BEAM PERFORMANCE WITH INTERNAL TARGETS IN THE HIGH-ENERGY STORAGE RING (HESR)

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Abstract

The High-Energy Storage Ring (HESR) of the future International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt is planned as an antiproton synchrotron storage ring in the momentum range of 1.5 to 15 GeV/c. An important feature of this new facility is the combination of phase space cooled beams and dense internal targets. In a first stage proton H_2 Pellet Jet Targets will be utilized. Later other nuclear targets will also be available. In this paper the main beam loss mechanisms are analyzed and luminosity limitations discussed.

INTRODUCTION

The HESR is dedicated to the field of high-energy antiproton physics, to explore the research areas of charmonium spectroscopy, hadronic structure, and quark-gluon dynamics with high-quality beams over a broad momentum range from 1.5 to 15 GeV/c [1,2,3].

The HESR lattice is designed as a racetrack-shaped storage ring, consisting of two 180° arc sections connected by two long straight sections. One straight section will mainly be occupied by the electron cooler. The other straight section will host the experimental installation with internal frozen H_2 pellet jet target, injection kickers/septa and RF cavities. Two pickup tanks for stochastic cooling are located close to the ends of one straight section while the stochastic kicker tanks are placed opposite in the other straight section, diagonally connected with signal lines. Details of the ion optical layout and features of the lattice design are discussed in [4].

COOLED BEAM EQUILIBRIA

Demanding requirements for high intensity and high quality beams are combined in two operation modes: high luminosity and high resolution. The high-resolution mode is defined in the momentum range from 1.5 to 9 GeV/c. To reach a momentum resolution down to $\sigma_p /p \sim 10^{-5}$, only 10^{10} circulating particles in the ring are anticipated. The high-luminosity mode requires an order of magnitude higher beam intensity with reduced momentum resolution to reach a peak luminosity of $2\cdot10^{32}$ cm^{-2} s^{-1} in the full momentum range. Calculations of beam equilibrium between electron cooling, intra-beam scattering and beam-target interaction are being performed utilizing different simulation codes like BETACOOL by I.N. Meshkov et al. (JINR, Dubna), MOCAC by A.E. Bolshakov et al. (ITEP, Moscow), and PTARGET by B. Franzke at al. (GSI, Darmstadt). Various studies of beam equilibria for HESR conditions with H_2 Pellet Jet Target have been carried out for electron and stochastically cooled beams [5,6,7,8]. They all indicate that the specified momentum spread of $\sigma_p /p \sim 10^{-5}$ for the high-resolution mode seems ambitious. Special arrangements for beam cooling are required, combining both beam cooling techniques.

BEAM LOSS MECHANISMS

The main restriction for high luminosities is beam losses, since the antiproton production rate is limited. Three dominating contributions of beam-target interaction have been identified: Hadronic interaction, single Coulomb scattering and energy straggling of the circulating beam in the target [9]. In addition, single intra-beam scattering due to the Touschek effect has also to be considered for beam lifetime estimations.

The relative beam loss rate for the total cross section σ_{tot} is given by the expression

$$(\tau_{loss}^{-1}) = n_t \sigma_{tot} f_0 , \qquad (1)$$

where τ_{loss} is the *1/e* beam lifetime, n_t the target thickness and f_0 the reference particle's revolution frequency.

Hadronic interaction

The total hadronic cross section decreases roughly from 100 mbarn at 1.5 GeV/c, to 57 mbarn at 9 GeV/c, and to 51 mbarn at 15 GeV/c [10]. With revolution frequencies of 443, 519 and 521 kHz at the given beam momenta, relative beam loss rates are estimated for a target thickness of $4\cdot10^{15}$ atoms/cm^2 (see table 1).

Single Coulomb scattering

Coulomb scattering is described by the Rutherford cross section. Small angle scattering can be compensated by phase space cooling. Particles single scattered out of the transverse acceptance are lost. The cross section for single Coulomb scattering is given by

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$$\sigma_{tot} = \frac{4\pi Z_t^2 Z_i^2 r_i^2}{\beta_0^4 \gamma_0^2 \theta_{acc}^2}, \qquad (2)$$

where Z_t and Z_i are the charge numbers of target and projectile, $r_i = 1.535 \cdot 10^{-16}$ cm is the classical proton radius, β_0 and γ_0 are the kinematical parameters of the circulating beam. For angles larger than the acceptance angle θ_{acc} scattered particles are lost $\theta_{acc} = \sqrt{A/\beta}$. The transverse acceptance A is related to the beam emittance providing sufficient beam-target overlap. β is the betatron amplitude at the interaction point. Without beam cooling, one could assume that scattered particles with a transverse emittance larger than $A = 1$ mm·mrad do not contribute to the luminosity any more. Due to beam cooling, scattered particles can be cooled back onto the target.

Energy loss straggling

Energy loss due to beam-target interaction out of the longitudinal acceptance of the accelerator leads to beam losses. The single collision-energy loss probability (with the energy loss ε) can be described by a Rutherford-like expression

$$w(\varepsilon) = \frac{\xi}{\varepsilon^2}\left(1 - \beta_0^2 \frac{\varepsilon}{\varepsilon_{\max}}\right), \qquad (3)$$

with a maximum energy transfer of

$$\varepsilon_{\max} = \frac{2 m_e c^2 \beta_0^2 \gamma_0^2}{1 + 2\gamma_0 \frac{m_e}{m_i} + \left(\frac{m_e}{m_i}\right)^2}, \qquad (4)$$

the electron mass m_e and incident particle (antiproton) mass m_i. The scaling factor reads

$$\xi = 153.4 \frac{\text{keV}}{\text{g/cm}^2} \frac{Z_i^2}{\beta_0^2} \frac{Z_t}{A_t} \rho x . \qquad (5)$$

Here, A_t is the mass number of the target and ρx the target density times the effective target thickness. The second moment of the energy loss probability yields the mean square energy deviation $\Delta\varepsilon_{rms}^2$. The corresponding mean square relative momentum deviation is given by

$$\delta_{rms}^2 = \left(\frac{\gamma_0}{\gamma_0 + 1}\right)^2 \frac{\Delta\varepsilon_{rms}^2}{T_0^2}, \qquad (6)$$

where T_0 is the kinetic energy of the reference particle. By integrating over the probability function one gets the relative beam loss rate

$$\begin{aligned}(\tau_{loss,\parallel}^{-1})_S &= f_0 \int_{\varepsilon_{cut}}^{\varepsilon_{\max}} w(\varepsilon) d\varepsilon \\ &= f_0 \xi \left(\frac{1}{\varepsilon_{cut}} - \frac{1}{\varepsilon_{\max}} - \frac{\beta_0^2}{\varepsilon_{\max}} \ln \frac{\varepsilon_{\max}}{\varepsilon_{cut}}\right)\end{aligned} . \qquad (7)$$

Assuming $\delta_{cut} = \left(\frac{\gamma_0}{\gamma_0 + 1}\right) \frac{\varepsilon_{cut}}{T_0} = 10^{-3}$, the relative beam loss probability can be calculated.

Touschek effect

For small transverse emittances, the beam can be lost due to single large-angle intra-beam scattering in the longitudinal ring acceptance. The beam loss rate is determined by the longitudinal diffusion coefficient

$$D_\parallel^{IBS} = \frac{\Lambda_\parallel^{IBS}}{\varepsilon_\perp^{3/2}}, \quad \Lambda_\parallel^{IBS} = \frac{\sqrt{\pi} N_i c r_i^2 L_c}{4\gamma_0^3 \beta_0^3 \left\langle \beta_\perp^{1/2} \right\rangle C} . \qquad (8)$$

$\varepsilon_\perp$ is the transverse rms beam emittance, N_i is the number of circulating ions, c is the speed of light, $L_c \approx 10$ is the Coulomb logarithm, $\left\langle \beta_\perp^{1/2} \right\rangle = \sqrt{7.5 \ m}$ is the average of the square root of the betatron amplitude in the ring, and C is the ring's circumference. The relative beam loss rate then reads

$$(\tau_{loss}^{-1})_{IBS} = \frac{D_\parallel^{IBS}}{L_C \delta_{cut}^2}, \qquad (9)$$

where δ_{cut} is the longitudinal ring acceptance. In table 1 the relative beam loss rate is listed for different beam momenta and a transverse beam emittances of 1 mm·mrad assuming a longitudinal acceptance of $\delta_{cut} = 10^{-3}$.

Beam lifetime

The upper limit of the total relative loss rate and corresponding beam lifetimes are listed in table 1 for a transverse beam emittance of 1 mm·mrad, 10^{11} circulating particles, and a longitudinal ring acceptance of $\delta_{cut} = 10^{-3}$ (for details see [8,11,12]).

Less than half an hour beam lifetime at low momentum is too low compared to the antiproton production rate of 1 to $2 \cdot 10^7$ /s. Beam lifetimes at low momenta strongly depend on the beam cooling scenario and ring acceptance. The beam loss rate for single Coulomb scattering could significantly be reduced by applying a larger electron beam diameter in combination with stochastic cooling.

TABLE 1. Upper limit for relative beam loss rate and beam lifetime at different beam momenta.

(τ_{loss}^{-1}) / s^{-1}			
Heating Process	1.5 GeV/c	9 GeV/c	15 GeV/c
Hadronic Interaction	$1.8 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
Single Coulomb	$2.9 \cdot 10^{-4}$	$6.8 \cdot 10^{-6}$	$2.4 \cdot 10^{-6}$
Energy Straggling	$1.3 \cdot 10^{-4}$	$4.1 \cdot 10^{-5}$	$2.8 \cdot 10^{-5}$
Touschek Effect	$4.9 \cdot 10^{-5}$	$2.3 \cdot 10^{-7}$	$4.9 \cdot 10^{-8}$
Total relative loss rate	$6.5 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
1/e beam lifetime t_{pbar}	~ 1540 s	~ 6000 s	~ 7100 s

AVERAGE LUMINOSITY

To calculate the average luminosity, machine cycles and beam preparation times t_{prep} have to be specified. After injection, the beam is pre-cooled to equilibrium (with target off). The beam is then ac-/decelerated to the desired beam momentum. A maximum ramp rate for the superconducting dipole magnets of 25 mT/s is specified, leading to acceleration duration of 100 s for maximum momentum. Beam cooling and pellet beam are switched on before the physics experiment can be performed.

To calculate the average luminosity, one has to integrate the time dependent luminosity over the experimental time (beam on target) t_{exp}. The average luminosity can then be written as

$$\bar{L} = f_0 N_{i,0} n_t \frac{\tau[1 - e^{-\frac{t_{\exp}}{\tau}}]}{t_{\exp} + t_{prep}}, \qquad (10)$$

where τ is the beam lifetime, and $t_{cycle} = t_{exp} + t_{prep}$ the total time of the cycle. $N_{i,0}$ is the number of available particles after the target is switched on. It depends on the production rate, beam lifetime and beam preparation time.

At lower momenta, beam losses are too large compared to the antiproton production rate. Average luminosities are below 10^{32} cm^{-2} s^{-1} at 1.5 GeV/c. An optimized beam cooling scenario and a factor of two larger longitudinal ring acceptance is required to reach average luminosities above 10^{32} cm^{-2} s^{-1}. Already at 2.4 GeV/c average luminosities of up to 10^{32} cm^{-2} s^{-1} are feasible without additional measures. Highest average luminosities of close to $2 \cdot 10^{32}$ cm^{-2} s^{-1} can be reached at maximum momentum of 15 GeV/c at the HESR. A detailed evaluation of average luminosities for different beam momenta can be found in [11,12].

CONCLUSION

The high-resolution mode is further investigated with respect to the achievable momentum resolution. Advanced simulation codes are applied, which include the dynamics of tail particles. For the high-luminosity mode beam losses are of major concern at low momenta. An optimized beam cooling scenario and a larger ring acceptance is required to reach average luminosities above 10^{32} cm^{-2} s^{-1} below 2.4 GeV/c.

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