A METHOD TO POLARIZE STORED ANTIPROTONS TO A HIGH DEGREE

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Abstract

The PAX collaboration proposed a method to prepare intense beams of polarized antiprotons [1]. Polarized antiprotons can be produced in a storage ring by spin-dependent interaction in a pure hydrogen gas target. The polarizing process is based on spin transfer from the polarized electrons of the target atoms to the orbiting antiprotons. In this paper, beside a description of the polarization technique and its potential, a preliminary lattice design and first ideas for beam cooling are discussed.

PRODUCTION OF POLARIZED ANTIPROTONS

The polarizing process is based on the electromagnetic spin transfer from a purely longitudinally polarized electron target to the antiprotons orbiting in a dedicated large acceptance Antiproton Polarizer Ring (APR). Spin Filtering has been established experimentally at the Test Storage Ring (MPI Heidelberg) in 1992 [2] and by the subsequent theoretical analysis [3].

The beam lifetime in the APR can be expressed as function of the Coulomb-Loss cross section and the total hadronic proton-antiproton cross section [1]. A polarized atomic beam is injected into a storage cell, located in a low-beta section ($\beta_{x,y}$= 0.2 m). The diameter of the beam tube of the storage cell should match the ring acceptance angle Ψ_{acc} at the target. As discussed in [1], the magnitude of the antiproton beam polarization based on electron spin transfer depends on the acceptance angle. The optimum beam energies for different acceptance angles at which the polarization build-up works best can be obtained from the maximum figure of merit (FOM) of the polarized antiproton beam as shown in Fig. 1. FOM = $P^2 \cdot N \cdot f_{rev}$, where P denotes the beam polarization, N the number of particles stored in the APR and f_{rev} the revolution frequency. The optimum beam energies for the APR appear below 170 MeV, with achievable polarizations after two beam lifetimes between P = 0.2 to 0.4. The calculations of the polarization build-up assume a polarized atomic beam intensity of $1.5 \cdot 10^{17}$ atoms/s, which reflects a moderate improvement of about 20% over the present performance [4].

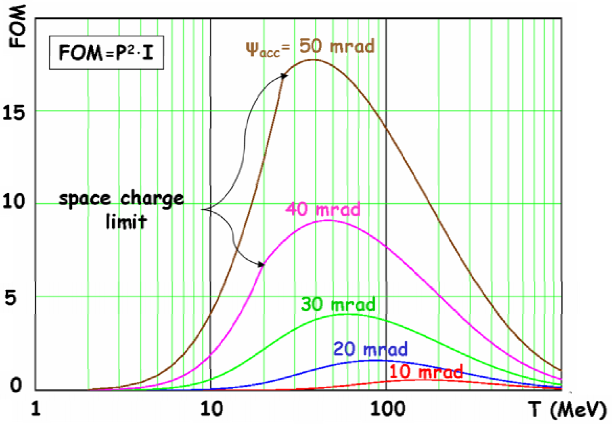

Figure 1: Figure of merit for the polarized antiproton beam for filtering times t =$2 \cdot \tau_{APR}$ (two beam lifetimes) as function of beam energy.

The optimum kinetic beam energies T for the antiproton beam in the APR for different acceptance angles at the target are listed in the Table 1.

Table 1: Kinetic beam energies and corresponding maximum FOM for different acceptance angles as taken from Fig. 1.

Ψ_{acc} (mrad)	T (MeV)	τ_{APR} (h)	P ($2\tau_{APR}$)
10	167	1.2	0.19
20	88	2.2	0.29
30	61	4.6	0.35
40	47	9.2	0.39
50	39	16.7	0.42

The polarized antiproton beam would be subsequently transferred to a cooler storage ring for measurements (see Fig. 2). Both the APR and the experimental storage ring should be operated with beam cooling to counteract emittance growth due to beam-target interaction. The longitudinal spin transfer cross section is twice as large as the transverse one [3]. The stable spin direction of the beam at the location of the polarizing target should therefore be longitudinal as well, which requires a Siberian snake (1.1 Tm solenoidal field) in a straight section opposite the target.

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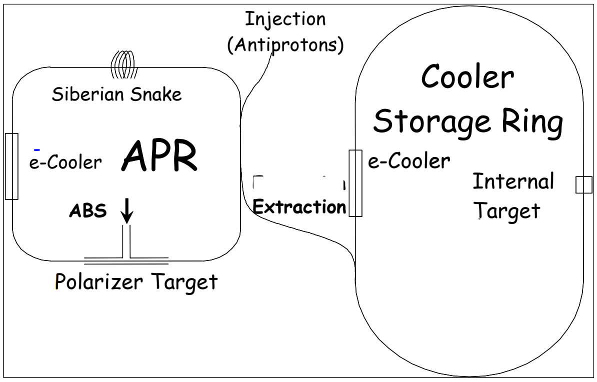

Figure 2: Scheme for an experiment with polarized antiprotons.

PRELIMINARY LATTICE DESIGN

The basic layout of the lattice is shown in Fig. 3. The main goal for lattice design is to provide large acceptance. It has to be in the range of several hundreds of mm mad to reach the required acceptance angle. Present state-of-the-art design with up to third-order multipole correction provides about 250 mm mad [5]. Further requirements for the ion optics are: dispersion free straight section at the target, the electron cooler straight and the injection kicker, a betatron amplitude of $\beta_{x,y} = 0.2$ m at the target, and an almost parallel round beam in the electron cooler section. The optical functions have also to be optimized for injection and extraction. In the proposed layout these constraints are fulfilled by the arrangement of quadrupole triplets. The main beam and ring parameters are summarized in Table 2. Up to 10^{12} antiprotons have to be injected into the APR. After two beam lifetimes, 10^{11} antiprotons can be provided for experimental purposes.

A special feature of the lattice is the location of the sextupoles, symmetrically placed between the bending magnets in the arcs. Three sextupoles are arranged per arc, in front, in the middle and at the end of the triplet. This scheme enables to control chromaticity and betatron resonance width almost independently, since places with maximum and very small dispersion are chosen. A concept for higher-order multipole correction has still to be worked in order to reach the ambitious ring acceptance.

Table 2: Main APR beam and ring parameters.

Ion species	Antiprotons
Kinetic energy, MeV	40
Momentum, MeV/c	276.9
Magnetic rigidity, Tm	0.924
Transverse acceptance, mm mrad	500
Energy acceptance, %	0.2
Number of injected particles	10^{12}
Number of polarized particles	10^{11}
Arc structure	D-F-D-B-D-F mirror symmetric
Number of periods	2
Number of bending magnets	4
Arc length, m	14.9
Straight length, m	24
Transition γ_t	9.2

FIRST IDEAS FOR BEAM COOLING

To estimate the capability of an electron cooling system for the APR the evolution of the antiproton distribution function during cooling was simulated using the BETACOOL program [6]. Parameters for the electron cooling system and beam equilibria are listed in Table 3. The simulation of the beam distribution contains the effect of intrabeam scattering, electron cooling, interaction with the internal target, and particle loss in the target due to acceptance and separatrix limitations. The number of model particles was chosen to be three thousand. An electron beam current of 0.12 A was applied, corresponding to an electron density of about 10^6 cm^{-3}.

The rms transverse emittance and momentum spread evolutions in time are presented in Figs. 4 and 5. As one can see, the rms beam parameters are fairly constant over time. However, beam distribution functions are varying significantly during cooling. After one hour of cooling the transverse profiles get a very dense core and wide tails, distributed over up to six rms compared to the initial values (see Fig. 6).

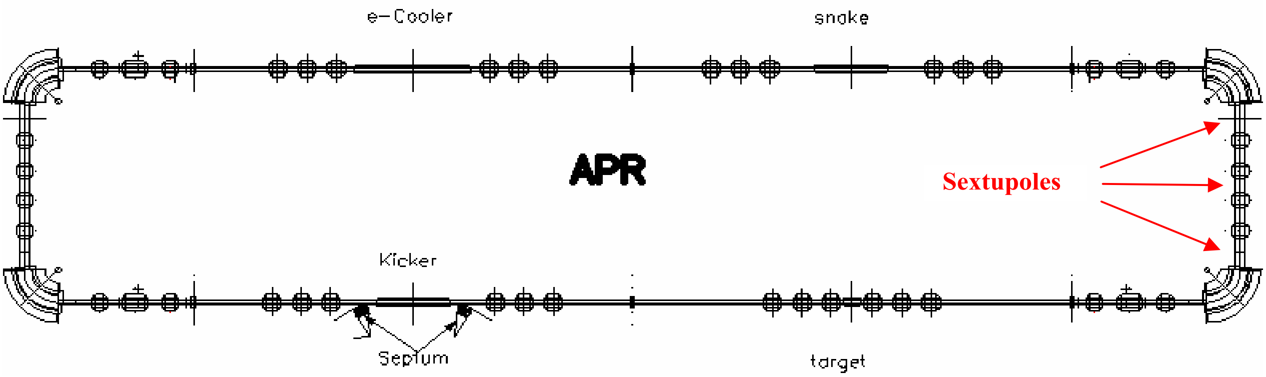

Figure 3: APR lattice layout. The location of sextupoles is indicated in the arc on the right-hand side.

Table 3. Beam equilibria and cooling system parameters.

Antiproton number	10^{12}
Rms emittance, π·mm·mrad	15
Rms momentum spread	$3\cdot10^{-3}$
RF amplitude, kV	3
Rms bunch length, m	28
Tune shift	0.15
Cooling section length, m	3
Magnetic field in the cooling section, G	800
Electron beam radius, cm	5
Electron beam current, mA	100 - 200
Magnetic field errors	$5\cdot10^{-5}$

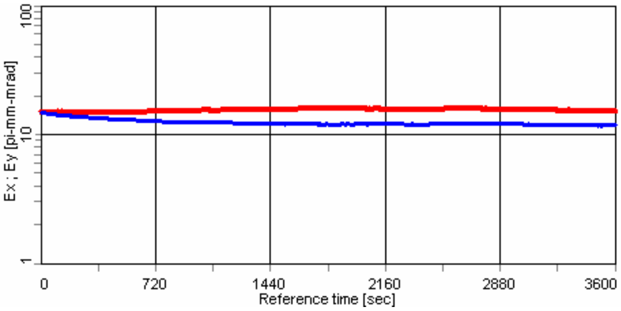

Figure 4. Rms transverse emittances versus time for uniform electron beam distribution.

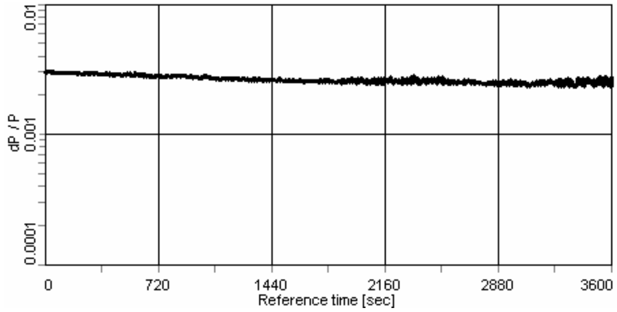

Figure 5. Rms momentum spread versus time for uniform electron beam distribution.

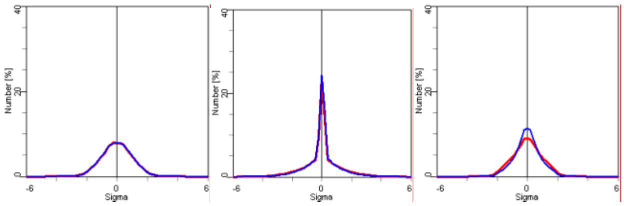

Figure 6. Transverse beam profiles: initial (left), after 1 h of polarization with uniform electron beam distribution (middle) and hollow electron beam distribution (right).

The dynamics of the tail variation is very slow. Characteristic times for the tail formation are in the order of few hours. In principle, this process can be controlled during cooling by a slow variation of the electron current, and RF voltage. A more important feature of the beam evolution is the formation of the dense core. The tune shift value has to be calculated in accordance to the core parameters. At stabilized rms parameters, it increases by a few times, eventually approaching thresholds of beam instabilities.

A new electron gun was proposed and tested in Novosibisk [7], permitting to form an electron beam with variable density profile. This development allows to significantly decrease the electron density in the central part of the beam. To get a rough estimate for the potential of such a hollow electron beam, simulations were carried out with the following beam parameters: the inner and outer radius of the hollow beam was chosen to be 2 cm and 4 cm, respectively, with an electron density of $3\cdot10^{5}$ cm^{-3} inside the inner radius, and $2\cdot10^{7}$ cm^{-3} between inner and outer radius. This corresponds to a total beam current of 1.15 A. It turned out that the evolution of rms beam parameters is practically the same as in the case of uniform electron beam distribution. However, the formation of the dense core does not take place (see right plot of Fig. 7) either in transverse or in the longitudinal phase space. Tails do also not appear to be as wide compared to the case with uniform electron distribution.

CONCLUSIONS

After spin filtering for about two beam lifetimes at energies of 40 to 170 MeV using a dedicated antiproton polarizer ring, the antiproton polarization would reach P = 0.2 to 0.4. The spin-filter technique requires a large acceptance ring, demanding careful design of the magnets and higher-order multipole correction schemes. A preliminary design is presented, optimized for higher-order mulitpole corrections. In principle, beam cooling can be provided by electron cooling during the polarization process. To avoid overcooling of the beam in the transverse direction the mean energy losses can be compensated by an RF cavity and decreased electron density in the central part of the beam by a special design of the electron gun. Alternatively, stochastic cooling could be utilized, which permits to provide different cooling rates in longitudinal and transverse directions. The cooling concept has to be further investigated to provide an optimized solution.

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