DESIGN STUDY OF ANTIPROTON ACCUMULATION AND DECELERATION RING IN THE KEK PS COMPLEX

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Abstract

An antiproton accumulation and deceleration ring in the KEK proton synchrotron (KEK PS) complex has been designed. The KEK PS top energy is 12 GeV and it is enough to produce 2 GeV/c antiprotons. As many as 10^5 of them would be collected each synchrotron cycle, that is 2 second. After stacking and stochastic cooling of the beams, 10^7 to 10^8 antiprotons per hour should be available for physics experiments. There are several R&D items such as compression of the nine bunch train in the PS. Preliminary simulation has been done to look at single turn transfer of antiprotons to the proposed ring whose circumference is 1/3 of the PS.

I. OVERVIEW

The complex of rings (ACOL, AA and LEAR) at CERN [1] is the only facility in the world that accumulates and decelerates antiprotons for versatile fields of physics. A lot of interesting work using low energy antiproton beams with this complex has been done and there are still increasing number of proposals. Atomic physics using antiproton beams is one of that growing fields. There is no doubt that if there were another low energy antiproton source in the world, even dedicated for atomic physics, it would be very useful.

At KEK, the proton synchrotron (KEK PS) which provides an intense proton beam at the energy of 12 GeV is in operation. Experiments using antiprotons is nothing new to the KEK PS users. However, there are vigorous demands for higher intensity of antiprotons with good beam quality to carry out more systematic study. A dedicated ring for antiproton accumulation and deceleration is desired, although there are manifest disadvantages compared with the CERN complex such as lower primary proton energy, which will produce less number of antiprotons.

In this report, a preliminary design of the ring for antiproton accumulation and deceleration, necessary change in the KEK PS operation, antiproton yield, and stochastic cooling are described. During the discussions of that ring, we examined simultaneously (not described in this report) whether the same ring could be operated for the acceleration of heavy ions as a booster synchrotron for the KEK PS. By that reason, we name the proposed new ring AA-HIB (Antiproton Accumulator - Heavy Ion Booster).

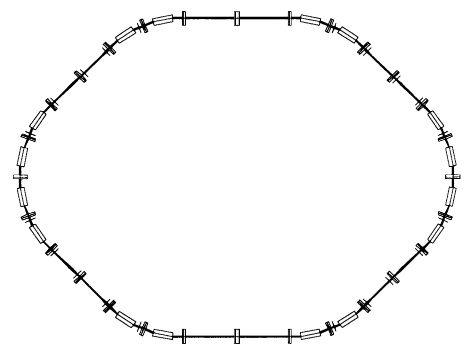

Figure. 1. Lattice layout of the AA-HIB.

II. LATTICE DESIGN FOR AA-HIB RING

In designing the antiproton facility, it is requested that accumulation and deceleration of antiproton beams should be done in one ring at the first stage. That is just because of the limited budget. In designing the lattice of the AA-HIB ring, the following criteria are to be considered.

1. The absolute value of the phase slip factor ($\eta = 1/\gamma_t^2 - 1/\gamma^2$) should be about 0.1 to have a good mixing condition in stochastic cooling.
2. The straight sections for beam injection and extraction should be dispersion free.

The maximum magnetic rigidity of the ring is $(B\rho)_{max} = 6.671$ T·m, where the momentum of accumulated antiprotons is 2 GeV/c. Since antiprotons and heavy ions are to be decelerated and accelerated, respectively, and considering requirement (1.) above, it is desirable that the transition energy should be far above the top energy.

In order to meet those requirements, a lattice based on three DOFO-cell configurations [2] consisting of one missing bending magnet cell between two cells is adopted. In this lattice, dispersion function at the bending magnets are relatively small and, on the other hand, it is large at the missing-bending magnet cell. This is a desirable feature for our purpose. That is, a beam with large momentum spread such as an antiproton beam does

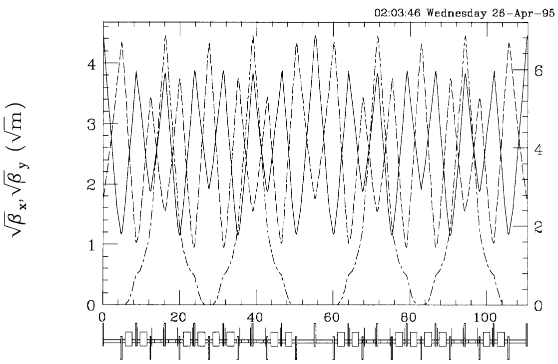

Figure. 2. Beam optics functions of the AA-HIB. β_x:solid line, β_y:dashed line, η_x:dotted line.

not necessarily require large horizontal aperture in the bending magnets.

Superperiod of the ring is two and one arc section consists of the two unit cell of DOFO configuration. There are sixteen bending magnets, and the effective length of each bending magnet is 1.8 m. The distance between the two quadrupole magnets of the unit cell is 3.5 m, which provides enough room for beam monitors and steering magnets for the optics correction. The lattice layout and beam optics function are shown in Fig. 1 and Fig. 2, respectively. An optics code SAD [3] is employed to calculate optics functions.

There are four straight sections which can be used for the injection and extraction systems, the rf cavities and the pick-ups and kicker magnets for stochastic cooling. The length of each straight section is 4.5 m. The dispersion function at both ends of an arc section is zero. The transition energy γ_t is 5.4, which is well above the maximum Lorentz γ of the beam. The operating tune can be changed by varying the field strength of a series of quadrupole magnets placed only in the straight sections. The nominal tune are selected as (ν_x, ν_y)=(3.6, 4.7).

Chromaticity correction can be made by a pair of sextupole magnets placed near the quadrupole magnets in the arc. Dynamic apertures for both horizontal and vertical planes when correcting the chromaticity using these sextupole magnets are evaluated by particle tracking simulation of 5,000 turns. In this simulation, the momentum dispersion of the beam is assumed to be zero. The estimated dynamic aperture for both planes turns out quite large, namely about 1,000 π mm·mrad. That is larger than the acceptance, which is 100 π mm·mrad for horizontal and 90 π mm·mrad for vertical.

The physical aperture of the bending magnets requires 220 mm (hor.) $\times$ 70 mm (ver.) because a momentum acceptance of at least $\pm$3% is necessary for rf stacking of accumulating antiprotons. The horizontal beam size becomes maximum at the position of the quadrupole magnet in the center of the unit cell of the arc section and reaches about 400 mm, requiring a large bore quadrupole magnet.

III. MANIPULATION OF BUNCH STRUCTURE IN THE KEK PS

In this section, we review the present beam parameters of the KEK PS and examine the necessary manipulation of the longitudinal bunch structure in order to match the design of the AA-HIB. The circumference of the AA-HIB lattice is about one third of the KEK PS. The transfer of antiproton beams into the AA-HIB should be done by one turn injection. The transverse emittance of antiproton beams is much larger than the primary proton beams so that the transverse ring acceptance is filled with the one turn injected beams; no room for multi-turn injection. If a very fast kicker is developed, and provided that antiproton beams have the same bunch structure as the primary proton beams, multi-turn injection filling the longitudinal phase could be another choice. However, it is not a realistic plan at the moment. To transfer all of the beams in the KEK PS to the AA-HIB with one turn injection, the length of the bunch train should be shortened before the extraction. In the concrete, nine bunches uniformly distributed in the KEK PS is gathered at the top energy so that the beams can occupy only one third of the circumference.

Table 1: Parameters of the KEK PS.

harmonic number	9
rf frequency (at the top)	8.0 MHz
rf voltage	92 kV
bucket height ($\Delta p/p$)	$\pm$0.55%
bunch spacing	37.7 m
maximum dispersion	3.8 m
maximum β_x and β_y	20 m
machine aperture (H*V)	145 mm*50 mm
Lorentz gamma	13.8
slip factor	1.67×10^{-2}
longitudinal emittance	3 eV·sec (full)
norm. horizontal emittance	45 π mm·mrad (full)
norm. vertical emittance	20 π mm·mrad (full)

The simplest way employs an additional rf system which has the harmonic number (h) of unity in the KEK PS. After the beams are accelerated to the top energy by the normal rf system with the harmonic number of nine, the normal rf system is turned off and, in turn, the $h = 1$ rf system is turned on. The switching timing of those two rf system gives several options with more detailed differences. Nevertheless, the primary use of the $h = 1$ rf system is to populate most of beams near the center of the rf bucket so that the bunch length can be within the range of one third or less of the circumference.

We examined the scheme in detail using multi-particle simulation. Table 1 shows the rf, lattice, and beam parameters of the KEK PS.

By exciting the $h = 1$ rf system at the top energy, only one rf bucket is made. In the bucket, we want to have less than 113 m (the circumference of the AA-HIB) bunch and its maximum $\Delta p/p$ = 1.5%. The maximum momentum spread was limited by the horizontal aperture in the KEK PS, that is 145 mm. In fact, it is the most optimistic estimate since we assumed that the closed orbit distortion can be perfectly corrected and beam size are simply determined by the transverse beam emittance and the momentum dispersion. Reduction of the useful aperture by sagitta is, though, included.

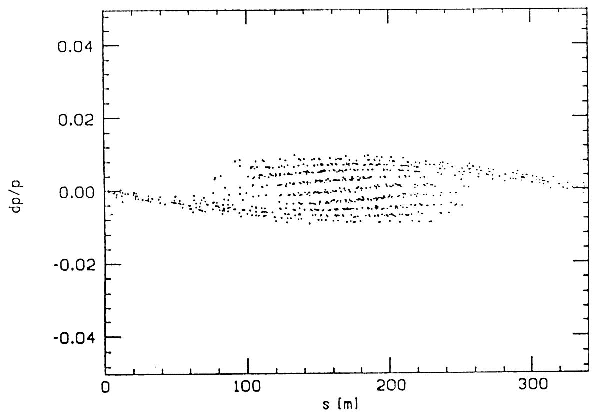

Figure. 3. A bunch from the KEK PS.

The following is the simulation results. The $h = 1$ rf system is excited to 22 kV suddenly (within 1 msec) after the $h = 9$ rf system is turned off. About one quarter of synchrotron oscillation period of $h = 1$, nine bunches, which are mismatched in the $h = 1$ rf bucket, are aligned in the momentum direction so that projection of the beam to the position axis has the narrowest profile as shown in Fig. 3. We counted the number of particles within 113 m in the position direction and $\Delta p/p = 1.5\%$ in the momentum direction. The ratio of the above counted number to the total particles is the capture efficiency and turns out to be 69%. The whole process takes 5.7 msec. Note that the higher voltage can populate more number of beam around the center of the bucket, but at the same time, the momentum spread becomes larger, that is limited by the horizontal aperture.

IV. ANTIPROTON YIELD

We have estimated antiproton yield based on the CERN parameters and scaled them in the following way. The production yield rate of 2.0 GeV/c antiprotons from 12 GeV protons is assumed to be 1/8 of that of 3.5 GeV/c antiprotons from 26 GeV protons. The antiproton yield rate at 24 GeV is 9.1×10^8 per 10^{13} protons and it is scaled to the yield at 26 GeV by multiplying 1.22 [1]. As the acceptance of a horn, we take $24\ \pi \times 10^{-4}$ sterad. The momentum acceptance is assumed to be 1.5%. Therefore, according to the simplified formula in [1] the antiproton into the AA-HIB per incident proton is

$$\begin{aligned} Y &= \frac{1}{8} \cdot 1.22 \cdot (9.1 \times 10^8/10^{13}) \cdot 1.5 \cdot (24\pi \times 10^{-4}) \\ &= 1.6 \times 10^{-7} \end{aligned}$$

V. STOCHASTIC COOLING AND TOTAL NUMBER OF ANTIPROTONS

The number of protons per PS machine cycle is 4×10^{12}. One cycle takes 4 seconds presently, but 1 to 2 seconds out of 4 seconds is spent for slow extraction. In the operation mode to produce antiprotons, we expect that the KEK PS cycle could be 2 seconds and therefore 4.5×10^5 antiprotons should be injected every 2 seconds, where transfer efficiency (69%) from the PS to the AA-HIB demonstrated above is included.

Once a bunch is injected into the ring, precooling is applied until the next bunch is injected. The momentum spread is reduced from $\pm 1.5\%$ to $\pm 0.5\%$ in 2 seconds. A stripline type pick-up and kicker whose total length is about 3 m each will be used with a notch filter. The pick-up and preamplifier are to be cooled down to 20 K. The required system bandwidth and total gain are 560 MHz and 160 dB, respectively. The power to the kicker is estimated to be 1.2 to 1.3 kW.

After 1,000 bunch injection, which takes about 40 minutes, more than 10^8 antiprotons are accumulated. Additional deceleration down to 100 MeV/c or lower makes one machine cycle of the ring the order of hour. With beam loss in the transport line and deceleration process included, as many as 10^7 to 10^8 antiprotons per hour are expected for physics experiments.

References

[1] P. Bryant and S. Newman (Editors), *CAS* (CERN Accelerator School), Antiprotons for Colliding Beam Facilities, Geneva, 1983.

[2] U. Wienands, R. V. Servranchx, R. C. York, X. Wu, S. Machida, A. A. Garren, F. Botlo-Pilat, E. D. Courant, “The High-γ_t Lattice of the SSC Low Energy Booster”, Proc. of 15th International Conference on High Energy Accelerators, Hamburg, 1992.

[3] SAD stands for “Strategic Accelerator Design” code. It is developed by K. Oide and colleagues at KEK.