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COMMISSIONING OF THE ELENA ELECTROSTATIC TRANSFER LINES FOR THE ANTIMATTER FACILITY AT CERN

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Abstract

ELENA is a small synchrotron ring that decelerates antiprotons down to a kinetic energy of 100 keV. With an experimental complex capable of housing up to 9 different experiments operating simultaneously, the transfer line design needed to be highly flexible. The low energy of the beam transported allowed the exploitation of electrostatic devices instead of magnets, to simplify design, production and operation.

This contribution presents the systematic characterisation of the beam optics at the different experimental handover locations during beam commissioning using H- ions from an external source, as well as the performance of the lines in operation with antiprotons. Finally, the effect of stray fields created by the experimental setup will be presented and compared with the first measurements.

INTRODUCTION

The Extra Low ENergy Antiproton storage ring (ELENA) [1] is the latest deceleration stage of the CERN antimatter factory. It decelerates antiprotons extracted from the Antiproton Decelerator (AD) from a kinetic energy of 5.3 MeV down to 100 keV. Such a low energy was motivated by the prospect of increasing the efficiency and physics opportunities of the antiproton facility [1]. However, it poses unique challenges to transport and control a beam at very low energy for instance due to potential stray fields.

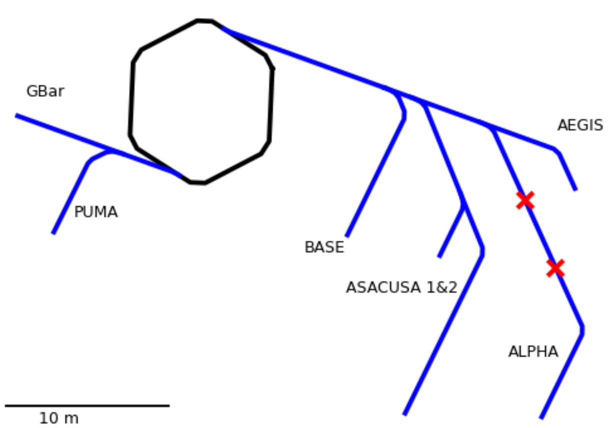

Figure 1: Layout of the ELENA experimental complex with the ring in black and extraction lines in blue. Locations of the 7 currently installed experiments are labelled and 2 red markers show vertical lines where experiments are not yet installed.

The extra low energy of the beams extracted from the ring made the use of electrostatic devices desirable. Figure 1 shows the extent of the extraction lines over the two sides of the ELENA ring. Totalling approximately 125 m of beam lines, they use 3 different types of electrostatic devices.

The first type of elements is a fast electrostatic deflector with a unique angle of 12.6° and using 400 mm long non-parallel but flat electrodes. Able to pulse (rise and fall) within less than 1 µs, it is used to deflect one or multiple bunches without affecting other bunches and it is also used in the ring to extract the circulating bunches. A total of 9 such elements are installed.

To accommodate the sharp turns between lines a second design uses a constant electrostatic field with quasi-spherical electrodes of varied angles and lengths, from 33° to 77°. There are 14 of such deflectors, including 2 of the largest angle to achieve a right angle for the branching towards the 2 vertical lines.

The third type of element is a quadrupole doublet assembly around a pair of dipole correctors, all within a single 390 mm long tank. Each quadrupole has an aperture of 60 mm and can provide an integrated quadrupole strength of up to 7.3 m^{-1}. The dipole correctors are composed of pairs of flat plates 37 mm long and may impart deflections of up to 0.57° to the beam. There are a total of 54 such assemblies installed in the beam lines to control and correct the shape and trajectory of the beam.

In total, there are 239 electrostatic elements in the ELENA extraction lines and twice that number of high voltage cables since positive and negative plates are connected to different power supplies. Each of the deflectors is connected to its own pair of power supplies while the 108 quadrupoles are connected to 75 pairs of power supplies. Such a large number of elements and limited experimental knowledge on the optical effect of such electrostatic devices makes commissioning with beam paramount to certify the performance of the lines.

BEAM COMMISSIONING

In preparation of the start of physics operation in the ELENA complex scheduled for the summer of 2021, a systematic commissioning of every extraction line was started in 2020. Using the H^- ion source [2], the beam dynamics in the extraction lines could be characterised and every element tested in advance of the scheduled start of the antiproton run. The ion source also permits a higher repetition rate of one cycle every less than 15 s compared to the antiproton repetition rate constrained by the AD cycle length of about 120 s.

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The extraction lines are equipped with 38 micro-wire monitors capable of measuring the beam profile while intercepting only a small fraction of the beam [3]. They are equipped with two perpendicular grids to monitor both planes and can be moved out of the beam during physics operation to maximise transmission. Each grid covers a square of 60 mm a side with 47 wires spaced by 0.5 mm in the center and 3 mm on the sides, to allow precise beam size measurement in the center while covering the full aperture of the electrostatic quadrupoles.

The micro-wire monitors were critical for the commissioning and allowed to precisely characterise the beam along every line. However, some of the wires did not provide good signal. The first commissioning task was therefore to scan the beam across the entire range of every grid in order to identify the broken wires and exclude them from both online and offline analysis. Figure 2 shows the horizontal profile measured on the first monitor of the line towards the BASE, ASACUSA, ALPHA and AEGIS experiments. On this particular grid 5 of 47 wires are masked but fitted beam parameters remained excellent with estimated uncertainties in the order of 0.1 mm.

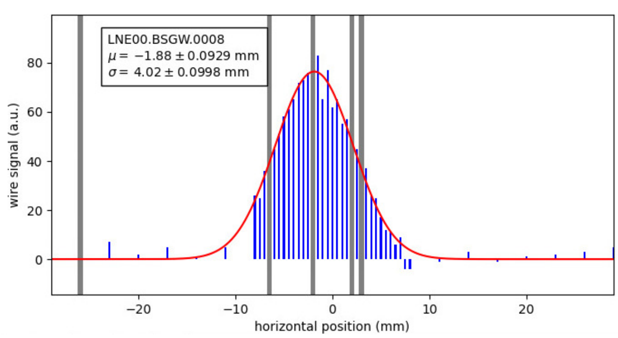

Figure 2: Horizontal beam profile measured in one of the ELENA extraction line on a micro-wire monitor. The wire signal is represented as blue bars while the grey bars show wires masked due to missing or bad signal. Fitted centroid μ and beam size σ are listed in the upper lefter corner with the associated profile in red.

The next step of beam commissioning was the precise characterisation of the optics along each line and, most specifically, at the handover point before each experimental area. Using the quadrupole scan technique allows to characterise the beam sigma matrix near every monitor. Often, the technique uses the thin lens approximation and a drift between the quadrupole and the monitor to obtain a simple relation between the observed beam size σ and the integrated quadrupole strength kl:

$$\sigma = \epsilon \left(\beta - 2L\alpha + L^2\gamma + 2L(L\alpha - \beta)kl + L^2\beta(kl)^2\right) \quad (1)$$

where ϵ, α, β and γ form the Twiss representation of the sigma matrix upstream the quadrupole and L is the drift length to the monitor. We have seen that the electrostatic quadrupoles can provide large strengths and a minimum focal length of 130 mm, on par with their physical length. The thin length approximation is therefore inappropriate. The evolution of the beam size on the monitor as a function of quadrupole strength may also be established using the thick lens expression of the quadrupole matrix and general transport matrix to the monitor.

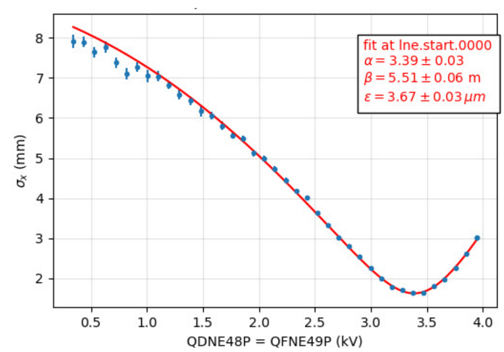

Figure 3: Evolution of the beam size measured in the horizontal plane as a function of the absolute voltage applied to 2 quadrupoles. The fitted beam parameters at the ring's extraction point and the associated curve are showed in red.

A more general approach was instead implemented using the MAD-X model [4] of the lines and adjusting the starting parameters to match the beam size at the monitors to the evolution of the beam size observed. This method allows using of an arbitrary number of quadrupoles. In practice, not every location could make use of the traditional quadrupole scan method where a single quadrupole is scanned. Figure 3 shows the result of this method using the joint scan of two quadrupoles.

This technique was applied at most beam profile monitors and at every handover point to ensure the transport of the beam conformed to the model and to measure the beam properties delivered to each experiment. Those measurements were completed before the start of Run3, in early 2021. Despite the large number of connections, only a single high voltage cable was found disconnected on a quadrupole assembly near the end of the line leading to the BASE experiment.

STRAY FIELDS

The effect of stray fields generated by strong magnets used in the experimental areas on the beam trajectory was anticipated in earlier studies, which concluded that it could be compensated with the electrostatic correctors [5]. However, we revisit this study in light of the current experiments and the results gathered in 2021.

The main concern for stray fields comes from experimental areas located closest to other lines, which is the case for the AEGIS experiment and the areas at the end of the vertical lines, which are currently not occupied. The AEGIS experiment is composed of one solenoid of 5 T with a bore diameter 180 mm followed by another solenoid with a field of 1 T and a bore diameter of 250 mm. The field produced

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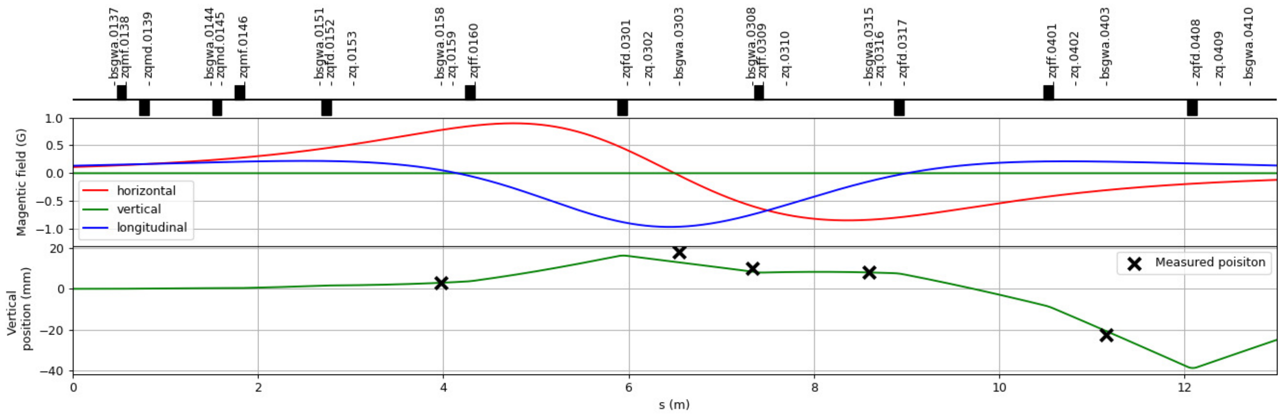

Figure 4: Synoptic, magnetic field and vertical beam position along the ELENA extraction line leading to the ALPHA experiment, under the influence of the AEGIS experimental magnets scaled at 1/3 of their nominal strength. Measured positions correspond to offset recorded on November 3rd 2021 at 13:00.

by those 2 superconducting magnets is dominated by the current distribution so we consider a simple model of loops of current. The python package *magpylib* [6] was used to model each solenoid as a stack of 15 loops of current. No other magnetic element is included in this model, which assumes vacuum magnetic permeability over the entire space. Figure 5 shows that the magnetic field mainly affects the nearby line highlighted in red, which supplies the ALPHA experiment. With a maximum field strength of around 3 G on the ALPHA line, this result is coherent with earlier studies [5].

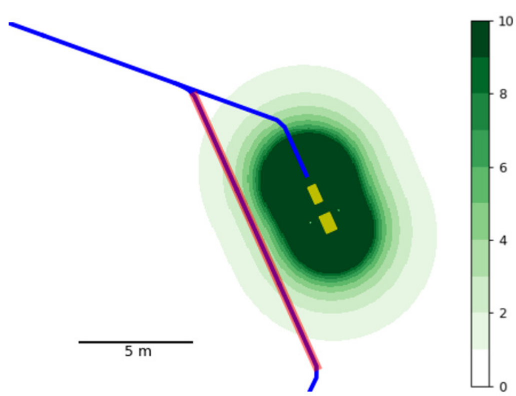

Figure 5: Layout of the beam lines nearest to the AEGIS experimental area with the two AEGIS solenoids in yellow. A heat map of the magnetic field strength clipped to 10 G in the plane of the beam lines is showed in green. The closest beam line is highlighted with a red line, on which this work focuses.

This magnetic field was used in conjunction with the MADX model to predict the effect on the beam. The magnetic field is evaluated along the section highlighted in red on Fig. 5 and in the local referential of MADX, which follows the reference trajectory. The MADX sequence is then sliced into thin elements and *KICKER* elements introduced every 10 mm to impart a deflection corresponding to the integrated effect of the stray field on the 5 mm upstream and downstream of the beam path. Only the effect of the transverse field is implemented and the longitudinal field is ignored.

On November 3rd 2021, the AEGIS solenoids were powered and reached around a third of their nominal strength by 13:00 on that day. The generated field caused, as expected, strong distortions of the vertical beam trajectory in the line leading to the ALPHA experiment, and a loss of beam somewhere between monitors *0403* and *0410*. Figure 4 shows the modelled magnetic field and vertical beam position along the straight line, using the expected strength of the AEGIS magnets. We can see a good agreement with the measured vertical position drift and an excursion around *0408* beyond the aperture of 60 mm that would explain the loss of the beam.

During the ramp of the AEGIS magnet the beam trajectory was corrected iteratively and allowed to reach a full beam transmission to the ALPHA experiment. The simple model used here reproduces well the measurements and could be used to predict both the effect and required correction for future experiments that will be installed on the vertical lines.

CONCLUSION

Beam commissioning of the ELENA extraction lines was lengthy due to the large number of elements and the use of the ion source was instrumental in allowing the characterisation of every line without antiprotons. Predictability of the beam dynamics in every line is excellent and no re-matching of the optics based on measured beam parameters was needed. The reproducibility is also very good with demonstrated stable operation of all lines over several months in 2021 and 2022. The early choice of using electrostatic devices is strongly validated by the experience gathered over the last 2 years.

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