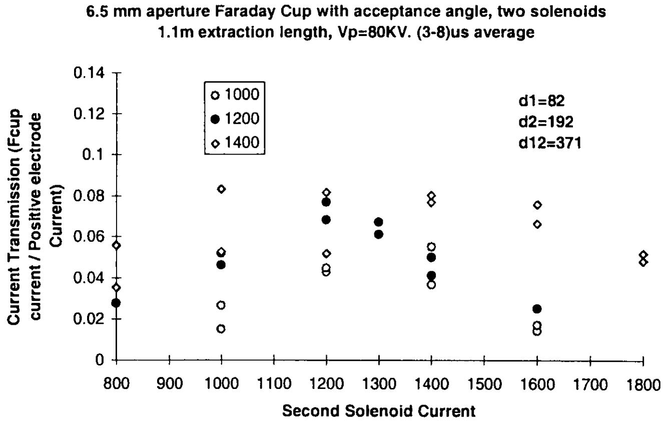
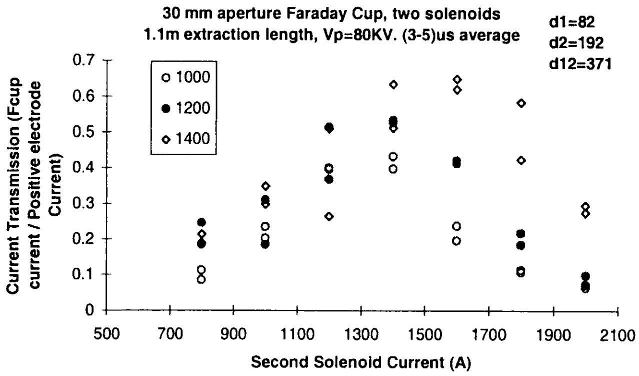
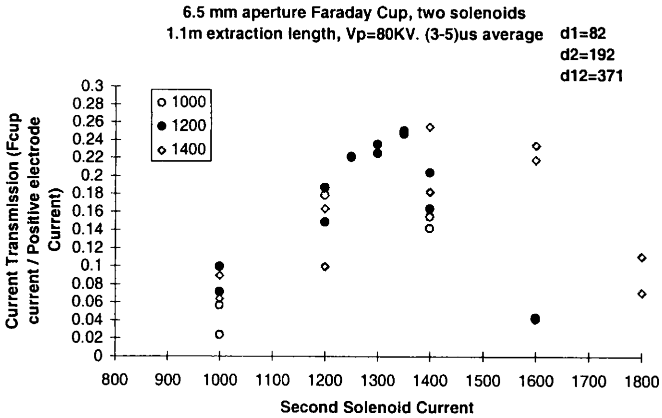


Figure 10. Transmission of two solenoid LEBT. 30mm, 6.5mm cup and 6.5 double aperture cup.





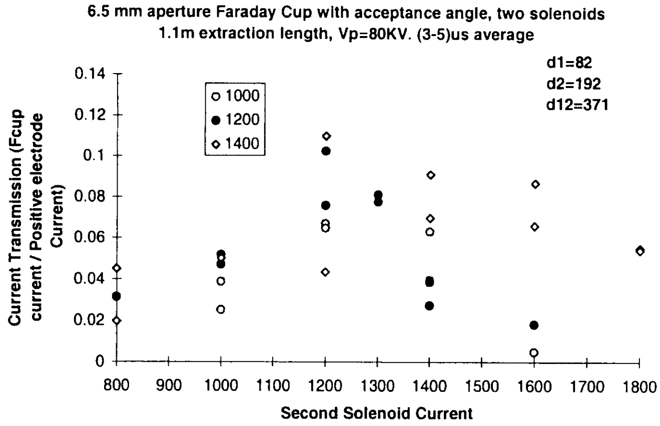


Figure 11 Transmission of two solenoid LEBT. Same as figure 10 but between (3-5)μs.

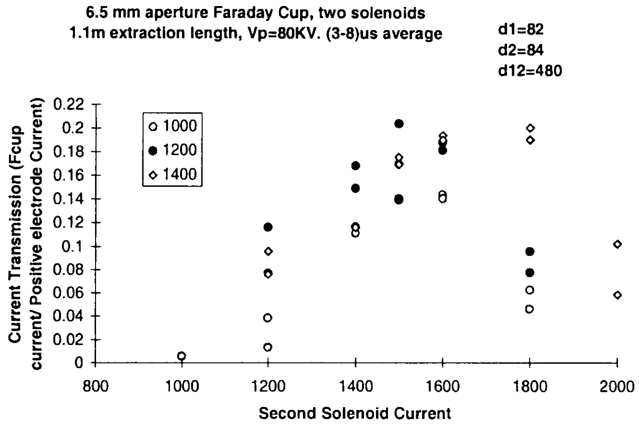


Figure 12. Transmission of two solenoid LEBT, d2=84mm. 6.5mm cup

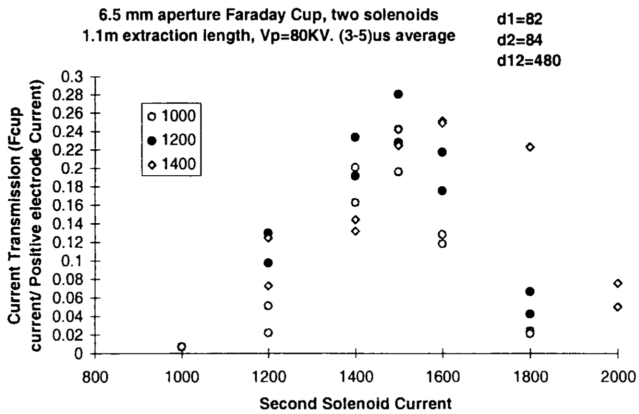


Figure 13 Transmission of two solenoid LEBT. Same as figure 12 but between (3-5)μs.

SECOND SOLENOID ALIGNMENT

We tested the alignment of the second solenoid by recording the beam transmission for various horizontal shifts of the solenoid. The measurement confirmed what already observed with the fluorescent screen, that the alignment was good.

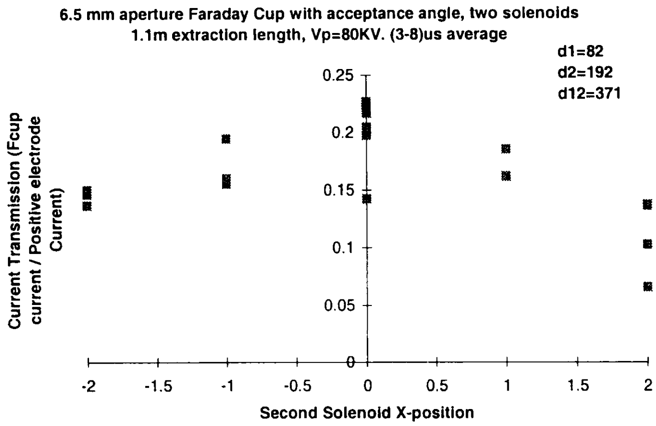


Figure 14 This measurement confirms that the second solenoid initial alignment was accurate

TWO SOLENOID LEBT CURRENT STABILITY

Given the importance of the shot to shot current fluctuations for the LIS source we did some 45 shots in order to quantify the stability of the system. We did this with a distance d2=192mm between solenoid frame and Faraday cup and a Faraday cup aperture of 6.5mm.
In figure 15 we show a summary of the statistics for the two solenoid LEBT and in figure 16 the relation between Source current and Faraday Cup current.
In figure 16 it is possible to see that there is a sharp increase in cup current when the source current lies in the range between 70mA and 80mA which seems to indicate correct LEBT and extraction matching.

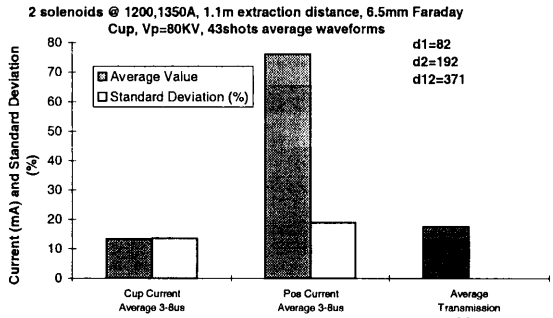


Figure 15. Two solenoid LEBT, transmission statistics

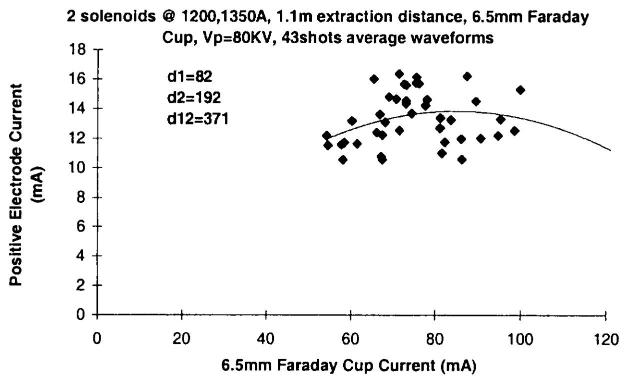


Figure 16. Two solenoid LEBT. Relation between transmitted current and source current.

Finally in Table 3 we report the summary of the two solenoid LEBT results

Faraday Cup Aperture (mm)	6.5	6.5*100mrad	30	6.5
First Solenoid Current (A)	1200	1200	1400	1200

Second Solenoid Current (A)	1350	1200	1400	1500
d2 (mm)	192	192	192	84
Transmission (%)	17.5	7.3	52	17.1
Source Current (mA)	76	81	63	84
Cup Current (mA)	13.3	5.9	33	14.1

Table 3. Summary of the results with the two solenoid LEBT. The data in the first column are based on many shots (45). While in the other columns are based on two shots with maximum transmission and a qualitative analysis of the transmission curves. This account for the fluctuations of the source current in the different columns.

CONCLUSIONS

Finally we remark that we get better current transmission performances from the one solenoid LEBT than from the two solenoid LEBT as both solenoids were aligned. In the first case a 23.5% transmission can be achieved for all charge states. In order to quantify which low energy transmission line is the best it would be opportune to analyse the charge composition of the transmitted beam, or ideally accelerate the beam in an RFQ. Probably a higher transmission for one single charge state is already there. The charge state analysis of the beam will be performed in the near future.

Moreover we make a few of observations:

We get fairly similar performances independently from the geometry (distances) and type of LEBT (one or two solenoid).

The large effect of the current waveform (current variations in a single shot) and charge (as the waveform average or integral) from shot to shot (figures 8 and 16).

The beam capture from the first solenoid, apparently around 60-70%, (since in no case was found a higher transmission) is probably a consequence of the extraction of a rapidly varying current density and thus space charge.

The higher stability of the current transmitted through a small aperture Faraday Cup respect to the total source current (figures 7 and 15) is probably consequence of some saturation of current density due to space charge in the beam transport.

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