AN ELECTRON COOLING SYSTEM FOR THE PROPOSED HESR ANTIPROTON STORAGE RING

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Abstract

The availability of antiprotons with high beam quality in the energy range 0.8-14.5 GeV in the storage ring HESR will be one of the features of the new FAIR accelerator facility. For the achievement of an excellent quality of the antiproton beam it is proposed to apply electron cooling. The electron cooling system will be based on an electrostatic acceleration system. The intense electron beam must be recovered with high efficiency. For the achievement of highest cooling rates the electrons will interact with the circulating antiproton beam in a 30 m long cooling section with a superimposed longitudinal magnetic guiding field of up to 0.5 T. Various novel techniques will be applied to achieve the required cooling performance in the high energy regime.

INTRODUCTION

The proposed new Facility for Antiproton and Ion Research (FAIR) offers many new features for experiments with antiprotons [1]. It has been proposed to provide cooled antiprotons in the High Energy Storage Ring (HESR) for experiments with an internal target [2]. The HESR is designed for a maximum antiproton energy of 14.5 GeV, thus exceeding the energy of previous antiproton storage rings considerably and opening the regime of highly excited hadronic states for precision spectroscopy. The required beam quality will be achieved by the application of electron cooling in the HESR.

This report summarizes the results of a feasibility study performed in the years 2002 and 2003. In the meantime the HESR consortium has been formed which is a close cooperation with TSL Uppsala, Sweden, and FZJ Jülich, Germany. The HESR consortium will continue this preliminary work and enter into the R&D phase for the HESR electron cooler.

REQUIREMENTS FOR COOLING IN THE HESR

Cooling in the HESR has to meet three major requirements. Firstly, the antiproton beam, which has been precooled by stochastic cooling after antiproton production and during accumulation of the antiprotons, must be cooled down to small emittances and momentum spread. The time for cooling down the beam after injection must be short compared to the measuring time with the stored beam. A total cooling time for the injected beam of 1 min will be acceptable. Secondly, the beam quality must be suitable for experiments with an internal target which is localized to a size in the order of 0.1 mm. Finally, the cooling system must compensate all heating processes degrading the quality of the stored antiprotons.

The compensation of heating requires cooling time constants in the order of seconds after initial cool down. Stochastic cooling cannot provide adequate cooling rates, particularly if the ring is filled with more than 10^{10} antiprotons for the achievement of highest luminosity. According to the experience at lower energies, electron cooling is able to provide the required cooling times. The application of electron cooling in the HESR will require the extension of the electron cooling technique to the MeV range.

A first attempt to develop electron cooling for MeV electron energies has been established for the recycler ring at FNAL [3]. At FNAL the required cooling times are about two orders of magnitude larger. As a consequence, magnetized cooling is not foreseen. For the HESR, strongest cooling, only achievable in the magnetized cooling regime, will be mandatory. This strongly affects the layout of the cooling device. Other electron beam devices like an electron linac or a special betatron have been proposed for cooling in the MeV-regime [4]. Except the electrostatic approach no other concept can provide a continuous electron beam. Cooling of coasting antiproton beams is an explicitly requested option for the HESR operation. To achieve an equivalent cooling rate by a bunched electron beam will require much higher peak currents in the electron bunch. Generally, the higher peak current results in larger longitudinal energy spread which will further reduce the cooling rate. Therefore, any concept using a bunched electron beam can hardly provide as high total cooling rates as a continuous electron beam generated in an electrostatic accelerator. Cooling of bunched antiproton beams, if required for specific experiments, will be possible with a dc electron beam in the same way as cooling of bunched ion beams in existing low energy storage rings.

PARAMETERS OF THE HESR

The storage ring HESR has been designed for highest luminosity in experiments with stored antiprotons interacting with an internal hydrogen target. The energy range 0.8-14.5 GeV is required for investigations of the structure of hadrons and their interaction with the nuclear medium. It is foreseen to operate the HESR at static magnetic field and inject antiproton beams with variable energy from the new synchrotron SIS100.

The preliminary parameters of the storage ring HESR are listed in Table 1 and described in Ref. [2]. The two long straight sections of the HESR with a length of 105 m are reserved for the installation of internal targets and associated detector setups and for the electron cooling system. The necessity of high cooling power requires a cooling section which covers a significant fraction of the storage ring circumference. Due to the large ring circumference, the interaction section of the electrons will extend over a length of 30 m in one of the two straight sections.

Table 1: Preliminary parameters of the storage ring HESR.

circumference	442.5 m
length of arcs	116.25 m
length of straight sections	105 m
maximum bending power	50 Tm
antiproton energy range	0.8-14.5 GeV
revolution frequency	0.54-0.68 MHz
betatron tune Q_x, Q_y	10.2, 7.7
transition energy	19.7
horizontal acceptance	40×10^{-6} m
vertical acceptance	20×10^{-6} m
momentum acceptance	± 0.5 %

The possibility of operating the ring with a large difference of the values of the optical beta-functions in the two opposite long straight sections has been studied. The focusing in the two straight sections can be adjusted individually. The values of the beta function must be high in the electron cooling section, up to 100 m, and small in the target section, down to 0.1 m, in order to maximize the cooling rate and minimize the heating rate in the target, particularly in the transverse degree of freedom.

ANTIPROTON BEAM PARAMETERS

The antiproton beam parameters after injection into the HESR are determined by the design of the antiproton production complex [5]. Due to stochastic pre-cooling in the antiproton collector ring CR and in the subsequent antiproton accumulator ring RESR a transverse emittance of about 5×10^{-6} m and a momentum spread below $\pm 1 \times 10^{-3}$ at the energy of 3 GeV is expected. If the normalized emittances of the antiproton beam can be conserved during acceleration and deceleration, the starting conditions for cooling in the HESR are nearly independent of the energy of the antiproton beam. With electron cooling, however, the cooling rate at higher energies will be reduced by the relativistic reduction of the electron density with increasing beam momentum.

The most demanding requirements come from experiments which employ a well localized internal target. Small emittance of the antiproton beam in combination with a strong focus at the internal target should result in an antiproton beam size below 0.1 mm. This corresponds to a transverse emittance of the antiproton beam below 1×10^{-7} m. An energy resolution of 100 keV is requested for energies up to 8 GeV, if possible, up to the maximum energy of 14.5 GeV. This corresponds, depending on the beam energy, to a momentum spread in the $10^{-6} - 10^{-5}$ range. A coasting antiproton beam is favored in order to reduce the instantaneous count rates of the experiments.

For the highest phase space density of the cooled antiproton beams, strong intrabeam scattering is expected, which will cause continuous beam heating and limit the achievable beam quality. An internal hydrogen target will be operated in the HESR with a thickness up to 10^{16} cm^{-2} in order to achieve luminosities up to 2×10^{32} cm^{-2} s^{-1}. The cooling system should be capable of counteracting both heating sources, by the target and by intrabeam scattering. The energy loss by electronic stopping in the target could be compensated by application of an rf voltage, but a bunched beam will be less favorable for the experiments. For high thickness of the internal target the scattering and energy loss in the target will limit the effective beam lifetime. A cooling system which is powerful enough to compensate all adverse effects on beam quality and lifetime will be preferable. If the experimental requirements are less demanding, the cooling power can be reduced by reducing the electron current to a value which matches the requirement. An independent control of the electron current is easily achieved by control of the gun anode.

ELECTRON BEAM PARAMETERS

The choice of electron beam parameters is a consequence of the range of required antiproton beam parameters. The full range of antiproton energies requires the corresponding electron energy range between 0.5 and 8 MeV.

The necessity of fast cooling after injection and the compensation of a thick internal target can be met by a high density of the electron beam and a long cooling section, as both quantities enter linearly into the total cooling power. The designed cooling section length of 30 m takes the required cooling rate into account.

Simulations of both processes, initial cooling and compensation of heating of the high quality stored beam, showed that an electron current of 1 A with a diameter of 6-10 mm can provide the required cooling rate. A total current of 1 A seems feasible for stable operation, the small diameter is not fully matched to the antiproton beam size. For larger flexibility, control of the electron beam size by variation of the extraction parameters in the gun and by the magnetic field distribution between gun and cooling section will be useful to optimize the cooling rate. The manipulations of the electron beam diameter must avoid the excitation of transverse velocity components in the electron beam. A high flexibility gun design has been recently tested for a low energy electron cooling system [6]. It allows control of the electron beam diameter by an additional electrode and can even be adjusted to a mode providing a hollow electron beam. Using this concept for the HESR electron cooling system, the electron gun will be located in a longitudinal magnetic field of 0.05 T. On the further transport to the cooling section the electron beam can be compressed by up to a factor of ten by increasing the longitudinal magnetic field up to 0.5 T. Thus the electron beam density can be increased by a factor of ten, if the reduced electron beam size does not impair the cooling rate. The compression factor of the beam diameter will be variable.

The strength of the magnetic field is limited both in the accelerating section and in the cooling section. In the accelerating section the solenoids have to be powered on the high potential of the acceleration section, which requires the transformation of power. For the cooling section the generation of a high quality 0.5 T longitudinal magnetic field over a length of 30 m is technically challenging. The strong magnetic field in the cooling system, which provides the magnetization of the electrons for highest cooling rates, will benefit from the application of superconducting solenoid technology. The straightness $B_\perp/B_\parallel$ of the magnetic field along the whole cooling section should be 1×10^{-5} or smaller in order not to degrade the cooling rate by transverse relative velocity components of the electron beam with respect to the ion beam. A field quality of this level will need regular inspection. An optical mirror system with an attached soft magnetic sensor installed inside the vacuum system will be used for the monitoring of the straightness. Similar systems have been used in low energy coolers to achieve good straightness of the magnetic field by superimposing the field of correction coils in the cooling section. A set of transverse correction coils, which are individually powered, allows the correction of unwanted field errors during operation.

Extremely high accuracy and stability of the electron energy is required to provide cooled antiproton beams of correspondingly well-defined energy. The voltage measuring devices used in electrostatic accelerators, based on capacitive probes, allow voltage control on the level of $10^{-5} - 10^{-4}$. A definition of the antiproton energy to 100 keV or better demands high voltage control to better than 50 V. For a stabilization of the acceleration voltage on this level a second beam could be used to probe the voltage. A low intensity beam of e.g. H^- could be accelerated in the same acceleration column as the electron beam. After analysis in a magnetic deflector the energy measurement of the probe beam can be employed to correct the acceleration voltage, thus stabilizing the energy of the electron beam to the required level.

Although current losses to ground should be of order 10^{-5} of the primary electron current, the operation of the electrostatic acceleration system will be eased if a charging current for the high voltage section of up to 1 mA is available. In order to provide high charging currents a concept for the charging of the high voltage section by a particle beam is considered. An H^--beam from a cyclotron appears as an economic and cost-effective method. Details of the beam transport from ground potential to the high voltage is an issue to be solved in future investigations. Open questions for this method are the regulation of the high voltage by control of the charging current and the variation of the acceleration voltage, either by variation of the energy of the charging beam or by stopping the particles at the high voltage end with considerable kinetic energy.

Even if the method of charging by a negatively charged ion beam fails, the conventional charging method by mechanical transport of charges by a belt or pelletron can be employed. The reduction of the electron beam losses to a level which is appropriate for this charging method has been demonstrated in the FNAL electron cooling project [3].

As the operation of the high voltage system is based on a low level of electron losses from high potential to ground, these losses have to be minimized. One method employed in all existing electron cooling systems is the suppression of electron escape from the electron beam collector by proper choice of electric and magnetic field distribution. An additional method foreseen for the HESR electron cooling system is the the use of electrostatic bending in the toroidal sections of the electron beam transport which are used to merge the electron beam with the circulating antiproton beam. In the electrostatic bending field reflected electrons escaping from the collector can return to the gun without deflection in the toroidal section. The reflected electrons can oscillate many times between gun and collector. This reduces the loss of full energy electrons to ground.

OUTLOOK

The basic technologies for the construction of a MeV-energy electron cooling device are available. The peculiarity of the device is the combination of these technologies and their extension to regimes of unprecedented precision and quality, e.g. the generation of the magnetic guiding field for the electron beam transport in the high electric field gradient region will be unique. Most of the crucial issues are associated with the size and complexity of the device. It seems inevitable to build a full scale device in order to demonstrate the feasibility. Successful demonstration of the technical feasibility will open a new energy regime for experiments with beams of highest phase space density.

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