DESIGN OF AN ANTIPROTON INJECTION AND MATCHING BEAM LINE FOR THE AD RECYCLER RING

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Abstract

A small antiproton recycler ring for use in the MUSASHI beam line at the CERN AD has been designed by the QUASAR Group for operation at energies between 3 and 30 keV. A highly efficient beam line for capturing the beam after extraction from the trap, transporting and injecting it into this small ring is very important to minimize losses and fill the ring up to its space charge limit. In this contribution, the beam optical design and overall layout of this injector is presented.

INTRODUCTION

There has been great interest in experiments with low-energy antiprotons after successful trapping of antihydrogen in 2010. All experiments use the Antiproton Decelerator (AD) at CERN [1], where the antiprotons are produced by a 26 GeV proton beam from the Proton Synchrotron (PS). They are then captured in the AD and decelerated from a momentum of 3.57 GeV/c to 100 MeV/c. Also, work is underway on a new Facility for Antiproton and Ion Research (FAIR) [2] at GSI in Germany. Within the FAIR complex, the Facility for Low Energy Antiproton and Ion Research (FLAIR) [3] will include the electrostatic Ultra-low-energy Storage Ring (USR), designed to enable a wide variety of novel experiments [4]. The QUASAR Group [5] is leading the developments towards the USR. The time gap between now and the start of the USR provides the motivation and opportunity for a small antiproton recycling ring [6]. The ring might be placed after the MUSASHI trap [7] at the AD and, in this application, would re-circulate antiprotons of energies between 3 and 30 keV. It would then enable progress to be made in atomic and molecular physics experiments [8] by incorporating a reaction microscope [9] into the ring.

For the recycling ring, 5 shots of antiprotons from the AD will be collected and cooled in the trap, then extracted in ‘fast extraction mode’ as a pulse, or ‘bunch’, of antiprotons of 150-500 eV kinetic energy and 1-2 μs bunch length. The injector, or transport beam line, that is the subject of this paper, will transport antiprotons from the trap to the ring, providing focusing and beam shaping and adjust the energy of the particles to match the recycling energy of the ring. The transport line has to form a beam acceptable for the ring which means that the beam quality is very important. As the beam has a very low energy and is divergent after the magnetic fringe field of the trap, and the injection line has to provide acceleration up to 3-30keV the electrodes and the voltages applied to those electrodes had to be chosen carefully. The ring can accept beams with an initial emittance of up to 30 π mm mrad without losses inside the ring.

INJECTION LINE

The injection beam line has three main parts. The first part is the acceleration section, where the energy of the antiprotons is increased from 150 eV to the re-circulating energy of the ring (3-30 keV). The second part of the injection line is the diagnostics block, which will include the necessary equipment for measuring all important beam parameters. In addition, this section will also contain a port for the incorporation of a test bench and ion source to enable the ring to be set-up and tested in the absence of antiprotons. The third part is the matching section, which comprises four electrostatic quadrupoles that match the shape and divergence of the beam to the ring parameters.

Acceleration Section

A schematic drawing of the acceleration section is shown in Fig. 1, where the y-axis has been expanded and the MUSASHI extraction electrodes are included. Fast extraction has already been demonstrated with antiproton energies of a few hundreds of eV. The acceleration section has been designed to provide transport of antiprotons with an initial energy range between 150 and 500 eV, and to accelerate them to energies between 3 and 30 keV. This section comprises two sets of accelerating electrodes, separated by a long drift tube. The first set of accelerating electrodes is placed immediately after the extraction electrodes in the MUSASHI trap. The first acceleration section consists of 5 electrodes with an inner diameter of 50 mm, a thickness of 5 mm and a gap of 15 mm. This part accelerates the beam by a factor of 2.67, thereby increasing the energy of a 150 eV beam to 400 eV (and a 500 eV beam to 1.3 keV). In addition, this section guides and focuses the beam so it can travel through the 1.5 m drift tube.

For a simple installation and later operation, the ring shall be kept on ground potential, together with the gate valve at the end of the MUSASHI vessel and hence the entire acceleration and matching section. Beam acceleration is achieved by means of a long drift tube. This shields the beam inside while the voltage on it is being switched to final energy. The beam is then

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accelerated to the ground potential of the ring. Thereby, the beam will not be affected by the electric field when the voltage is switched, allowing to accelerate it before as well as after the drift tube, i.e. in the first and second sets of electrodes. This requires that the drift tube needs to be long enough for the whole 2 μs bunch. For a beam with an initial energy of 150 eV the time required to travel through the 1.5 m long tube is ~5 μs and thus more than enough to guarantee a full switch of the drift tube potential. The length of the tube was chosen to allow for a possible increase of the initial energy up to 500 eV.

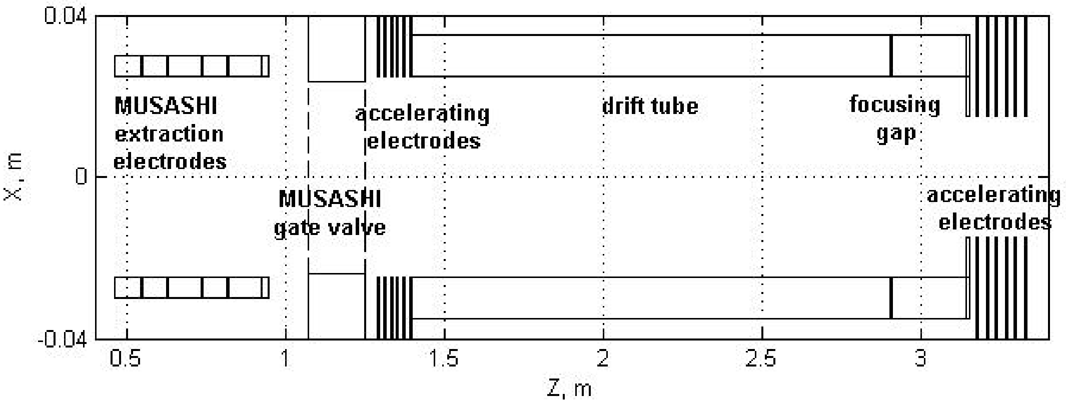

Figure 1: Scale model of the extraction and acceleration section.

The second set of accelerating electrodes consists of five disks with an inner diameter of 10 mm, a thickness of 5 mm and a gap of 20 mm. It provides focusing of the beam at the exit of the accelerating section and thus simplifies beam shaping in the final matching section.

Diagnostics Block

The diagnostics block is used to fully characterize the beam. It also links to a separate injector and ion source, allowing to inject H^- ions to commission the ring independent from AD operation. This section includes an H^- ion source, vacuum pumps, an Einzel lens, a pair of X-Y steerers, and a Faraday cup. The diagnostics elements include also beam position monitors [10] that will help to adjust the position of the beam using X & Y correctors.

Matching Section

The third part of the injection line is the matching section. It serves for matching the beam from the injection line to the ring. It is planned to use four electrostatic quadrupoles for this purpose.

Trace3D [11] was used to show the possibility of an appropriate matching. The strengths of the first two quadrupoles are selected to create a parallel beam from the incoming divergent beam. If the position of the focus after acceleration was shifted for any reason, then the strength of the first and second quadrupoles would also need to be changed. The last two quadrupoles focus the beam. The necessary astigmatism and shift of the position of both foci can be achieved by changing the strength of the last two quadrupoles.

BEAM DYNAMICS SIMULATION

The design of the injector was optimized using beam tracking simulations. In order to represent the antiproton beam coming from MUSASHI, the fringe magnetic field of the trap solenoid was taken into account in full 3D simulations. These were performed from the center of MUSASHI, using the core of the compressed beam [12]. The magnetic field inside the trap solenoid was assumed to be 2.5 T for all simulations described here.

The parameters of the beam inside the trap are given in [12]. In brief, the antiproton cloud in the trap after compression can be modeled using two Gaussian distributions, one with σ=0.25 mm including 45% of antiprotons and the other with σ= 4.0 mm including the other 55%. The antiproton cloud can be divided into two parts, the core and the halo. With the aim of forming a beam acceptable for the ring, the main interest lies in the core of the cloud, assuming that the halo part will be lost most probably.

For the simulations the particle distribution described above has been used. 3D simulations were then performed using MatLab, where a system of differential equations of motion was solved numerically. The results for particles extracted at 150 eV and accelerated to 30 keV are presented in Fig. 2. It can be seen that the beam is focused in the second acceleration section. This is important for further "reshaping" and matching of the beam by the quadrupoles.

One of the main objectives of the first set of accelerating electrodes is to provide a quasi parallel beam inside the drift tube. The second set of accelerating electrodes provides acceleration to the final energy. A focusing gap is introduced at the end of the drift tube to avoid over focusing of the beam in this second part. As the energy is increasing from 400 eV to 3-30 keV and the beam at the end of the drift tube fills about 25% of the aperture, the fringe fields of the accelerating electrodes have provided a very strong focusing effect on the beam, and it becomes impossible to keep the beam paraxial. But the focusing gap that accelerates the beam up to 600 eV allows to accelerate the beam while it is focused. This way the aperture of the accelerating electrodes can be reduced, minimizing the fringe field area.

Phase space graphs of the beam at the matching point of the ring are presented in Fig. 3 for a final energy of 3 keV (left) and 30 keV (right).

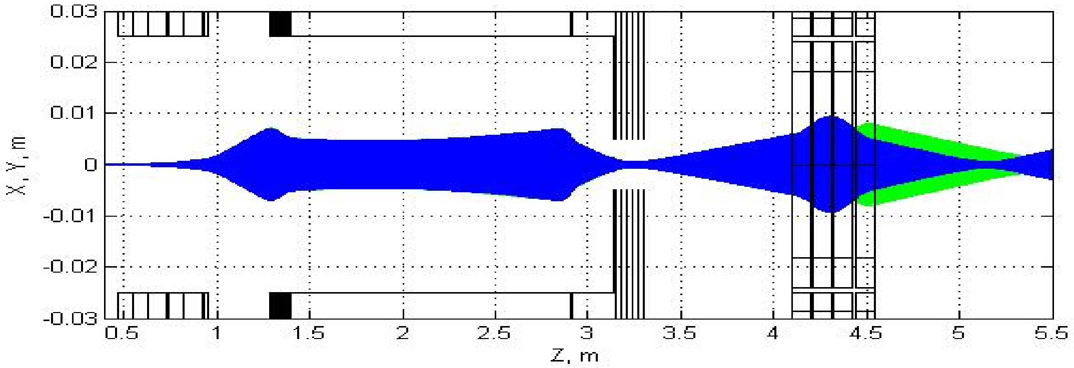

Figure 2: Trajectories of particles from the solenoid through the acceleration and matching section (energy from 150 eV to 400 eV, then to 30 keV). Blue lines correspond to an X projection, green lines to a Y projection.

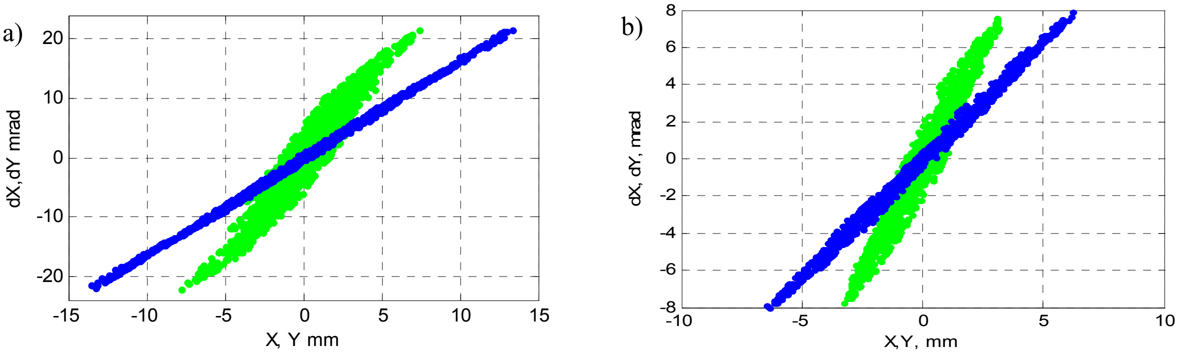

Figure 3: Antiproton distributions in the transverse phase space planes at the matching point, a) E=3 keV, b) E=30 keV.

As shown in Figs. 2 and 3, the injection line satisfies the necessary requirements for transporting and accelerating the antiprotons from the trap to the ring and matching the phase of the injected beam to the ring. 34% of all the antiprotons that are initially distributed inside a radius of 0.25 mm are transported without losses and have an emittance that is acceptable for the ring.

SUMMARY

An injection line has been designed to transport and accelerate antiprotons from the MUSASHI trap at the AD at CERN to a small recycler ring. The line has been designed to accept a beam with an initial diameter of 1 mm (in the center of the trap), an initial energy of between 150 and 500 eV, and an energy spread of 30 eV. It was shown that acceleration up to energies in the range of 3-30 keV can be achieved with acceptable losses. By using a quadrupole quadruplet in the final part of the injector, the necessary flexibility in terms of beam shaping and matching was demonstrated.

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