DESIGN AND SHIELDING OF A BEAM LINE FROM ELENA TO ATRAP USING ELECTROSTATIC QUADRUPOLE LENSES AND BENDS*

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Abstract

The construction of the Extra Low ENergy Antiprotons (ELENA) upgrade to the Antiproton Decelerator (AD) ring has been proposed at CERN to produce a greatly increased current of low-energy antiprotons for various experiments including anti-hydrogen studies. This upgrade involves the addition of a small storage ring and electrostatic beam lines. The 5.3-MeV antiproton beams from AD are decelerated down to 100 keV in the compact ring and transported to each experimental apparatus. In this paper, we describe an electrostatic beam line from the ELENA ring to the ATRAP experimental apparatus and magnetic shielding of the low-energy beam line against the ATRAP superconducting solenoid magnet. A possible rough conceptual design of this system is displayed.

INTRODUCTION

The Antiproton Decelerator (AD) has been providing slow antiprotons of 5.3 MeV for various experiments, ATRAP, ALPHA, ASACUSA, etc. at CERN since 2000. However, the antiproton utilization efficiency is very low since many are lost in the process of the deceleration for the experiments. Recently, an upgrade of AD has been proposed for more efficient experiments using low-energy antiprotons [1, 2]. The project, called Extra Low ENergy Antiprotons (ELENA), includes the construction of a small storage ring equipped with an electron cooling device for the further deceleration of antiprotons from 5.3 MeV to 100 keV and for lower emittance, and the renovation of the transport line of the low-energy antiproton beams to each experimental apparatus, as shown in Fig. 1.

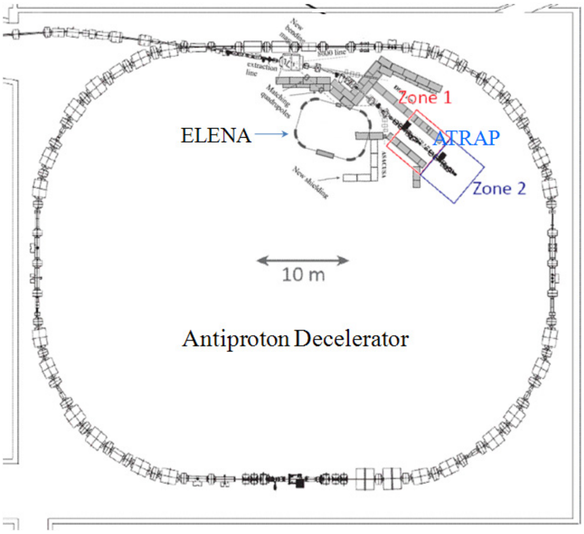

Figure 1: Schematic view of the layout of AD, ELENA, two ATRAP experimental zones, and their beam lines.

In this paper, we describe an electrostatic beam line from the ELENA ring to the ATRAP experimental apparatus and magnetic shielding of the low-energy beam line against the ATRAP superconducting solenoid magnet. A possible conceptual design of this system is displayed.

LOW-ENERGY BEAM TRANSPORT LINE

The present transport line of 5.3-MeV antiproton beams ($B\rho$ = 0.33 Tm) from AD to ATRAP is composed of quadrupole and dipole bending magnets. An electrostatic beam line is desirable for a compact system since the magnetic transport system is less efficient for 100-keV beams ($B\rho$ = 0.046 Tm). In addition, the emittance of the beam will be lowered (designed normalized emittance: 5π mm mrad) by the electron cooling system installed in the ELENA ring. To prevent a blow-up of the emittance during the transport, the lattice should be periodic and kept at as low phase advance as possible.

According to these requirements, a possible beam optics was designed. The main specifications of the beam line are listed in Table 1. The focusing lattice period is composed of an electrostatic quadrupole FODO doublet. Its phase advances per 1-m lattice period can be set at 60 degrees in the two transverse directions by applying the voltage of 2.9 kV at the quadrupole rods. The beta

Table 1: Main Specifications of the Designed Electrostatic Beam Line

Magnetic rigidity of 100-keV antiprotons	0.046 Tm
Normalized emittance (95%) [1]	5π mm mrad
Length of the focusing period	1.0 m
Axial length of the quadrupole	0.12 m
Bore radius of the quadrupole	40 mm
Voltage amplitude the quadrupole	± 2.9 kV
Phase advance per period	60 deg.
Bending radius of the vertical deflection	0.19 m

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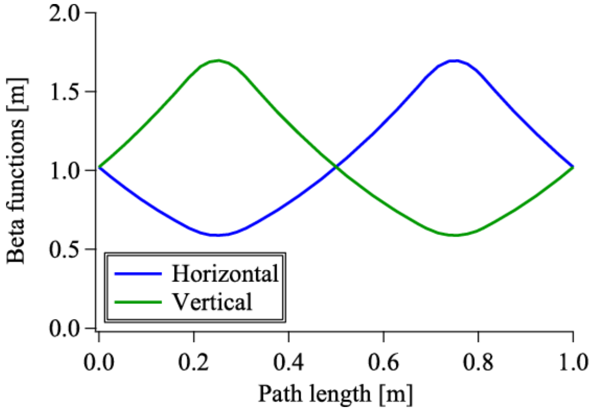

Figure 2: Beta functions of the periodic beam line designed. The phase advances are set at 60 degrees per period.

function of the focusing period is shown in Fig. 2. The maximum beam radius is 24 mm, which is well below the inner bore radius (40 mm) of the quadrupole rods. The surfaces of the quadrupole rods may be shaped to minimize aberrations, e.g., as approximate parabolas in the transverse plane.

The ATRAP experimental apparatus consists of a superconducting solenoid magnet for the confinement of anti-hydrogen [3]. The magnet is placed about 5 m above the floor level and the target position for beam diagnostics is set inside the magnet. Therefore, the beam line is bent up vertically. The 90-degree deflection can be done with the curvature radius of 0.19 m by the electrostatic bending of 1050 kV/m. The bend is made of parallel curved plates with 0.08 m separation and held at approximately ± 42 kV potential.

Note that ATRAP has two experimental zones. The beam line for the first zone branches vertically several meters back from the second one. For this purpose, the beam line for the first zone can be firstly deflected horizontally and then bent upward so that the upward-bending electrode cannot interfere with the beam line toward the second zone. This requires a modest transverse offset of the first experimental zone from the original beam path. No design of a system for focusing the beam onto the experimental target is presented here, but it is apparent that the fringing field of the solenoid will have a large effect due to the low value of the antiprotons' magnetic rigidity.

MAGNETIC SHIELDING OF THE BEAM LINE

The 100-keV antiproton beams must be precisely focused onto the small target (ϕ2mm) for further deceleration inside the solenoid magnet. However, the motion of such low-energy beams can be easily affected by the leakage field of the superconducting solenoid magnet operated between 1 and 3 T. The effect of the axial field in the vertical beam line before the solenoid magnet will be compensated by tuning the focusing force although the beam is rotated around the axis. On the other hand, the effect will be significant in the horizontal beam line before the vertical deflection because the field line crosses the beam propagation direction. Suppose that a 100-keV antiproton beam is traveling in the uniform transverse magnetic field of 10 G. The beam is deflected transversely about 1.1 cm as it travels 1 m. This deviation is comparable to the beam's radius predicted in the previous section. To reduce the effect of the leakage field on the beam motion, magnetic shielding of the beam line is considered using mu-metal as a shielding material. It is desirable that the leakage field should be reduced to 1 G or less. (Otherwise, several steering dipole lenses are

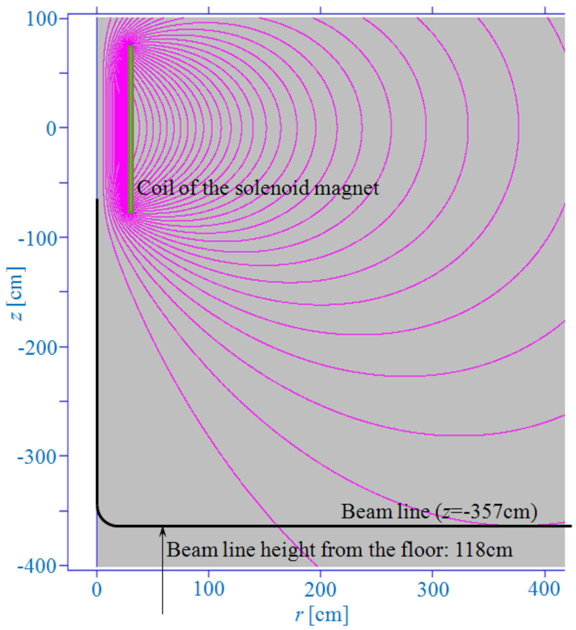

Figure 3: Layout of the electrostatic beam line (black line) and the magnetic flux around the solenoid magnet (pink curves). The origin of the coordinate is set at the center of the solenoid. The floor level coincides with z = -475 cm. The horizontal beam line is placed at z = -357 cm. The axial field in the middle of the magnet is set at 1 T. No shielding material has been introduced in the present case.

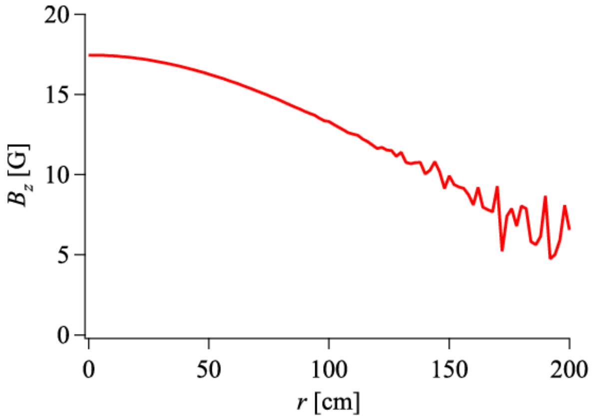

Figure 4: Magnetic field perpendicular to the beam propagation direction on the horizontal beam line (z = -357 cm in Fig. 3).

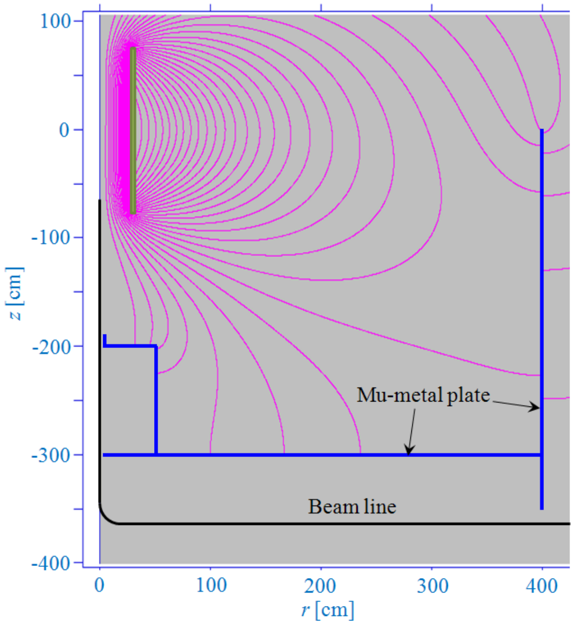

Figure 5: Layout of the electrostatic beam line (black line) and the magnetic flux around the solenoid magnet (pink curves). The simulation parameters are the same as those in Fig. 2 except for mu-metal plates are introduced around the beam line.

required to correct the beam deviation.) For this purpose, the simulation code, POISSON, has been used. In these simulations, we have assumed that the mu-metal has the relative permeability μ_r of infinity and that the system considered has the rotational symmetry around the solenoid axis for brevity.

Figure 3 shows a POISSON simulation result of the magnetic flux produced by the 1-T solenoid magnet without any shielding materials. The electrostatic beam line designed in the previous section is also indicated in the figure. The magnitude of the magnetic field perpendicular to the horizontal beam line exceeds 10 G as shown in Fig. 4. This fringing field is tripled to 50 G when the solenoid field is increased to 3 T.

The shielding effect with mu-metal was explored by varying its configuration. In Fig. 5, mu-metal plates (blue lines) parallel the horizontal and vertical beam line, and another plate is upright to prevent the field from coming around to the beam line. The transverse magnetic field along the horizontal beam line is approximately kept constant (0.6 G) in the present case, as shown in Fig. 6. If the parallel shielding plate is lengthened along the beam line and/or the upright one is lengthened, the transverse

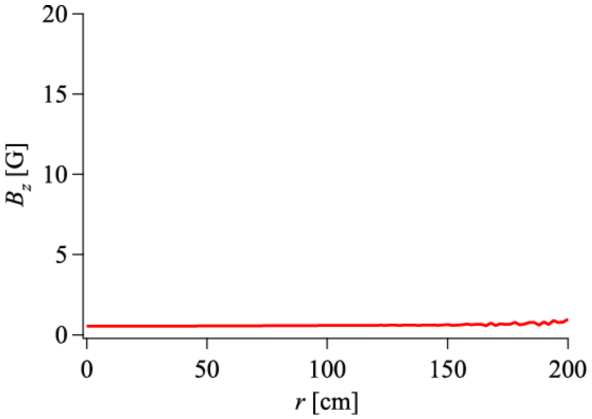

Figure 6: Magnetic field perpendicular to the beam propagation direction on the horizontal beam line (z = -357 cm in Fig. 5).

field can be further reduced. The main field inside the solenoid magnet is less sensitive to introducing the shielding plate. Note that the dependence of the thickness of the plate or stacking plates on the leakage field is weak in the present case since μ_r has been assumed as infinity.

SUMMARY

We have designed an electrostatic beam line for the transport of low-energy antiproton beams from the ELENA storage ring to the ATRAP experimental apparatus. The lattice of the beam line is periodic and its phase advance is low to prevent the emittance increase due to the space-charge force during the transport. The beam line is shielded against the leakage field of the 1-T solenoid magnet of ATRAP by settling mu-metal plates.

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