CONCEPTUAL DESIGN OF A FACILITY FOR INTERNAL TARGET EXPERIMENTS WITH ANTIPROTONS UP TO 15 GeV/c

B. Franzke, K. Beckert, O. Boine-Frankenheim, P. Beller, A. Dolinskii, F. Nolden, M. Steck,
GSI, Planckstrasse 1, D-64291 Darmstadt, Germany

Abstract

One of the major objectives of the new beam facility recently proposed for GSI [1] is to allow for high luminosity internal target experiments with stored and cooled antiprotons in the momentum range 1.5-15 GeV/c. The concept includes suitable accelerator/storage ring designs as well as adequate techniques for efficient production, fast cooling and accumulation of antiproton beams. In addition, extensive time/instrument sharing with heavy ion acceleration and rare isotope beam production is envisaged. A net accumulation rate of about 1×10^8 antiprotons every 5 s is aimed at, allowing for experiments at correspondingly high luminosity of up to $2\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The preliminary layout of the High Energy Storage Ring HESR is presented. Numerical calculations of equilibrium beam properties taking into account intra-beam scattering, internal target effects and electron cooling are discussed. As electron cooling is essential for the envisaged experiments, the development of an electron cooler for electron energies up to 8 MeV is crucial for the project.

1 BASIC REQUIREMENTS

The conceptual design of the facility for the production, accumulation and acceleration of antiprotons is basically determined by luminosity requirements for antiproton-proton-collisions in the proposed high energy storage ring HESR. The design is aiming at a maximum luminosity of $2\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for collisions between stored and electron cooled antiprotons and protons at rest in an internal hydrogen gas or pellet target. Assuming a total cross section of 100 mbarn we obtain the necessary antiproton consumption rate of $2\times10^{7}\,\mathrm{s}^{-1}$, which has to be compensated by a corresponding net rate of antiproton accumulation. This value is slightly higher than achieved at the former CERN antiproton complex [2, 3] and somewhat lower than envisaged by the improvement program for the antiproton facility at Fermilab/USA [4].

The proposed antiproton production and accumulation scenario makes use of the existing heavy ion synchrotron SIS18 as booster synchrotron and – to a large extent – of the synchrotron-storage ring complex envisaged as future extension of the GSI facilities [1]. Special devices to be added for antiproton beams are a 50 MeV proton linac, the antiproton production target with magnetic separator and the HESR itself. Specific installations for proton or antiproton beams will still be necessary also in the rings which will share the time of operation with heavy stable or radio-active ion beams. Basic design considerations of the accelerators and storage rings used for primary proton and secondary antiproton beams are discussed briefly in the following. A schematic plan view of the proposed accelerator/storage ring facility is given in Figure 1.

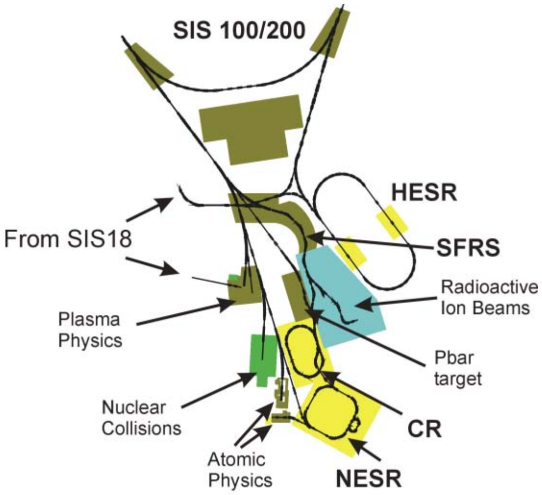

Figure 1: Proposed future GSI facilities.

2 PROTON ACCELERATION

A combination of RFQ with a 400 MHz CH linac for 50 MeV proton energy will serve as primary injector. Beam pulses of 60 mA current, 0.1 s duration and 5 Hz repetition frequency are envisaged. The injection energy may be upgraded later to 100 MeV in order to increase the antiproton production rate by nearly a factor of two.

The existing SIS18 with the new proton-linac as injector is used not only to boost the proton energy to 2 GeV (for injection to the new SIS100 synchrotron), but also to increase the number of accelerated protons by means of filling the large ring 4 or 5 times before acceleration. This way, up to 2.5×10^{13} protons per SIS100-cycle will be accelerated to the envisaged antiproton production energy of 29 GeV. 5×10^{12} protons per SIS18-cycle are obtained by injection over 10 to 15 (effective) turns. After the installation of suitable corrections for higher order magnetic field contents in the ring (being installed in 2002) the allowed betatron tune shift due to incoherent space charge effects will be close to $\Delta Q=0.5$. This value is compatible with the tune shift expected for a circulating proton beam current of 350 mA after multi-turn injection and RF bunching at 50 MeV.

The proposed SIS100 synchrotron [5] is used to accelerate protons to the envisaged antiproton production energy of 29 GeV and to accelerate or decelerate the antiproton-beam – after cooling and accumulation at about 3 GeV – to the desired operation energy of the HESR. The required cycling rate of SIS100 for protons is determined by the envisaged total cooling and accumulation time of about 5 s for antiprotons (see below). The technical design of SIS100 magnets aims at cycling rates of up to 0.5 Hz including the time of 0.8 s for filling the ring at 2 GeV. Hence, a time-sharing operation of about 40% for proton and 60% for heavy ion beams will be possible. After acceleration to the final energy of 29 GeV and before fast ejection to the antiproton production target the proton beam has to be compressed to a single bunch of approximately 15 m length (50 ns duration). This procedure is absolutely necessary for making use of fast momentum spread reduction by bunch rotation before starting stochastic cooling of the antiproton beam in the Collector Ring CR [7] (see below).

3 ANTIPROTON TARGET AND SEPARATOR

The concept for the antiproton production target and separation system is basically oriented at the design of the existing antiproton target area ("*dog leg*") for the AD-ring at CERN [2, 3]. Most of the relevant parameters (production energy, proton intensity, acceptance for collection etc.) are very similar, although the different bunch structure – single bunch at the proposed facility instead of five bunches at CERN – seems somewhat more critical with respect to target problems (shock waves). From a bunch of 2.5×10^{13} primary protons at 29 GeV approximately 1×10^{8} antiprotons are expected within the phase space acceptance of the following magnetic separator and CR.

4 ANTIPROTON COOLING AND ACCUMULATION

4.1 Collection and Pre-cooling

It has been demonstrated at the antiproton-facilities at CERN and FNAL, that collection and pre-cooling of antiproton-beams on one side and accumulation on the other side are optimised by means of two differently designed rings for the different purposes. In the proposed Collector Ring CR [7] with a maximum bending power of about 13 Tm, a large useful aperture is required to accept the hot, secondary antiproton-beam coming from the production target with a mean energy of 3 GeV. After injection the short antiproton bunch – captured by a strong stationary rf-bucket –rotates about a quarter of a synchrotron period in the longitudinal phase plane within a few milliseconds. The large momentum spread of $\delta p/p=\pm3\%$ (FW) is reduced to $\delta p/p\approx\pm1\%$ this way. Suitable conditions for starting stochastic cooling (over about 4 s) are obtained by means of subsequent adiabatic de-bunching.

4.2 Antiproton accumulation

The pre-cooled beam ($\delta p/p\approx\pm0.1\%$, $\varepsilon_{h,v}\approx5$ mm mrad) is re-bunched in the CR and transferred to the New Experimental Storage Ring NESR [8]. The design of the latter is mainly determined by the requirements from nuclear physics experiments with cooled radioactive ion beams. Because of comfortable transverse and longitudinal acceptances the ring seems – at first sight – to be well suited also for the accumulation of antiprotons by means of rf-stacking and permanent stochastic cooling. But it has to be confirmed still that the necessary high cooling rates for the envisaged accumulation rate $7\times10^{10}\ \mathrm{h}^{-1}$ are achievable in this ring. A dedicated accumulator ring could be the less problematic and even the more efficient solution.

The choice of the accumulation time, i.e. of the total number of accumulated antiprotons, will depend on the requirements for the experiment at the HESR. For the transfer to that ring, the antiproton beam is re-bunched to a single bunch (h=1) and transferred to SIS100 in reverse direction through the extraction beam line using the fast beam ejection equipment for positively charged particles. After acceleration or deceleration to the desired working energy for HESR experiments, the antiproton bunch is transferred to that ring using the beam injection components (kickers and septum magnets) and part of the injection beam line of SIS100 (see figure 1).

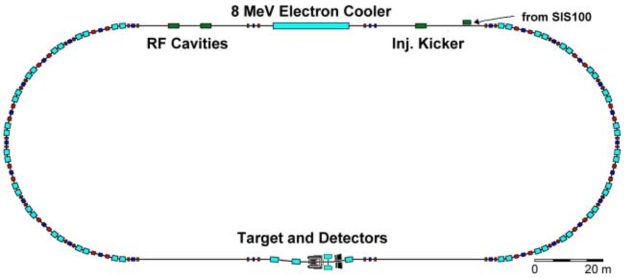

Figure 2: Scheme of the of the HESR layout.

5 HESR

5.1 Ring characteristics

The maximum magnetic bending power of the racetrack shaped storage ring HESR of 50 Tm will allow internal experiments with antiprotons at a maximum kinetic energies of 14.5 GeV. The layout of the ring, a "brother" of the formerly proposed Super-LEAR [6], is still in work. The arrangement of detectors has to be worked out before the ring structure can be finalised. A schematic view of the present layout, based on super-conducting 4 T-dipole and 35 T/m-quadrupole magnets, is shown in Fig. 2, basic ring and beam parameters are listed in Table 1.

One of the long straight sections is dedicated to the installation of one or two internal targets – either supersonic H_2-gas jets or frozen H_2 pellets of 30-50 μm diameter – and large detectors for secondary hadrons and leptons. Part of the detector concept might be also a large aperture dipole magnet for the separation of secondary particles at small laboratory angles. At the opposite long straight section space for beam injection elements and an electron-cooling device is provided. The latter is hoped to enable experiments with highest phase space resolution at high luminosity (given in Table 1). Stochastic cooling might be installed complementary to electron cooling, if the latter would not cover the required energy range.

Table 1: Basic ring and beam parameters for the HESR.

Orbit circumference	442.5 m
Magnetic bending power	5 - 50 Tm
Length of 180^0-arcs	116.25 m
Length of straight sections	105 m
Betatron tunes, horiz / vert	10.2 / 7.71
Transverse acceptance, horiz / vert	20/20 mm mrad
Natural chromaticity, horiz / vert	-13 /-21
Momentum acceptance	± 0.5%
Transition point, γ_t	19.7
Beta function at cooler, horiz / vert	200 / 200 m
Beta function at target, horiz / vert	0.1-5 / 0.1-5 m
Antiproton energy range	0.8 - 14.5 GeV
Revolution frequency range	0.54 - 0.68 MHz
Beam current for 10^{11} antiprotons	≤ 11.3 mA
Relative momentum spread	$0.3 - 3\times10^{-4}$
Beam diameter at target	0.1 - 5 mm
Max. target thickness (H atoms)	3×10^{15} cm^{-2}
Maximum luminosity	2×10^{32} cm^{-2} s^{-1}

5.2 Beam cooling up to 14.5 GeV

Beam quality and the luminosity in the HESR are limited by the capability to counteract beam heating caused by intra-beam scattering (IBS) and by collisions with internal target nuclei. Strong beam cooling is mandatory for high luminosity as well as for high energy and angular resolution. At lower kinetic energies up to 600 MeV ($\gamma \approx 0.75$) electron cooling (EC) has been demonstrated to be the most favourable method for pre-cooled beams with a small phase space volume, rather complementary to stochastic cooling (SC), which is powerful for hot beams.

The extension of EC to a kinetic energy of 14.5 GeV is straightforward from a physical point of view although the technical realisation seems to be rather challenging. Obviously, high cooling rate can be achieved only by the so-called magnetized cooling. It requires a strong longitudinal magnetic field ($B_{||} \geq 0.5$ T) that guides the electron beam along the entire interaction region of up to 30 m length. The tolerances for the parallelism of the field lines are $B_\perp/B_{||} \leq 1\times10^{-5}$. The generation of a cold electron beam at energies up to 8 MeV (i.e. $\gamma = 15$) with an electron current of up to 1 A is another technical challenge.

The acceleration of electron beams in commercially available electrostatic accelerators might be feasible if the electron beam current can be recuperated with high efficiency [4]. Current loss below 100 µA seems to be acceptable in this type of accelerator. The feasibility of magnetised cooling in the energy range of the HESR is going to be investigated in the frame of a dedicated research and development program.

5.3 Equilibrium Beam Parameters

The equilibrium between EC and beam heating by IBS and target effects has been calculated for two different energies (7 GeV and 15 GeV) and two targets of different thickness (5×10^{14} cm^{-2} and 1×10^{16} cm^{-2}). As an example, equilibrium momentum spread and both transverse emittances are plotted in Figure 3 vs. the luminosity at 7 GeV antiproton energy and 1×10^{16} cm^{-2} target thickness.

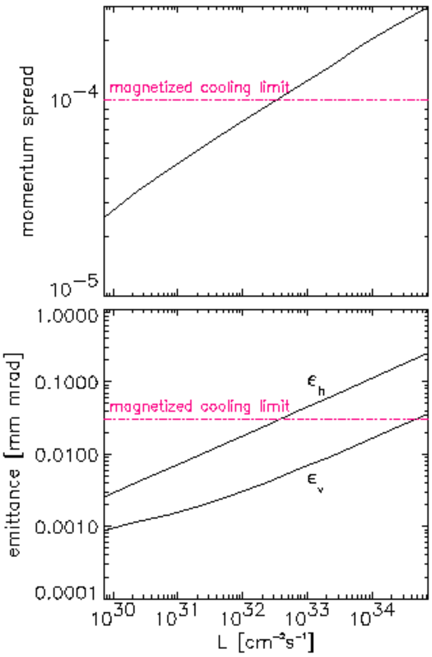

Figure 3: Equilibrium momentum spread and emittances of a coasting antiproton beam at 7 GeV vs. luminosity. EC, IBS and heating due to Coulomb interactions in the internal target) are taken into account. The thickness of the H_2-target is assumed to be 1×10^{16} cm^{-2}.

Equilibrium beam parameters above the magnetized cooling limit are expected to be much larger than plotted in Fig. 3. Because of a steep drop of cooling rates with increased beam temperature it has to be investigated carefully, whether the equilibrium exists or the beam is heated without any finite limit. Insofar, alternative target concepts (pellets, fiber targets) have to be investigated carefully with respect to corresponding heating rate limits.

6 REFERENCES

[1] *An International Accelerator Facility for Beams of Ions and Antiprotons*, Conceptual Design Report, GSI, November 2001 (see www.gsi.de)
[2] H. Koziol and S. Maury, CERN-PS-05-15 (AR/PD), May 1995
[3] D. Möhl, Hyperfine Interactions **109**, 33 (1997)
[4] J. A. MacLachlan, ed., Fermilab-TM-2016 (1998)
[5] P. Spiller et al., EPAC2002, contrib. THPLE078
[6] R. Giannini, P. Lefevre, D. Möhl, Nucl. Phys. **A 558**, 519c (1993)
[7] Dolinskii et al., EPAC02, contrib. THPLE076
[8] P. Beller et al., EPAC02, contrib. THPLE077