DESIGN AND VALIDATION WITH MEASUREMENTS OF THE LEIR INJECTION LINE

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Abstract

The CERN Low Energy Ion Ring (LEIR) commissioning started in the year 2005. O^{4+} and Pb^{54+} ion beams are transferred at 4.2 MeV/nucleon from Linac 3 to LEIR through a low energy transfer line, for which the constraints and the resulting optics design are presented. First trajectory and dispersion measurements agreed only poorly with the theoretical model. Iterations of a refined optics model and further measurements improved the agreement between experimental observations and expectations. In particular, the effect of quadrupole errors in the line dipole magnets is discussed.

INTRODUCTION

The LEIR accumulation ring is part of the accelerator chain that will bring heavy ions in collision in the Large Hadron Collider (LHC) and the first stage of its commissioning with beam has been recently completed [1].

The first phase of the commissioning concerned the ion transfer from Linac 3 to the LEIR injection region. The relevant transfer lines are shown in Fig. 1.

In the following we will discuss the matching of the transfer line optics and then demonstrate how the optics model has been improved and validated with beam based measurements.

TRANSFER LINES OPTICS

The optics matching concerned the transfer lines indicated in Fig. 1:

- the last part of the ITH line, equipped with 2 quadrupole triplets;
- the ITE line, composed of 4 horizontal bending dipoles deflecting the beam by 180 degrees and 5 quadrupoles;
- the ETL line, equipped with 2 horizontal and 2 vertical bending dipoles and 6 quadrupoles; this line is bi-directional and used, with different settings, to transfer the ions ejected from LEIR toward the PS;
- the EI line, where the beam passes through 1 horizontal and 2 vertical dipoles (to adjust the beam position at injection into LEIR) and 4 quadrupoles.

The total length of the considered transfer line is about 110 m.

The optics matching has been calculated with MAD [2] in order to cope with the following conditions and constraints:

- matching the Twiss parameters at the beginning of the ITH line, that can be inferred from the Linac 3 optics model and measurements.
- having the Twiss parameters along the loop in the ITE line symmetric with respect to the centre, by forcing the two parameters α_x and α_y to be zero at this location;
- keeping, in the ETL line, the betatron function amplitudes β_x and β_y smaller than 25 m and the horizontal dispersion D_x within $\pm 10\,m$, in order to avoid physical aperture limitations and to obtain a reasonably smooth focusing structure;
- reaching the LEIR injection at the end of the EI line with $D_x \approx 0$ and with $\beta_x = \beta_y$ =2 m in order to enhance the multi-turn injection efficiency [3].

The last two items require a particular minimization algorithm using the available free parameters (i.e. the quadrupole strengths), since a strong betatron phase advance (i.e. rapid variation of the betatron functions) is needed to achieve a vanishing dispersion at the end of the line.

The linac settings were tuned in order to optimize the beam dynamics, at first with O^{4+} and then Pb^{54+} ions. The values of the Twiss parameters at the beginning of the ITH line, to which the downstream optics must be matched, were measured by means of quadrupole scans that gave different results for the two ion species, as summarized in Table 1, where the resulting emittances are indicated too.

In addition, the linac design optics is expected to give vanishing D_x and D'_x. Measurements provided very small but non-zero values for these parameters, that were used in the model to compute the dispersion function along the line.

With the updated optics model and the measured initial values, good agreement between computed and measured dispersion was found for both ion species, by means of dedicated measurements that will not be presented in this paper.

Table 1: Twiss parameters and RMS geometric emittances as measured at the beginning of the ITH line.

	α_x	β_x [m]	α_y	β_y [m]	ϵ_x [μm]	ϵ_y [μm]
O^{4+}	2.2	38	-2.8	22	1.5	2
Pb^{54+}	0.4	13	2.1	18	1.9	2.1

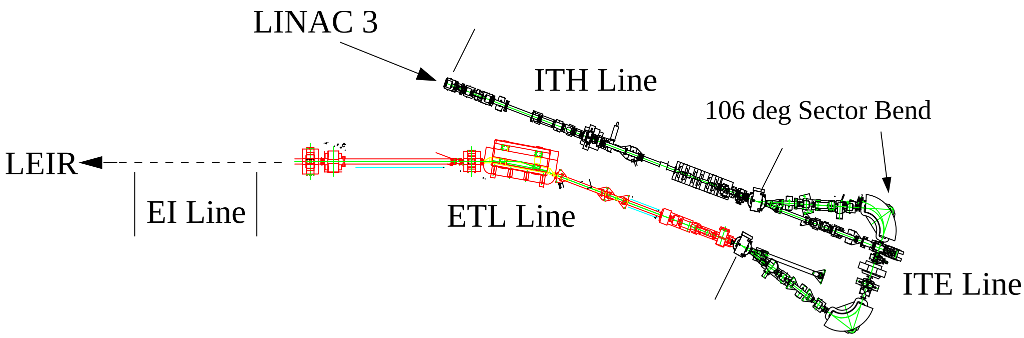

Figure 1: Transfer line drawing, the injection into LEIR is after the EI line.

SECTOR MAGNET MODEL

The accelerator modeling program MAD represents a sector magnet by means of its length L, the bending angle α and the half gap HGAP. Additional parameters can be given to the model in order to consider imperfections in the magnet design and construction. Such parameters account for the pole-face rotation angles and the focusing effects due to the non uniformity of the field in the core and fringe field regions.

As it will be shown in the next section, after the first trajectory measurements, it was particularly significant to consider these additional parameters for the two 106-degree bending dipoles in the ITE line. Information about the properties of the magnets could be retrieved from magnetic measurements performed before their installation, at 80 % of the maximum coil current. If the centre of the magnet is at the curvilinear coordinate s=0, the following parameters could be determined:

$$FINT = \int_{-\infty}^{0} \frac{B_y(s)[B_0 - B_y(s)]}{2 \cdot \mathrm{HGAP} \cdot B_0^2} ds = 0.47$$

$$K1 = \frac{1}{B_0 \rho} \frac{\partial B_0}{\partial x}\bigg|_{core} = 0.02\ [m^{-2}]$$

where $B_y(s)$ is the bending field and B_0 the field in the magnet core.

It is important to remark that, for both the parameters FINT and K1, an increase of their positive value implies a stronger vertical defocussing.

The pole face rotation angles resulted to be negligible and kept at zero in the model.

MEASUREMENTS WITH O^{4+}IONS

In the first part of the commissioning the aim was to transport the O^{4+}beam along the line with quadrupole settings provided by the MAD model discussed above. After a straight forward adjusting of the steering, trajectory measurements along the line have been carried out. The method consists in applying a kick (of known strength) with a corrector magnet situated at the beginning of the ITH line and measuring the beam position at several locations downstream. The measured position can be compared to the

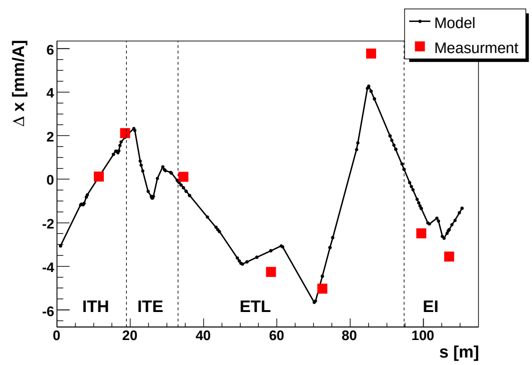

Figure 2: O^{4+}ions horizontal trajectory measurements and comparison with the optics model prediction.

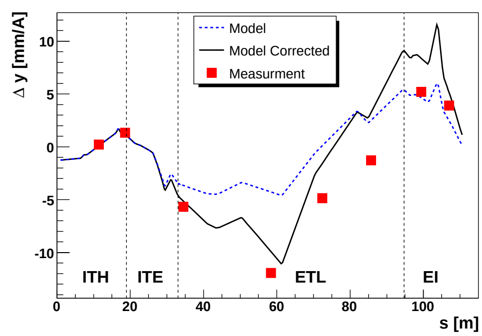

Figure 3: O^{4+}vertical trajectory measurements compared with the optics model prediction before and after the correction for the ITE bending dipoles quadrupole error.

value predicted by the beam transport model. To improve the measurement precision, we repeated the measurement for different kick strengths and plotted the results as beam displacement per unit of current fed to the corrector.

In total, there are 2 secondary emission monitors in the ITH line and 7 scintillation screens in the ITE, ETL and EI lines.

In the model, the ITE sector magnets parameters discussed in the previous section were set at first as FINT=0.35 (corresponding to a linear decay of the bending field from the core of the magnet to the field free region) and K1=0 (no gradient/focusing effects).

The results of the horizontal trajectory measurements are shown in Fig. 2. The agreement with the model is well within the measurement error, as it was verified also with Pb^{54+}ions. Therefore, no further investigations were needed.

On the contrary, the vertical trajectory measurements exhibited a disagreement with the initial model, as shown by the dashed blue line and the square red dots in Fig. 3. Additional vertical defocussing along the ITE loop was evident.

For this reason, we decided to refine the model of the ITE dipole magnets profiting from the magnetic measurements results discussed above. The change of the FINT parameter from 0.35 to 0.47 lead to a model prediction in better agreement with the measurements, by a small but visible amount. The agreement improved in a more evident way after inserting the parameter K1=0.02 [m^{-2}]. Then we applied a minimization algorithm with K1 as free parameter in order to find the best accordance with the measurements. This resulted in K1=0.039 [m^{-2}] and in the model prediction indicated by the black solid line in Fig. 3.

Therefore, the quadrupole effect inferred from the trajectory measurements is almost twice the one estimated from the magnetic measurements. This could be related to the fact that the magnetic measurements were taken severals years before and above all because, with O^{4+}ions, the ITE bends are operated in saturation in order to accomplish the steering in the ITE loop.

It must be noted that a residual descrepancy between the model and the measurements remains at the end of the ETL line and it will discussed at the end of the next section.

The correction for the ITE dipoles K1 factor introduces only neglibile effects in the horizontal trajectory, since the two magnets are located in regions where the horizontal betatron function is much smaller than the vertical one.

MEASUREMENTS WITH Pb^{54+} IONS

The same kind of measurements were carried out with Pb^{54+}ions. The transfer line settings differred from the ones used for O^{4+}because of the lower magnetic rigidity and different initial values of the Twiss parameters. As for oxygen, the horizontal trajectory agreed very well with the model, while the initial model for the vertical optics exhibited a disagreement with the measurements dowstream the ITE loop.

Also in this case the model accounting the quadrupole error in the ITE bending magnets better fits the data, even though the best gradient value was found to be $K1 = 0.025\,[m^{-2}]$, smaller than the value found for oxygen. The reason for this difference can be well explained by the fact that the magnets were less saturated. Another explanation could be that, due to the higher magnetic rigidity, oxygen ions could not be correctly steered in the center of the dipoles and experienced a higher gradient effect.

Similarly to what was observed for oxygen ions, a discrepancy between model and measurements remains in the EI line. This disagreement has not been fully understood yet, but it can be related to the presence of two other sector bend magnets at the end of the ETL line and at the beginning of the EI line. Also these two elements are located in regions with horizontal betatron function much smaller than the vertical ones and additional vertical focussing best fits the measurements.

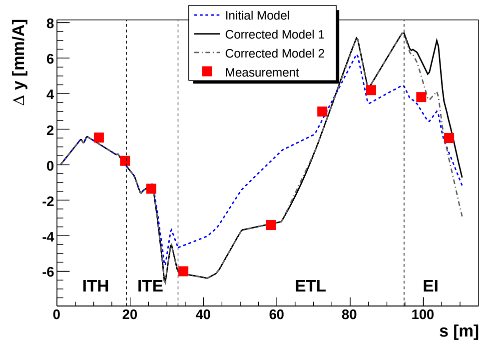

Figure 4: Pb^{54+}vertical trajectory measurements and comparison with the optics model prediction before and after the correction for the bending dipoles quadrupole error (see text for the difference between Model 1 and Model 2).

The comparison between the vertical trajectory measurements and the model prediction is shown in Fig. 4. The three curves describing the MAD prediction refer to the initial model, to the insertion of K1=0.025 [m^{-2}] to the ITE dipoles (Model 1) and to the additional parameter K1=-0.025 [m^{-2}] in the two dipoles at the end of the ETL line and the beginning of the EI line (Model 2).

CONCLUSIONS

The Linac 3-LEIR tranfer line optics was validated by means of trajectory measurements with $O^{4+}$and Pb^{54+}ions. The initial poor agreement between the optics model and the measurements has been successfully improved accounting for quadrupole effects in the ITE line sector bending magnets. Such a correction is consistent with the available laboratory magnetic measurements. A disagreement between the model and the measurements remains in the last part of transfer line. An additional correction, assuming quadrupole effects in other two bending dipoles should be verified with new measurements and preferably with studies about the geometry and field quality of the two magnets. Furthermore, the proper matching of the line was confirmed by the achievement of good injection efficiency into the LEIR ring [1].

Acknowledgments

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