FEASIBILITY OF ANTIPROTON ACCUMULATION IN THE RESR WITH BARRIER BUCKET AND STOCHASTIC COOLING

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Abstract

The barrier bucket antiproton accumulation scheme is investigated for the RESR ring, which is proposed to be constructed using the existing COSY ring magnets. In the baseline design of the FAIR project, the RESR serves as an intermediate storage and accumulation ring for antiprotons precooled in the Collector Ring (CR) by stochastic cooling. The main objective is the accumulation of up to 10^{11} antiprotons within a few hours, enabling high-intensity antiproton beam experiments in the High Energy Storage Ring (HESR). The feasibility and expected performance of the proposed barrier bucket accumulation scheme are discussed based on numerical simulations and beam dynamics considerations.

INTRODUCTION

The operation of the Recycler Experimental Storage Ring (RESR) is planned to be supported by precooling of secondary beams in the stochastic cooling system of the CR prior to injection [1]. Precooled batches of 10^8 antiprotons will be delivered from the CR every 10 s at a kinetic energy of 3 GeV [2,3]. Once approximately 10^{11} antiprotons have been accumulated, the beam will be transferred to the HESR for subsequent acceleration or deceleration, depending on the requirements of the experimental program [4]. In the original design, antiproton accumulation in the RESR was based on the momentum stacking method combined with stochastic cooling [5]. This approach required wide aperture magnets to provide sufficient transverse acceptance for the injection and stacking orbits. However, in the current cost-optimized design, which reuses components from the existing COSY facility, the magnet apertures are too narrow to accommodate conventional transverse stacking. To overcome this limitation, the barrier bucket accumulation technique combined with stochastic cooling using barrier voltages is proposed for longitudinal stacking [6]. The present paper describes a brief description of the RESR conceptual design based on COSY magnets and assesses the feasibility of antiproton accumulation in this ring using the stochastic cooling system previously built and tested at COSY [7]. The requirements for the RF barrier bucket and the injection system are also discussed.

RESR DESIGN BASED ON COSY

The new RESR lattice was designed using the existing COSY dipole and quadrupole magnets [8]. The main design objective was to keep the ring geometry as close as possible to the original RESR specifications, ensuring the machine fits within the planned building around the CR, as shown in Fig.1.

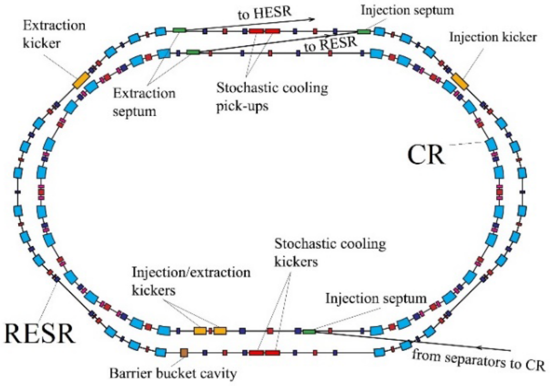

Figure 1: Conceptual layout of the CR/RESR.

The primary challenge was to facilitate compatible beam injection from the CR and extraction toward the HESR in accordance with the overall FAIR topology. The number and parameters of the available COSY magnets proved sufficient to create a suitable lattice that meets the RESR design requirements. The main parameters of the RESR are given in Table 1. It should be noted that the COSY dipoles were originally designed for a slightly lower maximum magnetic rigidity than that specified in the initial RESR design. This reduction is not critical for the accumulation process itself, but it slightly lowers the antiproton production yield (by a few percent) compared to the original energy [9]. The new injection and extraction systems are required.

Table 1: RESR Parameters for Antiproton Operation

Parameters	**Value**
Circumference, m	239.9
Magnetic rigidity, Tm	12
Acceptance hor/ver, mm·mrad	40 / 35
Momentum acceptance, %	±0.5
Injection energy, pbar GeV	2.8
Inj. number of particle per cycle	10^8
Inj.emittance hor / ver, mm·mrad	< 5
Rev. frequency (antiproton), MHz	1.209
Betatron tunes Q_x / Q_y	3.44 / 3.43
Momentum slipping factor, □	0.01549
Transition energy, γ_{tr}	4.5879

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BARRIER BUCKET ACCUMULATION SCHEME

To preserve the antiproton bunch structure during accumulation, a barrier RF waveform is applied to confine the beam and shape the bunch distribution in preparation for the next ring refill. Compared with conventional RF cavities, barrier RF gymnastics provide more flexible and precise control of the bunch length and momentum spread. In the RESR, a one-turn injection scheme with RF barrier buckets is employed, as illustrated in Fig. 2. By applying two half-sine-wave RF voltages, the one-revolution period is divided into stable and unstable regions. Each new batch is injected into the unstable region (outside the separatrix) and subsequently cooled by the stochastic cooling system into the stable region. After a 10 s interval, the next batch is injected into the same unstable region. This process is repeated until the required number of antiprotons is accumulated. Implementation of this scheme requires a fast kicker magnet with rise/fall time of < 100 ns capable of injecting the beam precisely into the unstable region of the longitudinal phase space.

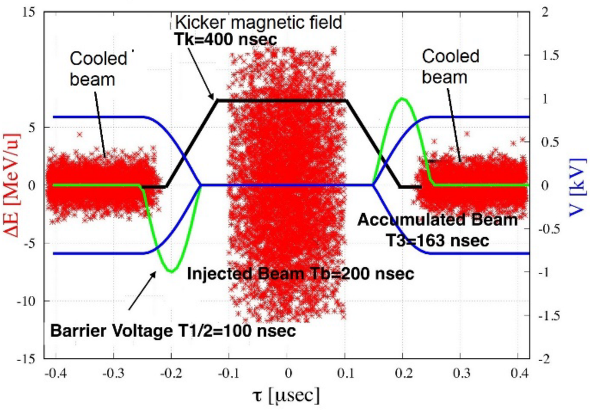

Figure 2: The injection scheme in one turn revolution period showing the allocation of barrier voltages (green), kicker magnetic field (black) and the separatrix (blue). The injected and cooled accumulated beam (red). The $\Delta p/p$ of the injected beam is 1.75 x 10-3 (rms) and $\pm 2\sigma$ truncated given with red dots.

STOCHASTIC COOLING PERFORMANCES

A key element of the accumulation scheme is the reduction of the longitudinal emittance of the injected antiproton beam in the time interval between successive injections. The stochastic cooling system must therefore be capable of cooling a batch of 10^8 antiprotons to the required final momentum spread within 10 s. The parameters of the stochastic cooling system, which has already been constructed and preliminarily tested with proton beam at COSY, are listed in Table 2 [10]. The cooling process was investigated on the base of theoretical formulation and a Fokker–Planck solver [11].

Table 2: Parameters of SC System

Parameters	**Value**
Bandwidth, GHz	2 - 4
Number of PU/ Kickers (slot-ring)	64 / 64
Shunt impedance (PU / Kicker), Ω	11.25 / 45
PU temperature, K	40
Kicker temperature, K	300
Preamplifier noise temperature, K	40
Total gain (adjustable), dB	140
Flight time from PU to kicker, ns	414
PU to kicker slipping factor, η_{pk}	0.01549
Cooling acceptance, $\Delta p/p$	$\pm 7.14\times10^{-3}$

In the simulations, the particle number was varied from 10^8 to 10^{11}, starting with an initial relative momentum spread $\Delta p/p = 1.7 \times 10^{-3}$ (rms) and a Gaussian distribution truncated at $\pm 2\sigma$. The system gain was varied from 140 dB to 110 dB according to the particle number. Fig. 3 illustrates the cooling performance - coherent and incoherent terms - for particle numbers of 10^8 and 10^{10}.

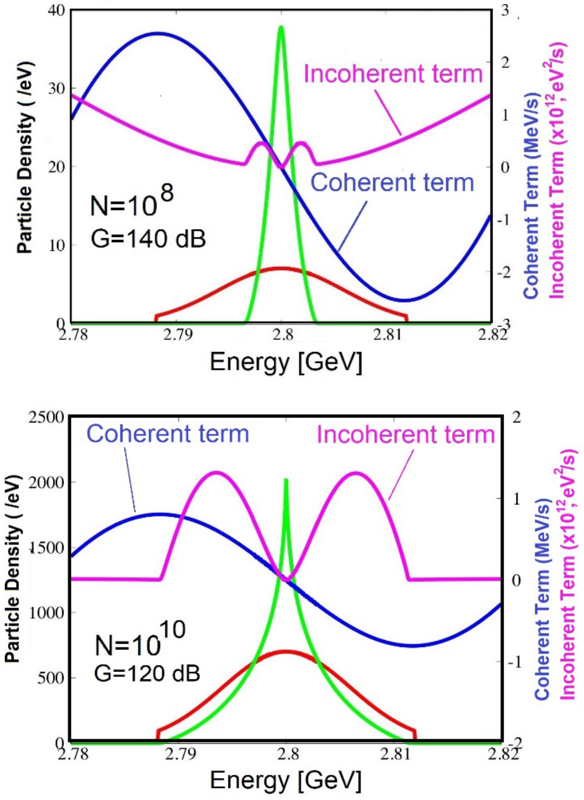

Figure 3: Stochastic cooling performances. N - number of antiprotons. G – gain. The particle distribution at t = 0 s in red. Top panel shows the particle distribution at t = 5 s and bottom panel at t = 10 s in green.

Due to the high transition energy the stochastic cooling has the relatively wide coherent term. As is characteristic of stochastic cooling, the efficiency decreases with increasing particle number due to the enhanced Schottky noise and resulting increase in the incoherent heating term as shown in the simulation results. The 10^8 - 10^9 particles are easily cooled within the 5 - 10 s. For more than 10^{10} particles the tails of the particle distribution are cooled slowly and requires cooling time up to 20 s depending on the number of particles. In this case a careful gain adjustment during the process is necessary.

SIMULATION

The barrier bucket accumulation process has been studied by means of multiparticle tracking. The basic equations governing the longitudinal motion are the coupled phase equations for the energy deviation ΔE of a particle from the synchronous energy and the time coordinate τ in the longitudinal phase space:

$$\frac{d(\Delta E)}{dt} = \frac{q\omega_0}{2\pi}V(\tau) + F(\Delta E) + \xi_s(\Delta E, t) + \xi_{th}(\Delta E) + \xi_{IBS}(t),$$

$$\frac{d(\tau)}{dt} = -\frac{\eta}{\beta^2\gamma E_0}\Delta E, \qquad (1)$$

where q – charge state, η - ring slipping factor, $V(\tau)$ - barrier voltage, $F(\Delta E)$ - cooling force, ξ_s – Schottky noise, ξ_{th} - thermal diffusion, ξ_{IBS} - IBS diffusion. Here the space charge effects are not taken into account because the antiproton particle number is as low as 10^{11} at the maximum even after the full accumulation and the energy is as large as 2.8 GeV. The allocation of barrier voltages and fast kicker magnetic field are illustrated in Fig. 2 in the one revolution time 419 ns. The flat top of kicker field should be 200 ns to cover the injected beam pulse width. The rising and falling time of kicker field are assumed as 100 ns, respectively. The accumulated particles in the separatrix should not be disturbed by the kicker magnetic field.

RESULTS OF SIMULATION

Simulations of the antiproton accumulation process show that after 100 cycles, 8.5×10^9 particles can be accumulated with an efficiency of approximately 85%, defined as the ratio of the accumulated particle number to the total number of injected particles. The injected beam is assumed to have a relative momentum spread of $\Delta p/p = 1.7\times10^{-3}$ (rms) and a bunch length of 50 ns (rms). The accumulation efficiency depends strongly on the proper adjustment of the stochastic cooling system gain. When the accumulated particle number exceeds 10^{10} the Schottky diffusion term becomes significant (see Fig. 3), degrading the cooling performance. To mitigate this effect, the amplifier gain is reduced by 3 dB at 100 s and again at 600 s. To simulate accumulation up to 10^{11} particles, it was assumed that 10^9 particles are injected per cycle, with a total of 100 injections. The results presented in Fig.4 show that 4.5×10^{10} antiprotons are accumulated with an efficiency of 45%. During practical operation, the cooling system gain must be carefully adjusted in real time according to the instantaneous accumulated particle number. The final accumulated beam reaches a relative momentum spread of $\Delta p/p \approx 3.5\times10^{-4}$ (rms), indicating the formation of a high-density core in the stacked region.

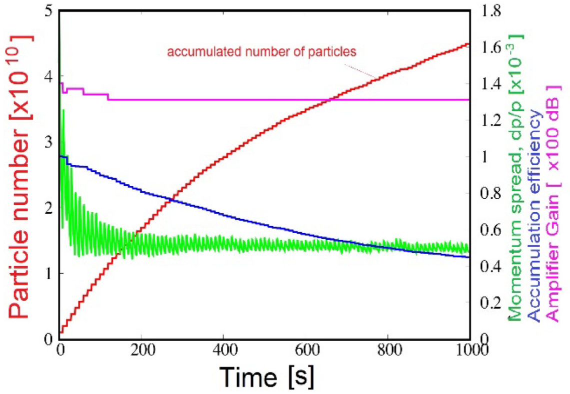

Figure 4: The accumulated particle number (red), accumulation efficiency (blue), Δp/p (green) and the system-gain (pink) are given as a function of time. The injection cycle time is 10 sec.

CONCLUSION

The present work demonstrates the feasibility of reusing the COSY ring magnet structure for the accumulation of antiprotons delivered from the CR. It has been shown that conventional stochastic stacking is not applicable in this case due to the severely limited aperture of the COSY magnets. As an alternative, the barrier-bucket accumulation scheme, performed solely in the longitudinal phase space, has been proposed and justified. When combined with the existing stochastic cooling system developed for the HESR based on a slot-ring structure, this approach enables high accumulation efficiency under tight aperture constraints. Numerical particle tracking simulations confirm that, with careful control and adjustment of the amplifier gain, accumulation up to 10^{10} antiprotons can be reliably achieved with an efficiency of approximately 85 %. Reaching an intensity of 10^{11} particles appears significantly more challenging, as the increased Schottky noise from the high-intensity beam substantially degrades the performance of the cooling. Overcoming this limitation will require dynamic adjustment of the cooling gain throughout the accumulation process. The proposed concept fully respects the stringent aperture limitations and is well aligned with the overall FAIR project timeline. Further studies will focus on detailed parameter optimization and hardware tests using the existing infrastructure. The barrier-bucket accumulation scheme combined with the existing stochastic cooling system represents a technically feasible and promising solution for antiproton accumulation in the RESR based on the COSY magnets.

REFERENCES

[1] A. Dolinskii *et al.*, “The CR-RESR Storage Ring Complex of the FAIR Project”, in *Proc. EPAC'08*, Genova, Italy, Jun. 2008, paper THPC011, pp. 2996-2998.

[2] M. Steck *et al.*, “The Concept of Antiproton Accumulation in the RESR Storage Ring of the FAIR Project”, in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper THPEC038, pp. 4140-4142.

[3] A. Dolinskii *et al.*, “Collector ring project at FAIR,” *Phys. Scr.*, vol. T166, p. 014040, Nov. 2015. doi:10.1088/0031-8949/2015/t166/014040

[4] A. Lehrach, “Design Work for the HESR High Energy Cooler Ring,” in *High intensity and high brightness hadron beams: 33rd ICFA advanced beam dynamics workshop on high intensity and high brightness hadron beams*, 2005, pp. 420–424. doi:10.1063/1.1949576

[5] T. Katayama *et al.*, “Numerical Design Study of Stochastic Stacking of 3 GeV Anti-Proton Beam in the RESR for the FAIR Project”, in *Proc. COOL'09*, Lanzhou, China, Aug.-Sep. 2009, paper MOA2MCIO02, pp. 41-45.

[6] J. E. Griffin, C. Ankenbrandt, J. A. MacLachlan, and A. Moretti, “Isolated Bucket RF Systems in the Fermilab Antiproton Facility”, in *Proc. PAC'83*, Santa Fe, NM, USA, Mar. 1983, pp. 3502-3505.

[7] R. Stassen *et.al*, The HESR Stochastic Cooling System, Design, Construction and Test Experiments in COSY”, in *Proc. COOL'17*, Bonn, Germany, Sep. 2017, pp. 89-93. doi:10.18429/JACoW-COOL2017-THA11

[8] U. Bechstedt *et al.*, “The cooler synchrotron COSY in Jülich” *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 113, no. 1–4, pp. 26–29, Jun. 1996. doi:10.1016/0168-583x(95)01352-0

[9] A. Dolinskii *et al.*, “Antiproton complex at the FAIR project,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 629, no. 1, pp. 16–24, Feb. 2011. doi:10.1016/j.nima.2010.11.037

[10] R. Stassen *et al.*, “COSY as Ideal Test Facility for HESR RF and Stochastic Cooling Hardware”, in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TU5PFP022, pp. 861-863.

[11] H. Stockhorst, T. Katayama and R. Maier, “Beam Cooling at COSY and HESR”, Theory and simulation, Part 1, FZJ, Key Technology, Vol, 120, 2015.