STATUS OF THE FERMILAB RECYCLER*

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Abstract

I present the current operational status of the Fermilab Recycler Ring. Using a mix of stochastic and electron cooling, we prepare antiproton beams for the Fermilab Tevatron Collider program. Included are discussion of stashing and cooling performance, operational scenarios, and collider performance.

THE RECYCLER RING AT FERMILAB

The Fermilab Recycler is an 8 GeV storage ring using strontium ferrite permanent magnets. It was designed to provide more antiprotons for the Tevatron collider program, though the use of stochastic and electron cooling [1]. By providing a second storage ring for the accumulation of antiprotons and allowing for the recycling of antiprotons from the Tevatron, the Recycler was a critical part of the luminosity improvements to a design goal of $2 \times 10^{32}/\mathrm{cm}^2/\mathrm{sec}$. The Run II luminosity upgrade program expanded on this original design, requiring the Recycler to be the repository of large stashes (6×10^{12}) with appropriate phase space characteristics to be used in the Tevatron collider stores, while abandoning the plan to recycle antiprotons. In order to maximize the stacking efficiency of the Fermilab antiproton Accumulator, small stacks of antiprotons ($\approx 5 \times 10^{11}$) are transferred every 2-3 hours to the Recycler. In the Recycler, the stash is initially cooled by stochastic cooling [2], then stored and cooled by electron cooling [3] until the antiprotons are to be used in the Tevatron. Table 1 presents basic parameters of the Recycler ring. As we inject and extract with stored beam in the Recycler, we use barrier potential wells to time separate the cold 'stashed' beam from the 'hot' injected beam (or the beam for extraction).

Table 1: Recycler Ring Design Parameters

Circumference	3310.8 m
Momentum	8.9 GeV/c
Transition γ	20.7
Average β Value	30 m
Typical Transverse Emittance	6 $\pi\mu$m rad
Number of antiprotons	$\leq 600 \times 10^{10}$
Average Pressure	0.5 nTorr

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ANTIPROTON COOLING

The Recycler utilizes both stochastic and electron cooling for antiprotons. Table 2 summarizes important parameters for the different cooling systems. As electron cooling can be viewed as an energy exchange process from the hot antiproton beam to the cold electron beam, achieving transverse overlap between the two beams is essential. The stochastic cooling systems are designed to cool the antiproton beam transversely, to be contained within the transverse size of the electron beam, so as to maximize the electron cooling force (see discussion in reference [4]).

Table 2: Stochastic and Electron Cooling System Parameters. There are two independent notch filter longitudinal stochastic cooling systems, in different frequency ranges.

Longitudinal Stochastic Cooling	
Frequency Range	0.5 – 1.0 GHz
Number of Pickup/Kicker loops	16
Frequency Range	1.0 – 2.0 GHz
Number of Pickup/Kicker loops	32
Operating Temperature	300 K
Transverse Stochastic Cooling	
Horizontal Frequency Range	2.0 – 4.0 GHz
Number of Pickup/Kicker loops	32
Vertical Frequency Range	2.0 – 4.0 GHz
Number of Pickup/Kicker loops	32
Operating Temperature	300 K
Electron Cooling	
Terminal Voltage	4.34 MV
Beam Current (max)	0.5 mA
Terminal Voltage Ripple (rms)	200 V
Cooling Section Length	20 m
Cooling Section Solenoidal Field	100 G
Cooling Section Beam Radius	3.5 mm
Electron Angular Spread (rms)	≤ 0.2 mrad

The stochastic cooling systems were commissioned and integrated in operations in early 2003. There are two independent longitudinal systems, spanning the ranges 0.5 –1.0 GHz and 1.0 – 2.0 GHz, which use notch filter cooling. The transverse systems (both horizontal and vertical) are in the frequency range 2.0 – 4.0 GHz. All stochastic cooling systems use planar loops for pickups and kickers [5]. Gated cooling studies, to show that the systems met the performance requirements, were performed in 2004 [2]. In figure 1, I show the transverse cooling performance of the systems. They effectively cool 15π mm mrad [6] beams to 10π mm mrad within 25 minutes. Beams of

STATUS OF THE ANTIPROTON DECELERATOR AND OF THE ELENA PROJECT AT CERN

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Abstract

The Antiproton Decelerator (AD) at CERN operates for physics since 2000 [1]. It delivers low energy antiprotons for production and study of antihydrogen, for atomic physics and for medical research. Two beam cooling systems, stochastic and electron, play key roles in AD operation. They make beam transverse and longitudinal emittances small, which is an obligatory condition for beam deceleration without losses, as well as for physics. The machine performance is reviewed, along with plans for the future. Significant improvement of intensity and emittances of the beam delivered to the experiments could be achieved with the addition of a small ring suitable for further deceleration and cooling. The details of this new extra low energy antiproton ring (ELENA) and its status are presented.

AD CYCLE

The 26 GeV/c proton beam from CERN PS is delivered to the target where antiprotons are produced and transferred to AD. The machine cycle is a sequence of plateaus and ramps (Figure 1).The first plateau is suited for injection of 4 bunches followed by 90° rotation in the longitudinal phase space to fit beam momentum spread to longitudinal acceptance of the stochastic cooling system. Then beam is cooled, decelerated down to 2 GeV/c and cooled again. Deceleration down to 300 MeV/c follows, where beam is cooled, now with electron cooling. Next ramp down to 100 MeV/c follows, where beam is cooled down to emittances required for AD experiments, bunched and extracted.

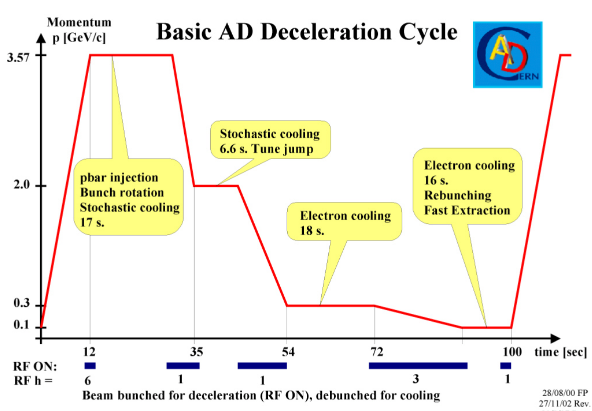

Figure 1: AD cycle.

STOCHASTIC COOLING

Due to lack of space only band I (1 - 1.65 GHz) from AC (AD predecessor) is used (H&V pickup tanks and H&V kicker tanks), bands II and III (1.65 GHz to 2.40 GHz and 2.40 GHz to 3.0 GHz) are dismantled. The momentum cooling is done by notch filter method with sum signal from both PUs sent to both kickers. The momentum acceptance of system is about ±1.0%, which is significantly smaller than momentum spread of injected beam which is ±3%. To fit the latter to the former, the advantage of short bunch length of production beam is used. Short antiproton bunches are rotated 90° in the longitudinal phase space with reduction of momentum spread to about ±1.2%. Cooling at 2 GeV/c is mainly aimed to reduce momentum spread of beam to fit the small longitudinal acceptance of RF cavity. The performance of stochastic cooling system is shown in Table 1.

Table 1: Performance of stochastic cooling system

Momentum, GeV/c	3.57	2.0
Duration, sec	17	6
$\varepsilon_x / \varepsilon_y$, π mm mrad	3 / 3	4 / 5
$\Delta p/p$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-4}$

ELECTRON COOLING

The AD electron cooler (Figure 2) is recuperated from LEAR, which stopped operation in 1996, with minimal upgrade (mechanical support, change from S-shape to U-shape). The parameters of cooler are given in Table 2.

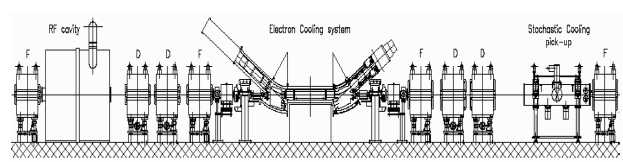

Figure 2: Layout of electron cooler.

The performance of electron cooling in AD is sensitive to orbit stability. Special procedure has been implemented to compensate slow orbit drift caused by decay of eddy currents in massive end plates of bending magnets. To avoid losses during cooling process, careful choice of tunes and coupling compensation have to be done.

Table 2: Main parameters of electron cooler

Cooling length, m	1.5
Electron beam energy, keV	2.8 - 35
Electron beam current, A	0.1 – 2.5
Field in solenoid, Gs	590
Electron beam radius, cm	2.5

PROGRESS OF HIGH-ENERGY ELECTRON COOLING FOR RHIC*

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Abstract

The fundamental questions about QCD which can be directly answered at Relativistic Heavy Ion Collider (RHIC) call for large integrated luminosities. The major goal of RHIC-II upgrade is to achieve a 10 fold increase in luminosity of Au ions at the top energy of 100 GeV/nucleon. Such a boost in luminosity for RHIC-II is achievable with implementation of high-energy electron cooling. The design of the higher-energy cooler for RHIC [1] recently adopted a non-magnetized approach which requires a low temperature electron beam. Such electron beams will be produced with a superconducting Energy Recovery Linac (ERL). Detailed simulations of the electron cooling process and numerical simulations of the electron beam transport including the cooling section were performed. An intensive R&D of various elements of the design is presently underway. Here, we summarize progress in these electron cooling efforts.

ELECTRON COOLING FOR RHIC-II

Research towards high-energy electron cooling of RHIC includes simulations and benchmarking experiments to establish with some precision the performance of the cooler and development of hardware for cost and risk reduction. Recent progress in intensive R&D program was described in detail in numerous contributions to the 2007 Particle Accelerator Conference. An overview of these contributions is reported in Ref. [2].

The present performance of the RHIC collider with heavy ions is limited by the process of Intra-Beam Scattering (IBS) [3]. To achieve the required luminosities for the future upgrade [4] of the RHIC complex (known as RHIC-II) an electron cooling system was proposed [5].

The baseline of the heavy-ion program for RHIC-II is operation with Au ions at total energy per beam of 100 GeV/nucleon. For such an operation, the electron cooling should compensate IBS and provide an increase by about factor of 10 in an average luminosity per store.

For RHIC-II operation with the polarized protons, the electron cooling should assist in obtaining required initial transverse and longitudinal emittances or prevent their significant increase due to IBS. Although IBS is not as severe for protons as for heavy ions, a proposed increase in proton intensity for RHIC-II upgrade makes IBS an important effect as well.

Although extensive studies of the magnetized cooling approach for RHIC showed that such approach is feasible [1], the baseline was recently changed to the non-magnetized one [6, 7].

Electron cooling at RHIC using the non-magnetized electron beam significantly simplifies the cooler design. The generation and acceleration of the electron bunch without longitudinal magnetic field allows us to reach a low value of the emittance for the electron beam in the cooling section. The cooling rate required for suppression of the Intra-Beam Scattering (IBS) can be achieved with a relatively small charge of the electron bunch ~ 5 nC.

Since non-magnetized cooling requires a low temperature of the electrons, a possible problem which one can encounter in cooling of heavy ions is a high recombination rate of ions with the electrons. In the present design, suppression of the ion recombination is based on employing fields of a helical undulator in the cooling section [8]. In the presence of undulator field, electron trajectories have coherent azimuthal angle which helps to suppress recombination.

To make sure that our representation of the friction force is accurate, an undulator field was implemented in the VORPAL code [9], and numerical simulations were performed for different strength of the magnetic field B and pitch period λ [10]. In all simulated cases, it was found that the friction force scales close to predictions based on a modified logarithm [8, 11]. This confirmed our expectations that with a modest reduction of the friction force values one can introduce relatively large azimuthal coherent velocity of electrons to suppress recombination [12]. Details on VORPAL simulations about undulator effects on the friction force can be found in Ref. [13].

In its 2006-2007 baseline (which presently undergoes some changes) the proposed electron cooler uses a double pass, superconducting ERL to generate the electron beam with maximum energy of 54.3 MeV [14]. The cooling power needed requires bunch charge of 5 nC with an emittance smaller than 4 microns (rms, normalized) and a repetition frequency of 9.38 MHz. The necessary transverse and longitudinal electron beam brightness will be generated by a superconducting 703.75 MHz laser photocathode RF gun. To test the hardware and to explore various beam dynamics questions a R&D ERL is presently under construction at BNL with commissioning being planned in early 2009 [15].

The electron cooler will be located at the 2 o'clock IR of RHIC. There are various RHIC lattice modifications, which result in sufficiently large space available for cooling (up to 100 meters) [16]. The cooling section includes modules of a helical undulator to combat recombination of heavy ions with the electron beam, as well as several pairs of solenoids to counteract space-charge defocusing and control the rms angular spread within electron beam to a required level [12].

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COOLING SIMULATIONS WITH THE BETACOOL CODE

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Abstract

The BETACOOL program developed by the JINR electron cooling group is a kit of algorithms based on a common format of input and output files. The general goal of the program is to simulate long term processes (in comparison with the ion revolution period) leading to a variation of the ion distribution function in six dimensional phase space. The BETACOOL program includes three algorithms for the simulation of the beam dynamics and takes into account the following processes: electron cooling, intrabeam scattering, ion scattering on residual gas atoms, interaction of the ion beam with an internal target and some others.

INTRODUCTION

The goal of the first version of the Betacool program [1] was to investigate the electron cooling process using formulae for the friction force derived in [2]. Presently the program is a kit of algorithms allowing to simulate long term processes (in comparison with the ion revolution period) leading to the variation of the ion distribution function in six dimensional phase space.

Evolution of the second order momenta of the ion distribution function is realized in the so called "*rms dynamics*" algorithm based on the assumption of a Gaussian shape of the distribution. Here all heating and cooling effects are characterized by rates of variation of the emittances or of particle loss.

The investigation of the beam dynamics at arbitrary shape of the distribution is performed using multi-particle simulation in the frame of the Model Beam algorithm. In this algorithm the ion beam is represented by an array of model particles. The heating and cooling processes involved in the simulations lead to a change of the components of the particle momentum and of the particle number.

During the last years the program was used for simulations of ion beam dynamics in the following fields of a cooling application:

- luminosity preservation in ion-ion colliders:
  RHIC-II (BNL), PAX (FZJ), NICA (JINR),
- simulations of experiments with internal pellet target:
  PANDA (GSI, FZJ), WASA at COSY (FZJ),
- benchmarking of IBS and electron cooling models:
  CELSIUS (TSL), RHIC (BNL), Recycler (FNAL), Erlangen University, TechX,
- beam ordering investigations:
  S-LSR (Kyoto University), COSY (FZJ), NAP-M (BINP), ESR (GSI),
- simulations of cooling-stacking process:
  LEIR (CERN), HIRFL-CSR (Lanzhou).

In this report a brief description of a few basic Betacool algorithms is presented.

PHASE DIAGRAMS

Usually a design of a cooling system is started from an estimation of the cooling rate required for reaching equilibrium at the necessary value of the beam emittance. By definition, the cooling (heating) rate is equal to

$$\frac{1}{\tau} = \frac{1}{\varepsilon}\frac{d\varepsilon}{dt}, \tag{1}$$

and in the general case it is a function of the beam phase volume and intensity. Here ε are the horizontal, vertical or longitudinal emittances. An equilibrium between heating and cooling processes corresponds to a vanishing sum of the rates:

$$\sum_j \frac{1}{\tau_j} = 0 \cdot \tag{2}$$

The index j is the number of processes involved in the calculations. Equations (2), written for each degree of freedom, form a system of non-linear algebraic equations describing the equilibrium emittance of the beam. For the solution of such systems the phase diagram method was developed in the Betacool program. In a phase diagram the sum of the rates is plotted as a function of the beam emittance (assuming that the horizontal emittance is equal to vertical one) and of the momentum spread. The crossing of the lines of vanishing sum of the rates at the phase diagrams for all three degrees of freedom corresponds to an expected equilibrium beam parameters. An analysis of the phase diagrams permits to predict some peculiarities of the cooling process without simulation of its dynamics. For example, the efficiency of this method was demonstrated in the simulations of the beam ordering process [4].

Calculation of the characteristic times is also the basis of RMS dynamics algorithm.

RMS DYNAMICS

The physical model used in the *rms* dynamics simulations is based on the following general assumptions:

1) the ion beam has a Gaussian distribution over all degrees of freedom and does not change during the process.

2) the algorithm for the analysis of the problem is considered as a solution of the equations for the *rms* values of the beam phase space volumes of three degrees of freedom.

3) the maxima of all the distribution functions coincide with the equilibrium orbit.

LONGITUDINAL ACCUMULATION OF ION BEAMS IN THE ESR SUPPORTED BY ELECTRON COOLING*

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Abstract

Recently, two longitudinal beam compression schemes have been successfully tested in the Experimental Storage Ring (ESR) at GSI with a beam of bare Ar ions at 65 MeV/u injected from the synchrotron SIS. The first employs Barrier Bucket pulses, the second makes use of multiple injections around the unstable fixed point of a sinusoidal rf bucket at h=1. In both cases, continuous application of electron cooling maintains the stack and merges it with the freshly injected beam. These experiments provide the proof of principle for the planned fast stacking of Rare Isotope Beams (RIBs) in the New Experimental Storage Ring (NESR) of the FAIR project.

INTRODUCTION

In order to reach the high intensity of RIBs required by the internal experiments in the NESR [1, 2] and in particular by the electron-ion collider [3], it is planned to stack the RIBs longitudinally at injection energy i.e. in the range 100-740 MeV/u [4]. The stacking will be supported by electron cooling. A stacking cycle time, i.e. the time between 2 successive injections, below 2 s would be optimal because of the short RIB lifetimes and in order to profit from the planned cycle time of 1.5 s of SIS100, where the primary heavy ion beam is accelerated. In this frame, two options of longitudinal beam accumulation have been investigated by beam dynamics simulations and by experiments in the existing ESR at GSI.

The first option uses a broadband Barrier Bucket (BB) rf system. Dedicated beam dynamics simulations [5] show that a maximum voltage of 2 kV is sufficient to compress cooled beams in the NESR. The stacking cycle time could be about 2 s, provided that the quality of the injected pre-cooled beam from the CR/RESR complex [2] allows cooling times below 1 s in the NESR. This is demonstrated in Fig. 1. At t=0 a bunch is injected between the BB sine pulses of 100 ns period. The injected beam debunches because the voltage is not sufficient to capture the particles. The BB pulses are decreased and switched off at t=0.2 s, while the beam is being continuously cooled. For the injected beam, an initial emittance of 0.5 π mm mrad and energy spread of 1.5 MeV/u was assumed. They correspond to the 2σ design values for the pre-cooled beam in CR with an additional 30% increase of the longitudinal emittance due to diffusion processes during the transfer through the RESR to the NESR. Parkhomchuk's formula [6] is used for the cooling rate, for an electron beam density of 3.2×10^8 cm^{-3}, a magnetic field strength of 0.2 T in the cooling section and an effective electron velocity corresponding to magnetic field errors of 5×10^{-5}. The resulting cooling time is about 0.8 s. Then, the BB pulses are adiabatically introduced into the beam and increased to 2 kV. One stays stationary while the other is shifted in phase to compress the cooled beam. At t=2 s a new bunch is injected.

The second option uses a h=1 rf system for bunching of the circulating beam and injection of a new bunch onto the unstable fixed point in longitudinal phase space [7]. The rf voltage is raised adiabatically so as to confine the bunch in a small fraction of the ring circumference. A new bunch is injected onto the free part of the circumference. Then the voltage is decreased (rather non-adiabatically in order to avoid dilution of the new bunch) to let the beam debunch.

In both schemes, continuous application of electron cooling (i) counteracts heating of the stack during the rf compression and (ii) merges the stack with the freshly injected bunch. The required rf voltages for the longitudinal beam compression are moderate since the momentum spread of the cooled stack is small (of the order of 10^{-4} or better). The cooled stack is repeatedly subjected to the same procedure until an equilibrium between beam losses and injection rate is reached.

EXPERIMENTAL PROCEDURE

Both stacking options have been tested in the ESR [8] under the same conditions. The experiments were performed with a $^{40}Ar^{18+}$ beam at 65.3 MeV/u injected from the synchrotron SIS. The SIS and ESR rf systems were synchronised to operate at f_{rf}=983 kHz, at h=2 and h=1, respectively, since the SIS has the double circumference of the ESR. One of the two bunches in SIS is fast extracted to the ESR. The bunches in SIS, measured with a sum pickup, had a FWHM between 300-350 ns. The ESR injection kicker pulse was typically 500 ns long (100 ns rise/fall time, 300 ns flat top). It was not straightforward to further reduce the kicker pulse length during the experiment, which restricted the flexibility in the longitudinal manipulation during the stacking with BB. In the case of stacking with the sinusoidal rf at h=1, a longer kicker pulse could in principle have been advantageous to reach higher injection efficiency. However, as it will be explained below, the experimental results indicate that the synchronisation of the kicker with the rf pulse at h=1 was not perfect and, as a consequence, losses occurred during stacking.

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BUNCHED BEAM STOCHASTIC COOLING AT RHIC*

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Abstract

Stochastic cooling of ions in RHIC has been implemented to counteract Intra-Beam Scattering and prevent debunching during stores for luminosity production. The two main challenges in cooling bunched beam at 100 GeV/n are the coherent components in the Schottky spectra and producing the high voltage for the kicker in the 5 - 8 GHz band required for optimal cooling. The technical solutions to these challenges are described. Results of cooling proton beam in a test run and cooling gold ions in the FY07 production run are presented.

INTRODUCTION

Stochastic cooling is an effective and well-established accelerator technology for improving beam quality. However, stochastic cooling of high frequency bunched beam has always proved problematic due to strong coherent components in the Schottky spectra of bunched beam.[1] We have built a stochastic cooling system for RHIC employing specialized techniques to overcome the problem of coherent components. The system works in the 5-8 GHz band and cooling in the longitudinal plane. The kicker of the system is realized in an unusual way by creating the kick voltage with 16 high-Q cavities. Even though the bandwidths of the cavities are much smaller than their separation in frequency the effective bandwidth of the cooling system is sufficiently covered. This follows from the fact the beam bunches are 5 ns long and the separation between cavity frequencies is 200 MHz, that is; the reciprocal of the bunch length.[2] The high-Q cavities greatly reduce the microwave power needed to operate the system. The system was first tested with protons during the FY06 polarized proton run. In the FY07 gold-on-gold run the cooling system was commissioned and proved effective in reducing the beam loss rate and debunching during 5 hour stores.

BUNCHED BEAM COOLING

Coasting beam formulae can be used to calculate cooling rate for bunched beam if the number of particles is replaced by an effective number which is the number that would be in the ring if it were filled at density equal to bunch density. For RHIC this is about 2e12, and implies a cooling time of about one hour for a 5-8 GHz system. This is an adequate cooling rate to counteract Intra-Beam Scattering in RHIC.

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Bunched beam cooling differs from coasting beam also in that mixing is strongly influenced by synchrotron motion. Particles tend to return to the sample in a half synchrotron period and with their same neighbours. In RHIC we are cooling the beam while it is stored in essentially full buckets and the spread of synchrotron frequencies for large amplitude particles tends to make the mixing comparable to coasting beam.

The key challenge of bunched beam cooling is to overcome the difficulties caused by the coherent components in the Schottky spectra. Figure 1 shows a spectrum with coherent components.

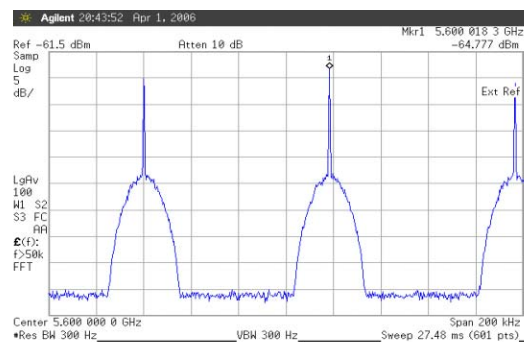

Figure 1: A Schottky spectrum showing coherent components.

Dealing with the Coherent Components

The true significance of the coherent components is not revealed in the frequency domain. However, their existence indicates that large instantaneous voltages are present in the time domain where they may easily overdrive active electronic components such as, low noise amplifiers, causing inter-modulation distortion which defeats the cooling loop. In order to reduce the peak voltages we employ the filter shown in figure 2, which is built from coaxial cables, in the cable lengths are adjusted to precise 5.000 ns intervals with small 100 ps coaxial trombones.

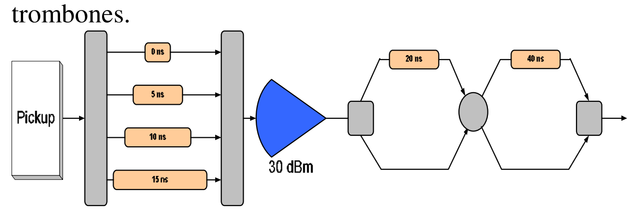

Figure 2: Coax filter used to reduce peak voltages from the pickup before the low noise amplifier and electrical to optical converter.

The filter repeats the beam pulse at reduced voltage at 5 ns intervals 16 times as shown in figure 3 and creates the

STOCHASTIC COOLING FOR THE HESR AT FAIR

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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 anti-proton cooler ring in the momentum range from 1.5 to 15 GeV/c. An important and challenging feature of the new facility is the combination of phase space cooled beams with internal targets. The required beam parameters and intensities are prepared in two operation modes: the high luminosity mode with beam intensities up to 10^{11} anti-protons, and the high resolution mode with 10^{10} anti-protons cooled down to a relative momentum spread of only a few 10^{-5}. Consequently, powerful phase space cooling is needed, taking advantage of high-energy electron cooling and high-bandwidth transverse and longitudinal stochastic cooling. A detailed numerical and analytical approach to the Fokker-Planck equation for longitudinal filter cooling including an internal target has been carried out to demonstrate the stochastic cooling capability. The great benefit of the stochastic cooling system is that it can be adjusted in all phase planes independently to achieve the requested beam spot and the high momentum resolution at the internal target within reasonable cooling down times for both HESR modes even in the presence of intra-beam scattering. Experimental stochastic cooling studies with the internal ANKE target to test the model predictions for longitudinal cooling were carried out at the cooler synchrotron COSY. The routinely operating longitudinal stochastic cooling system applies the optical notch filter method in the frequency band I from 1-1.8 GHz.

INTRODUCTION

The High-Energy Storage Ring (HESR) [1] of the future International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt [2] is planned as an antiproton cooler ring in the momentum range from 1.5 *to* 15 GeV/c. The circumference of the ring is 574 m with two arcs of length 155 m each. The long straight sections each of length 132 m contain the electron cooler solenoid and on the opposite side the Panda experiment. The stochastic cooling tanks will be located in the long straights and in one arc. Two injection lines are foreseen, one coming from the RESR [2] to inject cooled anti-protons [3] with 3 GeV kinetic energy and the other one to inject protons from SIS 18. An overview on the HESR ring is given in figure 1. Using a target thickness of $4 \cdot 10^{15}$ atoms cm^{-2} the high luminosity mode (HL) is attained with 10^{11} antiprotons yielding a luminosity of $2 \cdot 10^{32}$ cm^{-2} s^{-1}. The HL-mode has to be prepared in the whole energy range and beam cooling is needed to particularly prevent beam heating by the beam target interaction. Much higher requirements are necessary in the high resolution mode (HR) with 10^{10} antiprotons. The same target thickness yields here a luminosity of $2 \cdot 10^{31}$ cm^{-2} s^{-1}. This mode is requested up to 8.9 GeV/c with a rms-relative momentum spread down to about $4 \cdot 10^{-5}$.

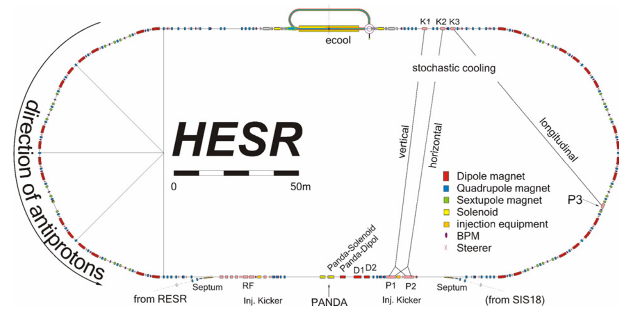

Figure 1: Layout of the HESR ring including the signal paths for transverse and longitudinal cooling.

The injected beam in the HESR at $p = 3.8\ GeV/c$ has the following emittance and relative momentum spread in

HR-Mode: $\varepsilon_{rms,HR} = 0.1\, mm\, mrad$ $\delta_{rms,HR} = 2 \cdot 10^{-4}$ and

HL-Mode: $\varepsilon_{rms,HL} = 0.6\, mm\, mrad$ $\delta_{rms,HL} = 5 \cdot 10^{-4}$.

The injected beam is then accelerated with an acceleration rate of 0.1 (GeV/c)/s to the desired experiment momentum.

COOLING SYSTEMS

In general a very broad cooling bandwidth must be chosen for fast cooling. However the upper frequency of the cooling system is restricted when considering the filter cooling method [4]. In this case a proper functioning is only achieved if there is no overlap of adjacent revolution harmonics so that each band can be covered separately by the notch filter. As a reasonable compromise a (2 – 4) GHz system has been chosen that can be operated in the whole momentum range from 3.8 GeV/c up to maximum momentum. The simulations assume quarter wave pickup and kicker loops [5]. For longitudinal stochastic cooling an optical notch filter will be implemented in the signal path. In figure 1 the cooling signal paths are shown. Cooling simulations applying a linear notch filter have been already presented in [6]. In this contribution the model utilizes a more realistic non-linear notch filter. The HESR optics [1] that has been used throughout has an imaginary transition energy with $\gamma_{tr} = 6.0\, i$. The target-beam interaction is treated in the formalism as outlined elaborately in [7].

Transverse Cooling

The theory of transverse cooling used in this contribution is outlined in detail in [8]. The formalism has

STOCHASTIC COOLING FOR THE FAIR PROJECT *

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Abstract

Stochastic cooling is used in the framework of the FAIR project at GSI for the first stage of phase space compression for both rare isotope and antiproton beams. The collector ring CR serves for the precooling of rare isotope and antiproton beams. The paper discusses mainly the stochastic accumulation in the RESR based on a new lattice design.

STORAGE RINGS IN THE FAIR PROJECT

The storage rings in the FAIR project are designed for the preparation of experiments with rare isotope (RI) or antiproton beams, which are produced by bombardment of short high intensity bunches from the SIS100 synchrotron [1] on appropriate production targets. As these beams have large longitudinal and transverse emittances, stochastic precooling is foreseen in the Collector Ring (CR) [2].

The antiprototon beams are accumulated in the RESR storage ring [3]. High energy antiproton experiments make use of stochastic cooling in the HESR storage ring [4].

PRECOOLING IN THE COLLECTOR RING

The stochastic cooling systems in the CR have been described in [5] and [2].

The development of slotline electrodes for the CR is described in [6]. A prototype of the 1 GHz - 2 GHz power amplifier has been built and will be tested at GSI in the near future. The integration of the slotline structures into a complete pick-up tank is presently prepared.

STOCHASTIC ACCUMULATION IN THE RESR RING

Overview

Stochastic accumulation in the RESR makes use of the same principle which has successfully been used in the AA at CERN [7], [8] and in the Accumulator at FNAL [9]. In any case, the accumulation works in the longitudinal phase subspace. Figure 1 shows a sketch of the vacuum chamber at the pick-up which is used for accumulation.

The beam is injected at the injection orbit (i). It is then deposited by rf to a deposition orbit (d). Before the next shot arrives, the stochastic cooling system must be fast enough to shift these particles to the stack tail (t). The repetition interval between single injection shots is mainly given by the time it takes to perform the shift between (d) and (t). Then the same pick-up signal is used to shift the particles gradually into the core. The pick-up sensitivity of the stack tail cooling pick-up should decrease exponentially towards the core.

In order to achieve this goal, the vertical β function at the pick-up must be small and the dispersion large (see below). However, experience from the CERN AA shows that in addition a twofold staggered notch filter may be needed in order to get the system gain down in the core region.

New RESR Lattice

The new lattice of the RESR [10] has the following advantageous properties with respect to antiproton accumulation:

- The lattice enables a flexible choice of the transition gamma up to $\gamma_t = 6.3$.
- There are straight sections with large dispersion and small vertical betatron function for the accumulation pick-up.
- There is enough space in dispersion free sections to take up the stochastic cooling kicker tanks.

RESR Cooling Systems

Four cooling systems are envisaged for the RESR:

1. The stack tail cooling system (longitudinal, see above)
2. The core cooling system (longitudinal)
3. A horizontal betatron cooling system
4. A vertical betatron cooling system

Figure 2 shows the locations for pick-ups and kickers in the new RESR lattice. Figure 3 shows the Twiss functions of an optical setting with $\gamma_t = 5.3$.

In a first stage, the system will work in the 1 GHz - 2 GHz band. Due to the chosen η value, an upgrade up to 4 GHz is feasible. The pick-ups and kickers will be of the Faltin [11] type. The core cooling system will use the same kicker as the stack tail system, just with an additional quadruplet of pick-up electrodes in the accumulation pick-up structure, and a low gain amplification.

* Work supported by EU design study (contract 515873 - DIRACsecondary-Beams)

ANTIPROTON PRODUCTION AND ACCUMULATION *

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Abstract

In the course of Tevatron Run II (2001-2007) improvements of antiproton production have been one of major contributors to collider luminosity growth. Commissioning of Recycler ring in 2004 and making electron cooling operational in 2005 freed Antiproton source from the necessity to keep large stacks in the Accumulator and allowed us to boost the antiproton production. That resulted in doubling average antiproton production during last two years. The paper discusses improvements and upgrades of the Antiproton source during last two years and future developments aimed at further stacking improvements.

INTRODUCTION

Improvements in the Tevatron resulted in that the fraction of antiprotons burned in collisions achieved ~40% in 2004. Since that time this number was not changed, and its further increase is limited by intrabeam scattering (IBS) in the proton and antiproton beams. Further growth of the collider luminosity would not be possible without growth of antiproton production. For past two years increased antiproton production has been our highest priority in Tevatron Run II. Figure 1 demonstrates the results of these efforts culminating in ~1.7 times antiproton production growth in FY'07 alone. Further growth is expected in FY'08.

The following items contributed to this growth of antiproton production. First, there has been an improvement of the proton source. A reduction of longitudinal emittance in the Booster allowed us to optimize slip-stacking in the Main injector [1], which resulted in an increase in the number of protons on the antiproton production target from $6.5\cdot10^{12}$ to $8\cdot10^{12}$ per pulse. Second, an optics correction in the transfer line from the Main Injector to the antiproton production target allowed us to reduce the rms beam size on the target to ~200 μm. The resulting increased target depletion rate limits further reduction of the beam size. Third, stabilization of the proton beam position on the antiproton production target resulted in more stable operation and ~5% growth in the average antiproton production (it did not change the peak production). Fourth, an upgrade of the lithium lens allowed us to increase its gradient from 60 to 75 kG/cm, which resulted in ~10% growth in the antiproton yield. Fifth, optics correction in the Debuncher [2] resulted in an increase in Debuncher acceptance from 30/25 to 35/34 mm mrad, correspondingly for horizontal and vertical degrees of freedom. This resulted in ~10% improvement of the antiproton yield.

After the above upgrades were finished by the end of FY'06 the remaining major limitation to the stacking rate was the Stacktail system. Therefore its improvement became the highest priority item for the last year. This project combines a few separate improvements that are described in detail below. The implementation of these improvements resulted in a growth of peak stacking rate from $20\cdot10^{10}$ to $23.2\cdot10^{10}$ hour^{-1} in FY'07 and positioned us well for further improvements of stacking rate. Figure 2 shows how the dependence of stacking rate on stack size has changed during the course of Run II. As one can see, the stacking rate drops fast with the stack size. Too minimize this harmful effect the transfer time from Accumulator to MI injector was decreased from ~50 to 9 min. That allowed us to reduce the maximum stack size to ~$50\cdot10^{10}$ and greatly decrease the difference between the peak and average stacking rates. This resulted in the best average weekly stacking rate of $16.5\cdot10^{10}$ hour^{-1}, which is only ~28% below the peak stacking rate. This number looks quite impressive if one takes into account that it also includes all interruptions to the stacking.

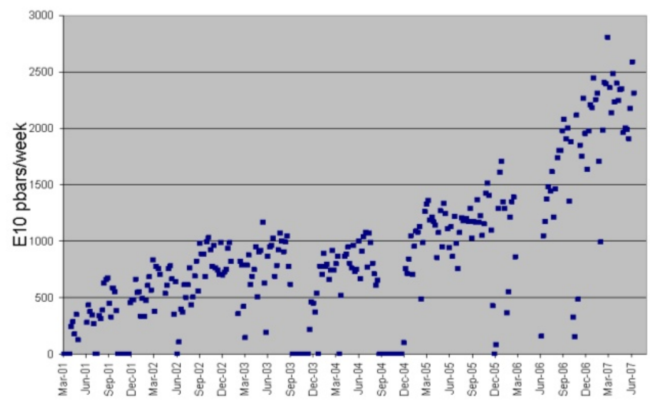

Figure 1: Weekly antiproton production rate during Run II (2001-2007).

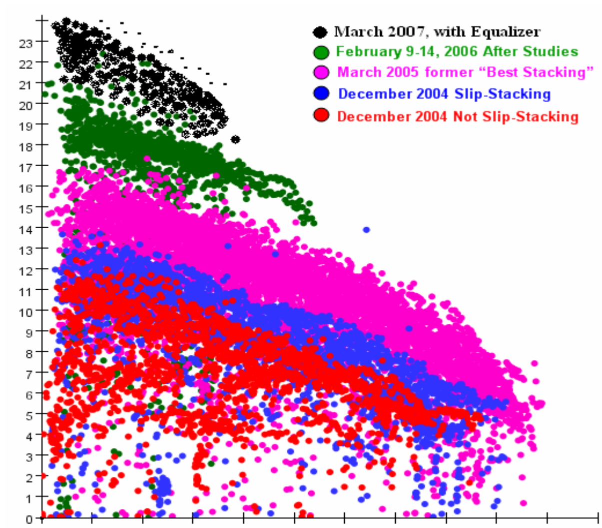

Figure 2: Dependence of antiproton production rate (units of 10^{10} hour^{-1}) on stack size (units of 10^{10}) during Run II.

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CALCULATIONS ON HIGH-ENERGY ELECTRON COOLING IN THE HESR*

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Abstract

PANDA will make use of a hydrogen pellet target. We discuss the choice of beam size at the target and emittance stabilization, and show some results of simulations made with BETACOOL. The simulations include the effects of the internal target, intra-beam scattering, electron cooling and in some cases also stochastic cooling.

HYDROGEN PELLET TARGET

In order to achieve luminosities in PANDA in the range $2\times10^{31} - 2\times10^{32}$ cm^{-2}s^{-1} with $10^{10} - 10^{11}$ stored antiprotons in HESR, an internal hydrogen target with thickness 4×10^{15} cm^{-2} is required. A hydrogen pellet target [1] is the only known kind of internal target, which meets this requirement. At the same time, the granular nature of this target will cause a temporally varying luminosity, particularly if the antiproton beam has small transverse dimensions compared to the vertical separation between pellets or the diameter of the pellet stream.

The hydrogen pellets move in a well-collimated cylindrical flow in which they are distributed rather uniformly, see figure 1. Experience from the use of the pellet target at CELSIUS [2] shows that the pellet flux diameter can be varied between about 1.5 and 3 mm by changing the size of a skimmer in the pellet generator. Since PANDA requires a very big luminosity, we have here chosen to assume that the pellet stream will have a diameter of 3 mm.

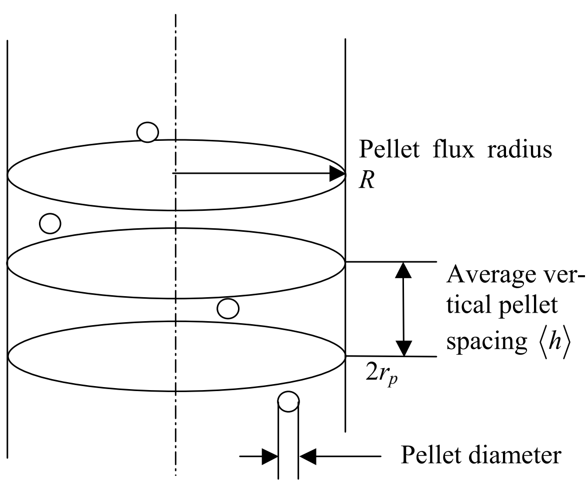

Figure 1: Schematics of the pellet target geometry. The pellets move from top to bottom with the same speed.

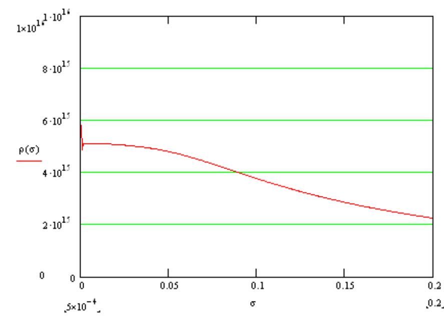

Figure 2: Mean effective target thickness in atoms/cm^3 as a function of the horizontal rms. beam size (in cm). Calculated for Gaussian distribution.

The required target thickness is then met if the average vertical separation between the pellets $\langle h \rangle$ is about 4 mm, which is what we have assumed in the following. With a pellet speed of 60 m/s, this corresponds to a pellet rate of 15,000 s^{-1}, which is well within the achieved performance of the hydrogen pellet target.

CHOICE OF BEAM SIZE AT TARGET

If the horizontal antiproton beam size on the target is made too large, then the luminosity will be reduced due to poor overlap between the beam and the target. The expression for a Gaussian beam is

$$\rho_{\text{eff,mean}} = \frac{\langle \Re \rangle}{\sqrt{2\pi}\sigma_x} \int_{-R}^{R} 2\sqrt{R^2 - x^2}\, \exp\left(-\frac{x^2}{2\sigma_x^2} \right) dx$$

where

$$\langle \Re \rangle = \frac{\frac{4}{3}\pi r_p^3}{\pi R^2 \langle h \rangle} \Re; \quad \Re = 4.3 \times 10^{22} \text{ atoms/cm}^3$$

This effect is illustrated for our parameters in figure 2. We see that the horizontal r.m.s. beam size should not be chosen bigger than about 0.8 mm in order to keep the effective luminosity above 80 % of the maximum possible.

At the same time, if the beam size is chosen too small, then the granular nature of the pellet target will cause fluctuations in the effective target thickness. For a Gaussian beam, the maximum instantaneous effective target thickness, which occurs when the beam hits a pellet head-on, is given by

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ELECTRON COOLING STATUS AND CHARACTERIZATION AT FERMILAB'S RECYCLER*

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Abstract

FNAL's electron cooler (4.3 MV, 0.1 A DC) has been integrated to the collider operation for almost two years, improving the storage and cooling capability of the Recycler ring (8 GeV antiprotons). In parallel, efforts are carried out to characterize the cooler and its cooling performance.

This paper discusses various aspects of the cooler performance and operational functionality: high voltage stability of the accelerator (Pelletron), quality of the electron beam generated, operational procedures (off-axis cooling, electron beam energy measurements and calibration) and cooling properties (in the longitudinal and transverse directions).

INTRODUCTION

The Recycler Electron Cooler (REC) [1] has been fully integrated to the collider operation since January 2005. However, over the past year, the average antiproton production rate in the Accumulator ring has almost doubled, reducing the average time between successive injections into the Recycler from 4 to 2.5 hours, hence increasing the need for fast cooling. In turn, the REC has been heavily relied upon for the storage and cooling of 8 GeV antiprotons destined for collisions in the Tevatron.

In this paper, we report on the status of the electron cooler, which has proved to be very reliable over the past year. We also discuss its overall cooling performance, through dedicated friction force and cooling rate measurements.

THE REC IN OPERATION

The REC employs a DC electron beam generated in an electrostatic accelerator, Pelletron [2], operated in the energy- recovery mode. The beam is immersed into a longitudinal magnetic field at the gun and in the cooling section (CS); other parts of the beam line use lumped focusing. The main parameters of the cooler can be found in Ref. [1].

Cooling Procedure

The cooling procedure described in Ref. [3] remains the norm to this date: the electron beam is used when needed and the cooling rate is being adjusted by increasing or decreasing the fraction of the antiproton beam that the electron beam overlaps (through parallel shifts). The driving consideration for this procedure is to avoid overcooling the center of the antiproton beam and preserve its lifetime.

A cooling sequence is illustrated on Figure 1 and in this particular case the electron beam was turned on just before the 3rd injection (out of 11) and kept on until extraction to the Tevatron. Throughout the storage cycle, the electron beam position is adjusted regularly according to the needs for longitudinal cooling. Note that stochastic cooling is always on (both the longitudinal and transverse systems).

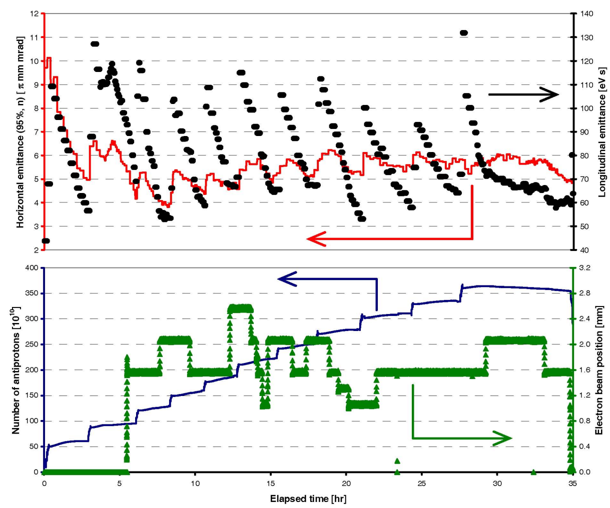

Figure 1: Example of the cooling sequence and electron beam utilization during a storage cycle. Bottom plot - Solid blue: Number of antiprotons; Green triangles: Electron beam position; Top plot – Solid red: Transverse (horizontal) emittance measured by the 1.75 GHz Schottky detector; Black circles: Longitudinal emittance measured by the 1.75 GHz Schottky detector. The electron beam current is kept constant (100 mA).

At the end of the storage cycle, just before mining [4], the beam is brought 'on-axis' (i.e. the electron beam trajectory coincides with the antiprotons central orbit) to provide maximum cooling when lifetime preservation is no longer an issue since the antiprotons are about to be extracted to the Tevatron. Recently, to accommodate the large number of particles often present in the Recycler (>300×10^10), the electron beam current is increased from 100 mA to 200 mA after the last injection of fresh antiprotons. The additional cooling strength obtained from the increased beam current is required to reach the longitudinal emittance needed for high transfer efficiencies in the downstream machines all the way to collision in the Tevatron.

The final cooling sequence (between the last injection from the Accumulator to extraction to the Tevatron) takes 2-2h30 (Figure 2). It is dictated by the needs for reducing the longitudinal emittance from 110-120 eV s (just after

* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy
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COOLING RESULTS FROM LEIR

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Abstract

The LEIR electron cooler has been successfully commissioned for the cooling and stacking of Pb^{54+} ions in LEIR during 2006. The emphasis of the three short commissioning runs was to produce the so-called "early" beam needed for the first LHC ion run. In addition some time was spent investigating the difficulties that one might encounter in producing the nominal LHC ion beam.

Cooling studies were also made whenever the machine operational mode made it possible, and we report on the preliminary results of the different measurements (cooling-down time, lifetime etc.) performed on the LEIR cooler. Our investigations also included a study of the influence of variable electron density distributions on the cooling performance.

INTRODUCTION

The LHC program foresees lead-lead collisions in 2009 with luminosities up to 10^{27} $cm^{-2}s^{-1}$. In LEIR, ion beam pulses from the LINAC3 are transformed into short high-brightness bunches needed for the LHC. This is obtained through multi-turn injection, cooling and accumulation. The electron cooler plays an essential role in producing the required beam brightness by rapidly cooling down the newly injected beam and then dragging it to the stack.

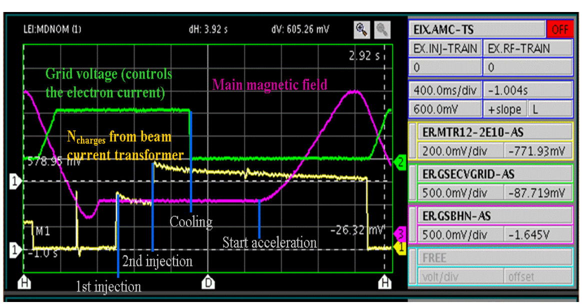

Figure 1: A standard 3.6s LEIR cycle during which 2 LINAC pulses are cooled-stacked in 800ms at an energy of 4.2 MeV/n. After bunching the Pb ions are accelerated to 72 MeV/n for extraction and transfer to the PS.

The goal of the LEIR commissioning runs in 2006 was to produce the Pb ion beam with the characteristics required for the first LHC ion run ($N_{ions} = 2.2x10^8$, $\varepsilon_{h,v} <$ 0.7 μm) and to subsequently transfer this beam to the next accelerator in the injection chain, the Proton Synchrotron (PS), for beam studies. Figure 1 shows a typical LEIR cycle in which two pulses are cooled and stacked to obtain the required intensity and emittance after which the beam is accelerated to top energy and extracted to the PS. These tests were so successful that the Pb ion beam was also extracted towards the Super Proton Synchrotron (SPS) for tests of the beam transport system and the stripping foil. Initial investigations into the production of the optimum beam ($N_{ions} = 1.2x10^9$, $\varepsilon_{h,v} <$ 0.7 μm) for LHC were also made on dedicated machine cycles. A full report of the LEIR commissioning can be found in [1].

ELECTRON COOLER HARDWARE COMMISSIONING

Hardware commissioning of the electron cooler concentrated on ensuring the vacuum [2] compatibility of the new device as well as exploring the performance limits. The main parameters of the cooler have been given in previous papers [3]. Two operational regimes can be used depending on the momentum of the ions to be cooled. If the small normalized emittances required cannot be reached at injection energy e.g. due to direct space charge detuning, operation of the cooler at the extraction energy will be necessary. In this scenario (unlikely for Pb ion operation, but a possible option for an eventual later upgrade to lighter ions), the LEIR magnetic cycle must contain an additional plateau at a suitable higher energy.

Electron Gun Characteristics

The high perveance gun provides an intense electron beam in order to decrease the cooling rate. However, in theory, increasing the electron density induces first an increase of the recombination rate (capture by the ion of an electron from the cooler), which is detrimental to the ion beam lifetime, and secondly increases the electron azimuthal drift velocity, thus increasing the cooling time. To combat the increase in electron-ion recombination, the electron gun has a "control electrode" used to vary the density distribution of the electron beam. The beam profile is adjusted in such a way that the density at the centre, where the cold stack sits, is smaller and thus the recombination rate is reduced. At larger radii, the density is large and allows efficient cooling of the injected beam executing large betatron oscillations.

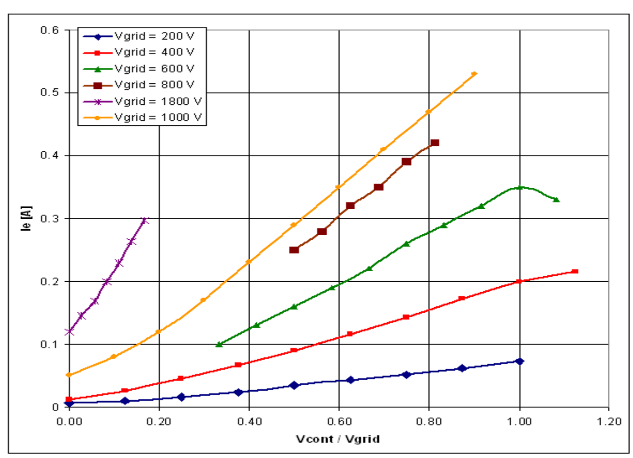

Figure 2: Electron beam current as a function of Vcont/Vgrid for Ee = 2.3 keV.

COMMISSIONING OF ELECTRON COOLING IN CSRM*

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Abstract

A new generation electron cooler has started operation in the heavy ion synchrotron CSRm which is used to increase the intensity of heavy ions. Transverse cooling of the ion beam after horizontal multiturn injection allows beam accumulation at the injection energy. After optimization of the accumulation process an intensity increase in a synchrotron pulse by more than one order of magnitude has been achieved. In given accumulation time interval of 10 seconds, 10^8 particles have been accumulated and accelerated to the final energy. The momentum spread after accumulation and acceleration in the 10^{-4} range has been demonstrated in five species of ion beams. Primary measurements of accumulation process varying with electron energy, electron beam current, electron beam profile, expansion factor and injection interval have been performed. The lifetimes of ion beam in the presence of electron beam were roughly measured with the help of DCCT signal.

INSTRUCTION

HIRFL-CSR is a new ion cooler-storage-ring system in IMP China. It consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC (K=69) and SSC (K=450) of the Heavy Ion Research Facility in Lanzhou (HIRFL) are used as its injector system. The heavy ion beams from HIRFL is injected into CSRm, then accumulated, e-cooled and accelerated, finally extracted to CSRe for internal-target experiments and other physics experiments.

Table 1: Parameters of the CSRm electron cooler

Maximum electron energy	35 keV
Maximum electron current	3A
Gun perveance	29 μP
Cathode diameter	29mm
Current collection efficiency	≥99.99%
Maximum magnetic field in gun section	0.25T
Maximum magnetic field in cooling section	0.15T
Field parallelism in cooling section	4×10^{-5}
Effective length of cooling section	3.4m
Vacuum pressure	≤ 3×10^{-11}mbar

CSRm is a 161m circumference cooler storage ring with sixteen 22.5 degree H-type bending dipole magnets. The maximum betatron functions are 15.3m and 30.5m in horizontal and vertical respectively. The maximum dispersion is 5.4m, and the dispersion at injection point is 4m. The betatron functions at electron cooler are 10m and 17m in the two transverse directions respectively, the dispersion is zero here. The emittance of ion beam from SFC and SSC is about 20πmmmrad and 10 π mmmrad, and the acceptance of CSRm is about 150πmmmrad.

Two modes of injection are used in CSRm, stripping for lighter ions and repeated multiturn for heavier ones. The accumulation duration of CSRm is about 10s, and the acceleration time of CSRm is nearly 3s, and the one whole cycle period is about 17s.

In CSRm, the electron cooling device plays an important role in the heavy ion beam accumulation at injection energy. The new state-of-the-art electron cooling device was designed and manufactured in the collaboration between BINP and IMP, it has three distinctive characteristics, namely high magnetic field parallelism in cooling section, variable electron beam profile and electrostatic bending in toroids. The main parameters are listed in table 1.

In 2005 the main construction of the CSR project was completed, and from then the preliminary commissioning of CSRm was performed, including the first turn commissioning as a beam line, the stripping injection, and the zero-bumping orbit test, fixed-bumping orbit test with four in-dipole coils, bumping orbit test, C-beam accumulation and some investigations of the closed orbit with BPM.

Shortly after last workshop of COOL2005, the cooler started routine operation during CSR commissioning. Up to now five species of ion were cooled and accumulated with the help of electron cooling. In this paper the recent results of commissioning of CSRm and its cooler are presented. The previous results have been given in the APAC2007-THXMA03 [1]

BEAM DIAGNOSTICS

The closed orbit is monitored by 16 shoebox-shaped BPMs, the length of electrodes is 150mm, the cross-section is rectangular, and the width and height are 170mm and 100mm respectively. Two additional cylindrical BPMs were installed at the ends of cooling section to measure the positions of electron beam and ion beam. A Schottky pickup was placed behind the cooler, the length of the plate electrodes is 395mm, and the widths are 160mm in horizontal and 100mm in vertical directions, the gaps between electrodes are 110mm in vertical and 160mm in horizontal. A DCCT developed by company Bergoz is used to monitor the ion beam current in the ring, with precision of about 0.5μA. The direct determination of beam's transverse emittance was presently ruled out due to the magnesium jet monitor was out of order during commission. In order to measure the work-point, the Schottky pickup electrodes were used to

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COMPARISON OF THE HOLLOW ELECTRON BEAM DEVICES AND ELECTRON HEATING

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Abstract

In the previous two years after COOL05 a new generation of low energy electron coolers with variable electron beam profile was successfully commissioned with Pb^{+54} ion beams at CERN LEIR and at IMP (China, Lanzhou) CSRm with C^{+6}. A hollow electron beam profile with low electron beam density at the center helps to suppress recombination at the accumulation zone and to increase the lifetime of the ion beam. First experiments with a vertically offset electron beam (with aim to control overcooling the storage stack of ion beam) were made at the RECYCLER high energy electron cooler (FNAL) with very different conditions for accumulation and cooling antiprotons. In this paper the parameters of these different experiments with electron cooling are discussed in the frame of a model of electron heating. The aim is to integrate the experience of using the hollow electron beam cooling, test model and to find recommendations for the next generation electron coolers for the FAIR p.

ELECTRON COOLING AND HEATING

Cooling manifests itself in damping single particle oscillations and coherent oscillations of ion beams. The presence of the electrons in the cooling section and high phase space density of the ion beam after cooling can be sources of the development of instabilities and beam losses [1]. These problems were the subjects of discussions of many reports [2,3] but their final understanding is still far in future. Modulation of the electron beam energy helps to increase the threshold current of the ions [4]. The square-wave modulation of the electron beam energy decreases the cooling rate for the central (equilibrium) energy but helps cooling of the tail energy ions. Control of the transverses ion beam profile after cooling was not so easy because of a very fast increase of the cooling power for small amplitude radial oscillations of the ions.

In order to avoid overcooling in the transverse direction a so called "painted" electron beam position has been proposed. A fast manipulation of the transverse positions and angle of the electron beam in a high energy cooler so that tails cooled more intensively was discussed for the projected cooler for RHIC [5]. At high voltage the cooling time is about a few hours and fast manipulation of the electron beam energy and of the transverse positions can be made relatively easyly. But for the low energy coolers with cooling times of a few milliseconds the electron gun with a special control electrode was designed to produce electron beams with variable profiles [6]. In this electron gun the control electrode voltage can produce a practically hollow electron beam in a steady mode. In the moment of passing the cooling section the ions with not have an equilibrium energy but move in the rest electron gas. By the action of the friction force they lose momentum as:

$$\delta p = -\frac{4\pi e^4 Z^2 n_e \ln(\frac{\rho_{\max}}{\rho_{\min}})\tau}{mMV^3} p = -\lambda \times p\,, \qquad (1)$$

where e is the electron charge, Z is the ion charge in units e, n_e is the electron beam density, m and M are the electron and ion masses, respectively, t is the time of flight through the cooling section in the reference frame of the beam system, r_{max}, r_{min} are the maximum and minimal impact distances, and l is the single pass cooling decrement. There is normal cooling interaction, but the neighbouring ions inside distance r_{max} obtain almost the same momentum kick δp and a slight increase of the kinetic energy in the ion beam (these ions do not have a correlation δp V and the term <δp*V>=0 is equal to 0):

$$\delta E_{ion} = -\delta p V + \frac{\delta p^2}{2M} n_i \frac{4\pi}{3}\rho_{\max}^3 = \qquad ,(2)$$
$$(-2\lambda + \lambda^2 \times N^*)E_{ion} = -2\lambda(1-\omega_e^2\omega_i^2\tau^4 g)E_{ion}$$

where ω_e, ω_i are the plasma frequencies of the electron and ion beams, N^* is the number of neighbouring ions inside the distance r_{max}, g is a numerical factor close to unity which can be calculated more carefully by numerical integration in the interaction zone of the ion. The meaning of this equation is that the single pass cooling decrement should be limited by the number of ions in the interaction zone $l<2/N^*$. Practically there exists a limit of the product of electron and ion beam densities [7]:

$$n_i \times n_e \le \frac{6}{r_e r_i (c\tau)^4 * g(4\pi)^2 \ln(\rho_{\max}/\rho_{\min})}\,. \quad (3)$$

Decreasing the electron beam density at the center of the storage zone opens additional space for the accumulation of a more intense ion beam.

FNAL COOLER EXPERIMENTS

In september 2005 cooling experiments have been performed with the RECYCLER cooler with a vertical offset of the electron beam. Initially the electron beam was shifted by 9 mm and then moved step by step inside the antiproton beam as demonstrated in fig.1. Straight lines along the longitudinal emittance data were used for the calculation of the longitudinal cooling time which changed from 40 hours for 9 mm offset to 2 hours for 1.5 mm offset. The experience of using electron cooling in

IONIZATION COOLING*

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Abstract

All three components of a particle's momentum are reduced as a particle passes through and ionizes some energy absorbing material. If the longitudinal momentum is regenerated by RF cavities, the angular divergence of the particle is reduced. This is the basic concept of ionization cooling. What can be done for a muon beam with this simple idea is almost amazing, especially considering that the muon lifetime is only 2.2 μs in its rest frame. In this paper we discuss the evolution and present status of this idea, where we are now ready to design muon colliders, neutrino factories, and intense muon beams with very effective cooling in all three dimensions. The discussion will include the heating effects and absorber Z-dependence of multiple scattering, numerical simulation programs, the accuracy of scattering models, emittance exchange, helical cooling channels, parametric-resonance ionization cooling, and the ionization cooling demonstration experiments, MICE and MANX.

INTRODUCTION

In the last year, several things have come together to reinvigorate muon collider enthusiasts: 1) There is a great interest to have a plan for a next-generation project that would continue the energy-frontier accelerator tradition in the US. 2) The uncertainties in need, cost, and siting of the International Linear Collider (ILC) have made it clear even to strong ILC supporters that a "Plan B" is prudent. 3) While impressive work has been done toward a neutrino factory based on a muon storage ring [1,2], the physics case for such a machine will have to wait for results of experiments that are just getting started. Thus there is some muon-related accelerator expertise that is available for muon collider development. 4) As discussed below, several new ideas have arisen in the last five years for six-dimensional (6D) muon beam cooling. The advantage of achieving high luminosity in a muon collider with beams of smaller emittance and fewer muons has been recognized as a great advantage for many reasons [3], including less proton driver power on target, fewer detector background issues, and relaxed site boundary radiation limitations.

Another advantage of small 6D emittance for a collider is that the cost of muon acceleration can be reduced by using the high frequency RF techniques being developed for the ILC. To the extent that muon beams can be cooled well enough, the muon collider is an upgrade path for the ILC or its natural evolution if LHC results imply that the ILC energy is too low or if its cost is too great.

Effective 6D cooling and the recirculating of muons in the same RF structures that are used for the proton driver may enable a powerful new way to feed a storage ring for a neutrino factory [4]. This would put neutrino factory and muon collider development on a common path such that a muon collider could be realized in several stages, each independently funded and driven by high-energy physics goals, e.g. a very cool stopping muon beam, neutrino factory, Higgs factory, energy frontier collider.

IONIZATION COOLING PRICIPLES

The idea that the transverse emittance of a beam could be reduced by passing it through an energy absorber originated in Novosibirsk many years ago [5,6]. Figure 1 is a schematic of the concept, showing how the angular divergence of a beam can be reduced.

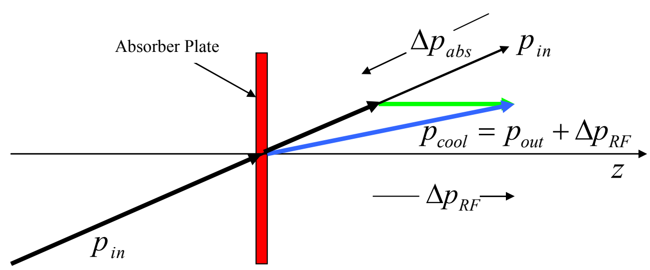

Figure 1: Conceptual picture of the principle of Ionization Cooling. Each particle loses momentum by ionizing an energy absorber, where only the longitudinal momentum is restored by RF cavities. The angular divergence is reduced until limited by multiple scattering, so that a low-Z absorber is favored.

Ionization cooling of a muon beam involves passing a magnetically focused beam through an energy absorber, where the muon transverse and longitudinal momentum components are reduced, and through RF cavities, where only the longitudinal component is regenerated. After some distance, the transverse components shrink to the point where they come into equilibrium with the heating caused by multiple coulomb scattering. The equation describing the rate of cooling is a balance between these cooling (first term) and heating (second term) effects:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0} \quad [1].$$

Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity. Muons passing through an absorber experience energy and momentum loss due to collisions with electrons. The derivations and discussions of the basic formulae of ionization cooling can be found in many places [7,8], where the energy loss is described by the Bethe-Bloch theory and the multiple-scattering heating is

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MICE: THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

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Abstract

An international experiment to demonstrate muon ionization cooling is scheduled for beam at Rutherford Appleton Laboratory (RAL) in 2008. The experiment comprises one cell of the neutrino factory cooling channel, along with upstream and downstream detectors to identify individual muons and measure their initial and final 6D emittance to a precision of 0.1%. Magnetic design of the beam line and cooling channel are complete and portions are under construction. This paper describes the experiment, including cooling channel hardware designs, fabrication status, and running plans. Phase 1 of the experiment will prepare the beam line and provide detector systems, including time-of-flight, Cherenkov, scintillating-fiber trackers and their spectrometer solenoids, and an electromagnetic calorimeter. The Phase 2 system will add the cooling channel components, including liquid-hydrogen absorbers embedded in superconducting Focus Coil solenoids, 201-MHz normal-conducting RF cavities, and their surrounding Coupling Coil solenoids. The goal of MICE Collaboration is to complete the experiment by 2010.

INTRODUCTION

The MICE experiment is part of the R&D programme towards a neutrino factory based on a muon storage ring, largely considered as the most precise tool to probe neutrino physics in the future. The cooling of muon beam is largely unexplored and is a major source of uncertainty on the cost and construction time of a neutrino factory. MICE has been designed to demonstrate that it is possible to engineer, build and operate safely and reliably a section of linear muon ionization cooling channel similar to the one proposed in the US Feasibility Studies [1].

The MICE collaboration started in 2001 [2] and now rallies about 140 people, engineers, accelerator and particle physicists from more than 40 institutes in Europe, USA, China and Japan. The MICE collaboration is also working together with the US MuCool Collaboration with whom we are sharing several objectives.

GENERAL DESIGN

An introduction to Ionization Cooling can be found in [3]. Basically, under certain conditions, cooling is obtained when the beam passes through some energy absorbing material where it loses energy by ionization. The conditions are 1) the Z of the material is low, in order to maximize the ratio between the stopping power, responsible for cooling, and the multiple scattering cross section, responsible for heating; 2) The transverse β function is small at the position of the absorber. Additionally, in order to avoid de-bunching effects, the energy loss in the forward direction should be compensated for. In line with these principles, the MICE cooling channel is made of three liquid hydrogen absorbers alternating with two linac sections, each composed of four RF cavities. Rapid evaluation has shown that this system should be able to cool a 6π mm rad beam by about 10% [4]. The aim of the experiment is to measure this cooling effect with a precision of 1%, requiring a precision of 0.1% on the emittance measurement before and after the cooling channel. Such a precision can't be obtained with standard beam diagnostic instrumentation hence we had to adopt a particle per particle tracking approach. It has been shown as well [5] that pion and electron contamination in the beam introduces a bias on the emittance measurement, imposing the presence of some detectors dedicated to Particle Identification (PID), both upstream and downstream. The tracker and PID detectors have been designed using a simulation code based on GEANT4 [6] but developed especially for MICE. This code, called G4MICE, after validation by precise experimental data, can be considered as one of the most important deliverable of the experiment since it should become a reliable tool for the design of future cooling channels.

THE BEAM LINE

MICE will be hosted by the Rutherford Appleton Laboratory (RAL) in the UK. A new muon beam line is under construction using the existing, 800 MeV, 300 μA, proton synchrotron, ISIS. The beam line components are shown in Figure 1 and detailed in [7]. A short description is given below.

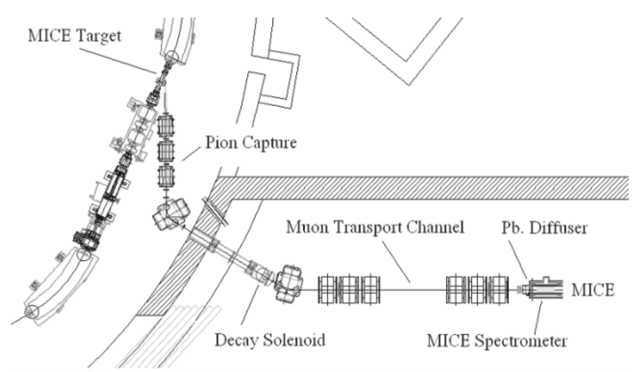

Figure 1: Schematic view of the MICE beam line at ISIS, Rutherford Appleton Laboratory, UK.

The Target System

A dedicated system has been designed in Sheffield to dip the Ti target into the halo of the beam in the few milliseconds preceding the extraction of the primary

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A COMPLETE SCHEME FOR A MUON COLLIDER *

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Abstract

A complete scheme for production, cooling, acceleration, and ring for a 1.5 TeV center of mass muon collider is presented, together with parameters for two higher energy machines. The schemes starts with the front end of a proposed neutrino factory that yields bunch trains of both muon signs. Six dimensional cooling in long-period helical lattices reduces the longitudinal emittance until it becomes possible to merge the trains into single bunches, one of each sign. Further cooling in all dimensions is applied to the single bunches in further helical lattices. Final transverse cooling to the required parameters is achieved in 50 T solenoids.

Table 1: Parameters of three muon colliders. Note 1: Depth is relative to any nearby low land, e.g. Fox river at FNAL. Note 2: Survival is from the end of phase rotation to the collider ring.

$E_{\rm c.m.s}$ (TeV)	1.5	4	8
$\mathcal{L}$ (10^{34} cm^{2}sec^{-1})	1	4	8
Beam-beam $\Delta\nu$	0.1	0.1	0.1
μ/bunch (10^{12})	2	2	2
$< B_{\rm ring} >$ (T)	5.2	5.2	10.4
$\beta^* = \sigma_z$ (mm)	10	3	3
rms dp/p (%)	0.09	0.12	0.06
Depth for ν rad [1] (m)	13	135	540
Muon Survival [2]	≈0.07	≈0.07	≈0.07
Rep. rate (Hz)	13	6	3
$P_{\rm driver}$ (MW)	≈4	≈ 1.8	≈ 0.8
$\epsilon_\perp$ (π mm mrad)	25	25	25
$\epsilon_\parallel$ (π mm rad)	72	72	72

INTRODUCTION

Muon colliders were first proposed by Budker in 1969 [1], and later discussed by others [3]. A more detailed study was done for Snowmass 96 [4], but in none of these was a complete scheme defined for the manipulation and cooling of the required muons.

Muon colliders would allow the high energy study of point-like collisions of leptons without some of the difficulties associated with high energy electrons; e.g. the synchrotron radiation requiring their acceleration to be essentially linear, and as a result, long. Muons can be accelerated in smaller rings and offer other advantages, but they are produced only diffusely and they decay rapidly, making the detailed design of such machines difficult. In this paper, we outline a complete scheme for capture, phase manipulation and cooling of the muons, every component of which has been simulated at some level.

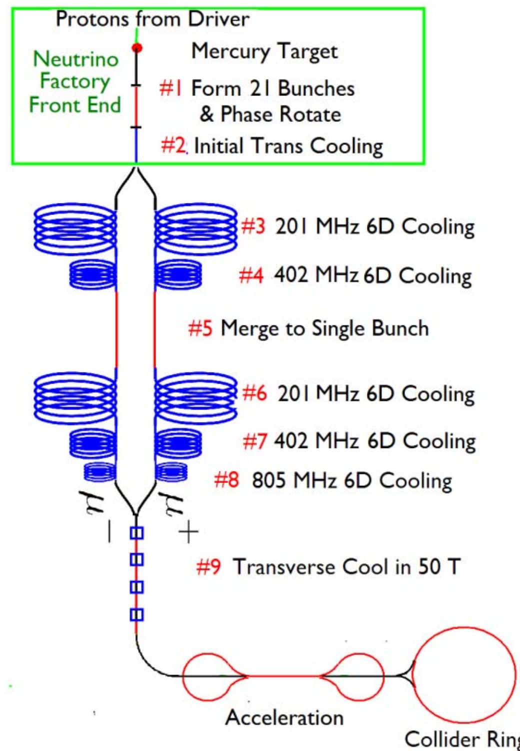

Figure 1: (Color) Schematic of the components of a Muon Collider.

The work in this paper was performed as part of the NFMCC collaboration [5], the recently formed MCTF [6], and Muons Inc. [7].

COLLIDER PARAMETERS

Table 1 gives parameters for muon colliders at three energies. Those at 1.5 TeV correspond to a recent collider ring design [9]. The 4 TeV example is taken from the 96–

*This work was presented by A. Sessler at the workshop. This work was supported by US Department of Energy under contracts AC02-98CH10886 and DE-AC02-76CH03000

THEORETICAL STUDY OF EMITTANCE TRANSFER*

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Abstract

The beam emittance, i.e. the volume of a charged-particle ensemble in six dimensional phase space, is approximately conserved in common accelerators. The concept of "cooling" is thus crucial in improving the beam quality for various machine users. In contrast to cooling, it is rather easy to change the ratios of emittance projections on to the three spatial degrees of freedom. This paper addresses a possible method of controlling the projected emittances with conservative interactions; not only a full emittance exchange but also a partial emittance transfer can readily be achieved in a dedicated storage ring operating near resonance. In a process of eimttance transfer, strong correlations between three directions are naturally developed, which may be useful for specific purposes.

INTRODUCTION

Liouville's theorem implies that the six-dimensional (6D) phase-space volume occupied by a charged-particle beam is an approximate invariant unless the beam is subjected to dissipative interactions (such as in cooling). Symplectic conditions, in a Hamiltonian system (once again, no dissipation), put constraints upon emittance transfer between the various degrees of freedom [1]. We can, however, even in non-dissipative Hamiltonian systems arrange for partial emittance transfers. This process results in phase space correlations and change in the emittance projections on to various phase planes; namely, the projected emittances in three degrees of freedom are controllable while the direction and amount of a possible emittance flow are not very flexible because of the symplectic nature of Hamiltonian systems. In some applications, it is clearly advantageous to optimize the ratios of projected emittances despite the effect of correlations. Since the three emittances are not always equally important, we may consider reducing the emittance of one direction at the sacrifice of the other emittance(s). Emittance exchanging systems have been seriously discussed these days to improve the performance of free electron lasers (FELs) [2,3].

As a possible scheme to achieve efficient emittance control, we study a compact storage ring operating near resonance. The basic features of linear and nonlinear emittance flow are briefly described with numerical examples. A general discussion touching on some of these matters was made over ten years ago and recently published in Ref. [4].

COUPLING STORAGE RING

For a full emittance exchange between the longitudinal and transverse directions, Cornacchia and Emma designed a beam transport channel that employs a special radio-frequency (rf) cavity placed in the middle of a magnetic chicane [5]. Their rectangular rf cavity, excited in a deflective mode, is identical to the *coupling cavity* previously considered for three-dimensional (3D) laser cooling [6]. Although the present scheme is based on a compact ring rather than a short beam transport, we have much higher flexibility in manipulating phase spaces. It is actually straightforward to accomplish a wide range of emittance ratios simply by switching coupling potentials on and off. Furthermore, various linear and nonlinear correlations can be introduced in phase spaces if we switch off coupling (or extract the beam) on the way to a full emittance exchange.

Neglecting interparticle Coulomb interactions, the dynamic motion of a particle in a storage ring can be approximated as the superposition of three harmonic oscillators. The Hamiltonian of interest to us is given by

$$H = \frac{1}{2}\sum_{q=x,y,z}\left[p_q^2 + \left(\frac{\nu_q}{R}\right)^2 q^2\right] + \phi_c(x,y,z;s), \qquad (1)$$

where x, y, and z stand, respectively, for the horizontal, vertical, and longitudinal directions, ν_q $(q = x, y, z)$ is the tune of each direction, R is the average radius of the ring, and the independent variable s is the path length measured along the design beam orbit. Here, $\phi_c(x,y,z;s)$ is an artificial potential that couples three degrees of freedom if required. As an example, let us take a symmetric coupling

$$\phi_c / R = g_x x^m z^n \delta_p(s - s_x) + g_y y^m z^n \delta_p(s - s_y), \qquad (2)$$

where m and n are positive integers, and $g_{x(y)}$ are coupling constants. Since coupling sources are generally electromagnetic devices localized and fixed at specific positions of the ring, we have multiplied each coupling term by a periodic delta function $\delta_p(s)$ with periodicity $2\pi R$. For the sake of simplicity, we assume that the two

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NECESSARY CONDITION FOR BEAM ORDERING

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Abstract

The very low momentum spread for small number of particle was reached on different storage rings. When the sudden reduction of the momentum spread ("phase transition") was observed during decreasing of the particle number it was interpreted as ordered state of ion beams. The most extensive study of ordered ion beams was done on storage rings ESR (GSI, Darmstadt) [1] and CRYRING (MSL, Stockholm) [2]. Recently, for the first time, the ordered proton beam has been observed on S-LSR (ICR, Kyoto University) [3].

This article presents the experimental investigation of low intensity proton beams on COSY (IKP, Juelich) and S-LSR which have the aim to formulate the necessary conditions for the achievement of the ordering state. The experimental studies on S-LSR and numerical simulation with the BETACOOL code [4] were done for the dependence of the momentum spread and transverse emittances on particle number with different misalignments of the magnetic field at the cooler section.

INTRODUCTION

Since very low momentum spread of proton beam was obtained with a help of electron cooling in NAP-M experiments [5] (BINP, Novosibirsk) the deep cooling of low intensity ion beams was studied in a few scientific centres. Essence of the experiments is a measurement of an ion beam momentum spread under cooling during long period of time when the beam intensity slowly decreases. At given value of the particle number the momentum spread is determined by equilibrium between the electron cooling and heating effects, main of which is an intrabeam scattering in the ion beam. The intrabeam heating rates decrease with the particle number that leads to decrease of the equilibrium momentum spread. At large intensity the momentum spread $\Delta p/p$ is scaled with the particle number N in accordance with a power law $\Delta p/p \sim N^{\xi}$, where ξ is some constant depending on settings of a storage ring and cooling system. When the particle number becomes less than certain threshold value the momentum spread can saturate (like in NAP-M, COSY experiments) or suddenly drop down by about one order of magnitude (ESR, SIS, CRYRING, S-LSR), which was interpreted as a phase transition to the ordered state.

Initially the ordered state was observed at ESR for heavy ions only [6], for light ions C^{6+}, Ne^{10+}, Ti^{22+} (except protons) the ordering was reached much later [7]. A few attempts for ordering of the proton beam were made at COSY (FZJ, Juelich), however the sudden reduction of the momentum spread was not observed [8]. Firstly the proton beam ordering was reached at S-LSR (Kyoto University) [3].

From analysis of the ESR experimental results one can conclude that the ordered state was reached when the dependence of momentum spread on particle number had a power coefficient $\xi \le 0.3$ [6, 7]. In the first experiments at ESR with the light ions this condition was not satisfied and the beam ordering did not occur. This condition can explain why in experiments at COSY (where ξ was larger than 0.5) and NAP-M (where ξ was about 1) a sudden reduction of the proton beam momentum spread was not observed. First attempt to reach ordered proton beam at S-LSR in 2006 was not successive also, the ξ value in this experiment was about 0.4 [10].

EXPERIMENTS AT COSY

A few attempts for searching of the ordered proton beams were made at COSY ring [8]. The Schottky spectrum of proton beam was measured at injection energy (45 MeV) at different electron current values for different proton number in the beam. After injection the proton number was being reduced with introducing of the horizontal scraper that decreased the ring aperture and led to a fast proton loss.

The last measurements have shown that minimum value of the proton momentum spread can be reached at proton number below $1 \cdot 10^6$ protons and does not decrease below $2 \cdot 10^{-6}$ (Figure 1). The result does not depend actually on the feedback of high voltage power supply. The value ξ was about 0.5 in these experiments and the sudden reduction of the momentum spread was not observed.

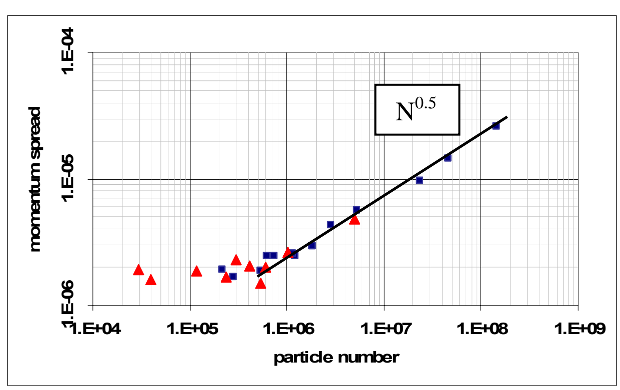

Figure 1: Momentum spread vs particle number: squares - fedback OFF, triangles – feedback ON. I_e=70 mA.

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HIGH-ENERGY COLLIDING CRYSTALS - A THEORETICAL STUDY*

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Abstract

Recent theoretical investigations of beam crystallization using computer modeling based on the method of molecular dynamics (MD) and analytical approach based on the phonon theory [1, 2, 3] are motivated by the study of colliding crystalline beams [4]. Analytical study of crystal stability in an alternating-gradient (AG) focusing ring was previously limited to the smooth approximation. In a typical ring, results obtained under such approximation largely agrees with that obtained with the MD simulation. However, as we explore ring lattices appropriate for beam crystallization at high energies (Lorentz factor γ much larger than the transverse tunes ν_x, ν_y) [5], this approximation fails. Here, we present a newly developed phonon theory in a time-dependent Hamiltonian system representing the actual AG-focusing ring and predict the stability of 1D crystals at high energies. Luminosity enhancement is illustrated in examples of rare-ion colliders based on ordered 1D strings of ions.

INTRODUCTION

It is well-known that to create a crystal, two conditions need to be satisfied. First, the storage ring must operate below the transition energy so that the particle motion is in a positive-mass regime. Second, resonances between the oscillations of a crystal and the AG-focusing lattice structure must be avoided so as to prevent heating and thus destruction of the crystal. This requires that the phase advance per lattice period must not exceed 127° (in practice not more than 90° [6, 7]).

In this work, we are motivated by the desire to collide one ion crystal with another or to collide an electron beam with an ion crystal. We desire to do so because in such colliders the usual beam-beam limit can be greatly exceeded. The usual limit is roughly a change in tune, $\Delta\nu_{bb}$ of less than 0.01, but for a crystal the limit (destruction of the crystal or an ordered avoidance of ions colliding) occurs for $\Delta\nu_{bb} \sim 1$. Since the luminosity varies as the square of $\Delta\nu_{bb}$, the enhancement is of the order of 10^4.

Colliders are of significant interests at high energies. So, the very first question we want to address is can we make crystals at high energy. We shall show that the answer is positive. Then we go on to explore lattices appropriate for high energy and, in particular, low-momentum-compaction compact lattices where the transverse tunes are relatively low, i.e., $\gamma_T^{-2} \ll \nu_x^{-2}$. These lattices can not be described by the smooth approximation based on which previous phonon theory was developed [3]. We develop a new formalism appropriate for studying 1D crystal stability in general AG lattices. In comparison, we study both 1D and multi-dimensional high-energy crystals using the MD method. Finally, we present examples of ion-ion and electron-ion colliders with 1D ordered ions.

* Work performed under the auspices of the Chinese Academy of Sciences and the U.S. Department of Energy.

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COLLIDING-BEAM HAMILTONIAN

The rest-frame motions of particles interacting through the Coulomb fields are governed by the Hamiltonian [8]

$$\begin{aligned} H &= \frac{1}{2}\sum_\ell \left(P_{x,\ell}^2 + P_{y,\ell}^2 + P_{z,\ell}^2\right) - \sum_\ell \gamma x_\ell P_{z,\ell} \\ &+\frac{1}{2}\sum_\ell \left(\nu_x^2 x_\ell^2 + \nu_y^2 y_\ell^2\right) + V_C + V_{bb}, \end{aligned} \tag{1}$$

where ν_x and ν_y are the transverse tunes, γ is the Lorentz factor, and the summation extends over all particles l in the beam traveling in one direction. In Eq. (1), all canonical variables are scaled as dimensionless by expressing the time, t, in units of $\rho/\beta\gamma c$, the spatial coordinates x, y, and z in units of the characteristic inter-particle distance $\xi \equiv \left(r_0\rho^2/\beta^2\gamma^2\right)^{1/3}$, and the energy in units of $\beta^2\gamma^2 e^2/\xi$, where βc is the velocity of the reference particle, r_0 is its classical radius, and ρ is the bending radius of the ring under the dipole magnetic field. The Coulomb potential is given by

$$V_C = \frac{1}{2}\sum_{\ell\neq m} \frac{1}{|\mathbf{r}_\ell - \mathbf{r}_m|}, \tag{2}$$

where

$$|\mathbf{r}_\ell - \mathbf{r}_m| = \left[(x_\ell - x_m)^2 + (y_\ell - y_m)^2 + (z_\ell - z_m)^2\right]^{1/2}.$$

Interaction with the colliding beam occurs once per lattice period in a very short time, so it is treated as a lumped kick in momentum. The kick on particle l can be represented by

$$V_{bb} = \sum_j \frac{(1+\beta^2)\gamma\xi}{\rho\sqrt{b_{min}^2 + b_{lj}^2}} \tag{3}$$

where $b_{lj}^2 = (x_l - x_j)^2 + (y_l - y_j)^2$ is the square of the transverse separation and $b_{min} = (1+\beta^2)r_0/(4\beta^2\gamma^2\xi)$ is the minimum separation in the beam rest frame, and the summation, j, is over all the particles in the opposite beam. We find that if the kick is large comparing with that of the crystalline space charge, then the ground state is two crystals separated in space at the crossing point; i.e. there are

INTRODUCTION TO THE SESSION ON LATTICE OPTIMIZATION FOR STOCHASTIC COOLING

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Abstract

Lattices that circumvent the 'mixing dilemma' for stochastic cooling have repeatedly been considered but were not adopted in the original design of existing cooling rings. Recently new interest has arisen to modify existing machines and to design future 'optimum mixing rings'. This talk is meant to summarize the advantages and disadvantages with the aim to introduce the discussion.

INTRODUCTION

For efficient stochastic cooling a small dispersion (η_{PK}) in the time of flight is desirable on the beam-path from pickup to kicker and a large dispersion (η_{KP}) on the way kicker to pickup. For a regular lattice one has (at least approximately)

$$\eta_{PK} = \eta_{KP} = \eta = \gamma_{tr}^{-2} - \gamma^{-2}$$

i.e. the local η-factors are equal to each other and given by the off-momentum factor of the whole ring. Then the spread of the flight times ΔT_{PK} (leading to undesired mixing) and ΔT_{KP} (desired mixing) are related by the corresponding lengths L_{PK} and L_{KP} along the circumference

$$\Delta T_{PK} = \eta\,(L_{PK}/\beta c)(\Delta p/p)$$
$$\Delta T_{KP} = \eta\,(L_{KP}/\beta c)(\Delta p/p)$$

Thus in the special case of a regular lattice and a cooling loop that cuts diagonally through the ring one has $\Delta T_{PK} = \Delta T_{KP}$. One can however design an 'asymmetric' (also called 'split ring-' or 'optimum mixing-') lattice [1], which combines sections with small local η in one part with large η-sections in the other part. In this way ΔT_{PK} and ΔT_{KP} can be adjusted independent of each other. In addition if the local momentum compaction factors $\alpha = \gamma_{tr}^{-2}$ are tuneable, then optimum mixing can be envisaged for different energies and one can even envisage η-tuning dynamically during cooling at fixed energy. The potentially large gain in cooling speed has to be balanced against difficulties such as complexity of the lattice, and 'single particle' and collective beam stability.

GAIN WITH AN ASYMMETRIC LATTICE

It can be concluded from [1] that by optimising the mixing one can gain a factor of ~3.4 in the initial cooling rate. This is when the system noise is negligible and the cooling loop cuts diagonally through the ring. To ease the discussion this 'standard case' will mostly be assumed in the following. For low energy rings where the distance L_{PK} can be made considerably smaller than L_{KP} and also for cooling systems with poor signal to noise ratio, the gain is less pronounced. On the other hand for momentum the cooling the improvement factor can be larger than 3.4 because with a regular lattice the mixing situation degrades as the Δp decreases. For momentum spread reduction by e^{-1} (e^{-2}) the overall improvement turns out to be 4.4 (5.8) in our standard case.

The gain concerns transverse cooling and longitudinal cooling by the "Palmer method" [2] where the momentum error is detected via the transverse displacement of the particle. For the filter method of Thorndahl [3] where the in essence the momentum error is deduced from the change in time of flight for a whole revolution, the "split lattice" is not helpful. However for the further momentum cooling methods, that use the time of flight over part of the circumference [4,5], the advantage remains. In this case one has to provide a well chosen finite, and if possible even tuneable η (instead of η=0) over the distance where the flight time is observed, and again large η for the section kicker to pickup. This can be achieved, at least in principle, by placing the observation interval partly into the low mixing and partly into the strong mixing branch of the lattice.

In summary: a factor of three to six in cooling speed can be gained with an optimum mixing lattice. The gain concerns transverse cooling as well as longitudinal cooling by the Palmer and local time of flight approaches but not the filter method.

LATTICE MODULES

Small η_{PK} requires a local momentum compaction $\alpha_{PK} = \gamma_{tr\,PK}^{-2}$ close to the beam's γ^{-2}. Big η_{KP} can be realized by large negative α_{KP}. There is a long list of references that deal with adjusting the momentum compaction (starting with the 1955 paper of Vladimirski and Tarasov [6] who proposed reverse bend dipoles to make the momentum compaction negative). The original aim was to avoid crossing of transition energy by making γ_{tr} large or even imaginary (α negative). In the 1970s the additional task of performing a jump of γ_{tr} without a too large change of the betatron tune [7-9] came up. The aim of the jump is to cross transition rapidly and this was achieved successfully, first in 1969 and operationally since 1974 in the CERN PS [7]. Later γ_{tr}-jumps were incorporated in the Booster and the Main Injector at

A SPLIT-FUNCTION LATTICE FOR STOCHASTIC COOLING *

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Abstract

Lattice for a 3-GeV cooler ring with split functions is presented. The ring consists of two half-rings of different properties: in one half-ring, the phase-slip factor is near-zero; in the other half-ring, the phase-slip factor is large. The near-zero phase slip minimizes the "bad mixing" between the stochastic-cooling pick-ups and kickers, while the high phase slip maximizes the "good mixing" between the kickers and the next-turn pick-ups.

INTRODUCTION

In Ref. [1] we reported the lattice design for rapid-cycling synchrotrons used to accelerate high-intensity proton beams to energy of tens of GeV for secondary beam production. After primary beam collision with a target, the secondary beam can be collected, cooled, accelerated or decelerated by ancillary synchrotrons (or cooler rings) for various applications [2, 3, 4].

To increase the efficiency of stochastic cooling in the cooler ring, the phase-slip factor between the cooling pick-ups and kickers shall be small to minimize the "bad mixing", and the phase-slip factor between the kickers and the next-turn pick-ups should be large to enhance the "good mixing" [5, 6]. In this paper, we present the preliminary lattice design for a 3-GeV cooler ring with split functions. The ring consists of two half-rings of different properties: in one half-ring, the phase-slip factor is near-zero; in the other half-ring, the phase-slip factor is large.

LATTICE LAYOUT AND FUNCTIONS

Two different lattice structures are adopted for each half of the split-function ring. We choose a normal FODO structure to achieve near-zero phase-slip factor in one half-ring, and choose Flexible Momentum Compaction (FMC) lattice to achieve large phase-slip factor in the other half-ring [7, 8, 9, 10]. The magnet layout of the ring is shown in Figure 1.

FMC Module Structure for Large Phase Slip

We use the FMC lattice to realize a small momentum compaction factor α_p, so that the absolute value $|\eta|$ of the phase-slip factor

$$\eta = \alpha_p - \frac{1}{\gamma^2} \quad (1)$$

is large. Here, γ is the Lorentz factor. For protons or anti-protons of 3-GeV kinetic energy, $\gamma = 4.2$.

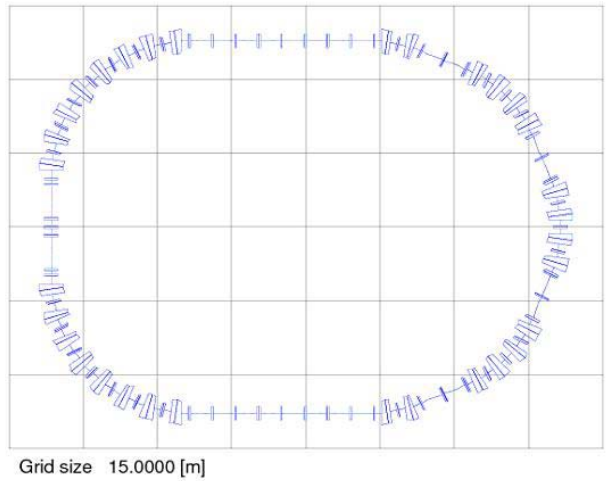

Figure 1: Main magnet layout of the cooler ring.

A FMC lattice without negative bending requires negative dispersion at locations of bending dipoles. Figure 2 shows the lattice module consisting of three FODO cells with missing dipole in the middle cell. The horizontal phase-advance of about 90° per cell excites dispersion oscillation so that high dispersion occurs at locations of missing dipoles.

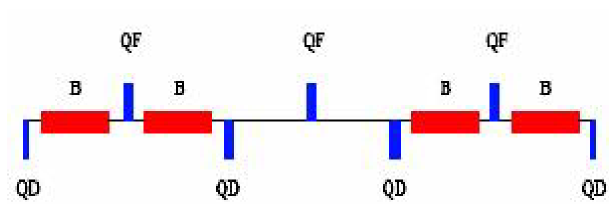

Figure 2: FMC module with missing dipoles.

The half-ring of large phase-slip factor is designed by using the modules shown in Figure 2. The lattice consists of four modules, as shown in the right-hand-side of Figure 1. The horizontal phase advance is near but not equal to 270° across each three-cell module. The horizontal phase advance across the four-module arc is exactly 6π, so that the dispersion is completely suppressed outside of the arc.

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ADVANCED HESR LATTICE WITH NON-SIMILAR ARCS FOR IMPROVED STOCHASTIC COOLING

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Abstract

The advanced HESR lattice with two arcs of identical layout and different slip factors has been developed. The conception of arcs with three families of quadrupoles makes it easy to adjust the imaginary transition energy in one arc and the real transition energy in another arc with the absolute value close to the beam energy in the whole required region from 3.0 GeV to 14 GeV. The arcs have the special feature that the high order non-linearities are fully compensated inside each arc, and therefore the dynamic aperture of the whole machine is conserved. We consider and compare two lattices with the same absolute value of transition energy: the current lattice with a negative momentum compaction factor in both arcs and correspondingly the lattice with negative and positive momentum compaction factors in different arcs. Simultaneously, we analyzed the 4- and 6- fold symmetry arc machine. Thus allows us to conclude that the 4-fold symmetry lattice is more suitable for acquiring slip factors. At the lowest energy 3 GeV, this is $\eta_{imag}/\eta_{real} \approx 4 \div 5$ in the imaginary and the real arc, respectively. For the higher beam energy this ratio is much bigger.

INTRODUCTION

To intensify the stochastic cooling process it is desirable to have the mixing factor between the pick-up and kicker as large as possible, and, on the contrary, in the case of mixing between the kicker and pick-up we should try to make it smaller. This option can be realized if the lattice has different local optical features between pick-up – kicker and kicker – pick-up.

The idea with different slip factors was first proposed by Möhl [1,2]. Later many authors tried to design such a lattice, for instance [3, 4]. However, this involved a more complicated lattice with a large number of quadrupole and sextupole families and the need to have different optical settings at different energies. As result the dynamic aperture in such lattices is usually unacceptably small, and it has very difficult tuning. Therefore the compromise was to scarify some of the desired re-randomization in order to avoid too much unwanted mixing. In the classical lattice the slip factors between pick-up and kicker η_{pk}, kicker and pick-up η_{kp} are similar, and by Möhl's definition [2] the mixing factors are approximately equal. In paper [5] the comprehensive analysis of the stochastic cooling was done in the HESR lattice with similar arcs and the negative momentum compaction factor ($\gamma_{tr} = 6.5i$) [6]. In this paper, we consider the advanced HESR lattice with different slip factors η_{pk} , η_{kp} in two arcs.

ARCS WITH DIFFERENT SLIP FACTOR

The HESR lattice consists of two arcs and two straight sections for the target and cooling facilities with a circumference ~500÷600 m. The arcs have 6-fold (or 4-fold) symmetry with superperiodicity S =6 (or 4). The phase advance per arc is $\nu_{x,y} = 5.0$ (or $\nu_{x,y} = 3.0$) in both planes. Each superperiod consists of three FODO cells with 4 superconducting bending magnets (B=3.6T) and superconducting quadrupoles with G<60T/m (see fig. 1).

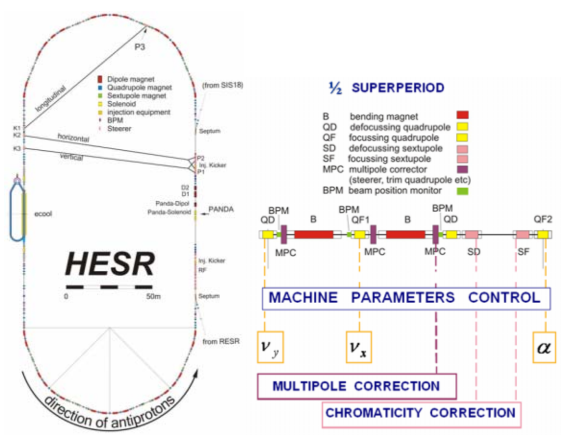

Figure 1: HESR layout and half super-period.

The momentum compaction factor is one of the most important characteristics of any accelerator, and defines its transition energy. The slip factor, $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ determined by transition γ_{tr} and current γ energy, should be as high as possible in order to increase the microwave stability threshold.

The most successful solution for the control of the momentum compaction factor has achieved in [7] by simultaneously correlated curvature and gradient modulations. This lattice was used in the following projects: the Moscow Kaon Factory, the TRIUMF Kaon Factory, the SSC Low Energy Booster, the CERN Neutrino Factory and in the Main Ring of the Japan Proton Accelerator Research Complex facility constructed now [8]. In the HESR lattice the same idea was used [6].

In the advanced HESR lattice for the stochastic cooling we propose modifying the conception to provide different slip factors in two arcs, but with conservation of sequence of all bending, focusing elements and drift between them.

LATTICE CONSIDERATIONS FOR THE COLLECTOR AND THE ACCUMULATOR RING OF THE FAIR PROJECT*

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Abstract

Two storage rings (Collector Ring (CR) and Recycled Experimental Storage Ring (RESR)) have been designed for efficient cooling, accumulation and deceleration of antiproton and rare isotopes beams at the FAIR project (Darmstadt, Germany). The large acceptance CR must provide efficient stochastic cooling of hot radioactive ions as well as antiproton beams. The RESR will be used as an accumulator of high intensity antiproton beams and as decelerator of rare isotopes. Different lattice structures have been considered in order to achieve good properties for the stochastic cooling and at the same time the maximum dynamic aperture. The structure of the ring lattices and its ion optical properties are described in this contribution. The beam dynamics stability and flexibility for operation in the different modes are discussed.

INTRODUCTION

Production, fast cooling, and accumulation of intense secondary beams, antiprotons and rare isotopes are key issues of the FAIR accelerator facility [1]. The rather hot secondary particles, rare isotopes coming out of the Super-FRS [2] or antiprotons coming out of the antiproton separator will be injected into the Collector Ring (CR), where fast RF bunch rotation and debunching followed by fast stochastic pre-cooling in all phase planes is foreseen. The envisaged total precooling times are 10 s for 3 GeV antiprotons and 1.5 s for fully stripped radioactive isotopes at 740 MeV/u. The CR will be operated at static magnetic field corresponding to the magnet rigidity of 13 Tm. After precooling in the CR the batches of 10^8 antiprotons will be delivered to the RESR, where the accumulation up the 10^{11} particles takes place during several hours at the beam energy of 3 GeV. Then accumulated antiprotons are either transferred to the HESR [3] for further acceleration/ deceleration or transferred to the NESR [4] for experiments with low energy antiprotons at FLAIR [5]. The accumulation scheme in the RESR foresees longitudinal stacking in combination with stochastic cooling. This will be achieved by a momentum stacking scheme. The RESR will be used also as the fast decelerator of rare isotopes from an energy of 740 MeV/u to energies between 100 MeV/u and 500 MeV/u within 1 s in order to be able to provide short-lived rare isotope beams at low energy for electron-ion collision experiments in the NESR. As an

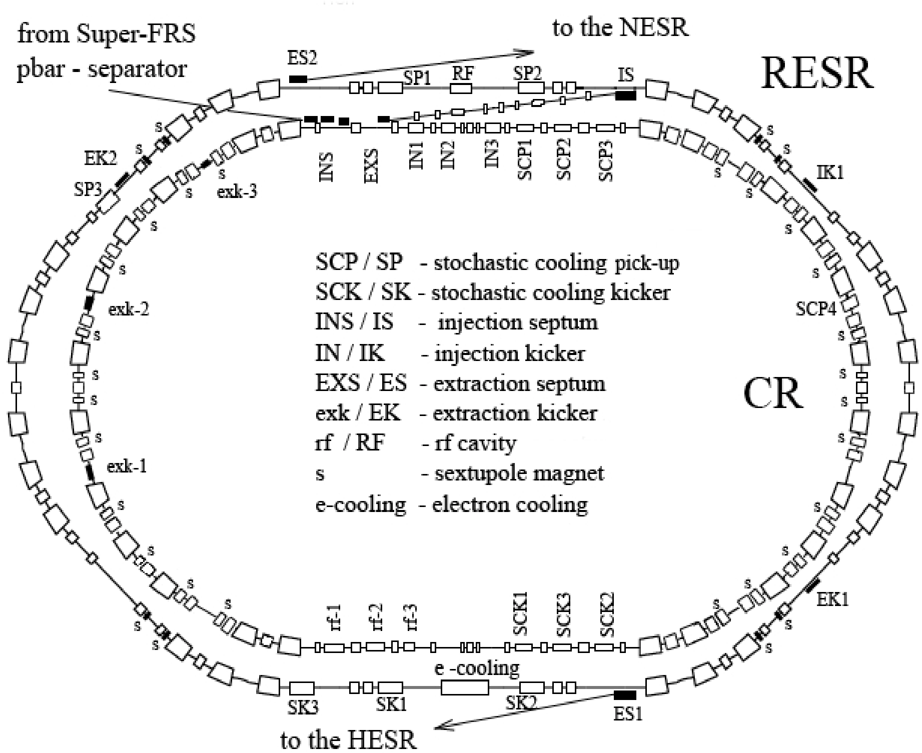

Figure 1: Layout of the CR – RESR rings.

* Work supported by EU design study (contract 515873 – DIRAC Secondary-Beams)

LATTICE OPTIMIZATION FOR THE STOCHASTIC COOLING IN THE ACCUMULATOR RING AT FERMILAB

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Abstract

New efforts are under way at Fermilab to increase the rate of antiproton production. This program includes optimization of machine optics in the Antiproton Accumulator to improve stochastic cooling. The new lattice was implemented in May of this year. Results are discussed, as well as some aspects of model development and lattice measurements.

INTRODUCTION

A broad effort to increase antiproton production for the Tevatron accelerator complex at Fermilab was initiated in 2005. The goal was to optimize the performance of all machines in the production chain: Booster, Main Injector, Debuncher, Accumulator and beam lines, in order to maximize the flux of antiprotons to the Accumulator. This effort succeeded in reaching the peak rate of 20 mA/hr in February 2006.

Further increase of the stacking rate was limited by the capability of the stacktail stochastic cooling system in the Accumulator such that any further increase in the incoming flux would not result in an appreciable increase in the antiproton accumulation rate.

The new effort that started after the shutdown of 2006 concentrated primarily on the stacktail cooling system. Subsequently, there was a further increase in the peak rate (23mA/hr in April, 2007), but more importantly, also the average stacking rate. This progress, combined with very successful improvements in the Fast Transfer Protocol [1], resulted in nearly doubled average weekly production of antiprotons for the Tevatron in March, 2007.

A significant outcome of this effort was the development of an integrated physics model of Accumulator stochastic cooling [2] that identified physical and technological limitations of the system, as well as the way to improve its performance. Here we discuss the optimization of the Accumulator lattice as suggested by this model, the implementation of the optimized lattice, and first results.

ACCUMULATOR LATTICE

The Accumulator has a periodicity of 3, and mirror symmetry in each of 3 sectors. It has 3 straight sections and 3 arcs. The Accumulator lattice functions are shown in Figure 1. Continuous injection of the antiproton beam from the Debuncher is maintained using stochastic stacking. Beam arrives at the injection orbit at an energy that is approximately 140 MeV higher than that of the circulating core beam. 100 msec later the injected beam is adiabatically bunched and RF displaced to the deposition orbit, which is approximately at the center of aperture. From this point it falls under the action of the stochastic cooling force (Stacktail system) that starts pushing it towards the main core beam (60 MeV below the central orbit energy). A 6D-cooling of the main core beam is performed by separate core stochastic cooling systems.

Large dispersion in the arcs (10m) separates the beam according to energy, whereas in straight sections beams of all energies are merged together and compressed in order to fit into the very narrow aperture of the stochastic cooling tanks. Beam focusing and flattop dispersion in the arcs are maintained by the quad quadruplets on each side of the small straight sections inside the arcs. These high dispersion sections house extraction/injection kickers and the momentum stochastic cooling pickups. In the long straight sections the dispersion is cancelled at the small bend magnets on each side. These low dispersion sections accommodate stochastic cooling kickers, RF cavities, a DCCT transformer, and dampers.

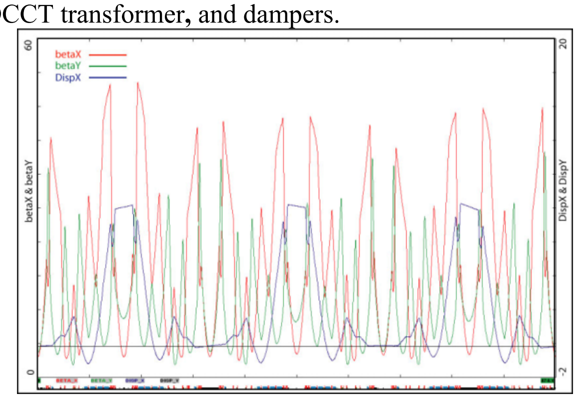

Figure 1: Accumulator Twiss-functions. Red and green traces show the horizontal and vertical beta-functions. The horizontal dispersion is shown with the blue trace.

It is important to keep dispersion as low as possible in the long straight sections. Any residual dispersion here would couple the longitudinal kicks of the stacktail kickers into the transverse dimensions causing transverse heating of the beam.

LATTICE OPTIMIZATION

Objectives

The main objective for the lattice optimization was to increase the slip factor (η). This would directly help the stack tail cooling as the maximum flux is proportional to η [2]:

$$J_{\max} = |\eta| T_0 W^2 x_d$$

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STATUS OF THE LEPTA PROJECT*

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Abstract

The Low Energy Positron Toroidal Accumulator (LEPTA) is under commissioning at JINR. The LEPTA facility is a small positron storage ring equipped with the electron cooling system. The project positron energy is of 4-10 keV. The main goal of the facility is to generate an intense flow of positronium atoms–the bound state of electron and positron. The focusing system of the LEPTA ring after solenoidal magnetic field remeasurement and correction has been tested with pulsed electron beam by elements. Some resonant effects of beam focusing have been observed.

The experiments aiming to increase the life time of the circulating electron beam and test the electron cooling elector beam are in progress. Construction of the pulsed injector of the low energy positrons is close to the completion.

The injector is based on ^{22}Na radioactive isotope and consists of the cryogenic positron source (CPS), the positron trap and the acceleration section. In the CPS positrons from the ^{22}Na tablet are moderated in the solid neon and transported into the trap, where they are accumulated during about 80 seconds. Then accumulated positrons are extracted by the pulsed electric field and accelerated in electrostatic field up to required energy (the injector as a whole is suspended at a positive potential that corresponds to required positron energy in the range of 4-10 keV). In injection pulse duration is about 300 nsec. The CPS has been tested at the low activity of isotope ^{22}Na tablet (100 MBq). The continuous positron beam with average energy of 1.2 eV and spectrum width of 1 eV has been obtained. The achieved moderation efficiency is about 1 %, that exceeds the level known from literature. The accumulation process in the positron trap was studied with electron flux. The life time of the electrons in the trap is 80 s and capture efficiency is about 0.4. The maximum number of the accumulated particles is $2 \cdot 10^8$ at the initial flux of $5 \cdot 10^6$ electrons per second.

LEPTA RING DEVELOPMENT

The Low Energy Particle Toroidal Accumulator (LEPTA) is designed for studies of particle beam dynamics in a storage ring with longitudinal magnetic field focusing (so called "stellatron"), application of circulating electron beam to electron cooling of antiprotons and ions in adjoining storage electron cooling of positrons and positronium in-flight generation.

For the first time a circulating electron beam was obtained in the LEPTA ring in September 2004 [1]. Experience of the LEPTA operation demonstrated main advantage of the focusing system using longitudinal magnetic field: long life-time of the circulating beam in a low energy range. At average pressure on the ring orbit of about 10^{-8} Torr the life-time of 4 keV electron beam of about 20 ms was achieved that is about 2 orders of magnitude longer than in usual strong focusing system. However, experiments showed a decrease of the beam life-time at increase of its energy. So at the beam energy of 10 keV the life time was not longer than 0.1 ms. The possible reasons of this effect are the magnetic field errors and resonant behaviors of the beam focusing.

Magnetic System Improvements

The first experiments were performed without correction coils at junctions of solenoid sections of different cross-section. Moreover, the initial design of reverse current bars didn't provide the necessary distribution of the current between bars that led to an additional imperfection of the magnetic field. During testing of the straight section the electron beam didn't pass through the vacuum chamber due to influence of the magnetic fields of the reverse bars, and they were disconnected from the power supply. Therefore the whole magnetic system of the LEPTA ring was assembled without the reverse current bars, as result a magnetization of magnetic shields took a place.

To improve the magnetic field quality the LEPTA was disassembled at the end of 2005. The longitudinal magnetic field was measured on the axis of the magnetic system with Hole probe. The measured imperfections of the magnetic field were on the level of about 20% at the junctions of solenoids (Figure 1). On the basis of the measurement results the correction coils were designed using SAM program. After installation of the coils the homogeneity of the magnetic filed was achieved on the level of 2.5%.

During the disassembling of the LEPTA ring the design of the reverse current bars was improved. The using of the reverse bars permitted to improve reproducibility of experimental results.

The LEPTA injection system consists of septum windings and electric kicker located inside a septum solenoid. The injection system testing with an electron beam showed that the magnetic axis doesn't coincide with the geometry axis of the vacuum chamber. The vacuum chamber diameter in the septum windings is 50 mm and one needs a high precise adjustment of the septum winding position inside the septum solenoid. In the initial design the possibility of the septum winding displacement was restricted. The horizontal size of the septum windings was decreased by 36 mm that permitted to shift them by

* The work is supported by RFBR grant # 05-02-16320.
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OPTICAL STOCHASTIC COOLING EXPERIMENT AT THE MIT-BATES SOUTH HALL RING

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Abstract

Optical stochastic cooling (OSC) is a technique formulated for very fast cooling of charged particle beams of high energy and high brightness which has yet to be experimentally realized. An experiment to demonstrate the principle of OSC has been designed using electrons at 300 MeV in the MIT-Bates South Hall Ring (SHR). The SHR is a particularly suitable location for studying OSC physics due to its layout, energy range, and availability for dedicated use. The experiment will operate the SHR in a configuration designed for simultaneous transverse and longitudinal cooling. The cooling apparatus including a magnetic chicane, undulator system, and optical amplifier has been designed for compatibility with existing technology. Such studies are a necessary prerequisite to implementation in a high-energy collider environment.

INTRODUCTION

Many of the proven techniques for beam cooling diminish in effectiveness for beams of high energy and high brightness. Stochastic cooling [1], a beam-based feed-forward technique for cooling of stored particle beams, encounters limits on the cooling time of very intense bunched beams due to the bandwidth of RF amplification systems. The use of higher bandwidth feed-forward systems would effectively divide bunches into a larger number of samples with fewer particles in each to be cooled, thereby allowing for more rapid cooling.

The yet-to-be-demonstrated technique of optical stochastic cooling [2] combines aspects of microwave stochastic cooling with techniques developed for coherent radiation in light sources. Based on an ultra-broadband feed-forward system, OSC would significantly reduce the bandwidth-limited cooling time present for microwave stochastic cooling. The transit-time method of OSC, formulated by Zolotorev and Zholents [3], would provide momentum kicks to a stored charged particle beam via interaction with its own amplified radiation while traversing a magnetic undulator for reduction of the emittance. Successful implementation of the OSC technique is expected to yield fast cooling of protons/antiprotons and heavy ions at energies in excess of several hundred GeV per nucleon.

The OSC technique, shown schematically in Figure 1, entails construction of a nearly isochronous magnetic delay line for charged particles, installation of two undulators, development of a high gain optical amplifier, and use of fast diagnostic and feedback systems. Estimates of OSC times and design parameters have been made for existing facilities, including RHIC [4], and the technique has been considered for future facilities such as a muon collider.

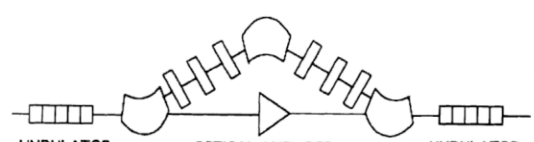

Figure 1: Schematic of an optical stochastic cooling insertion in a storage ring.

There are significant technical challenges in producing a working OSC system. The costs and time required for implementation of such systems in a new or existing high-energy hadron machine will be high. For hadrons or ions, presently achievable optical amplifier output power would necessitate operation of an OSC system well below optimal gain, thereby limiting the achievable cooling time. The development of necessary OSC diagnostic

ANALYSIS OF RESONANCES INDUCED BY THE SIS-18 ELECTRON COOLER*

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Abstract

Besides the beam cooling effect, an electron cooler also acts as a non-linear optical element. This may lead to the excitation of resonances possibly resulting in an increase of the beam emittance. The aim of this work is the calculation of resonances driven by the electron space charge field in the cooler installed in the SIS heavy ion synchrotron at GSI Darmstadt. For our calculations, we used a numerical model consisting of a rotation matrix representing the ideal lattice together with a non-linear transverse kick element representing the electron cooler. Within this model, we studied the non-linear tune shift and the dominant resonance lines resulting from the interaction with the cooler.

INTRODUCTION

The space charge field in an electron cooler acts as a non-linear optical element in the lattice of a storage ring. This may lead to the excitation of additional ring resonances. Depending on the machine working point these resonances cause emittance growth and an effective heating of the beam, as it was observed e.g. in the CELSIUS cooler storage ring [1].

Electron cooling at medium energies will play an essential role in the proposed FAIR storage rings [2]. Electron cooling is already available to improve the beam quality of the intense ion beams at low energy in the existing SIS synchrotron. At low or medium beam energies, the transverse tune shift due to the direct space charge force plays an important role. The resonances excited by the non-linear space charge field of the cooler electron can potentially limit the reachable beam intensity and quality.

In this work, the excitation of resonances driven by an electron cooler is calculated within a simplified numerical model. The electron cooler is represented through a non-linear kick element in an otherwise ideal lattice. This enabled us to study only the resonances driven by the electron cooler. The MAD-X code [3] was used to perform resonance scans over a large working point area. The study is performed for parameters relevant to the electron cooler in the the SIS heavy ion synchrotron at GSI Darmstadt. This theoretical study provides the necessary information for dedicated measurements of cooler induced resonances and effects in SIS.

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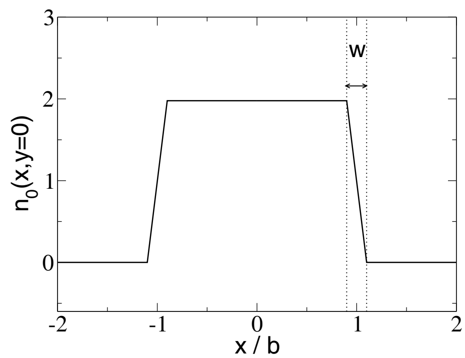

Figure 1: Normalised charge density profile used for the electron beam as provided by the beambeam element of MAD-X [3] as a function of x for $y = 0$. An edge layer with a width $w = 0.01\,b$ was used in the calculations.

PARTICLE TRACKING MODEL

In our calculations we used a simple model consisting of a rotation matrix providing the phase advance of the lattice of SIS–18 and a non-linear transverse kick introducing the force of the electron cooler in the thin lens approximation. The coordinates of a particle after the $(n+1)$-st revolution are calculated from those of the n-th revolution by

$$\begin{pmatrix} z_{n+1} \\ z'_{n+1} \end{pmatrix} = \begin{pmatrix} \cos 2\pi\nu_z & \hat{\beta}_z \sin 2\pi\nu_z \\ -\frac{1}{\hat{\beta}_z}\sin 2\pi\nu_z & \cos 2\pi\nu_z \end{pmatrix} \times \begin{pmatrix} z_n \\ z'_n + \Delta z'(x_n, y_n) \end{pmatrix} \quad (1)$$

with $z = x, y$. Here, ν_z is the bare tune of the lattice, $\hat{\beta}_z$ is the unperturbed beta function in z direction at the location of the electron cooler, and

$$\Delta z'(x,y) = \frac{qq'N'}{2\pi\varepsilon_0 m_0 c^2 \beta_0^2 \gamma_0^3}\frac{z}{R^2}\int_0^R \mathrm{d}r\, r\, n_0(r) \quad (2)$$

with $R = \sqrt{x^2+y^2}$ is the transverse momentum kick depending on both spatial direction x, y. Here,

$$N' = \left|\frac{I_e L_{\mathrm{cool}}}{q'\beta_0 c}\right| \quad (3)$$

is the number of electrons in the electron cooler. q, q' are the charges of the particles in the beam considered and in the electron beam, i.e. it is $q' = -e$. n_0 is the normalised radial current distribution in the electron beam.

The electron beam of an electron cooler usually has a radial shape with a constant current density in the centre

BUNCHED BEAM STOCHASTIC COOLING SIMULATIONS AND COMPARISON WITH DATA*

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Abstract

With the experimental success of longitudinal, bunched beam stochastic cooling in RHIC [1] it is natural to ask whether the system works as well as it might and whether upgrades or new systems are warranted. A computer code, very similar to those used for multi-particle coherent instability simulations, has been written and is being used to address these questions.

INTRODUCTION

A stochastic cooling system is a wide band feedback loop[2, 3]. A pickup signal is processed, amplified and used to drive a kicker. The difference between coasting and bunch beam stochastic cooling theory is similar to the difference between coasting and bunched beam instability theory. While the former is quite simple, the latter is still evolving.

A theory of bunched beam cooling was developed in the early eighties [4, 5, 6]. As with bunched beam stability theory, there are parameter regimes in which accurate, closed form results can be obtained. In other regimes the bunched beams act like coasting beams [7, 8]. These sort of considerations were used in the design of the RHIC longitudinal cooling system, which is now operational. Uncooled and cooled bunches are shown in Figures 1 and 2, respectively. While the general beam parameters are in line with expectations, we know of no theory capable of explaining the detailed evolution of the cooled beam. Simulations of proton test bunch cooling were fairly successful [9]. We have generalized to code to include intrabeam scattering (IBS) and transverse cooling. This note gives a detailed account of the algorithms and compares data with simulation.

Table 1: Machine and Beam Parameters for Gold

parameter	value
h=360 voltage	300 kV
h=2520 voltage	3 MV
initial FWHM bunch length	3 ns
particles/bunch	10^9
initial emittance	$15\pi\mu$m
betatron tunes	$Q_x = 28.2, Q_y = 27.2$
Lorentz factor	107
circumference	3834 m
transition gamma	22.89

* Work performed under the auspices of the United States Department of Energy.

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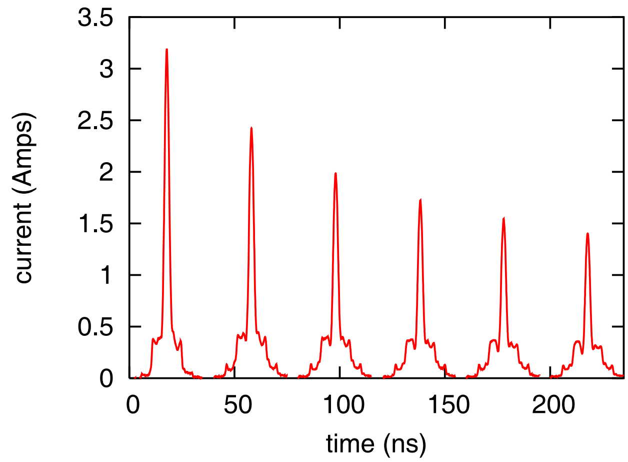

Figure 1: Evolution of the average bunch profile over a five hour RHIC store with gold beam and no cooling. Initial conditions are shown on the left and each trace to the right is one hour later.

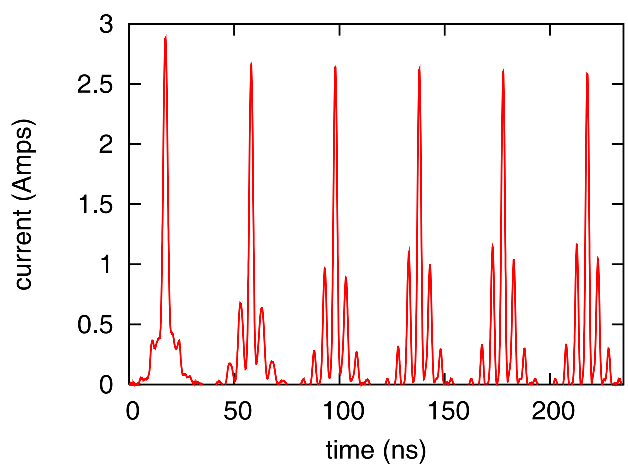

Figure 2: Evolution of the average bunch profile over a five hour RHIC store with gold beam and good longitudinal cooling. Initial conditions are shown on the left and each trace to the right is one hour later.

SIMULATIONS

The code involves single particle dynamics and multiparticle kicks. First consider the single particle motion. The longitudinal update for a fraction of a turn χ is

$$\bar{\epsilon} = \epsilon + \chi \frac{q}{mc^2} V_{rf}(\tau) \quad (1)$$

$$\bar{\tau} = \tau + \chi \frac{T_0 \eta}{\beta^2 \gamma_0} \bar{\epsilon} \quad (2)$$

SIMULATION OF COOLING MECHANISMS OF HIGHLY-CHARGED IONS IN THE HITRAP COOLER TRAP

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Abstract

The use of heavy and highly-charged ions gives access to unprecedented investigations in the field of atomic physics. The HITRAP facility at GSI will be able to slow down and cool ion species up to bare uranium to the temperature of 4 K. The Cooler Trap, a confinement device for large numbers of particles, is designed to store and cool bunches of 10^5 highly-charged ions. Electron cooling with 10^{10} simultaneously trapped electrons and successive resistive cooling lead to extraction in both pulsed and quasi-continuous mode with a duty cycle of 10 s. After an introduction to HITRAP and overview of the setup, the dynamics of the processes investigated via a Particle-In-Cell (PIC) code are shown, with emphasis on the peculiarities of our case, namely the space charge effects and the modelling of the cooling techniques.

INTRODUCTION - SCIENTIFIC GOALS

At the HITRAP facility in GSI, a series of precision experiments will be possible via the use of heavy and highly-charged ions; species up to U^{92+} can be produced and delivered by the accelerator complex, and radioactive nuclides can be provided by the Fragment Separator (FRS). Heavy atoms that have been previously stripped of all or most of their electrons allow indeed studies on residual electrons in the so-called high-field regime, where tests on the theory of quantum electrodynamics (QED) can reach new levels of accuracy; among these experiments we can mention the *g-factor* measurement of the bound electron or the width of the ground-state hyperfine splitting in H-like ions. Other planned experiments include nuclear mass measurements, collision studies and more [1].

The HITRAP setup will also be part of the Facility for Low-energy Antiproton and Ion Research (FLAIR); there $\overline{p}$ will allow fundamental symmetry tests.

THE HITRAP FACILITY

The HITRAP facility is located in the Reinjection Tunnel between the Esperimental Storage Ring (ESR) and the Heavy Ion Synchrotron (SIS); ions are accelerated and partially stripped in the Universal Linear Accelerator (UNILAC) and taken up to 400 MeV/u in the SIS. The particles lose all electrons on a thin target; deceleration to 4 MeV/u in the ESR allows their injection in the HITRAP decelerating section, where a double-drift buncher shapes them for improved acceptance into a IH-Linac operated in deceleration mode. A RadioFrequency Quadrupole (RFQ) structure further slows the bunch from 0.5 Mev/u to 6 KeV/u, after which the ions can be stored in the Cooler Trap that cools them down to 4 K and ejects them in pulsed or quasi-continuous mode. A bending magnet and a vertical beam line guide the beam to the platform on top of the tunnel, where a distribution beam line delivers the cold ions to the various experiments.

THE COOLER TRAP

The Cooler Trap, currently in the construction stage, is the element where the ion beam is not only decelerated but also cooled and shaped in such a form to fit the experiments' requirements. It consists of a cryogenic, cylindrical Penning trap, i.e. a series of cylindrical electrodes immersed in a longitudinally directed magnetic field provided by a superconducting solenoid. The latter, with a strength of 6 T and a maximum inhomogeneity below 0.1% over a volume of 10-mm diameter and 400-mm length, allows for the radial confinement via the Lorentz' $\vec{v} \times \vec{B}$ force. The longitudinal trapping of the 10^5 ions is obtained by lifting the last electrode's potential, so that the bunch is reflected back at the end of the trap. If the first electrode's potential is raised before the ions reach the entrance, the bunch is trapped. The energy and length of the incoming bunch (6 KeV/u $\approx$ 15.5 KV/q, $\approx$ 400 ns) dictate the length of the electrode stack (400 mm excluding the outermost trapping electrodes) and the trapping potential, that is about 20 KV.

The manipulation of the potential of the 21 equally-shaped internal electrodes gives the possibility to create nested traps where simultaneous confinement of ions and electrons is achieved. Indeed, as many as 10^{10} electrons, created in a pulsed laser source located in the downstream beam line, are injected in order to perform electron cooling (see Fig. 1). Due to the presence of a strong magnetic field, the electrons maintain the low temperature of the cryogenic environment (4 K) losing energy via synchrotron radiation with a time constant $\tau_s = 3\pi\varepsilon_o\frac{m^3c^3}{e^4B^2} \approx 0.1$ s [2]. The axial bounce of the ion cloud through the electron-filled regions lowers the ions' energy via Coulomb collision [4]; to avoid radiative recombination as the electrons' and ions' energies get closer, the process must be stopped at some point and a different cooling scheme has to be introduced:

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COMMISSIONING AND PERFORMANCE OF LEIR

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on behalf of the LEIR and I-LHC teams

Abstract

The Low Energy Ion Ring (LEIR) is a key element of the LHC ion injector chain. Under fast electron cooling, several long pulses from the ion Linac 3 are accumulated and cooled, and transformed into short bunches with a density sufficient for the needs of the LHC. Experience from LEIR commissioning and the first runs in autumn 2006 and summer 2007 to provide the so-called "early LHC ion beam" for setting-up in the PS and the SPS will be reported. Studies in view of the beam needed for nominal LHC ion operation are carried out in parallel to operation with lower priority.

INTRODUCTION

The LHC [1,2], presently under construction at CERN will, in addition to proton operation, provide ion collisions for physics experiments. For the moment, only lead ion operation is part of the approved program, but other species may be used as well. The ion accelerator chain existing before the LHC era was not capable to provide the ion beams needed for the LHC.

Thus, fundamental upgrades of the CERN ion accelerator complex, based on ion accumulation experiments [3] carried out with LEAR, had to be implemented. The resulting ion accelerator chain is depicted in Fig. 1 and nominal values for some key parameters are listed in Tab. 1.

Since nominal LHC ion operation is very demanding for both the LHC and the injector chain, first LHC ion operation will take place with a lower luminosity and less bunches using the so-called “early scheme” [3-5]. In this scheme, every LEIR/PS pulse will provide only one LHC bunch, the SPS will accumulate only up to four batches and the LHC will be filled with 62 bunches per ring.

OVERVIEW OF LEIR

The most fundamental upgrade of the CERN ion accelerator chain [4-6] for the LHC was the addition of the Low Energy Ion Ring LEIR (reconstructed and upgraded LEAR). The role of this small accumulator ring, equipped with a new state-of-the-art electron cooler (constructed in the frame of a collaboration by BINP), is to convert several 200 µs long Linac3 pulses into short high brilliance bunches needed for LHC ion operation.

Fig.2 shows the LEIR ring after installation. A typical 3.6 s LEIR cycle needed for nominal operation and producing the beam intensity for four LHC bunches is shown in Fig. 3. On an accumulation plateau several Pb^{54+} pulses from Linac3 are accumulated alternating:

- An elaborate multiturn injection of the 200 µs long Linac pulses with stacking in momentum and in both transverse phase spaces [4]. For this injection scheme, momentum ramping of the Linac3 (mean beam energy increases by ~4 10^{-3} during the duration of the Linac3 pulse) is required as well as a large dispersion at the injection and an inclined injection septum.
- Fast (in 200 ms to 400 ms) electron cooling [4,7,8] .

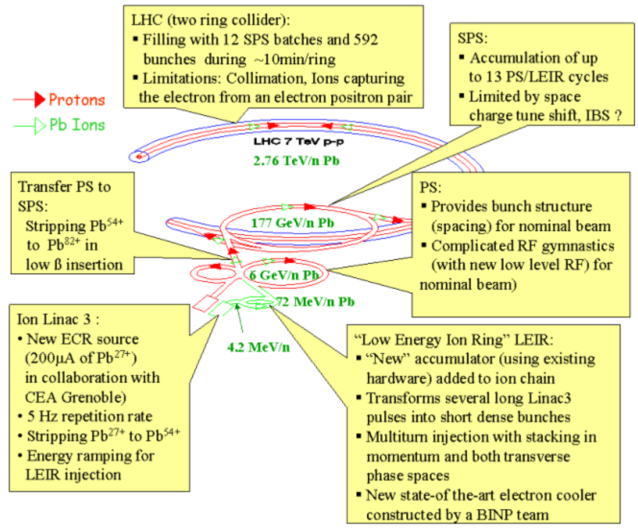

Figure 1: Overview of the LHC ion injector chain.

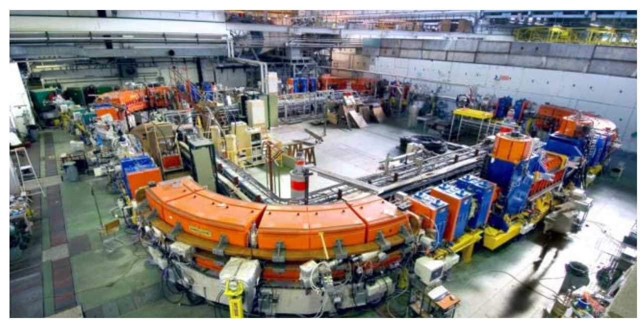

Figure 2: LEIR ring after completion of installation.

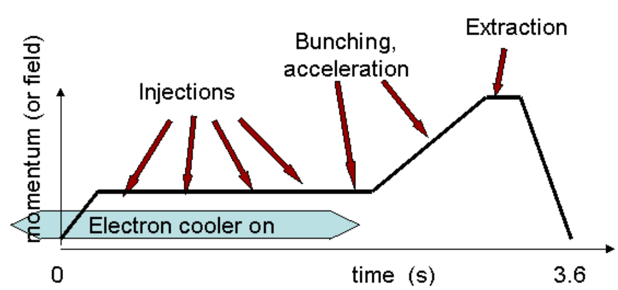

Figure 3: Nominal LEIR cycle.

After accumulation of a sufficient intensity, the beam is bunched with harmonic number two and accelerated during about 1 s. Finally the two bunches, each one corresponding to two LHC bunches, are ejected and

ELECTRON COOLING EXPERIMENTS AT S-LSR

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Abstract

The electron cooler for S-LSR was designed to maximize the cooling length in the limited drift space of the ring. The effective cooling length is 0.44 m, while the total length of the cooler is 1.63 m. The one-dimensional ordering of protons is one of the subjects of S-LSR. Abrupt jumps in the momentum spread and the Schottky noise power have been observed for protons at a particle number of around 2000. The beam temperature was 0.17 meV and 1 meV in the longitudinal and transverse directions at the transition, respectively. The normalized transition temperature of protons is close to those of heavy ions at ESR. The lowest momentum spread below the transition was 1.4×10^{-6}, which corresponded to the longitudinal beam temperature of 26 μeV (0.3 K). It is close to the longitudinal electron temperature.

INTRODUCTION

S-LSR is a compact ion storage/cooler ring at Kyoto University to study physics of cooled ion beams and applications of beam cooling. S-LSR has an electron beam cooler and a laser cooling system. The laser cooling system has been developed for the study of the crystalline beam [1] and the laser cooling experiments have been carried out since 2007 [2].

The commissioning of the electron cooling was started from October 2005. The 7 MeV proton beam from the linac was used and the first cooling was observed on October 31. The proton and electron beam current were 50 μA and 60 mA, respectively. The initial momentum spread of 4×10^{-3} was reduced to 2×10^{-4} after the cooling. The initial beam size of 26 mm was reduced to 1.2 mm.

In 2006 and 2007, the following experiments have been carried out using the electron cooling:

- Development of the induction accelerator sweep cooling for the hot ion beam with large momentum spread [3].
- Short pulse generation using the electron cooling and the RF phase rotation [4].
- Study of the coherent instability of the electron cooled proton beam with high intensity and the damping by the feedback system [5].
- One-dimensional ordering experiments of electron cooled protons [6, 7].

In this paper, the electron cooler at S-LSR is introduced at first. Figure 1 shows the cross-sectional view of the electron cooler and table 1 shows the main parameters of S-LSR and the electron cooler. Then, the results of the one-dimensional ordering of protons are mainly reported.

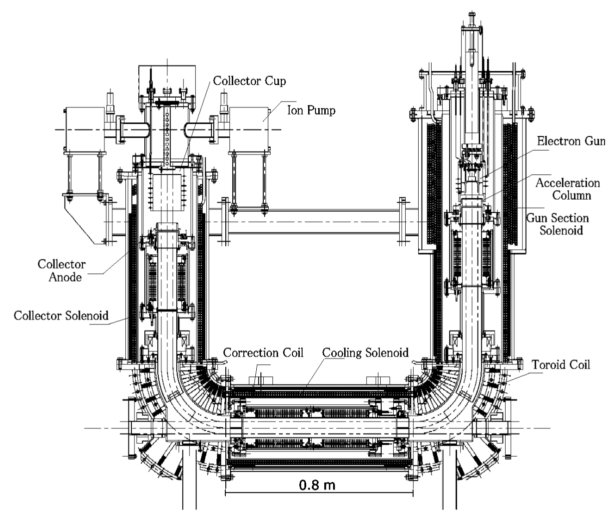

Figure 1: Cross-sectional view of the electron cooler at S-LSR.

Table 1: Main parameters of S-LSR and the electron cooler.

Ring	
Circumference	22.557 m
Length of Drift Space	1.86 m
Number of Periods	6
Average Vacuum Pressure	1×10^{-8} Pa
Electron Cooler	
Maximum Electron Energy	5 keV
Electron Beam Current	25 mA - 300 mA
Beam Diameter	50 mm
Solenoid Field in the central	500 Gauss
Expansion Factor	3
Cooler Solenoid Length	800 mm
Effective Cooling Length	440 mm

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PROGRESS WITH TEVATRON ELECTRON LENSES*

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Abstract

The Tevatron Electron Lenses (TELs) were initially proposed for compensation of long-range and head-on beam-beam effects of the antiproton beam at 980 GeV. Recent advances in antiproton production and electron cooling led to a significant increase of antiproton beam brightness. It is now the proton beam that suffers most from the beam-beam effects. Discussed are the motivation for beam-beam compensation, the concept of Electron Lenses and commissioning of the second TEL in 2006. The latest experimental results obtained during studies with high energy proton beam are presented along with the LIFETRAC simulation results.

MOTIVATION

The luminosity of storage ring colliders is limited by the effects of electromagnetic (EM) interaction of one beam with another which leads to a blowup of beam sizes, a reduction of beam intensities and unacceptable background rates in HEP detectors. This beam-beam interaction is described by a beam-beam parameter $\xi \equiv r_0 N/4\pi\varepsilon$, where $r_0 = e^2/mc^2$ denotes the particle's classical radius, N is the number of particles in the opposing bunch and ε is its rms normalized emittance. This dimensionless parameter is equal to the tune shift of the core particles caused by beam-beam forces. While the core particles undergo a significant tune shift, halo particles with large oscillation amplitudes experience negligible tune shift. The EM forces drive nonlinear resonances which can result in instability of particle motion and loss. The beam-beam limit in modern hadron colliders is $\xi^{max} \cdot N_{IP} \approx 0.01$ - 0.02 (N_{IP} is the number of IPs), while it can exceed $\xi^{max} \cdot N_{IP} \approx 0.1$ in high energy electron-positron colliders [1].

Operation with a greater number of bunches allows a proportional increase of luminosity but requires careful spatial separation of two beams everywhere except at the main IPs. Long-range EM interaction of separated beams is also nonlinear and also limits the collider performance. These long-range effects usually vary from bunch to bunch, making their treatment even more difficult.

One of the most detrimental effects of the beam-beam interaction in the Tevatron is the significant loss rate of protons due to their interaction with the antiproton bunches in the main IPs (B0 and D0) and due to numerous long-range interactions [2]. The effect is especially large at the beginning of HEP stores when the positive proton tune shift due to focusing by antiprotons at the main IPs can reach $2\xi^p = 0.016$. Figure 1 shows a typical bunch-to-bunch distribution of proton loss rates at the beginning of an HEP store.

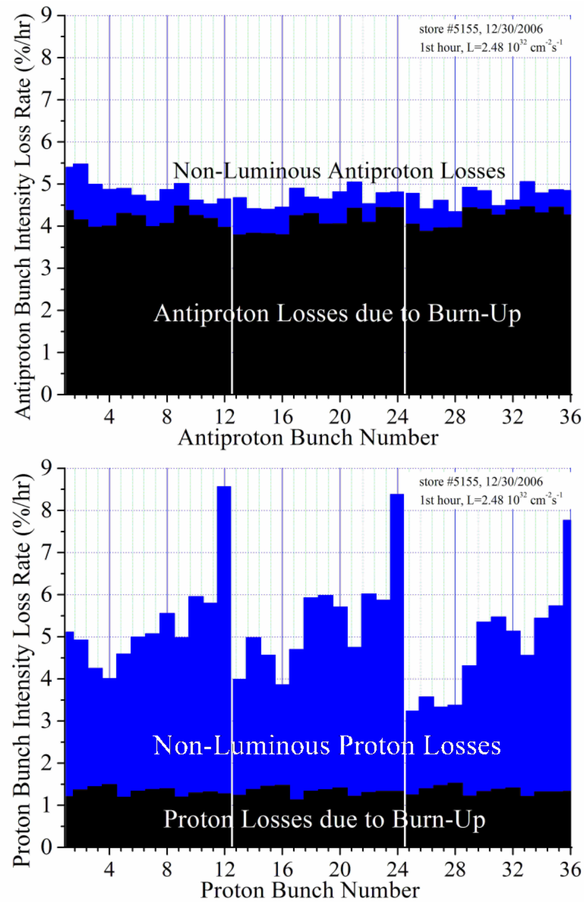

Figure 1: Proton bunch intensity loss rates at the beginning of store #5155.

In the Tevatron, 36 bunches in each beam are arranged in 3 trains of 12 bunches separated by 2.6 μs long abort gaps. Proton bunches P12, P24, and P36 at the end of each bunch train typically lose about 9 % of their intensity per hour while other bunches lose only (4-6) %/hr. In the beginning of high luminosity stores these losses are a very significant part of the total luminosity decay rate of about 20 % per hour. The losses due to burn-up at the two main IPs are much smaller (1.1–1.5%/hr). Figure 1 shows large bunch-to-bunch variations in the beam-beam induced proton losses within each bunch train but similar rates for equivalent bunches in different trains, e.g. P12, P24, and P36. Figure 2 shows the vertical proton bunch-by-bunch tunes about six hours into a store. Proton bunches at the end of each train have the lowest vertical tune due to the missing long-range collisions in the proximity of the main IPs.

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USE OF AN ELECTRON BEAM FOR STOCHASTIC COOLING*

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Abstract

Microwave instability of an electron beam can be used for a multiple increase in the collective response for the perturbation caused by a particle of a co-moving ion beam, i.e. for enhancement of friction force in electron cooling method. The low scale (hundreds GHz and higher frequency range) space charge or FEL type instabilities can be produced (depending on conditions) by introducing an alternating magnetic field along the electron beam path. Beams' optics and noise conditioning for obtaining a maximal cooling effect and related limitations will be discussed. The method promises to increase by a few orders of magnitude the cooling rate for heavy particle beams with a large emittance for a wide energy range with respect to either electron and conventional stochastic cooling.

INTRODUCTION

The high-energy cooling plays a critical role in raising the efficiency of existing and future projects of hadron and lepton-hadron colliders: RHIC with heavy ion and polarized proton-proton colliding beams [1] and electron-ion collider eRHIC [2,3] of Brookhaven National Laboratory; ELIC [2,4] of Jefferson Laboratory; the proton-antiproton collider of Fermilab; and, perhaps, even the LHC of CERN.

Electron cooling proved to be very efficient method of cooling intense hadron- and ion-beams at low and medium energies [5]. The electron cooler of 9 GeV antiprotons in the Fermilab recycler represents state-of-the-art technology [6] and already led to significant increase luminosity in the proton-antiproton collider. Development of the ERL-based electron cooler at BNL promises effective cooling of gold ions with energies of 100 GeV per nucleon [7].

Realization of effective cooling in hadron (proton, antiproton) colliders of higher energies requires new conceptual solutions and techniques. Currently, an ERL-based EC scheme is under study which includes a circulator-cooler ring as a way to reduce the necessary electron current delivered by an ERL [8]. It should be noted, that the ERL-based electron cooling should be operated in staged regime (cooling starts at an intermediate energy e.g. injection energy of a collider ring) to be continued in the collider mode after acceleration. Finally, for best performance of a collider an initial transverse stochastic cooling of a coasted beam should precede use of EC [8].

An extremely challenging character of high energy cooling projects for hadron beams quests to search for possible ways to enhance efficiency of existing cooling methods or invent new techniques.

It was noted by earlier works [9], that potential of an electron beam-based cooling techniques may not be exhausted by the classical electron cooling scheme. Namely, the idea of *coherent electron cooling* (CEC) encompasses various possibilities of using collective instabilities in the electron beam to enhance the effectiveness of interaction between hadrons and electrons. CEC combines the advantages of two existing methods, electron cooling (microscopic scale of interaction between ion beam and cooling media, the electron beam) and stochastic cooling (amplification of media response to ions). It is based on use of a co-transported electron beam in three roles – a receiver, amplifier and kicker. Such principle seems flexible for implementation in hadron facilities of various applications in a wide energy range from non-relativistic beams to beams in colliders.

Below we will review the CEC principles and limitations referring to earlier works [9] as well as recent work [10] which is specifically devoted to development of CEC system for colliding beams by use of SASE FEL as amplifier.

PREREQUISITES OF CEC

A General CEC Idea

The electron cooling-a method of damping the angular and energy spread of the beams of heavy charged particles- is, as known, [11-13] that the beam in the straight section of an orbit is passing through an accompanying electron beam having lower temperature. In this case, heavy particles are decelerated with respect to electron medium similarly to that as is occurred in usual plasma at Ti >Te .

A principle suggested here of an amplification is naturally inserted into logical scheme of the method. On the cooling section such conditions should be arranged that the moving "electron plasma" should become unstable in the given range of the wave lengths. Then, an excitation caused by an input ion will be transferred by electron flux developing exponentially independent of the ion; at the output from electron beam the ion acquires the momentum correlated with its input velocity (Figure 1).

A firm correlation between input and output signals is maintaned unless the excitation reaches the nonlinear regime, i.e. the density modulation within the required scale of distances remains relatively small. It is, of course, necessary to provide the optimum output phase relations in the position, and velocity of an ion with respect to electron "avalanche" produced by the ion. Such a task is facilitated by the motion of ions and electrons in the fields

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ELECTRON BEAMS AS STOCHASTIC 3D KICKERS

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Abstract

This article describes an idea combining electron and stochastic cooling in one device. The amplified signal of displacements of the ion from the pick-up electrode is applied to the control electrode of an electron gun. Thus, a wave of space charge in the electron beam is induced. This wave propagates with the electron beam to the cooling section. The space charge of the electron beam acts on the ion beam producing a kick. The effectiveness of the amplification can be improved with using a structure similar to a traveling-wave tube.

INTRODUCTION

Stochastic cooling is a typical feedback systems used in accelerators [1]. A displacement of a particle induces a signal on a pickup electrode. This signal from the pickup is amplified and applied to the kicker device acting on the particle. With a proper choice of the feedback parameters the oscillations of the target particle are damped. Other particles of the beam cause a parasitic noise and limit the maximum cooling rate. A typical kicker device is an electrodynamics structure like a strip line or slow-wave array. The bandwidth of the system is about 1 GHz with a power of few kW.

Experiments [2-4] with electron beams show that the space-charge field can be an effective tool for impacting on an ion. The space charge of the electron beam can be used as the kicker in stochastic cooling systems. A sketch of such a device is shown in Figure 1. The signal from the pick-up or array of pick-ups is applied to the amplifier system. The signal from the amplifier is applied to the control system of the electron gun which produces a fluctuation of the electron current of required form. After that the electron beam is accelerated and the space charge fluctuation proceeds to the cooling section. Here the fluctuation moving together with an ion acts via the electrical field of the space charge.

The effective kicker device should satisfy many requirements. The rate of cooling depends on the system bandwidth. The bandwidth is limited by its highest frequency. Aside from technological issues, there is a limit of the typical aperture of the kicker. Problems appear when the kicker aperture becomes comparable to the wavelength at high frequencies when the particle with $\beta<1$ does not have time to fly through the kicker during the impulse. Most of the problems are easily solved in high-energy accelerators but for low and medium energy range new criteria may be useful. The physical size of the electron kicker is small. The size may be easily changed in proportion to the size of the ion beam, thus the kicker parameters will be optimal. The size of the electron kicker does not depend on the aperture of the vacuum pipe. It is not necessarily a plunging device.

From the physical point of view the electron cooler device as kicker enables one to obtain 40 GHz ranges of frequencies. One of the imiting factors is the size of the electron beam. A wave with wave-length about thr transverse size of the beam is difficult to inject by usual RF methods and may have strong dispersion and damping.

The electron kicker is effective for the velocity matching of kick impulse and ion. Adjusting the energy of the electron beam the phase velocity of the space-charge wave may be equalized to the ion velocities with high accuracy. This result may be obtained at large variation of the ion velocities $0<\beta<1$.

The space charge of the electron beam enables one to obtain the 3D distribution of the electric field at the same time. So, if the control structure of the electron gun can modulate the electron gun axial-asymmetrically then all 3D kick types (vertical, horizontal and momentum) are available in one single device.

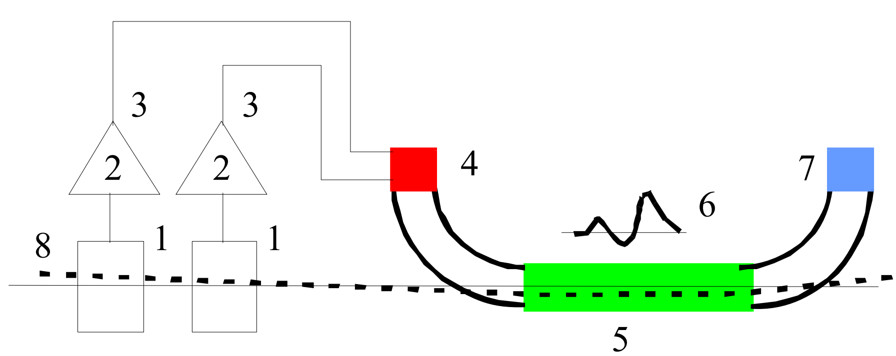

Figure 1: Scheme of stochastic cooling with electron cooler as 3D kicker. 1 – pick-up system, 2 – hybrid and amplifier, 3 – cable system, 4 – electron gun with the current modulation, 5 – cooling section, 6 – modulation of the space-charge density in the cooling section, 7 – collector of the electron beam, 8 – ion trajectory.

ELECTRON COOLING SIMULATION FOR ARBITRARY DISTRIBUTION OF ELECTRONS

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Abstract

Typically, several approximations are being used in simulation of electron cooling process, for example, density distribution of electrons is calculated using an analytical expression and distribution in the velocity space is assumed to be Maxwellian in all degrees of freedom. However, in many applications, accurate description of the cooling process based on realistic distribution of electrons is very useful. This is especially true for a high-energy electron cooling system which requires bunched electron beam produced by an Energy Recovery Linac (ERL). Such systems are proposed, for instance, for RHIC and electron – ion collider. To address unique features of the RHIC-II cooler, new algorithms were introduced in BETACOOL code which allow us to take into account local properties of electron distribution as well as calculate friction force for an arbitrary velocity distribution. Here, we describe these new numerical models. Results based on these numerical models are compared with typical approximations using electron distribution produced by simulations of electron bunch through ERL of RHIC-II cooler.

INTRODUCTION

A traditional electron cooling system employed at low-energy coolers is based on a uniform electron beam immersed in a longitudinal magnetic field of a solenoid. In this case the action of electron cooling on the ion dynamics inside a storage ring can be described using a few standard simplifications:

1. Angular deviation of the longitudinal magnetic field line is sufficiently less than the ion beam angular spread.
2. Ion transverse displacement inside the cooling section is small compared to the electron beam radius.
3. Ion beam temperature is substantially larger than electron one and ion diffusion in the electron beam can be neglected.
4. Electron beam has a cross-section with a round shape and uniform density distribution in the radial direction.

Under these assumptions and using analytic asymptotic representation of the friction force, the formulae for characteristic times of emittance and momentum spread decrease for electron cooling were obtained (see, for example, Ref. [1]). This model was used in several programs dedicated to electron cooling simulation, for example, in the first version of the BETACOOL [2]. An uncertainty in predictions of the cooling rate based on such an estimate is typically a factor of two or three, which is acceptable for most designs of a traditional cooling system. However, this model can not cover all possible versions of the electron cooling system design, and its accuracy is insufficient for a design of high energy electron coolers.

Recently, modifications of the usual configuration of the low energy electron cooling system were proposed. To avoid instability of the ion beam related to an extremely large density of the cooled beam it was proposed to use so called “hollow” electron beam – the beam with small density in the central part. The “hollow” electron beam is efficient for ion beam storage using cooling-stacking procedure. The low electron density in the stack region avoids overcooling of the stack and decreases (for heavy ions) recombination in the cooling section. Therefore, a few electron cooling systems with hollow electron beam were recently constructed.

Extension of the electron cooling method to the region of electron energy of a few MeV, which was successfully realized at Recycler in Fermilab and proposed for HESR (GSI, Darmstadt) and COSY (FZJ, Juelich), led to some changes of the electron beam properties. Accurate matching of an intensive electron beam with transport line in the cooling section is a complicated task in this energy range. The electron beam mismatch leads to fast decrease of the electron beam quality in the radial direction from the central part to the beam edge that can significantly affect the ion distribution under cooling.

Further increase of the electron energy is related with an RF acceleration of the electrons. In this case one can have Gaussian distribution of the electrons in radial plane and, if the electron bunch is shorter than the ion one, in longitudinal direction also. Simulation of the cooling process in this case requires modification both of the electron beam and the physical model.

Successful operation of the Recycler electron cooling system demonstrated good cooling efficiency in the case when the longitudinal magnetic field is used for electron beam transport only and does not influence the friction force significantly. This indicates that a strong magnetic field is unavoidable only in the case when a deep cooling of the ion beam is necessary (as, for example, for HESR in high resolution mode of operation). When the electron cooling is used for compensation of heating effects and stabilization of the ion beam phase volume at relatively large value, the non-magnetized cooling can be competitive as well. For example, although extensive studies of the magnetized cooling approach for RHIC showed that it is feasible [3] and would provide required luminosities for the RHIC-II, the baseline of the project was recently changed to the non-magnetized one. Application of electron cooling using the non-magnetized electron beam significantly simplifies the RHIC-II cooler

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IMPLEMENTATION OF SYNCHROTRON MOTION IN BARRIER BUCKETS IN THE BETACOOL PROGRAM*

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Abstract

The model of ion synchrotron motion in a stationary square wave barrier bucket was implemented into both main algorithms of the Betacool program: rms dynamics and Model Beam algorithm. In the frame of rms dynamics the calculation of the cooling and heating rates was modified in accordance with analytic expression for the ion phase trajectory in the longitudinal phase plane. In the Model Beam algorithm the generation of matched stationary particle array and simulation of the synchrotron motion were developed.

INTRODUCTION

Moving barrier RF bucket is an effective ion beam accumulation method used, for instance, in Fermilab's Recycler and proposed for NESR at FAIR project. A possible application of a stationary RF bucket is to compensate ionization energy loss in experiment with internal target. The ionization energy loss is the main physical effect limiting the experiment duration. The barrier bucket application permits to sufficiently decrease of required power of a cooling system when a high resolution in experiment is necessary. It is essentially true for dense internal target, for instance a pellet target. So an application of stationary RF bucket for WASA at COSY experiment can allow sufficiently decrease requirements for maximum electron current in proposed high voltage electron cooling system [1].

The mean energy loss can be compensated by usual sinusoidal RF system at relatively small voltage amplitude; however this leads to sufficient increase of intrabeam scattering (IBS) growth rates. Even at long length of the bunch the particle density in its central part increases significantly in comparison with a coasting beam. At a barrier RF bucket application the particle density inside the bucket is almost uniform. Therefore the IBS growth rates increase by a factor equal to ratio of the ring circumference to the bucket length only. This advantage of the barrier bucket is of great importance when the experiment requires high momentum resolution and, correspondingly, the ion beam momentum spread has to be as small as possible.

Recently a new program was developed for barrier RF bucket simulation for FAIR rings [2]. To compare predictions of different models and to estimate efficiency of the barrier bucket application in internal target experiments the new algorithms were implemented into Betacool program [3] also.

* This is work is supported by grant of president of Russian Federation for young scientists - candidates of science program 2007-2008.

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The general goal of the BETACOOL program is to simulate long term processes (in comparison with the ion revolution period) leading to the variation of the ion distribution function in six dimensional phase space. Therefore the Betacool is not a tracking code, and simulation of transverse and longitudinal ion motion is based on analytical expressions for the phase trajectories.

Evolution of the second order momenta of the ion distribution function is realized in so called "rms dynamics" algorithm based on assumption of Gaussian shape of the distribution. Here all the heating and cooling effects are characterized by rates of emittance variation or particle loss.

The investigation of the beam dynamics at arbitrary shape of the distribution is performed using multi particle simulation in the frame of the Model Beam algorithm. In this algorithm the ion beam is represented by an array of model particles. The heating and cooling processes involved into the simulations lead to a change of the particle momentum components and particle number.

Therefore implementation of the new model required corrections in algorithms for heating and cooling rate calculation, development of algorithms for generation of the model particle array matched with RF system and simulation of the model particle synchrotron motion. New tools for the data post processing and visualization of the results were developed also.

General behaviours of the synchrotron motion are determined by integrated RF pulse strength, and essential physics is independent on the exact shape of the barrier RF wave. Simplest analytical solution for the phase trajectory can be obtained at square wave barrier bucket; therefore this model was implemented into the program at the first step. In future we plan to develop the algorithms for synchrotron motion simulation at arbitrary RF shape and moving barrier bucket.

SINCHROTRON MOTION IN SQUARE WAVE BARRIER BUCKET

The RF voltage time dependence at square wave barrier bucket can be written as

$$V(t) = \begin{cases} sign(\eta)V_0 & if \quad -(T_2+T_1)/2 \le t \le -(T_2-T_1)/2 \\ -sign(\eta)V_0 & if \quad (T_2-T_1)/2 \le t \le (T_2+T_1)/2 \\ 0 & otherwise \end{cases},$$

where V_0 is the voltage height, T_1 is the pulse width, T_2 is the gap duration, η is the ring off-momentum factor.

The equations of the synchrotron motion of the ion at charge eZ written in the variables (s-s$_0$, $\delta = \Delta p / p$) are

OPTIMIZATION OF THE MAGNET SYSTEM FOR LOW ENERGY COOLERS

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Abstract

Aspects of magnet design and field measurements are discussed in the view of low energy coolers construction. The paper describes some engineering solutions for the magnetic field improvement which provides appropriate conditions for the cooling process as well as electron and ion beams motion.

INTRODUCTION

In installations of electron cooling, the electron beam passes from the cathode of an electron gun then through bending section to cooling solenoid and then up to absorbing collector in a continuous longitudinal magnetic field. Requirements of quality of a magnetic field are various for various parts of installation. Most they are high for cooling section - the central solenoid. Efficiency of the cooling process strongly depends on quality of the guiding magnetic field produced by the solenoid. Acceptable of cooling rate can be achieved, if non-parallelism of the field force lines, in relation to an axis of the solenoid $B_{\perp}/B_{\parallel}$ in a vicinity of ion trajectories does not exceed size of angular spread of the ion beam. The aspiration to achieve extreme high cooling rate produces rigid requirements to straightforwardness of the field force lines - from 10^{-4} for low energy electrons up to 10^{-5} and even less - for high energy. For achievement of these high requirements the special designs of the central solenoid, as well as a technique of correction of heterogeneity of a magnetic field and precision system of its measurement were developed.

CORRECTION OF THE MAGNETIC FIELD AT COOLING SECTION

Asymmetry of the magnetic system leads to inhomogeneous magnetic field rise at the cooling section. This effect can be eliminated by the inclination of the solenoid coils. As a step of a commissioning such a procedure was performed for EC-300 cooler (IMP China) at 0.75 kG longitudinal field. Also small-scale disturbances of the transverse field were minimized those originated from imperfectness of the coils alignment. Data obtained is shown in fig.1 – curve 1,[1].

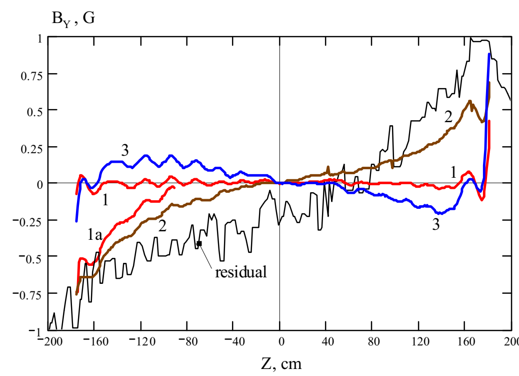

Figure 1: Vertical fields at cooling section of EX-300 measured at longitudinal field: curve 1: 0.75 kG, curve 2: 0.5 kG, curve 3: 1 kG. Curve 1a: 1-st switching on after return to a field of 0.75 kG. “Residual” – result of Hall probe measurements of the residual field.

However non-uniform vertical fields appeared to show up again at a change of the longitudinal field. Plots of the vertical field distribution are shown in Fig.1 (curves 1,2,3). It can be easily estimated that these fields have linear and cubic components. It is visible, that small-scale disturbances are proportional to a field. On the other hand horizontal component kept stably small independent on longitudinal field.

It appears, that (curve 1) at return from *1kG* to *0.75kG* the achieved field slickness is restored only after several turning on and off of the magnet system (normalization cycle). After 1-st turning on the vertical component is restored only in the central part of the solenoid (curve 1a). After normalization cycle in the solenoid it is formed rather steady and about a linear vertical residual field (curve ‘residual’ in Fig.1). Apparently, a course of curves 2 and 3, is determined by this residual field especially in the central part of the solenoid namely, inclination of the coils overcompensate the residual field at *1kG* an under compensate at *0.5kG*.

So, the technique of alignment of the field by coils inclination [2], [3] suits only for a fixed longitudinal field. Therefore special correctors of a linear and cubic field should be used for operative reaction to a change of a longitudinal field.

Measures to Enlarge Good Field Region

According to design requirements, effective length of cooling section has to be as close as possible to the mechanical length of the solenoid. Therefore effort should be made to enlarge good field region.

COOLING IN A COMPOUND BUCKET

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Abstract

Electron cooling in the Fermilab Recycler ring is found to create correlation between longitudinal and transverse tails of the antiproton distribution. By separating the core of the beam from the tail and cooling the tail using "gated" stochastic cooling while applying electron cooling on the entire beam, one may be able to significantly increase the over all cooling rate. In this paper, we describe the procedure and first experimental results.

INTRODUCTION

Presently, antiprotons in the Fermilab Recycler ring [1] are stored between rectangular RF barriers and are cooled both by a stochastic cooling system in the full duty-cycle mode (primarily in the transverse planes) and by a DC electron beam (primarily in the longitudinal phase-space). As the number of antiprotons, N_p, in the Recycler increases, the rate of stochastic cooling decreases according to $1/N_p$ [2]. In the case of electron cooling, the cooling strength does not depend on N_p, but it is significantly stronger on the core particles as compared to that in the tail region of the 6D-phase-space [3]. These properties combined result in a formation of a dense core but long tails and a poor beam life time. In this paper, we propose a technique of separating core and tail particles to combine advantages of both cooling techniques in the Recycler.

COMPONENTS OF THE SCHEME

Tail Correlation

Measurements in the Recycler have shown [4] that the longitudinal cooling force quickly drops at a radial offset inside the electron beam of ≤1 mm. Typical rms radius of newly arrived antiprotons from the Accumulator ring is about 2 mm. Consequently, particles with large transverse actions are only weakly affected by the electron cooling. Eventually, the tail of the momentum distribution is populated primarily with particles of large transverse action (see Fig.3 in Ref. [4]). Note that this feature is not observed in an antiproton beam cooled by stochastic cooling alone.

Compound bucket

The effect of tail correlation can be used for longitudinal separation of the core and tails by application of a so-called compound bucket. The scheme of the compound bucket is illustrated in Fig.1. Normally, the beam is stored between two rectangular barriers, labeled as #6 and #7 in Fig.1 in accordance with the internal Recycler system. In the compound bucket, two lower-width "mini-barriers"#3 and #4 create an additional step in the effective RF potential, so that only particles with a large energy offset travel between barriers #4 and #7. Below we refer to this area as to the tail region.

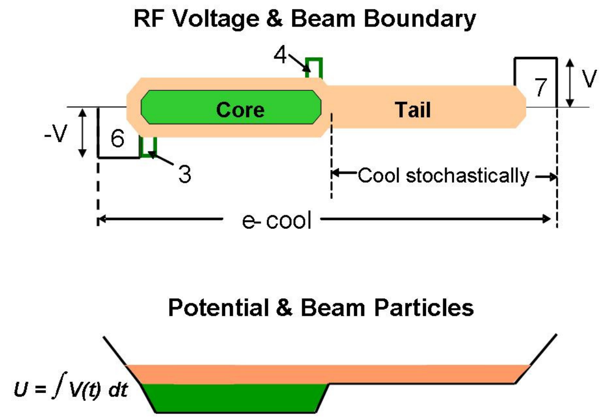

Figure 1: Scheme of the compound bucket. Horizontal axis shows the longitudinal phase (usually expressed as a time delay from the arrival of the bunch head) and corresponds to one revolution period. The top plot shows positions of RF barriers and tlongitudinal phase space of antiprotons (with vertical axis representing energy deviation). The bottom plot pictures corresponding effective RF potential.

Momentum Coating

The concept of the compound bucket was first introduced in Ref. [5] for the momentum coating injection scheme.

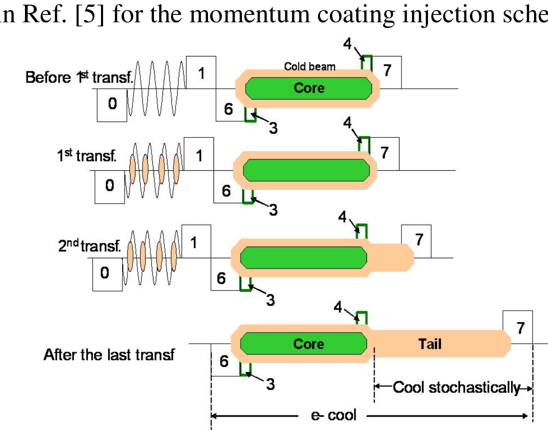

Figure 2: Injection with the compound bucket. RF forms and momentum distributions are shown for the case of two transfers.

In this scheme (Fig.2), the cold beam in the Recycler ring is kept between mini-barriers #3 and #4 while the new particles arriving from the Accumulator are injected in

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ELECTRON COOLING IN THE RECYCLER COOLER

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Abstract

A 0.1-0.5 A, 4.3 MeV DC electron beam provides cooling of 8 GeV antiprotons in Fermilab's Recycler storage ring. The most detailed information about the cooling properties of the electron beam comes from drag rate measurements. We find that the measured drag rate can significantly differ from the cooling force experienced by a single antiproton because the area of effective cooling is significantly smaller than the physical size of the electron beam and is comparable with the size of the antiproton beam used as a probe. Modeling by the BETACOOL code supports the conclusion about a large radial gradient of transverse velocities in the presently used electron beam.

INTRODUCTION

Since the first demonstration of relativistic electron cooling in the Recycler Electron Cooler (REC) [1], cooling measurements of various types have been performed. In some, the cooling force was derived from the longitudinal distribution of the antiproton beam being in equilibrium with either IBS [1] or an external wide band noise source [2]. The most relevant figures of merit for operation, the cooling rates, were measured as changes of the time derivative of the longitudinal momentum spread and transverse emittances, when the electron beam is turned on [3]. In this paper, we concentrate primarily on drag rate measurements. First, we analyze the conditions, for which the measured drag rate correctly represents the cooling force experienced by a single antiproton, then present the results of the measurements, and compare them with simulations.

DRAG RATE AND COOLING FORCE

In a drag rate measurement, the electron energy is changed by a jump, and the time derivative of the average antiproton momentum, $\dot{\bar{p}}$, is recorded [4]. For a pencil-like antiproton beam with a small enough momentum spread, this derivative is equal to the cooling force applied to an antiproton with momentum offset $\delta p = \bar{p} - p_0$, where p_0 is the equilibrium momentum. Generally speaking, for the beam with finite emittances, the drag rate is given by integration over the 6D antiproton and electron distributions. For typical REC parameters, several simplified assumptions are valid:

- in the time of a drag rate measurement, the transverse antiproton distribution does not change, so that transverse diffusion and cooling can be neglected for the longitudinal dynamics;
- the antiproton beam is axially symmetrical in the cooling section;
- direct effect of the transverse antiproton velocities is negligible, because the transverse electron velocities are much larger. Therefore, the cooling force depends on the radial position of an antiproton with respect to the electron beam center r but not on the antiproton transverse velocity.

In this case, the drag rate can be written as an integral of the non-magnetized cooling force over the radial and momentum antiproton distribution as follows:

$$\dot{\bar{p}} = \int\int F(\delta W, \alpha_e, j_e, \Delta p) \cdot f(p,r)\, 2\pi \cdot r\, dr\, dp\,, \qquad (1)$$

where the cooling force is shown dependent on the electron energy spread δW, angle α_e, and current density j_e averaged over the length of the cooling section, as well as on the antiproton momentum offset $\Delta p = p - p_0$. Similarly, changes of the r.m.s. momentum spread $\sigma_p^2 = \int\int (p-\bar{p})^2 \cdot f(p,r)\, 2\pi \cdot r\, dr\, dp$ are given by

$$\frac{d}{dt}\sigma_p^2 = D + 2\int\int F(\delta W, \alpha_e, j_e, \Delta p) \cdot f(p,r) \cdot 2\pi \cdot r\, dr\, dp\,, \qquad (2)$$

where D is the longitudinal diffusion coefficient.

Dependence of the cooling force on the radius comes from the radial distributions of the current density and angles, while the electron energy spread is determined primarily by the terminal voltage fluctuations. If the electron beam is cold, its current density distribution in the cooling section follows the one on the cathode $j_{cath}(r_{cath})$:

$$j_e(r) = j_{cath}\left(r \cdot \sqrt{\frac{B_{cs}}{B_{cath}}}\right) \cdot \frac{B_{cs}}{B_{cath}}\,, \qquad (3)$$

where B_{cs} and B_{cath} are the magnetic field magnitudes in the cooling section and at the cathode, respectively.

Gun simulations and Eq.(3) give for j_e a distribution close to parabolic in the main portion of the beam

$$j_e(r) \approx j_0 \cdot \left(1 - \frac{r^2}{a^2}\right), \qquad (4)$$

with $j_0 = 0.96$ A/cm^2 and $a = 2.9$ mm.

Angles are composed of a component α_0 constant across the beam (associated with thermal velocities and dipole perturbations in the cooling section magnetic field) and a component linear with radius (caused by envelope scalloping), added in quadratures,

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BEAM-BASED FIELD ALIGNMENT OF THE COOLING SOLENOIDS FOR FERMILAB'S ELECTRON COOLER*

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Abstract

The cooling section of FNAL's electron cooler (4.3 MeV, 0.1 A DC) [1] is composed of ten (10) 2 m-long, 105 G solenoids. When it was first installed at the Recycler ring, the magnetic field of the cooling solenoids was carefully measured and compensated to attain the field quality necessary for effective cooling [2]. However, the tunnel ground motion deteriorates the field quality perceived by the beam over time. We have developed a technique which uses the cooling strength as an indication of the relative field quality and allowing us to re-align the longitudinal magnetic field in the successive solenoids of the cooling section assuming that the transverse component distribution of the field within each solenoid has not changed.

INTRODUCTION

For electron cooling purposes, a cold (i.e. with low transverse velocities, or angles in the lab frame) electron beam must be generated, transported to the cooling section (CS), where electrons interact with the particles that need cooling, and must remain cold until the beam exits the CS. While there are many sources contributing to the total rms angle in the beam [4], having a magnetic field in the CS with a large transverse component would prevent any efficient cooling. Assuming that all solenoids were perfectly aligned, we estimated that the field quality achieved for the compensated magnetic field lead to a total rms angle of 50 μrad for the electron beam [2]. However, we observed its deterioration over time, which needed to be corrected.

In this paper, we present our observations of the field degradation, and described the procedure we developed to correct it (different in nature than the one proposed in Ref. [3]), using the cooling strength as a diagnostic for the 'straightness' of the field. Results of this method are discussed.

OBSERVATIONS

Once the compensation of the magnetic field has been optimized and set, the electron beam trajectories in the cooling section should remain the same for fixed initial conditions of the centroid. However, over several months, we find that the trajectories get perturbed. This is illustrated in Figure 1, which shows the difference of trajectories taken a few months apart, and where one set of trajectories was obtained after the field had been re-aligned for the first time using the procedure we will describe. Beam position monitors (BPM) are located between each solenoid, with the first BPM being at the entrance of the first solenoid. On Figure 1, '0 cm' is a reference point outside of the first solenoid.

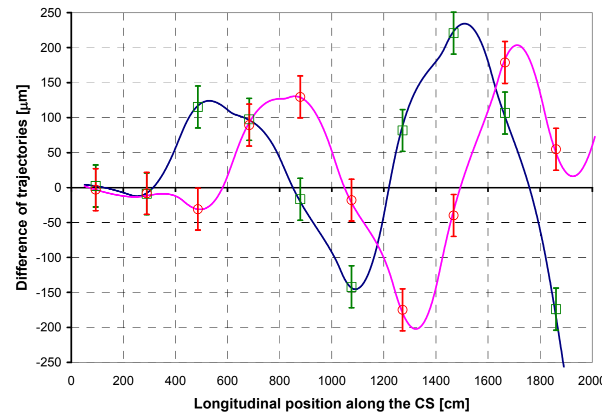

Figure 1: Difference of trajectories taken 3 months apart. Green squares: Horizontal; Red circles: Vertical. I_b = 100 mA, on-axis. The solid lines are fitted trajectories using the measured magnetic fields and solenoid-to-solenoid magnetic offsets as fitting parameters.

Note that the trajectories are taken for the same beam current (100 mA) and initial conditions where the beam is so-called 'on-axis', meaning that, ideally, trajectories coincide with the antiprotons central orbit. Moreover, the beam position monitors (BPM) are calibrated such that the antiprotons central orbit corresponds to zero position after the calibration procedure. The BPMs typically move, randomly from BPM to BPM, by 50 μm rms for all BPMs (100 μm in the worst BPM) over one year [5]. On the other hand, the electronic drift is <3 μm rms for all the BPMs (± 10 μm peak-to-peak in the worst BPM) over several weeks [5]. Both sources of error are about 5 times (or more) smaller than the effect shown on Figure 1.

PRINCIPLE OF THE METHOD AND PROCEDURE

The reason for the beam trajectories to change with time is likely because of ground motion in the tunnel, which moves the solenoids independently to one another, so that they appear inclined to a beam going through (Figure 2). Because each solenoid behaves like a rigid object [6], we can assume that the transverse component distribution of the magnetic field within each solenoid does not change. Hence, as illustrated in Figure **2**, the beam experiences a transverse magnetic field, $B_\perp$, when it travels from one solenoid to the next and oscillates in a fashion consistent with the trajectories shown in Figure 1.

Changing currents in all correctors in a solenoid by the same amount creates a nearly constant dipole field

* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy
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STATUS OF DESIGN WORK TOWARDS AN ELECTRON COOLER FOR HESR*

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Abstract

The HESR-ring of the future FAIR-facility at GSI will include both electron cooling and stochastic cooling in order to achieve the demanding beam parameters required by the PANDA experiment. The high-energy electron cooler will cool antiprotons in the energy range 0.8 GeV to 8 GeV. The design is based on an electrostatic accelerator and shall not exclude a further upgrade to the full energy of HESR, 14.1 GeV. The beam is transported in a longitudinal magnetic field of 0.2 T and the requirement on the straightness of the magnetic field is as demanding as 10^{-5} radians rms at the interaction section. Furthermore, care must be taken in order to achieve an electron beam with sufficiently small coherent cyclotron motion and envelope scalloping. This puts demanding requirements on the electron beam diagnostics as well as the magnetic field measuring equipment. Prototype tests of certain components for these tasks are being performed. The paper will discuss these tests and recent development in the design including the high-voltage tank, electron gun and collector, magnet system, electron beam diagnostics and the magnetic field measurement system.

INTRODUCTION

The High Energy Storage Ring (HESR) is a part of the future FAIR facility [1] and will be dedicated to Strong interaction studies with antiprotons in the momentum range of 1.5 to 15 GeV/c. In order to meet the demanding requirements of the experiments both stochastic cooling [2] and electron cooling will be employed. Electron cooling is needed, in particular, to reach the low momentum spread requirements for the high-resolution mode of PANDA.

The design work of HESR is carried out in a consortium formed between FZ Jülich, GSI and Uppsala University. Earlier studies of the electron cooling system for HESR were carried out by the Budker Institute of Nuclear Physics (BINP) and GSI [3].

The design of the high-energy electron cooler is based on an electrostatic accelerator and will be used to cool antiprotons in the energy range 0.8 GeV to 8 GeV. However, the design should not exclude a future upgrade to the full energy of HESR, 14.1 GeV. This was one reason to base the design on a Pelletron which is modular and is possible to extend in energy. [4]. A similar electron cooling system is in operation at Fermilab [5].

The PANDA experiment will use an internal target, most probably a hydrogen pellet target. The cooler will have to compensate for the effects of this target on the antiproton beam. For this to take place efficiently, magnetised cooling is required. The details of the interaction between the target effects and electron cooling in HESR are further discussed in Ref. [6]

Technical Challenges

One challenge for the electron cooler design is beam alignment between electrons and anti-protons. The deviation of the electron beam relative to the anti- proton beam should be smaller than 10^{-5} radians rms to fulfil the beam quality and lifetime demands of the anti-protons. This requires very accurate procedures for beam diagnostics and alignment along the 24-meter interaction section.

Another difficult requirement on the solenoid is that the magnetic field must be continuous enough, that the straightness of the magnetic field, measured within 5 mm distance from the nominal path of the electron beam must be within 10^{-5} radians rms.

The field must also be continuous enough or shaped so than an electron beam with diameter 10 mm and energy anywhere in the range from 0.45 to 8 MeV must not be "heated" by any variation of the magnetic field. The dipole and envelope oscillations created by the total effect of all such transitions in the system should be smaller than a corresponding Larmor radius of 0.1 mm.

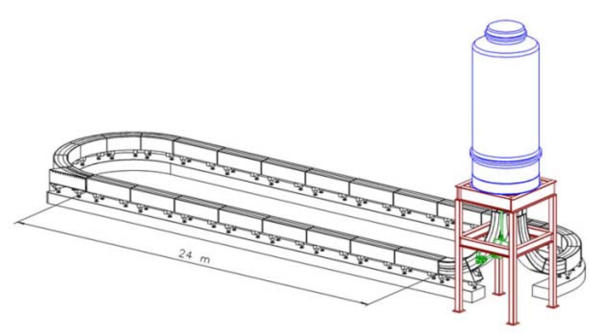

Figure 1: Layout of the HESR electron cooler showing the Pelletron tank and the beam line system of solenoid magnets. The length of the interaction section is 24 m.

ELECTRON COOLING FOR A HIGH LUMINOSITY ELECTRON–ION COLLIDER*

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Abstract

A conceptual design of a polarized ring-ring electron-ion collider (ELIC) based on CEBAF with luminosity up to 10^{35} $cm^{-2}s^{-1}$ has been developed at Jefferson Lab. A vital component of this collider is high energy electron cooling (EC) of ion beams. This cooling facility consists of a 30 mA, 125 MeV energy recovery linac (ERL) and a 3 A circulator-cooler ring (CCR) operating at 15 and 1500 MHz bunch repetition rate respectively. Fast kickers of frequency bandwidth above 2 GHz have been designed for switching bunches between the ERL and CCR. Design parameters of this cooling facility, preliminary studies of electron beam transport, stability and emittance maintenance in the ERL and CCR, and the scenario of forming and cooling of ion beams will be presented.

INTRODUCTION

At Jefferson Lab, a polarized high luminosity electron-ion collider (ELIC) based on the CEBAF facility, as shown in Figure 1, was proposed as a future facility for nuclear science quest [1,2]. The ultra high luminosity of ELIC calls for a green-field design of its ion complex and a new approach to organization of the interaction region. For the ELIC electron complex, selection of a storage ring over an energy recovery linac (ERL) relaxes the high average current requirement on the polarized source while still preserving high luminosity. The 12 GeV CEBAF accelerator will be utilized as a full-energy injector of electron bunches into a ring of a 2.5 A stored current [3]. The ELIC ion complex, consisting of a SRF linac, a pre-booster, a large booster and a collider ring, will generate and store up to a 1 A polarized (p, d, ^{3}He and Li) or non-polarized (up to A=208) ion beam with energy up to 225 GeV for protons or 100 GeV/n for ions [1]. The figure 8 topology of the ELIC booster and collider rings provides preservation and easy manipulation of spins for all species. There are four interaction points arranged symmetrically on the two crossing straights for high science productivity. Table 1 summarizes ELIC's main design parameters.

The luminosity concept of ELIC has been established on careful consideration of multi beam physics effects including beam cooling, space charge, beam-beam interactions and intra-beam scattering (IBS) [3,4]. In this paper we present a scheme of forming of high intensity ion beams and cooling of these beams to meet requirements of ultra high luminosity. To assist ion beam stacking and accumulation, stochastic cooling will be utilized in the pre-booster and the collider ring [1]. Electron cooling (EC) will provide initial longitudinal cooling and a continuous 6D cooling of the ion beam in collisions mode. In cooperation with a strong bunching SRF field of high frequency in the collider ring, EC delivers very short (5 mm or less) ion bunches with desired small emittances, thus enables *super-strong focusing* at collision points and *crab crossing colliding beams* required for a high bunch collision rate (1.5 GHz) [5].

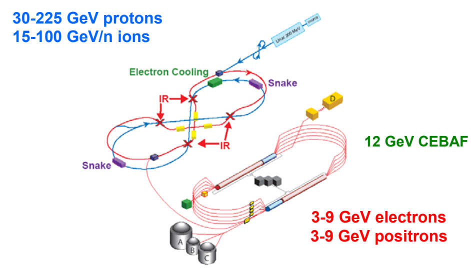

Figure 1: A schematic drawing of ELIC ring-ring design.

Table 1: Basic parameters for ELIC.

Beam energy	GeV	225/9	150/7	30/3
Collision rate	GHz		1.5	
Particles/bunch	10^{10}	.42/.77	.42/1	.13/1.7
Beam current	A	1/1.85	1/2.5	.3/4.1
Ener. spread, rms	10^{-4}		3	
Bunch length, rms	mm		5	
Beta-star	mm		5	
Hori. emit. norm.	μm	1.2/90	1.06/90	.21/37.5
Vert. emit., norm.	μm	.05/3.6	.04/3.6	.21/37.5
Beam-beam tune shift (vert.) per IP		.006/ .086	.01/ .086	.01/ .007
Space charge tune shift in p-beam			.015	.06
Lumi. per IP, 10^{34}	$cm^{-2}s^{-1}$	5.7	6	0.6
Lumi. lifetime	hours	24	24	>24

ION STACKING AND COOLING SCENARIO

Forming and Pre-cooling of Ion Beams by Stochastic Cooling

An ion beam from a 285 MV SRF linac will be stacked in a 3 GeV pre-booster with stochastic cooling. Our estimates show accumulation of a 1 A ion beam of space charge limited emittances of 10-15 μm within several minutes. Accumulated beam, after bunching and accelerating to 3 GeV, will be injected into the large booster which has common arcs with the electron ring. About 10 to 15 injections are needed to fill the whole orbit of the large booster ring. The beam will then be accelerated to 30 GeV for protons or up to 15 GeV/n for ions and injected into the ion collider ring. Here

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RECENT DEVELOPMENTS FOR THE HESR STOCHASTIC COOLING SYSTEM

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Abstract

Two cooling systems will be installed in the High-Energy Storage Ring (HESR) of the future international Facility for Antiproton and Ion Research (FAIR) [1] at the GSI in Darmstadt: an electron cooler (1.5-8 GeV/c) and a stochastic cooling system from 3.8 GeV/c up to the highest momentum of the HESR (15 GeV/c). Both coolers are mandatory for the operation of the HESR with the PANDA pellet target. The relative low aperture (89mm) of the HESR suggests fixed structures without a plunging system. An octagonal layout was chosen to increase the sensitivity of the electrodes. Two different types of electrodes were built and tested. We will report on the comparison of printed lambda/4 loops and new broadband slot couplers.

HESR STOCHASTIC COOLING

The modified (2-4GHz) AC CERN [2] loop pairs with a distance of 20mm [3] are basis for the simulations of the HESR stochastic cooling system. For practical reasons and costs reduction aspects we prefer fixed pickup loops without plunging system. One loop pair with a distance of the HESR aperture will give a poor response. The loss of particle image current is not tolerable. The coupling impedance can be increased by combining several rows of electrodes arranged in an octagonal array.

Printed loop Coupler

Printed loops [5] are a cost saving alternative to the mechanical complex structures like the CERN AC structures [2] or the COSY pickups [4]. The first design of the HESR stochastic cooling pickups uses 50-Ohm printed loop couplers containing rectangular electrodes with rounded corners. Each loop ends at a 50-Ohm SMD resistor. These loops are combined via several impedance transforming networks and are located at the combiner side, whereas the coupling is done through the dielectric material of low permittivity (ε_r=3.27). Only simple through-holes are needed to connect the terminating resistors at the electrodes. Loops and combining network are located on the same board. This simplified the whole structure and minimized the fabrication costs. New structures can be easily exchanged. The relatively high bandwidth of 2-4 GHz requires at least two-stage transforming networks. Compared to Wilkinson couplers these combiners are a little bit more space consuming but have lower losses. The printed loop boards have been constructed as a part of a universal modular octagonal structure (fig. 1). Different modes of signal combinations outside the vacuum envelopes will allow to pick up different transversal beam positions as a part e.g. of a core or a halo cooling system.

We compared the transversal sensitivity of the new printed loops to that of the COSY-loop structure of 1.8 to 3 GHz [6] simulating the beam by an air microstrip line.

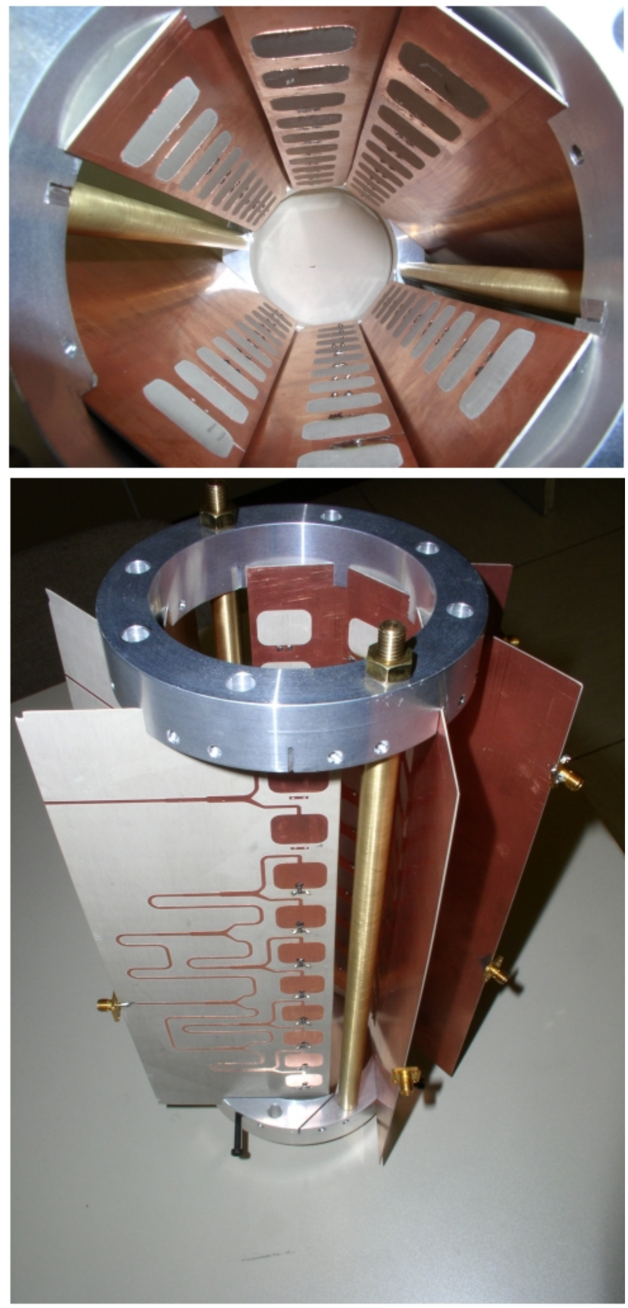

Figure 1: Octagonal pickup structure, equipped with 6 λ/4-electrode rows.

The width of the COSY loops, which were adapted

PICK-UP ELECTRODE SYSTEM FOR THE CR STOCHASTIC COOLING SYSTEM*

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Abstract

The collector ring (CR) of the FAIR project will include a fast stochastic cooling system for rare isotope beams ($\beta = 0.83$) and antiprotons ($\beta = 0.97$). To reach a good signal to noise ratio of the pick-up even with a low number of particles, a cryogenic movable pick-up electrode system based on slotlines is under development. The sensitivity and noise properties of an electrode array has been calculated using field-simulation and equivalent circuits. For three-dimensional field measurements, an electric near-field probe moved by a computer controlled mapper has been used.

SLOTLINE PICK-UPS FOR THE CR

The pick-ups must have a large bandwidth, a high S/N ratio and a large aperture. A new planar electrode is developed [1] to meet these requirements. The electrodes consist of a slotline perpendicular to the beam and a microstrip circuit on the rear side of a planar Al_2O_3 substrate (Fig. 1, top, left). The mirror currents induce traveling waves in both directions of the slotline. At approx. $\lambda/4$ from the end of the slotline, the signal is coupled out to the microstrip line. The $\lambda/4$-section at the beginning of the microstrip is a virtual short to one of the two conductors of the slotline. The exact length of these sections has been used to optimize the frequency response. The two signals are coupled out to 110 Ω microstrip lines and are combined in a 100 Ω to 50 Ω Wilkinson combiner. The position of the 110 Ω to 100 Ω transition has also been optimized.

The figure 1 (top, left) shows the layout of an eight slot pick-up board on a scale of 1:3. A pick-up tank will consist of two times eight modules. The modules will be cooled down to 30 K using cold heads and will be movable. The two figures below show a simplified design of a module. The right figure shows a cut across the first module prototype. Beside the PU board, the module also contains vertical connection boards. On these Al_2O_3 boards, a cryogenic low noise amplifier is foreseen. A small antenna can be used to test all connections and amplifiers of the module

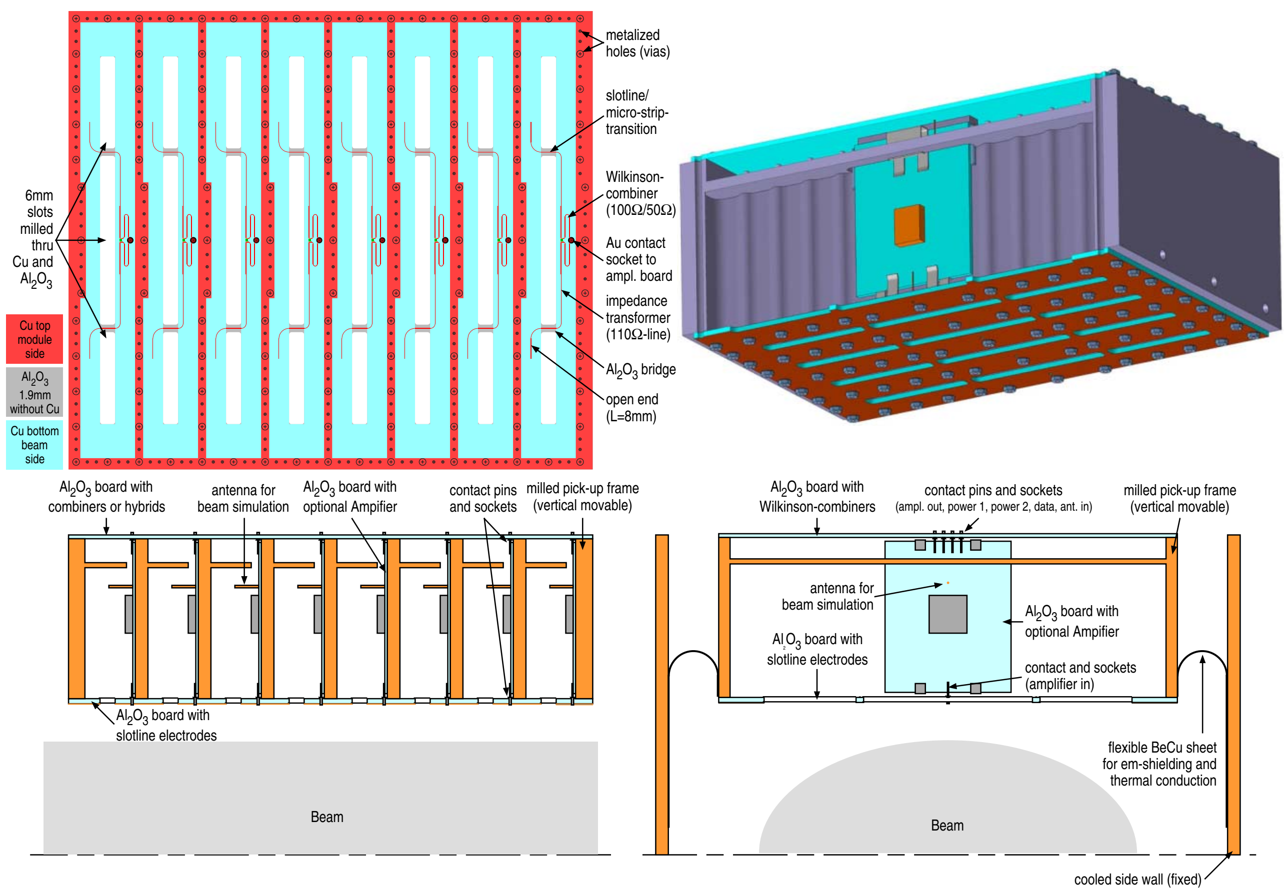

Figure 1: Layout of eight slot pick-up module prototype on a scale of 1:3.

* Work supported by EU design study (contract 515873 -DIRACsecondary-Beams)

BEAM BASED MEASUREMENTS FOR STOCHASTIC COOLING SYSTEMS AT FERMILAB *

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Abstract

Improvement of antiproton stacking rates has been pursued for the last twenty years at Fermilab. The last twelve months have been dedicated to improving the computer model of the Stacktail system.[1] The production of antiprotons encompasses the use of the entire accelerator chain with the exception of the Tevatron. In the Antiproton Source two storage rings, the Debuncher and Accumulator are responsible for the accumulation of antiprotons in quantities that can exceed $2x10^{12}$, but more routinely, stacks of $5x10^{11}$ antiprotons are accumulated before being transferred to the Recycler ring. Since the beginning of this recent enterprise, peak accumulation rates have increased from $2x10^{11}$ to greater than $2.3x10^{11}$ antiprotons per hour. A goal of $3x10^{11}$ per hour has been established. Improvements to the stochastic cooling systems are but a part of this current effort. This paper will discuss Stacktail system measurements and experienced system limitations.

STACKTAIL DESCRIPTION

The Stacktail[2] system (Figure 2) is the largest and most complicated of the nine stochastic cooling systems in the Accumulator. This one system is responsible for taking freshly injected antiprotons and decelerating them to the core while increasing the longitudinal density. Accordingly, the Stacktail system requires a dynamic range in excess of 40 dB as 2 x 10^8 injected antiprotons per pulse every 2.2 seconds yields a core exceeding 5 x 10^{11} in a few hours. (Figure 1) The front-end pickups have three distinct energy positions which, along with the pre-amplifiers, are cooled to liquid nitrogen temperatures to maximize signal to noise ratio. Three notch filters provide gain shaping and "protection" for the core. The high level consists of eight kicker tanks powered by 32 200-Watt Traveling Wave Tubes (TWT).

TRANSFER FUNCTION MEASUREMENTS

Transfer function measurements with a network analyzer are made by placing a narrow momentum bite of antiprotons at various revolution frequencies corresponding to the different beam positions of the pickups, (which are located in a high dispersion section of the Accumulator). Of the three pickup legs, the leg at the deposition orbit (leg 1) has the largest number of antennas. The nonlinear beam density profile in Figure 1 is a consequence of the exponential gain profile (Figure3) of the Stacktail cooling system. This results in very large gain at all revolution frequencies corresponding to the deposition energy. For this reason, transfer function measurements must be performed with a comparatively small beam current depending on the beam energy to avoid saturation of the front-end preamplifiers. Finding this linear beam current limit took several iterations of transfer function measurements before the maximum beam current for each beam position was determined. In addition to limiting the beam current, the momentum width must also be controlled with the use of longitudinal scrapers or in the case of core and near core measurements, with the 4-8 GHz core momentum cooling. With a large gain slope, a wide momentum profile would provide a different transfer function than a narrow distribution with the same beam current.

To verify the linearity of the results, two sets of measurements were taken. The first set of transfer functions is obtained with the network analyzer in frequency list mode set to harmonics of the revolution frequency (between 1.5-4.5 GHz) of the beam distribution centroid. The network analyzer excites a coherent mode on the beam motion resulting in a response in all three legs (Figure 4). If the excitation and/or beam current are too large, the resulting response may saturate the preamplifiers.

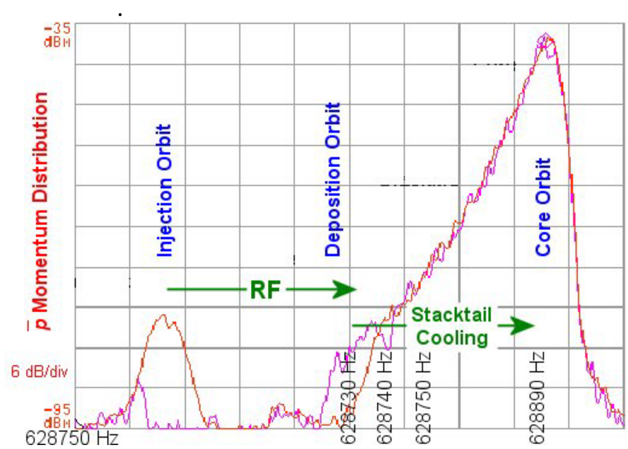

Figure 1: Stacktail Schottky profile vs. revolution frequency. Red trace with freshly injected antiprotons on the injection orbit, purple trace shows remnant antiprotons not picked up by the RF system and the resultant momentum displacement due to the Stacktail cooling.

*Work supported by Fermi Research Alliance under contract to the US Department of Energy.

NEW EQUALIZERS FOR ANTIPROTON STOCHASTIC COOLING AT FERMILAB *

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Abstract

In the continuous effort to improve antiproton stacking rate, a new type of equalizers has been developed and installed in antiproton accumulator. The R&D of these new equalizers is described in this paper.

INTRODUCTION

Equalizers are used in Fermilab antiproton stochastic cooling to compensate frequency response of the cooling system. Usually both amplitude and phase compensations are needed. However in most cases it is difficult to achieve a satisfactory compensation for both because of their interdependence. To make it more difficult is that in some cases large compensations (10 to 20 db of amplitude compensation or more than 100 degree of phase compensation) are needed near the low or high ends of a frequency band. Recently a new compensation scheme of equalizers is proposed for Fermilab antiproton accumulator. This scheme originated from the requirement to maximize the system performance resulting in a request for the phase of the cooling system transfer function to be extremely flat. For this kind of phase correction, a new type of equalizers has been developed.

NEW EQUALIZERS

The feature of this new type of equalizer is that it consists of two separate parts: the phase equalizer and the amplitude equalizer. Each part is made and tuned separately. The function of the phase equalizer is to correct only the phase. Then the amplitude equalizer corrects the amplitude (including the distortion caused by the phase equalizer part) to a desired shape. This approach not only makes the equalizer perform as required but also increases the adjustability of the equalizer. Each equalizer part can be categorized as a transversal or analog FIR (Finite Impulse Response) filter, though the FIR filter design algorithm was not followed during design of these filters. Shown in Fig. 1 is a schematic of one of these new equalizers.

The phase equalizer part of the new equalizer consists of power splitters, two or more two-port low-Q resonant circuit components, attenuators and delay lines. Shown between point A and B in Fig. 1 is a schematic of a phase equalizer part consisting of three resonant components. The input signal is first split into several signals.

*Work supported by Fermi Research Alliance under contract to the US Department of Energy.

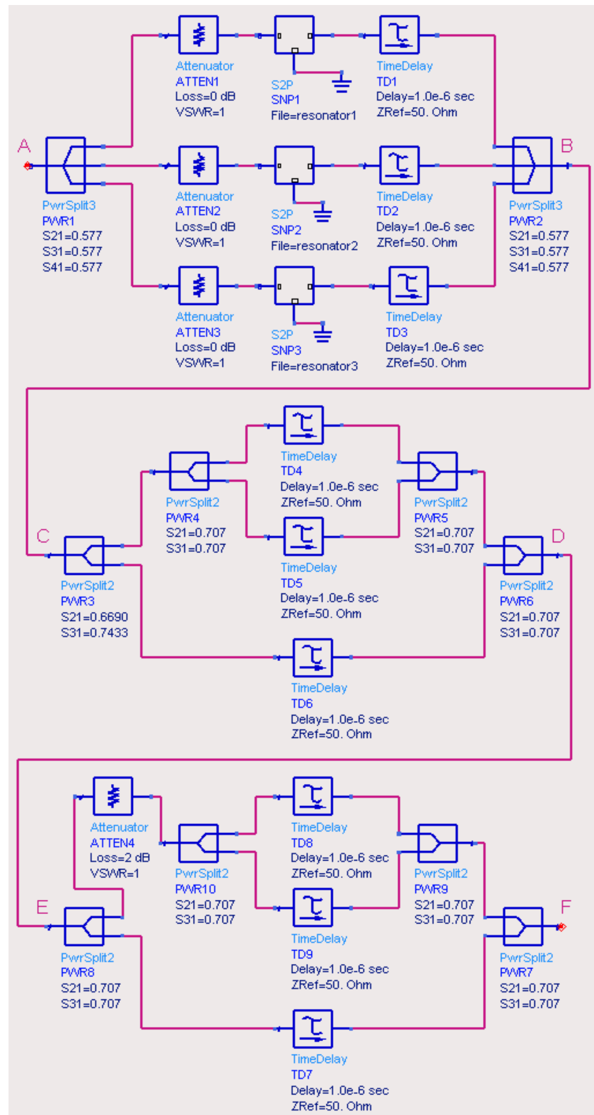

Figure 1: Schematic of a new equalizer.

Then the split signals are attenuated to various levels and fed into resonant components. After the resonant components, the split signals are recombined with various delay time for each sub-signal. Parameters of each individual circuit component such as resonant frequency, Q, attenuation, and delay time are used to control the location and slop of the phase change. Resonant components in Fig. 1 are implemented with parallel coupled microstrip (or stripline) lines. Shown in Fig. 2 is one of such resonant components. Other structures can also be used as long as they can generate desired phase change. To shorten R&D time, commercial power

INFLUENCES OF SPACE CHARGE EFFECT DURING ION ACCUMULATION USING MOVING BARRIER BUCKET COOPERATED WITH BEAM COOLING*

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Abstract

A longitudinal ion storage method by using a moving barrier bucket with a beam cooling can accumulate the ions in a storage ring, effectively. After the multicycle injections of the beam bunch by the method, the space charge effect due to the stored particles can interfere the next accumulation of the ions, because the space charge potential can cancel the effective barrier voltage. Using numerical simulations, we employ the longitudinal particle tracking, which takes into account the barrier bucket voltage, the beam cooling and the space charge effect, for the study of the beam dynamics during the accumulation operations. As a result, it is found that the space charge effect limits the accumulation of the ions in the longitudinal storage method.

INTRODUCTION

Longitudinal beam stacking by using a moving barrier bucket system with a stochastic momentum cooling has been proposed [1]. In the proposal, not only the stochastic cooling was applied, but also the electron cooling can be a candidate for the operation [2]. The ion storage experiment by using a barrier bucket with the electron cooling has been carried out, and the experimental results are succeeded for the ion beam stacking [3].

During the ion beam stacking, the beam current will be increased with the injection numbers. The high current beam can create the strong space charge potential. The electric field induced by the space charge may interferer the large number of the bunch injections and the higher stacking ratio.

In this study, we developed the longitudinal particle tracking code with the space charge effect, and the beam dynamics is numerically investigated by using the developed code. The numerical simulation results indicate the limitation of the ion accumulation derived from the self electric field in the stacking method. Also the space charge effect can be predicted by the simple ellipsoid shape model, and it is useful to estimate the stacking limit.

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OPERATION OF ION ACCUMULATION BY MOVING BARRIER BUCKET WITH ELECTRON COOLING

The longitudinal ion accumulation by using the moving barrier bucket with the electron cooling can be operated as follows [2, 4]. First, the bunch is injected into the region between two barrier voltages. The energy spread of the beam is decreased by the electron cooling. After the cooling, the beam with the small energy spread is separated by the moving barrier bucket operation for the partitioning. To repeat the above procedure, the ions are accumulated with the new injections.

LONGITUDINAL PARTICLE TRACKING OPERATED BY MOVING BARRIER BUCKET WITH SPACE CHARGE EFFECT

Basic Equations of Motion in Phase Space

The energy difference $\Delta E = E - E_s$ [eV/n] from the synchronous energy E_s in the barrier bucket is calculated by

$$\frac{d\Delta E}{dt} = \frac{q}{m}\frac{V_{bb}}{T_0} - E_{cool} - \frac{q}{m}\frac{g}{4\pi\epsilon_0\gamma^2}\frac{d\lambda}{d\tau}. \qquad (1)$$

where q is the charge state of the beam ion, m is the atomic mass number, $V_{bb} \equiv V_{bb}(t,\tau)$ is the voltage of the moving barrier bucket, T_0 is the revolution period, E_{cool} is the beam cooling term, g is the geometry factor, ϵ_0 is the permittivity of free space, and λ is the line charge density.

The time τ in the moving frame depends on time t in the laboratory frame is calculated by

$$\frac{d\tau}{dt} = \frac{\eta}{\beta^2}\frac{\Delta E}{E_0},$$

where β is the velocity divided by light speed c, $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ is the phase slip factor with the transition gamma γ_{tr}. Here $E_0 = E_k + m_0c^2$ is the synchronous energy per nucleon, where E_k is the kinetic energy per nucleon and $m_0c^2 = 931.481$ MeV is the rest energy of the atomic mass unit based on ^{12}C.

Barrier Bucket Voltage

Figure 1 shows the barrier bucket voltage waveform at each injection time. The barrier bucket shape is a sinusoidal waveform, and the pulse duration T_1 is 200 ns. The duration between the left and right barrier pulses $T_2 \equiv T_2(t)$

INTERNAL TARGET EFFECTS IN THE ESR STORAGE RING WITH COOLING

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Abstract

The accurate description of internal target effects is important for the prediction of operation conditions which are required for future experiments in the storage rings of the FAIR facility at GSI. A number of codes such as PTARGET, MOCAC, PETAG01 and BETACOOL have been developed to evaluate the beam dynamics in the storage ring, where an internal target in combination with an electron cooling is applied. The systematic benchmarking experiments were carried out at the ESR storage ring at GSI. The 'zero' dispersion mode (dispersion at target position is only 0.09 m) was applied to evaluate the influence of the dispersion function on the small beam parameters when the internal target is on. The influence of the internal target on the beam parameters is demonstrated. Comparison of the experimental results with the Bethe-Bloch formula describing the energy loss of the beam particles in the target as well as with simulations with the BETACOOL code will be given.

INTRODUCTION

Nuclear physics and fundamental interaction studies in collisions of rare isotope or antiproton beams with internal targets, play an important role in the NESR and HESR storage rings of the future FAIR facility [1]. High luminosities of up to 2×10^{32} $cm^{-2}s^{-1}$ are required for experiments with a hydrogen pellet target in the HESR. Therefore, an understanding of the process of beam-target interaction is crucial for prediction of the target effects which effect on the parameters of the stored beam. Investigations of the interplay between electron cooling, intrabeam scattering (IBS) and target effect is essential for the prediction of equilibrium beam parameters. Some experiments with gas targets in light ion storage rings have been reported before [2,3]. Recently the first systematic investigation of internal target effects in a storage ring for highly charged ions was performed at GSI [4]. The blow-up measurement was performed in 'zero' dispersion mode (the dispersion function at the target position was about 0.09 m) in the recent experiment. This experiment was performed in the Experimental Storage Ring (ESR) [5], which is equipped with an electron cooler [6] and an internal gas-jet target at GSI [7].

EXPERIMENTAL PROCEDURE

The experiment was carried out with a stored coasting beam of bare nickel ions (Ni^{28+}) with an intensity of a few times 10^7 particles and a kinetic energy of 400 MeV/u. The electron cooler was used to increase the phase space density of the injected beam and provide a high quality, dense stored beam for experiment and to compensate heating by the target. Two target gases (Ar and Kr) were used in the gas-jet, with thickness of about 6×10^{12} atoms/cm^2 for both gases (gas-jet diameter ≈ 5 mm).

The momentum spread was determined by Schottky noise analysis from the frequency spread Δf/f according to $\Delta p/p = \eta^{-1}\,\Delta f/f$, where η is the frequency slip factor $\eta = \gamma^{-2} - \gamma_{tr}^{-2}$, with $\gamma_{tr} = 2.78$. The horizontal emittance ε_x was non-destructively measured with the residual gas beam profile monitor (BPM). The beam size measured with the BPM was cross-checked by beam scraping, taking into account the ratio of the beta function values at the locations of the diagnostic devices (see [6]). Transverse Schottky noise power spectra from a stochastic cooling pickup (measured at the central frequency 1.3 GHz of the system) were used to measure the transverse beam emittances $\varepsilon_{x,y}$ due to the fact that the area under a sideband is proportional to the $\varepsilon_{x,y}$ [8]. The transverse emittance $\varepsilon_{x,y}$ values obtained in this way were calibrated against measurements with scrapers both in the horizontal and in the vertical plane and cross-checked with the BPM in the horizontal plane. The $\varepsilon_{x,y}$ values are estimated to be accurate within 30%. This accuracy is essentially given by the precision of the BPM and scrapers. Obviously, for relative effects such as the time evolution of beam parameters, the accuracy is much higher and benchmarking of simulations is possible.

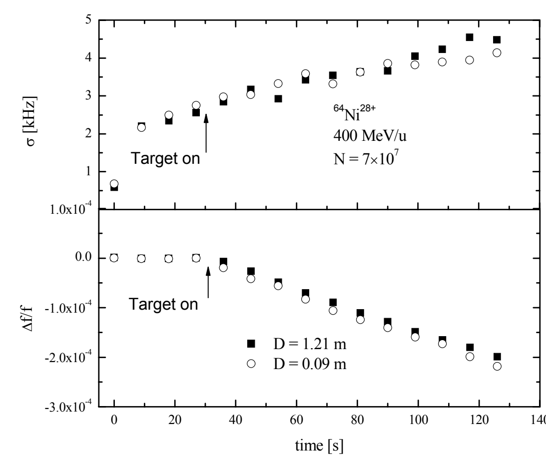

Figure 1: Relative change of the mean frequency Δf/f caused by the energy loss due to the internal target (Kr-target 6×10^{12} atoms/cm^2). The change of the width of distribution σ with the time.

There are two main procedures in our study. Firstly, the blow-up measurements were performed to investigate 'pure' target effects. A possible influence of dispersion function, particularly, at the pick-up position, on the horizontal emittance decrease was investigated (see [4]). The blow-up measurements were performed at the 'zero'

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LONGITUDINAL SCHOTTKY SIGNALS OF COLD SYSTEMS WITH LOW NUMBER OF PARTICLES

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Abstract

Very cold systems of ions with sufficiently low number of particles arrange in an ordered string-like fashion. The determination of the longitudinal momentum spread and of the transverse temperature then is no longer possible by normal Schottky diagnosis. In this paper we simulate such systems in an infinitely long beam pipe with periodic boundary conditions under the influence of all long-range Coulomb interactions by Ewald summation. Then we derive the behaviour of the longitudinal Schottky signals for cold string-like systems as well as for the transition to warmer systems when the strings break, up to hot gas-like systems. Here effects from the finite number of particles, of higher harmonics and of temperature agree with those derived analytically in the limits of very low and very high temperatures.

INTRODUCTION

Schottky analysis has been an efficient tool for the determination of the momentum spread of a heavy ion beam. After the construction of the electron cooler [1] in the ESR ring, see [2], at GSI in 1990 a pickup was installed and connected to a Schottky device. From the width of the signal the momentum spread $\delta p/p$ can be deduced, see e.g. Fig. 1.

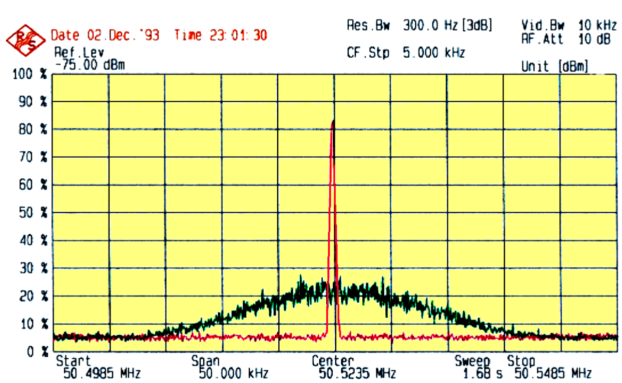

Figure 1: Early (1993) Schottky spectra from the ESR before (green) and after (red with $\delta p/p = 2 \times 10^{-5}$) electron cooling.

At high intensities of cooled systems momentum spreads below 10^{-5} could be reached. For very low densities, on the other hand, and if cooled properly, $\delta p/p$ decreases until intrabeam scattering breaks down [3]. Then the momentum spread levels off at a very low level of the order of 10^{-6} only due to ripples of the power supplies etc, see Fig. 2. These two regions are well separated by a a well defined jump in $\delta p/p$.

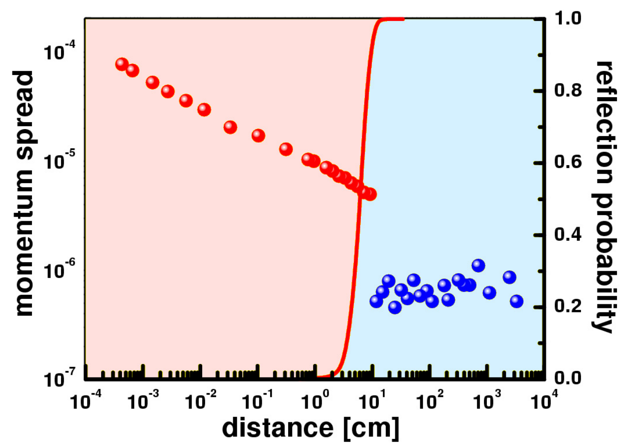

Figure 2: Momentum spreads of an U^{92+} beam at 360 MeV/u. The red line is the calculated reflection probability, see below. After Steck [3] and Hasse [4].

This effect has been detected in the ESR for various ions from protons and carbon up to uranium. Afterwards it was also confirmed in different storage rings like SIS18 at GSI [5], Cryring at Stockholm [6], and, recently, at the S-LSR at ICR, Kyoto University [7].

These results posed a challenge to theory and were soon explained in ref. [4]: If the interparticle distance becomes as small as 10 cm and if the ions are sufficiently cold in the transverse direction then the ions arrange in a string-like fashion and they repel each other rather than passing. Lateron in ref. [8] simple general criteria were derived for the existence of such Coulomb strings which turned to be out to be valid for all storage rings.

SCHOTTKY SIGNALS

A particle passing by at the Schottky pickup induces a signal called the Schottky noise. The theory of Schottky noise has first been applied to stochastic cooling at CERN. It can be found in various CERN accelerator school lectures e.g. by Chattopadhyay [10] or Boussard [11]. For an ideal (hot) gas at high density the signal is proportional to the longitudinal kinetic energy (or temperature),

$$|P_{\rm gas}|^2 \propto T_{||} \,, \qquad (1)$$

LIMITATIONS TO THE OBSERVATION OF BEAM ORDERING

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Abstract

The observation of beam ordering for low intensity cooled ion beams depends on various parameters. Experimental observations concerning the influence of fluctuations of beam energy and magnetic field on the lowest measured momentum spread detected by Schottky noise analysis are reported. Further measurements illustrate the limits due to the sensitivity of the Schottky noise detection system and the resolution of transverse beam size measurements.

INTRODUCTION

Experiments with electron cooled heavy ion beams have evidenced a linear ordering of the ions at low beam intensity. The main criterion was a discontinuous reduction of the momentum spread of the ion beam when the particle number was reduced to a few thousand [1], [2], [3]. Later, a similar reduction of the transverse emittance for these low intensity beams measured by destructive beam scraping confirmed the transition from a gaseous to a liquid-like state with longitudinal ordering [4]. The beam quality in the high intensity gaseous state is determined by an equilibrium between intrabeam scattering and cooling. For the low intensity ordered beam intrabeam scattering is suppressed and the beam temperature is dependent on the ability to provide most powerful cooling in order to achieve lowest beam temperature. The detection of this low beam temperature requires highest stability of all technical systems and diagnostics systems with exceptional resolution for the beam parameters, longitudinal momentum spread and transverse emittance. Therefore the observation of the transition to the ordered state depends on various technical parameters which influence the lowest achievable and detectable beam temperature. In addition a significant increase of beam temperature in the intrabeam scattering dominated regime, which means a large heating rate, is required to distinguish the two regimes. As a consequence, the strongest reduction of the beam temperature was observed for highly charged ions, as for these the intrabeam scattering rate is highest.

INFLUENCE OF INTRABEAM SCATTERING

The transition from the gaseous to the ordered beam state is most pronounced, if the intrabeam scattering rate and therefore also the beam temperature is high. The highest intrabeam scattering rate is achieved, if the ion beam is cooled in full six-dimensional phase space under optimum cooling conditions. An intentional reduction of the cooling rate of the electron cooling system can be easily achieved by a misalignment between the ion and the electron beam in the cooling section. Normally the ion and electron beam are aligned parallel to each other with an angular error of less than 0.1 mrad. The increase of the transverse ion beam emittance caused by the misalignment results in a reduced intrabeam scattering rate. Consequently, the longitudinal momentum spread can be reduced, if the reduction of the longitudinal heating rate outbalances the reduction of the cooling rate due to the misalignment.

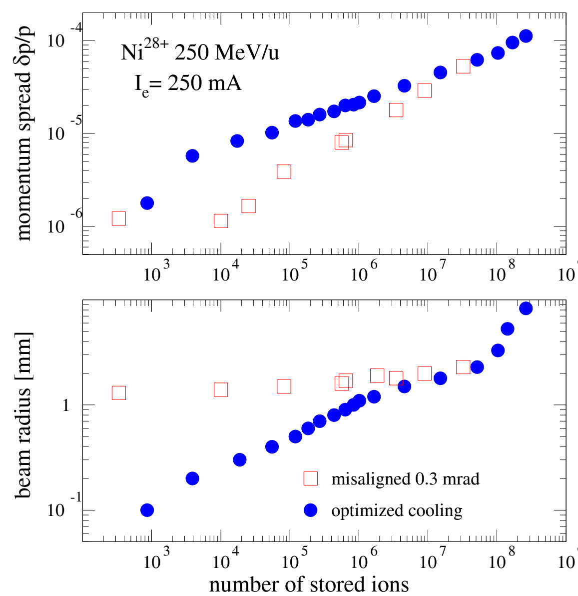

Figure 1: Measurement of the momentum spread and the beam radius of an ion beam ($^{58}Ni^{28+}$ 250 MeV/u) with perfect alignment of ion and electron beam and with an intentional misalignment of the electron beam by 0.3 mrad. At low intensity the ion beam radius is determined by the misalignment angle, whereas an even smaller momentum spread can be achieved with the misaligned electron beam.

The method of intentional misalignment can also be useful if a reduced longitudinal momentum spread at the expense of an increased transverse emittance is beneficial for the experiment. Therefore, with misaligned beams, already at higher ion beam intensity the momentum spread can be as small as the one in the low intensity ordered state (Fig. 1). Even if there is a transition to the ordered state, it cannot be observed in the usual way as a reduction of the

PRESENT STATUS AND RECENT ACTIVITY ON LASER COOLING AT S-LSR *

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Abstract

Laser cooling of an 40 keV 10^8 - $^{24}Mg^+$ ion beam combined with induction deceleration reduced the momentum spread to 2.9×10^{-4} which was limited by intra-beam scattering. An optical observation system for laser cooling applicable for smaller number of ions has been developed and just installed into S-LSR. With the special feature of the S-LSR lattice allowing for reduction of the shear force and with the newly developed optical measurement system, further approaches towards the realization of a multi-dimensional crystalline ion beam are to be started from now on.

INTRODUCTION

At ICR of Kyoto University, an ion storage and cooler ring, S-LSR was constructed between 2001 and 2005 by collaboration with NIRS. Beam commissioning started in October, 2005. Up to now electron cooling of a hot ion beam [1] was studied. At very low proton numbers of 2000, a one dimensional ordered state of a 7 MeV proton beam could be achieved [2]. The onset of transverse coherent instabilities in the vertical direction, induced by electron cooling stacking, could be suppressed by a feedback system [3]. Furthermore the formation of very short bunches could be successfully realized by the application of the bunch rotation method and electron cooling [4]. In addition, the S-LSR is optimized to realize a multi-dimensional crystalline beam with laser cooling [5]. In the present paper, the special feature of the S-LSR in connection with the above motivation is described briefly and then recent experimental results by the laser cooling applied to 40 keV $^{24}Mg^+$ ions are presented together with an overview of the future development.

SPECIAL FEATURE OF S-LSR

Basic Structure

According to the theoretical studies using MD simulations to achieve a crystalline ion beam, the ring has to satisfy the following conditions

$$\gamma \le \gamma_t , \quad (1)$$

$$N_{sp} \ge 2\sqrt{\nu_H{}^2 + \nu_H{}^2} , \quad (2)$$

where γ_t, $\nu_{H,V}$ and N_{sp} are the transition γ of the ring, the betatron tunes in horizontal, vertical directions and the superperiodicity, respectively. Eqs. (1) and (2) represent the so-called formation and maintenance conditions for a crystalline beam, respectively [6,7]. The ring S-LSR is designed with 6-fold symmetry in order to enlarge the region of operation points satisfying the above maintenance condition. A further condition to avoid the

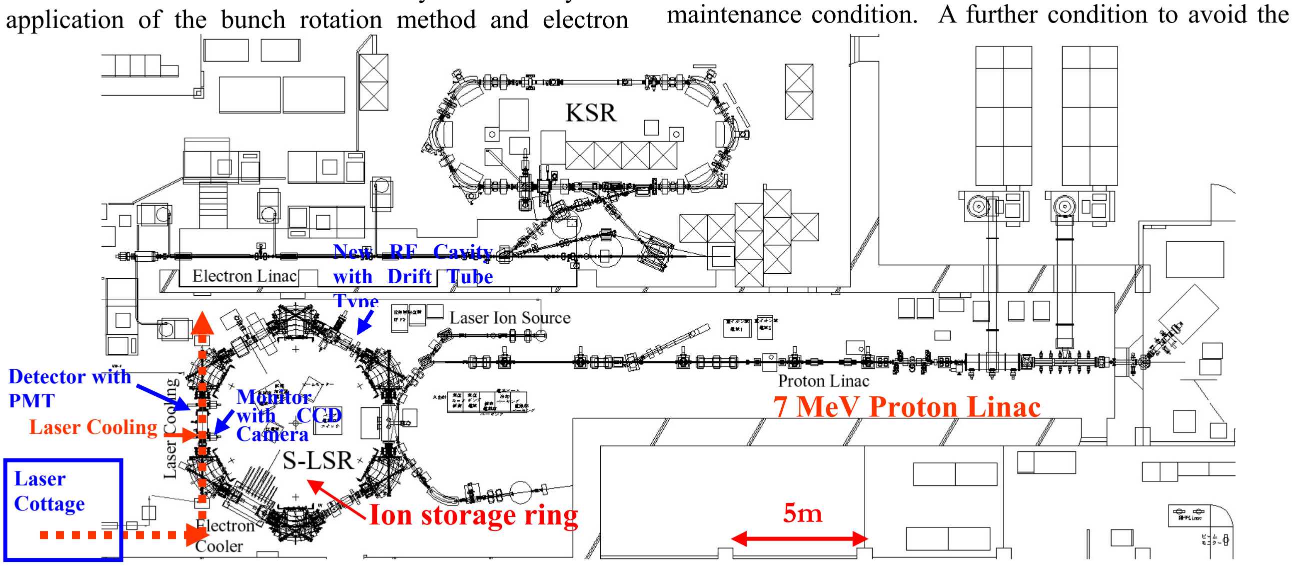

Figure 1: Layout of the radiation controlled experimental room where S-LSR is installed. As the injection beam for S-LSR, 7 MeV proton from the linac and 40 keV $^{24}Mg^+$ ion beam has been utilized up to now.

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SCHOTTKY NOISE SIGNAL AND MOMENTUM SPREAD FOR LASER-COOLED BEAMS AT RELATIVISTIC ENERGIES

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Abstract

We present results on laser-cooling of relativistic bunched $C3^+$ ion beams at the the Experimental Storage Ring at GSI, Darmstadt. With moderate bunching at a few volts, beams of triply charged carbon ions with a beam energy of 122 MeV per nucleon have been laser-cooled to relative longitudinal momentum spreads of about 2×10^{-6} and below at beam currents of the order of several μA. By detuning the bunching frequency relative to the laser frequency, the acceptance range of the laser force can be increased to match the beam momentum spread. Subsequently decreasing the detuning reduces the momentum spread to values below the resolution of the Schottky noise spectrograph. The reduction of the beam momentum spread is accompanied by a drop in the Schottky noise power by seven to eight orders of magnitude until the signal vanishes completely.

INTRODUCTION

The Experimental Storage Ring (ESR) (see Fig.1) establishes an ideal testbed for laser-cooling experiments at relativistic energies using standard laser equipment (see Tab. 1 for experimental parameters). Exploiting the relativistic Doppler-shift of the laser frequency from the laboratory frame to the rest frame of the ions, a variety of ions can be directly laser-cooled using a single laser system and choosing the appropriate beam energy [1]. The results presented in the following serve as a valuable input for laser-cooling experiments at the future FAIR facility [1, 2].

Different to typical laser-cooling setups in traps, for laser cooling of ion beams at relativistic energies, moderately bunching the beam is necessary to provide for a counteracting force to the laser force [3] (see Tab. 1 for a listing of all experimental parameters). The combined force of the bucket and the laser results in a momentum-dependent force with a controllable, stable cooling point in momentum space. For the data sets discussed here, bunching of a few volts was applied at the 20th harmonic of the revolution frequency $f_{\rm rev}$, while the mixing frequency at which the Schottky signal was observed was set to the 47th harmonic.

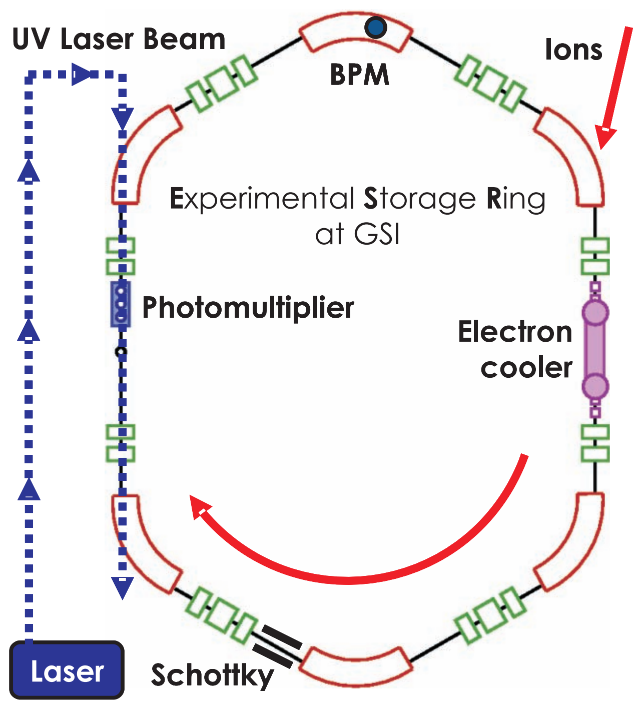

Figure 1: View of the ESR at GSI, Darmstadt. Laser beam and ion beam are brought in overlap in a straight section of the ring. The focus of the laser beam is adjusted to the position of the photomultiplier where the fluorescence signal of the ion beam is recorded. Also marked are the position of the electron cooler, the beam profile monitor (BPM) and the pickup electrode (Schottky). The ions revolve clockwise in the ring, the laser beam is counterpropagating to the ion beam.

A combination of two laser systems, namely two frequency-doubled argon ion lasers, has been used for laser cooling. While the first of the two laser beams is frequency-stabilized by measuring the absorption signal of the beam passing through an iodine vapor cell, the frequency of the

ELECTRON COOLING WITH PHOTOCATHODE ELECTRON BEAMS APPLIED TO SLOW IONS AT TSR AND CSR

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Abstract

We report electron cooling experiments using a cold electron beam of 53 eV produced by a cryogenic GaAs photocathode. With this device a beam of CF^+ (mass 31) of only 97 keV/u (3 MeV) was cooled down to a very small equilibrium beam size of about 0.04×0.2 mm^2. A transverse cooling time below 2 seconds was obtained.

INTRODUCTION

Cold electron beams at low energies are currently a subject of high interest in view of next-generation electrostatic storage rings where electron cooling of very slow ions as well as high-resolution electron-ion merged beam experiments are planned to be performed. The use of electrostatic rings (instead of magnetic ones normally used for lighter high energy beams) is the only possibility to store heavy molecules, clusters and biomolecules. The energies of stored ions in electrostatic rings are about 20-300 keV (per charge state), limited by the maximum voltage applied to the ring optics. Thus velocities of stored heavy molecules are very low.

An electrostatic Cryogenic Storage Ring (CSR) for ion beams, including protons, highly charged ions, and polyatomic molecules, is under construction at MPI-K [1]. Electron cooling at electron beam energies from 165 eV for 300 keV protons down to a few eV for polyatomic singly charged ions will be applied. The quality of an electron beam with respect of density and longitudinal temperature degrades at low energies. Thus electron beams of low emission energy spreads are needed. For the CSR cooler, the cryogenic photocathode source developed for the Heidelberg TSR target [2] will be used to generate electron beams with emission energy spreads of about 10 meV [2,3], that is at least by a factor of 10 better compared to conventional thermocathode sources. At high energies the main drawback of photocathode coolers is the limited extraction current (at the TSR target a maximum current of 1 mA is presently obtained from GaAs source). At low voltages, however, this disadvantage vanishes as the current becomes limited by gun perveance anyway to about 1-2 mA at 100 V.

Electron cooling experiments of slow CF^+ molecules were performed at the Heidelberg TSR target using an ultracold electron beam of 53 eV, produced by a cryogenic GaAs photocathode. A transverse cooling time below 2 seconds to a very small equilibrium beam size was observed with an electron current of 0.3 mA (corresponding to an electron density of about $3\cdot10^6$ cm^{-3})

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LOW-ENERGY ELECTRON BEAMS

The key parameters of electron beams used for ion cooling and merged beam experiments in storage rings are density as well as transverse and longitudinal temperatures. The transverse temperature of the electrons is not affected by electron acceleration and it can be reduced by an adiabatic magnetic expansion α down to $kT_\perp = kT_c/\alpha$ [4], where T_c is the cathode temperature. The use of a cryogenic photocathode source makes it possible to obtain transverse temperatures below 1 meV [2]. The longitudinal temperature and density of the electron beams, however, degrade strongly at low energies. Indeed, the electron current I and density n_e are limited by gun perveance P (with typical values of about 1-2 μPerv):

$$n_e = \frac{4PU}{\pi D^2 e\sqrt{2\eta}} \approx 6\times10^6\ cm^{-3}\left(\frac{P}{1\,\mu Perv}\frac{U}{100V}\right)\left(\frac{15mm}{D}\right)^2$$

$$I = PU^{3/2} = 1mA\left(\frac{P}{1\,\mu Perv}\right)\left(\frac{U}{100\ V}\right)^{3/2}, \quad (1)$$

where D is the diameter of the electron beam in the interaction section.

The longitudinal electron temperature $kT_{||}$ of the electron beam is described by the following expression:

$$kT_{||} \approx \frac{(kT_C)^2}{W} + C\frac{e^2 n_e^{1/3}}{4\pi\varepsilon_0}, \quad (2)$$

where $W=e\cdot U$ is the electron energy and C is the acceleration constant. The first term is due to kinematic transformation of the electron temperature from the laboratory to the co-moving system. It is also taking into consideration that the part of the transverse energy is transferred to the longitudinal temperature during adiabatic magnetic expansion increasing the first term by a factor of about 2 [5]. The second, density term, is connected to a relaxation of the potential energy of the accelerated beam [6]. The acceleration constant C for high acceleration voltages was found to be of about 1.9 [6]. Our studies (work in progress) show, however, that a value of about 0.9 appears to be more appropriate for the C constant. Moreover, for low energies with the first term being dominant the description of the longitudinal temperature for different acceleration energies with a fixed value of C is found to be inaccurate. Figure 1 shows the longitudinal temperatures of electron beams as a function of the kinetic energy calculated for thermocathode (kT_c=100 meV) and photocathode (kT_c=10 meV) electron sources. For the calculations we assumed a gun perveance of 2 μPerv and a beam diameter of 13.5 mm. We see that for the thermocathode the longitudinal

STUDIES OF COOLING AND DECELERATION AT CRYRING FOR FLAIR

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Abstract

FLAIR will be a facility for low-energy ions and antiprotons at FAIR, the proposed centre for nuclear and hadron physics in Darmstadt, Germany. As a preparation for a possible transfer of CRYRING from the Manne Siegbahn Laboratory to FLAIR, where it would serve to decelerate antiprotons and ions, machine studies have been performed at CRYRING to ensure that that it meets the requirements at FLAIR. In these experiments, the space-charge limit for protons at 300 keV, cooling times for H^- ions and deceleration of protons from 30 MeV to 300 keV have been investigated. It is found that CRYRING as it is configured already today can decelerate more than 3×10^8 protons from 30 MeV to 300 keV.

FLAIR

At FAIR [1], the proposed new centre for nuclear and hadron physics in Darmstadt, Germany, antiprotons will be produced at rates at least as high as at CERN during the time of operation of the proton–antiproton collider, and much higher than today's rates at the antiproton decelerator AD. Also, beams of radioactive ions will be available at intensities far superior to those at RIB facilities like GSI today. While much of the physics at FAIR will use these beams of antiprotons and ions at high energies, FLAIR, the Facility for Low-energy Antiproton and Ion Research [2], will give the possibility to make experiments with antiprotons and ions at very low energy, or even at rest.

Figure 1: Layout of the FLAIR hall.

FLAIR was not part of the original conceptual design report for FAIR that was submitted to the German government in 2003. Since then, however, a thorough review has been made of the experimental programme at FAIR, and the FLAIR proposal has been part of this process. As a result of the very positive review of the physics programme with low-energy antiprotons, and also of the atomic-physics programme within the SPARC [3] collaboration, FLAIR is now part of the proposed core experimental programme at FAIR.

FLAIR will receive beams from a chain of synchrotrons and storage rings at FAIR ending with the NESR ring. These beams can supply FLAIR experiments, including HITRAP, directly, or they can be directed to the first deceleration ring in the FLAIR hall, the LSR (Low Energy Storage ring). Antiprotons will be transferred to LSR at a fixed energy of 30 MeV, and ions will be transported at the same rigidity as 30 MeV antiprotons, independently of their charge-to-mass ratio.

LSR will bring the antiprotons from 30 MeV down to a minimum energy of 300 keV, and ions will be decelerated through the same range of magnetic rigidities. This matches the energy range of CRYRING, which is approximately 200 keV to 96 MeV for (anti-)protons. CRYRING also has the electron cooling required to keep the beam emittance small at deceleration, good vacuum (better than 1×10^{-11} torr N_2-equivalent pressure which is necessary for storing highly charged ions), operational deceleration, easy and frequent shifting between positive and negative particles, etc., and it is therefore proposed that CRYRING will be transferred from the Manne Siegbahn Laboratory to FLAIR for use as the LSR ring.

LSR will provide beams of antiprotons to HITRAP, the electrostatic USR ring or directly to experiments, and the same possibilities will exist for ions. The USR ring will decelerate antiprotons from 300 keV to 20 keV and cool them, and from 20 keV, antiprotons can be brought to rest for capture in traps just by using a small voltage gap. Compared to today's Antiproton Decelerator, AD, at CERN, antiprotons at FLAIR will thus be cooled at much lower energies, providing phase-space densities of very-low-energy antiprotons which are orders of magnitudes higher than at the AD.

Several experiments have been made at CRYRING in order to evaluate its performance relating to deceleration of antiprotons at FLAIR. The throughput of antiprotons

SIMULATION STUDY OF BEAM ACCUMULATION WITH MOVING BARRIER BUCKETS AND ELECTRON COOLING

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Abstract

An effective ion beam accumulation method for the NESR of the FAIR project, is investigated numerically. The principle of the proposed accumulation method is as follows. The ion beam bunch from the Collector Ring is injected in the longitudinal gap prepared by two moving barrier pulses. The injected beam becomes coasting after switching off the barrier voltages and merges with the previously stacked beam. After the momentum spread is well cooled by electron cooling, the barrier voltages are switched on and moved away from each other to prepare the empty space for the next beam injection. This process is repeated to attain the required intensity. We have investigated this stacking process numerically, including Intra Beam Scattering which limits the momentum spread of the stacked beam and hence the stacked particle number in the ring. Calculated results are compared with experimental data from the ESR where a proof of principle experiment of the proposed method was performed. This experiment is described in a companion paper at the present workshop.

INTRODUCTION

The Barrier Bucket (BB) method is a new way of beam manipulation in longitudinal phase space in synchrotrons and storage rings. One important application of the BB method is a beam injection and accumulation into a storage ring with simultaneous use of beam cooling. As an example, we reported a feasibility study of 3 GeV antiproton beam accumulation in a storage ring with use of BB operation and stochastic cooling in the last workshop [1].

In the present paper, we study a scheme of BB operation for the injection and accumulation of rare isotope beams, typically $^{132}Sn^{50+}$ ions, into the storage ring, NESR (New Experimental Storage Ring), which is conceived as a key experimental ring for the FAIR project at GSI [2].

In the scenario of FAIR, a beam of radioactive nuclei is produced through the nuclear reaction of projectile fragmentation of a high energy heavy ion beam with a target nucleus. Among the many kinds of unstable nuclei produced, the required nuclei beam is selected in the fragment separator and is injected into the Collector Ring (CR). In the CR, momentum spread and transverse emittances of the rare isotope beam are cooled down with stochastic cooling. The cooling time in the CR is a key limitation of repetition time for the injection into the NESR. For the $^{132}Sn^{50+}$ beam with 10^8 ions, and an initial relative momentum spread of 10^{-3} (2σ), the e-folding cooling time is estimated at around 2 sec. The pre-cooled rare isotope beam in the CR is re-bunched with RF field of harmonic number h=1, and is fast extracted. If necessary the beam will be decelerated to 100 MeV/u in another storage ring RESR before injection into the NESR.

The accumulated rare isotope beam in NESR will be used for experiments with an internal target or for head on collision experiments with an electron beam or antiproton beam. To achieve high intensity of the rare isotope beam in the NESR in order to realize a sufficient luminosity, a short cycle time and a highly efficient beam accumulation method is required.

In the present paper, a BB method assisted by electron cooling for stacking of the rare isotope beam is investigated from the point of view of beam dynamics and simulation results are presented. The calculated results are compared with experimental data from the ESR where a proof of principle experiment was performed to verify the accumulation method of the present scenario [3].

OPERATION OF BEAM STACKING

Typical beam parameters of the $^{132}Sn^{50+}$ beam from the Collector Ring are tabulated in Table 1.

Table 1: Beam parameters of $^{132}Sn^{50+}$

Beam energy	740 MeV/u
Number of ions	10^8/batch
Momentum spread at coasting (2σ)	0.05%
Beam duration	400 nsec
Energy spread	±0.6 MeV/u
Transverse emittance (H&V)	0.5π·mm·mrad

Several operation schemes of BB stacking are conceivable, e.g. use of a fixed barrier pulse instead of moving barriers, or use of half wavelength barrier pulses instead of full wave length ones. However we believe that the scheme studied here is the most appropriate option. The operation of the barrier pulses during the first Injection

ELECTRON COOLING SIMULATIONS FOR LOW-ENERGY RHIC OPERATION*

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Abstract

Recently, a strong interest emerged in running the Relativistic Heavy Ion Collider (RHIC) at low beam total energies of 2.5-25 GeV/nucleon, substantially lower than the nominal beam total energy of 100 GeV/nucleon. Collisions in this low energy range are motivated by one of the key questions of quantum chromodynamics (QCD) about the existence and location of critical point on the QCD phase diagram. Applying electron cooling directly at these low energies in RHIC would result in significant luminosity increase and long beam stores for physics. Without direct cooling in RHIC at these low energies, beam lifetime and store times are very short, limited by strong transverse and longitudinal intrabeam scattering (IBS). In addition, for the lowest energies of the proposed energy scan, the longitudinal emittance of ions injected from the AGS into RHIC may be too big to fit into the RHIC RF bucket. An improvement in the longitudinal emittance of the ion beam can be provided by an electron cooling system at the AGS injection energy. Simulations of electron cooling both for direct cooling at low energies in RHIC and for injection energy cooling in the AGS were performed and are summarized in this report.

INTRODUCTION

RHIC has completed seven successful physics runs since commissioning in 1999. RHIC was built to study the interactions of quarks and gluons and test QCD, the theory describing these interactions. At RHIC, nuclear matter at energy densities only seen in the very early universe is created with relativistic heavy-ion collisions. It was found that at these very large energy densities the matter equilibrates very rapidly, flows as a nearly perfect liquid (small viscosity), has large color fields, collective excitations, and final hadron distributions that reflect the underlying quark structure.

Exploration of the fundamental questions of QCD at RHIC requires large integrated luminosities, as well as high polarization of proton beams. Equally important is the ability to collide various ion species at the full range of available energies. The planned RHIC upgrades are summarized in Ref. [1]. The major upgrade of RHIC calls for 10-fold increase in the luminosity of Au ions at the top energy of 100 GeV/nucleon (termed RHIC-II). Such a boost in luminosity for RHIC-II is achievable with implementation of high-energy electron cooling which is summarized in a separate report [2].

In addition to RHIC-II program at high energies there is a significant interest in low-energy RHIC collisions in the range of 2.5-25 GeV/nucleon total energy of a single beam, motivated by a search for the QCD phase transition critical point [3, 4]. RHIC data will complement existing fixed-target data from AGS and SPS. In this energy range an energy scan will be conducted over about 7 different energies. Although required integrated luminosities needed in this scan are relatively low (5M events minimum per energy), there are several challenges to operate RHIC at such low energies. To evaluate the severity of these challenges and make projections for low-energy operation there have been two one-day test runs during RHIC operations in 2006 and 2007. Results of these test runs are summarized in Ref. [5].

In this report, we present some results of simulations which were performed to evaluate limitations caused by intrabeam scattering (IBS) at these energies, as well as various schemes of electron cooling systems that could be used to counteract IBS growth. All simulations presented in this report were done using the BETACOOL code [6].

PERFORMANCE AND LUMINOSITY LIMITATIONS

For heavy ions at 2.5 GeV/nucleon (total beam energy) the beam size is larger than the nominal injection energy beam size by over a factor of two. As a result, simply fitting low-energy beam into RHIC aperture is challenging. Luminosity lifetime is limited by IBS. An example of emittance growth due to IBS is shown in Fig. 1 for this lowest energy, corresponding to a beam kinetic energy of E_k=1.57 GeV/nucleon. Simulation parameters are given in Table 1, and the corresponding intensity loss due to IBS is shown in Fig. 2. In these simulations it was assumed that the initial longitudinal emittance of the ion bunch is small enough to fit into the bucket acceptance of 0.08 eV-s. To obtain such small emittance, pre-cooling in AGS before injecting into RHIC may be needed; this is discussed later in this paper.

Table 1: Parameters of Au beam for lowest energy scan.

Parameter	Value
Beam total energy E, GeV/nucleon	2.5
Kinetic energy E_k, GeV/nucleon	1.57
Relativistic γ	2.68
Bunch intensity, 10^9	1.0
Rms momentum spread	4×10^{-4}
Rms bunch length, cm	155
Rms emittance (unnormalized), μm	1.04
RF harmonic	387
RF voltage, kV	300

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