STATUS OF ANTIPROTON ACCUMULATION AND COOLING AT FERMILAB'S RECYCLER*

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Abstract

The Recycler ring is an 8 GeV permanent magnet storage ring where antiprotons are accumulated and prepared for Fermilab's Tevatron Collider program. With the goal of maximizing the integrated luminosity delivered to the experiments, storing, cooling and extracting antiprotons with high efficiency has been pursued.

Over the past two years, while the average accumulation rate doubled, the Recycler continued to operate at a constant level of performance thanks to changes made to the Recycler Electron Cooler (energy stability and regulation, electron beam optics), RF manipulations and operating procedures. In particular, we discuss the current accumulation cycle in which ~400×10^{10} antiprotons are accumulated and extracted to the Tevatron every ~15 hours.

INTRODUCTION

Fermilab's Recycler was designed to provide an additional storage ring for the accumulation of 8 GeV antiprotons [1] and is now a critical component of the accelerator complex, without which the latest initial and integrated luminosity records for a hadron collider would not have been possible. The Recycler receives antiprotons from the Accumulator ring, and, through the combined use of stochastic [2] and electron cooling [3], stores up to 500×10^{10} particles, which are then extracted to the Tevatron collider. Over the past two years, the average antiproton accumulation rate more than doubled, imposing more stringent requirements for cooling and storing in the Recycler.

In this paper we characterize the Recycler performance by considering its ability to maintain the proper throughput of antiprotons in order to optimize the use of the whole accelerator chain, its efficiency storing the antiprotons, and the parameters of the bunches to be extracted to the Tevatron. In particular, we discuss the Recycler Electron Cooler (REC) [4] most recent improvements as well as modifications of the RF manipulations and procedures developed to limit losses.

RECYCLER PERFORMANCE

Accumulation & Cooling Scenario

At Fermilab, antiprotons are produced by striking an Inconel target with 120 GeV protons coming out of the Main Injector every 2.2 s. 8 GeV antiprotons are collected in the Debuncher ring where they are cooled stochastically and then transferred to the Accumulator ring. The rate at which antiprotons are accumulated in the Accumulator is referred to as the stacking rate.

Table 1 summarizes side by side the different running conditions between the summer of 2007 [5,6] and the summer of 2009. Antiprotons are transferred to the Recycler every 30 minutes in sets of two 'parcels' instead of 3 or 4 'parcels' every 2-3 hours two years ago. The transfer efficiency was kept >95%. In turns, the optimum collider store duration was found to be ~15 hours, during which a 'stash' (*i.e.* number of antiprotons stored in the Recycler as opposed to the 'stack' that refers to the Accumulator) of ~400×10^{10} antiprotons is built for extraction to the Tevatron [7].

Table 1: Summary of the Main Antiproton Production Parameters in the Summers of 2007 and 2009

	Summer '07	Summer '09
Average stacking rate, $\times10^{10}$ antiprotons per hour	19	26
Stack size for transfers	45-50$\times10^{10}$	25-30$\times10^{10}$
Frequency of transfers, hr	2-3	0.5
Average stash size	~300×10^{10}	~400×10^{10}
Collider store duration, hr	~25	~15

Figure 1 shows a comparison of the evolution of the number of antiprotons as well as the rms momentum spread during typical accumulation sequences in the Recycler in June 2007 and May 2009. It illustrates the move from larger transfers at large intervals to smaller transfers more often.

After the last transfer from the Accumulator, the longitudinal emittance is reduced to 60-70 eV s (95%) and 94-96% of the beam is 'mined'. Mining is the RF manipulation which takes the stored antiprotons from a single 6.1 μs-long bunch to 9 macro-bunches captured in mini barrier buckets while leaving high momentum particles in the so-called 'hot bucket' [8]. From there, each macro-bunch is successively divided into four 2.5 MHz bunches, which are then extracted to the Main Injector with >98% efficiency and from the Main Injector to the Tevatron for collisions. Note that the time between the last transfer from the Accumulator and extraction to the Tevatron was also diminished considerably as it currently lasts 1-1.5 hours, while 2-2.5 hours were typical 2 years ago.

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ANTIPROTON DECELERATOR STATUS REPORT

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Abstract

The Antiproton Decelerator (AD) has been delivering 5.3 MeV antiprotons to the experiments for 10 years now. Beam cooling is essential for the AD operation. We review the AD machine and in particular the cooling performance. We give an overview of the present and future experiments and also the possible further deceleration of the beam from 5.3 MeV to 100 keV kinetic energy.

INTRODUCTION TO AD

The Antiproton Decelerator (AD) started regular operation [1] in 2000. The AD has been constructed from the parts of the AC machine in order to provide 5.3 MeV antiprotons for initially 3 experiments, ASACUSA, ATRAP and ALPHA. The experiments have the ultimate goal to produce antihydrogen in their trap and measure its properties with spectroscopy in order to verify CPT symmetry with a high precision. ASACUSA has been doing spectroscopy with antiprotonic helium. Later a fourth experiment ACE joined. They have been studying living tissue irradiation with antiprotons in order to investigate the possibility to use antiprotons for cancer therapy. AEgIS is a recently approved fifth experiment aiming to measure directly the effect of the Earth's gravity on antihydrogen. This will be the first experiment of this kind.

THE DECELERATION CYCLE

Antiprotons are produced by sending a 26 GeV/c proton beam onto a water cooled iridium target. Antiprotons on the downstream are focused by a magnetic horn to collect as many as possible. Then a dogleg shaped part of the injection line separates the antiprotons from the other types of particles. Four bunches are injected into the AD ring by a magnetic septum and a kicker. The momentum spread of the beam is large at injection, about a $\pm3\%$. In order to decrease the dp/p to fit more beam inside the momentum acceptance of the stochastic cooling, which is around $\pm1\%$, a bunch rotation is applied. After bunch rotation the dp/p is $\pm1.3\%$. There are two bunch rotation cavities in the ring, each gives about 500 kV at harmonic 6. The cavities are ramped up already when the beam is injected and after a quarter of synchrotron turn they are turned off. The AD cycle has 4 flat parts, these are introduced in order to cool the beam. After injection and the bunch rotation, stochastic cooling is applied at 3.57 GeV/c. The second stochastic cooling process takes place at the 2 GeV/c plateau. The machine operates with two different tunes, one for higher energies and one for lower energies. The tune is changed after the second stochastic cooling. The beam is decelerated to 300 MeV/c where electron cooling is applied. After further deceleration to the final momentum, electron cooling is applied for a second time at 100 MeV/c. Figure 1 shows the AD cycle.

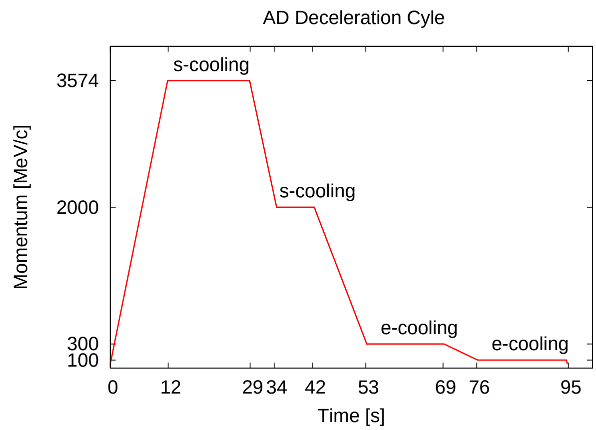

Figure 1: The AD deceleration cycle.

Table 1: AD Main Parameters

Circumference [m]	182
Prod. beam [protons/cycle]	1.3×10^{13}
Injected beam [pbars/cycle]	4×10^{7}
Momentum [GeV/c]	3.57-0.1
ϵ_{tr} $[\pi \times mm \times mrad]$	180-0.8
$\pm$dp/p	$3 \times 10^{-2} - 7 \times 10^{-5}$
Average vacuum [Torr]	4×10^{-10}
Cycle length [s]	96
Dec. efficiency [%]	85

OPERATIONAL PERFORMANCE

The AD operates non-stop during the entire run since 2004. Machine supervisors are working during the day and providing an on-call service outside working hours, including weekends. In the last two years AD suffered several major breakdowns. A consolidation budget and program has been approved in order to improve the reliability of the hardware and make the necessary maintenance and preventive actions. In 2008 the number of injected antiprotons has decreased by 30 %. Many things have been verified in order to find the cause of the lower injected intensity, like injec-

* on behalf of the AD team

ELECTRON COOLING FOR LOW-ENERGY RHIC PROGRAM*

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Abstract

Electron cooling was proposed to increase luminosity of the RHIC collider for heavy ion beam energies below 10 GeV/nucleon. Providing collisions at such energies, termed RHIC "low-energy" operation, will help to answer one of the key questions in the field of QCD about existence and location of critical point on the QCD phase diagram [1-4]. The electron cooling system should deliver electron beam of required good quality over energies of 0.9-5 MeV. Several approaches to provide such cooling were considered. The baseline approach was chosen and design work started. Here we describe the main features of the cooling system and its expected performance.

EXPECTED PERFORMANCE

In a preparation for Low-Energy RHIC physics program, several short test runs were carried out at an intermediate energy point of interest, γ=4.9, for projections of future low-energy RHIC operations [5]. During the first test run with gold ions in June 2007, the beam lifetime was very short and dominated by machine nonlinearities. These nonlinearities were intentionally increased to suppress head-tail instabilities. During the latest test run in March 2008, beam lifetime was improved using a new defocusing sextupole configuration. The store length was extended from 15 minutes in 2007 to 1 hour in 2008 [5].

Some improvements in the useful luminosity are straightforward. For example, doubling the number of bunches (to the nominal 108) will double the event rate. We also expect some improvement in the machine performance with additional tuning. An estimate of run time needed for the proposed low-energy physics program is given in Ref. [6, 7]. Luminosity projections are relatively low for the lowest energy points of interest.

Luminosity decreases as the square of bunch intensity loss due to longitudinal intra beam scattering (IBS) and transverse emittance growth from transverse IBS. Both transverse and longitudinal IBS can be counteracted by electron cooling. This allows one to keep the initial peak luminosity constant throughout the store without beam loss. In addition, the phase-space density of the hadron beams can be further increased by providing stronger electron cooling.

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LUMINOSITY LIMITATIONS

Intra-beam Scattering

IBS is one of the major effects contributing to RHIC heavy ion luminosity degradation, driving bunch length and transverse beam emittance growth. IBS-driven bunch length growth causes beam losses from the RF bucket.

At these low energies, strong IBS growth can be counteracted with electron cooling [6, 8]. If IBS were the only limitation, one could achieve small hadron beam emittance and bunch length with the help of electron cooling, resulting in a dramatic luminosity increase. Unfortunately, the defining limitation is expected to be space charge at the lowest energy points in RHIC.

Space-charge Tune Shift

In circular accelerators, the figure of merit for space-charge effects is the shift of incoherent betatron oscillation frequencies. This is called the "space-charge tune shift". When the space-charge tune shift becomes significant, the beam overlaps many machine imperfection resonances, leading to large beam losses and poor lifetime. For machines where beam spends only tens of msec in high space-charge regime, and machines where the resonances are compensated, the tolerable space-charge tune shift can be as big as ΔQ=0.2-0.5. However the acceptable tune shifts are much smaller for long storage times. In some machines, lifetimes of a few minutes were achieved with tune shifts higher than 0.1. For RHIC, we are interested in much longer lifetimes. As a result, we take space-charge tune shift values of about 0.05 as a limit for our present estimate.

For a Gaussian transverse distribution, the maximum incoherent space-charge tune shift can be estimated:

$$\Delta Q = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{F_c}{B_f}, \tag{1}$$

where F_c is a form factor which includes correction coefficients due to beam pipe image forces (the Laslett coefficients), r_p is the proton classical radius, N_i is the number of ions per bunch, A and Z are the ion atomic and charge numbers, γ, β are relativistic factors, ε is the un-normalized RMS emittance, and B_f is the bunching factor (mean/peak line density). Here we assume F_c =1.

For low-energy RHIC operations, the present RF bucket acceptance is relatively small due to limited RF voltage. The injected ion beam longitudinal emittance is comparable to or larger than the RF bucket acceptance. As a result, the RF bucket is completely filled after injection. For the estimate of the space-charge tune shift ΔQ in this full bucket case, we assume a parabolic ion beam longitudinal profile [9].

APPLICATION OF COOLING METHODS TO NICA PROJECT

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Abstract

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) is a new accelerator complex being constructed at JINR aimed to provide collider experiments with heavy ions up to Uranium at maximum energy (center of mass) equal to 11 GeV/u. It includes new 6.2 MeV/u linac, 600 MeV/u booster synchrotron (Booster), upgraded superconducting (SC) synchrotron Nuclotron and collider consisting of two SC rings, which provide average luminosity of the order of 10^{27}cm^{-2}s^{-1}. A few cooling systems are proposed for the NICA project. The Booster will be equipped with an electron cooling system. Two cooling methods – stochastic and electron ones - will be used at the collider rings. Main parameters of the cooling systems and peculiarities of their design are presented here.

INTRODUCTION

The goal of the NICA project [1] is construction at JINR of the new accelerator facility that consists of (Fig.1)

- cryogenic heavy ion source KRION of Electron String Ion Source (ESIS) type,
- source of polarized protons and deuterons,
- the existing linac LU-20,
- a new heavy ion linear accelerator,
- a new Booster-synchrotron (that will be placed inside of the yoke of the decommissioned Synchrophasotron),
- the existing heavy ion synchrotron Nuclotron (being developed presently to match the project specifications),
- two new superconducting storage rings of the collider,
- new set of transfer channels.

The facility will have to provide ion-ion (1 ÷ 4.5 GeV/u), ion-proton collisions and collisions of polarized proton-proton (5 ÷ 12.6 GeV) and deuteron-deuteron (2 ÷ 5.8 GeV/u) beams. As a result of the project realization, the potential of the Nuclotron accelerator complex will be sufficiently increased in all the fields of its current physics program: both fixed target experiments with slowly extracted beams and experiments with internal target. The Booster will be equipped with a slow extraction system to provide medicine, biological and applied researches.

The collider will have two interaction points. The Multi Purpose Detector (MPD) aimed for experimental studies of hot and dense strongly interacting QCD matter and search for possible manifestation of signs of the mixed phase and critical endpoint in heavy ion collisions, is located in one of them. The second one is used for the Spin Physics Detector (SPD).

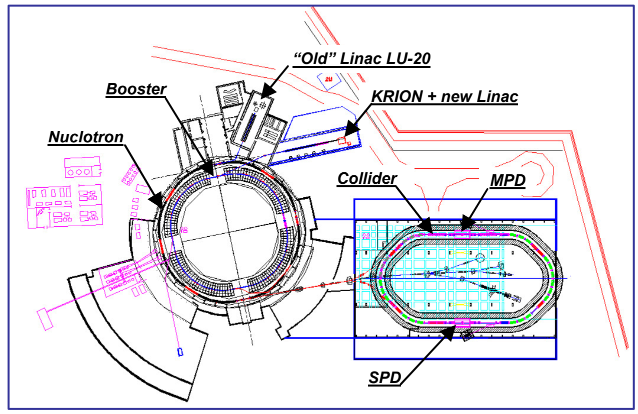

Figure 1: Schematics of the NICA accelerator complex.

Collider will be operated at a fixed energy without acceleration of an injected beam. Correspondingly the maximum energy of the experiment is determined by the Nuclotron magnetic rigidity that is equal to about 45 T·m. Main goal of the NICA facility construction is to provide collider experiment with heavy ions like Au, Pb and U at average luminosity above $1\cdot10^{27}$ cm$^{-2}\cdot$s^{-1} (at the energy of 3.5 GeV/u). Therefore in this report we discussed the heavy ion mode of the facility operation only, and the Gold nuclei $^{197}Au^{79+}$ are chosen as the reference particles.

To reach the required parameters a beam cooling is proposed both in the Booster and in the collider rings. During R&D stage we plan to test a prototype of the stochastic cooling system at the Nuclotron on a magnetic field plateau.

BOOSTER ELECTRON COOLER

The maximum design ion energy of 4.5 GeV/u can be achieved in the Nuclotron with fully stripped ions only. To provide high efficiency of the ion stripping one has to accelerate them up to the energy of a few hundreds of MeV/u. For this purpose a new synchrotron ring – the Booster is planned to be used (Table 1). Heavy ion injector-linac is designed for acceleration of Au^{32+} ions. The Booster has maximum magnetic rigidity of 25 T·m that corresponds to about 600 MeV/u of the ion energy, and the stripping efficiency is no less than 80%.

The Booster is equipped with an electron cooling system that allows providing an efficient cooling of the ions in the energy range from the injection energy up to 100 MeV/u.

The magnetic system of the Booster is superconducting. Its design is based on the experience of construction of the Nuclotron SC magnetic system [2] and SC magnetic system of SIS-100 developed later at FAIR project.

ALL-OPTICAL ION BEAM COOLING AND ONLINE DIAGNOSTICS AT RELATIVISTIC ENERGIES

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Abstract

Recent experiments [1, 2] at the Experimental Storage Ring (ESR) at GSI have shown that relativistic Li-like C^{3+} ion beams can be cooled to an unprecedented momentum spread of $\Delta p/p \approx 10^{-7}$ using a single-frequency laser tuned to the Doppler-shifted $2S_{1/2} \rightarrow 2P_{1/2}$ and $2S_{1/2} \rightarrow 2P_{3/2}$ atomic transitions.
Although these results encourage the application of laser cooling to beams of other Li-like and Na-like ions at even higher energies as will be available at future storage rings at FAIR (Facility for Antiproton and Ion Research), two major concepts have to be demonstrated experimentally: First, efficient laser cooling of ion beams with large initial momentum spread, thus avoiding additional electron cooling to match the large momentum spread to the usually small momentum acceptance of the laser force. Second, all-optical measurements of the relevant beam parameters, thus overcoming the limited resolution of standard storage ring detectors such as the Schottky pickup electrode at ultra-low momentum spreads. The aim of this paper is to discuss the technical realization of these concepts as planned for an upcoming beam time at ESR.

PROSPECTS OF LASER COOLING ION BEAMS AT RELATIVISTIC ENERGIES

Future ion storage ring facilities such as FAIR will provide access to ultra-high energy beams of stable and rare ions for fundamental research. Many of the experiments planned at these facilities, such as in-ring mass spectrometry of short-lived rare nuclei, tests of strong-field quantum electrodynamics with highly-charged ions or in-beam x-ray spectroscopy of atomic transitions in heavy nuclei will greatly benefit from ion beams with ultra-low momentum spread. When considering relativistic ions at energies of several hundred MeV/u to GeV/u, however, cooling the ion beams to a momentum spread $\Delta p/p$ below 10^{-4} using electron cooling suffers from the fact that the energy transfer in Coulomb collisions between electrons and ions depends on their relative velocity v_{rel} as[1] $dE_{\mathrm{ecool}}/ds \propto v_{\mathrm{rel}}^{-2}$ [3]. At highly relativistic energies, efficient electron cooling thus requires the use of electron beams of several hundred mA and energies of several MeV [4, 5] - therefore electron cooling has been proposed only for the FAIR New Experimental Storage Ring (NESR) and High Energy Storage Ring (HESR) and not for the Schwerionen-Synchrotron SIS100/300.
With laser cooling of ion beams in storage rings, the situation changes drastically. For increasing beam energy the laser cooling force increases both due to the relativistic Doppler shift as well as the properties of the atomic cooling transition of the ion of interest [6, 7]. Unlike to the laser cooling of ions in traps, which is limited to a few ion species due to the lack of suitable laser sources, tuning the laser frequency ω_l in the laboratory frame to the cooling transition frequency in the rest frame $\omega_r = (1+\beta)\gamma\omega_l, \beta = v_{\mathrm{beam}}/c$ via a change in beam energy γ provides for laser cooling of a variety of Li-like and Na-like ions using a single laser system [8]. The saturation of cooling transitions exploiting this relativistic Doppler frequency shift allows for precision spectroscopy for a wide range of wavelengths up to the x-ray spectrum [7, 9, 10].

CHALLENGES OF LASER COOLING ION BEAMS AT RELATIVISTIC ENERGIES

Besides the benefits of laser cooling ion beams, recent results [1, 11] indicate several challenges when considering laser cooling to be applied at future high energy storage rings[2]:

1. Laser cooling is efficient only along the direction of the propagation of the laser beam.

2. Thus, additional coupling between the longitudinal motion of the ions along the beam axis to their transverse betatron motion is required to efficiently cool all three degrees of freedom of the ion motion.

3. At previous beam times at ESR, initial moderate electron cooling of the beam was required to yield enough fluorescence for optical detection, although laser cooling proved to be efficient.

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[1] Here and in the following text we omit the energy dependence of the Coulomb logarithm for the sake of simplicity.

[2] For an in-depth discussion see [8]

IMPROVEMENTS TO THE STACKTAIL AND DEBUNCHER MOMENTUM COOLING SYSTEMS*

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Abstract

Upgrades and improvements to the stacktail and Debuncher momentum cooling systems have contributed to the success of Tevatron Run II. This paper describes measurements and simulations that facilitated achievement of peak stacking rates of $30 \cdot 10^{10}$ hour^{-1} as well as a better understanding of the principles of the system design and operation. The heating of the antiproton core by the stacktail system is a serious limiting factor to the maximum stacking rate. The paper also discusses heating mechanisms and ways to mitigate them.

INTRODUCTION

Antiprotons are produced by a 120 GeV Main Injector proton beam hitting the antiproton production target every 2.2 s. The antiprotons coming out of the target are focused by the lithium lens to the AP-2 line and transported to the Debuncher where they are stochastically precooled. They are then transferred to the Accumulator where they are momentum-cooled into a dense core by stochastic cooling systems. The stacking rate decreases with stack size, therefore after achieving a stack size of about $30 \cdot 10^{10}$ antiprotons, they are transferred to the Recycler. In the Recycler, the antiprotons are cooled using both stochastic and electron cooling, to be used for collider operations.

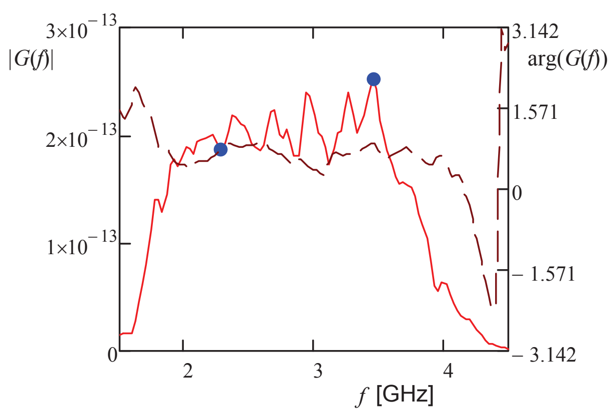

Figure 1: Dependence of the magnitude and phase of the total stacktail gain on frequency after equalizer installation for the revolution frequency 628830 Hz.

The sequence of upgrades carried out over the last 3 years and their results are presented in Refs. [1] and [2]. Here we mention only two the most important ones: a correction of the system gain with an equalizer and an increase of the lattice slip factor [4]. The magnitude and phase of the total stacktail gain after the equalizer installation are shown in Figure 1. The slip factor increase resulted in the bands being close to overlap at the high frequency end. The upgrades resulted in an increase of the peak stacking rate from $20 \cdot 10^{10}$ to $30 \cdot 10^{10}$ hour^{-1}. That is quite close to expectations based on model prediction. Recent developments of the stochastic cooling theory [3, 4] have been extremely useful in choosing the upgrade path and to follow up the problems encountered along the way. In this paper we discuss the present stacking rate limitations and possible ways to overcome them.

STACKING IN THE ACCUMULATOR

Figure 2 presents measured and simulated particle distributions during the first 100 s of stacking in the Accumulator. The measurements were performed by recording the beam Schottky noise of the longitudinal Schottky monitor operating at the 126th harmonic of the revolution frequency (~79 MHz). The signal was mixed down and digitized during the 100 s period by an 8 bit digital scope with a sampling rate of 156 kHz. The data were split into arrays belonging to different stacking cycles (2.2 s long). Then, each stacking cycle data were additionally split into 160 arrays with a length of 2048 words and subjected to the FFT. Averaging 16 consecutive spectra resulted in 10 Schottky noise spectra per stacking cycle. A low pass filter installed before the digitizer reduced the core signal and allowed us to achieve the required dynamic range with only an 8 bit scope resolution. The effect of the filter is visible in Figure 2 as a noise floor that increases with frequency.

The stacking process has the following steps. First, antiprotons precooled in the Debuncher are transferred to the Accumulator. They arrive at the deposition orbit with a revolution frequency of 628756 Hz. There are $\sim 2.3 \cdot 10^8$ antiprotons in one transfer with rms revolution frequency spread of 3 Hz. Then, the injected antiprotons are RF displaced to the deposition frequency of 628831 Hz. The width of the RF bucket is chosen to maximize the stacking rate. This results in about ~2% of the injected particles being left at the deposition orbit. They are presented as a small peak in the spectrum at the frequency of 628750 Hz. The large peak represents the injected beam. The stacktail system pulls the injected particles into the core located at 628897 Hz. One can see a step by step propagation of particles to the core in Figure 2. The particles which were not moved out of the deposition region before the next pulse arrives are RF displaced in

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PROTOTYPE PICK-UP TANK FOR CR STOCHASTIC COOLING AT FAIR*

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Abstract

A prototype pick-up tank for stochastic precooling in the CR storage ring of the FAIR project at GSI was built. It will be equipped with movable electrodes driven by linear motors. The electrodes can be operated at cryogenic temperatures. The design of the tank and first test measurements are presented.

INTRODUCTION

The Collector Ring CR [1, 2] is a storage ring within the FAIR project at GSI which has three purposes: stochastic cooling of radioactive ion beams, stochastic cooling of antiproton beams, and nuclear mass measurements of short-lived nuclei in an isochronous optical setting. These beams are injected at high emittances and momentum spreads immediately after production. They have a short bunch length of about 50 ns; their momentum spread is therefore reduced by bunch rotation and subsequent adiabatic debunching. Two different optical settings are required for ions and antiprotons. Due to their different energies, the frequency slip factors must be different in order to achieve optimum conditions for stochastic cooling.

Table 1: Basic Parameters of the CR

	rare isotopes	antiprotons
circumference	216.25 m	
max. magnetic rigidity	13 Tm	
energy	740 MeV/u	3.0 GeV
Lorentz β	0.83	0.97
Lorentz γ	1.80	4.20
max. number of particles	$1 \cdot 10^9$	$1 \cdot 10^8$
charge state	up to 92	-1

The beam parameters after adiabatic debunching and at the end of the cooling process are listed in Table 1. Three pick-up tanks and three kicker tanks will be installed at locations of zero dispersion in the long straight sections. A further pick-up tank is needed for Palmer cooling of radioactive beams, which is located in an arc at high dispersion.

Here we discuss the prototype design of a pick-up tank at zero dispersion. The design is made such that it could serve as either a horizontal pick-up or, after rotation by 90 degrees, as a vertical pick-up.

Table 2 displays the initial and final beam parameters for rare isotope and antiproton beams. In order to reach the required final emittances, a good signal-to noise ratio is indispensable. Therefore a tank design with movable (plunging) electrodes was adopted.

Table 2: Initial and Final Beam Parameters for CR

	rare isotopes	
	$\delta p/p$ (2σ)	ϵ_{xy} [mm mrad]
injected	1.5 %	200
debunched	0.4 %	200
cooled	0.05 %	0.5
total cooling time [s]	1.5	
	antiprotons	
	$\delta p/p$ (2σ)	ϵ_{xy} [mm mrad]
injected	3.0 %	240
debunched	0.7 %	240
cooled	0.1 %	5
total cooling time [s]	10	

The layout of the straight sections in the CR follows a FODO design [3]. Along the length of the 2m long pick-up tank, the slope of the betatron function is non-negligible, and the beam envelopes change substantially. Table 3 lists the vertical radius inside the pick-ups P1 and P2 in the beginning and at the end of cooling, both at the entrance and the exit of the tank. Table 4 shows the analogous data for the tank P3, where the electrodes are arranged horizontally. The signal from these tanks is produced by electrodes arranged above and below the beam (vertical pick-up). In the course of the cooling process the beam size decreases substantially, in particular for the radioactive beams.

Table 3: Vertical Beam Radius (in mm) for Pick-ups P1 and P2

	P1			
	initial		final	
	entrance	exit	entrance	exit
pbar	56	41	8	6
RIB	58	49	3	3
	P2			
	initial		final	
	entrance	exit	entrance	exit
pbar	37	43	6	6
RIB	42	52	2	3

Table 4: Horizontal Beam Radius (in mm) for Pick-up P3

	initial		final	
	entrance	exit	entrance	exit
pbar	52	40	7	6
RIB	57	47	3	2

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

TWENTY-FIVE YEARS OF STOCHASTIC COOLING EXPERIENCE AT FERMILAB*

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Abstract

In the early 1980s, it was decided that Fermilab would build a proton antiproton collider to search for the top quark following the success at CERN with the discovery of the W and Z bosons in the SPS pbar p collider. The effort was designated the Tevatron I project. Design of the antiproton source began in earnest in 1981 with a construction start in 1983. The Tevatron started fixed target operations that same year. The first antiprotons were delivered to the Tevatron in October of 1985 and first collisions were observed in the CDF detector. The Antiproton Source consists of two 8 GeV kinetic energy accelerators, the Debuncher and Accumulator. The Debuncher ring performs bunch rotation and pre-cooling, the Accumulator ring utilizes stochastic cooling for antiproton collection. The addition of the Recycler ring (also 8 GeV) in 2003 as a depository for antiprotons changed the scope of cooling in the Accumulator. This paper will present the chronology of the cooling systems development from those early days to the current record setting performance.

DEBUNCHER COOLING SYSTEMS

The original design of the stochastic cooling systems in the Debuncher included only transverse cooling operating from 2-4 GHz.[1, 2] Incoming flux was predicted to be 3×10^7 pbars per second, but was significantly lower due to insufficient protons on target. Bunch rotation and longitudinal cooling takes the incoming 4.25% momentum spread and reduces it to 0.037%. The acceptance of the Debuncher was designed at 20π mm-mrad in both planes and has been improved with lattice modifications and careful placement of aperture restricting devices to 35π. The horizontal and vertical cooling reduces the beam to under 2π mm-mrad. With the expected flux, it was clear from the outset that front-end effective noise temperature of the stochastic cooling systems would need to be significantly below tunnel temperature of 311^{O}K. The original Debuncher stochastic cooling systems employed liquid nitrogen to cool the pickups and amplifiers to 80^{O}K. Total front-end effective noise temperatures were of the order of 120^{O} K.

A significant upgrade to the cooling system was begun in 1996 and completed in 1998 with increased bandwidth to 4-8 GHz. [3] The octave band is split into eight 500 MHz wide bands for the pickups then combined to four 1 GHz bands for the kickers utilizing slotted waveguide structures. [4] This decision was based on minimizing the number of cold to warm transitions on the cryogenic pickups, and the need for more kicker drive ports. The slotted waveguide structure bandwidth is dependent on the length of the array, facilitating this requirement. Liquid helium cooled pickups, amplifiers, and components [5] are responsible for a front-end effective noise temperature ranging from 10^{O}K to 30^{O}K. [6] This four to ten fold decrease in effective noise temperature dramatically improved cooling performance. With an enhanced S/N ratio, it was now possible to make beam transfer function measurements with pbars. Prior to this upgrade, the only way transfer functions could be measured was to reverse magnet polarity and inject forward protons, a cumbersome effort taking two to three days to complete.

Momentum cooling was realized by using the same pickups and kickers simultaneously in sum and difference mode. Unlike the accumulator, where high dispersion straights are available for utilizing Palmer cooling, notch filter cooling was implemented for momentum cooling. The first notch filter consisted of four independent Bulk Acoustic Wave (BAW) delays. Momentum spread now became sufficiently narrow that small drifts in notch filter frequency between the four systems became problematic limiting the asymptotic momentum spread. A solution was to combine all four bands of momentum cooling into one trunk, then passing through an octave wide optical notch filter, splitting back into separate bands, effectively eliminating notch frequency drift between bands. The Debuncher Momentum system has been upgraded to a single/double turn optical notch filter. After the first second of the cooling cycle, a single turn delay is switched to a double turn increasing the gain near the central momentum. The resulting momentum spread being 3.26 MeV/c (0.037%). An automated tuning program is run periodically to adjust the filter to the correct revolution frequency, typically only a few picoseconds of adjustment.

Because the tune of the Debuncher is close to the three quarter integer, it is possible to improve system signal to noise in the transverse cooling with the addition of two turn delay notch filters. These filters suppress any common mode signal from the pickup and notch thermal noise between bands where no Schottky signal exists, all while providing balanced gain and phase to the desired transverse Schottky signal.

The upgrade consists of eight each cryogenically cooled pickup tanks and water-cooled kicker tanks. Sixty-four 200 Watt traveling wave tube amplifiers (TWT) running at the 1 dB compression point drive the kicker tanks.

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NUMERICAL DESIGN STUDY OF STOCHASTIC STACKING OF 3 GEV ANTI-PROTON BEAM IN THE RESR FOR THE FAIR PROJECT

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Abstract

The accumulation of anti-proton beam up to the 1e11 particles with high density in longitudinal phase space is planned at the FAIR project. Following the experiences at CERN and FNAL, the accumulation with stochastic stacking method will be employed at the accumulator ring RESR. In the present paper, firstly the characteristics of incoming anti-proton beams are given as well as the basic design parameters obtained from the analytical method. Then the stochastic stacking process is numerically investigated with use of Fokker-Planck approach. The key elements for the stacking process are explained and then some results of simulation of stacking are described.

INTRODUCTION

At the FAIR project, the sequence of anti-proton production, cooling and stacking is as follows. Proton beam is accelerated at the SIS100 up to 29 GeV with the intensity of 2e13 per 10 sec. After passing through the production target of nickel, the anti-proton flux of 4e8 is produced within the transverse emittance of 240 π mm.mrad and the momentum spread of +/- 3% (uniform). The bunch length from the SIS100 is +/- 25 n sec. Thus produced anti-proton beam is injected into the Collector Ring (CR) with the circumference of 216.25 m and the ring slipping factor of 0.0107. In the CR the injected bunch is rotated to reduce the momentum spread from +/- 3 % (uniform) to 2.45e-3 (rms) with use of harmonic=1 RF of 100 kV. Subsequently the stochastic cooling is applied to further reduce the momentum spread to 5.0e-4 (rms) with the notch filter cooling system of band width 1-2 GHz and the microwave power 1.2 kW. The transverse cooling system is also envisaged to reduce the emittance from 240 π mm.mrad to 5 π mm.mrad.

The stacking ring, RESR, has a little bit larger circumference 239.9 m comparing with that of CR, and the ring slipping factor is adjustable from 0.03 to 0.11. The stochastic stacking system is in principle similar to those at CERN AAC and FNAL AS. The anti-proton beam is injected on the injection orbit of the RESR, and is accelerated to the deposit orbit which aparts from the injection orbit by around Δp/p=1.0 %. There prepared a stochastic stacking system, being composed of radial aligned two tails and core cooling system.

The goal of the RESR stacking system is to stack the 1e11 particles in the core region with the deposited particle number 1e8 from the CR Ring. While the cycle time is planned at 10 sec at the 1st phase of the project, it will be shortened to 5 sec at the goal. Then all the stacking system have to be designed to accommodate this final goal.

SIMPLIFIED ANALYTICAL APPROACH

A simplified theoretical model of the stacking process was developed by van der Meer [1]. It is based upon the assumptions that the voltage on the kicker is exactly in phase with the particles, and the diffusion terms by electronic noise, and intra-beam scattering effects are neglected. In addition the beam feedback effects and the difficulty of achieving the designed coherent term is not taken into account. While these assumptions are not fulfilled in the real stacking system, the simplified approach could give some basic parameters of the stacking system.

The stacked beam profile and the required voltage gain/turn to attain this profile are given as

$$\Psi(E)=\Psi_1 \exp(E-E_1)/E_d]$$

$$V(E)=2\phi_0 T/\Psi_1 \exp[(E_1-E)/E_d] \quad (1)$$

where E_1 and Ψ_1 are the deposit energy and particle density. At the numerical calculation, Ψ_1 is given by $N/\Delta E_1$ where N is the deposited particle number and ΔE_1 is energy width (4 sigma) of the newly deposited batch. Ed is the characteristic energy defining the exponential profile of density and voltage gain.

$$E_d=4A\phi_0 T^2=\beta pc\Lambda\phi_0/TW^2\eta \quad (2)$$

with the particle flux which can be transported

$$\phi_0=TW^2\eta E_d/\beta pc\Lambda \quad (3)$$

where

$$A=\beta pc\Lambda/4T^3W^2\eta$$
$$\beta=v/c,\ W=Bandwidth\ (f_{min}-f_{max}),\ \Lambda=ln(f_{max}/f_{min})$$
$$T=Revolution\ period,\ \eta=1/\gamma^2-1/\gamma^2_t$$

The required total width of the stack region is given by

$$\Delta E_{stack}=E_d \ln(\Psi_2/\Psi_1) \quad (4)$$

where Ψ_2 is a particle density at the core region. Thus obtained exponential profile of density and gain

MUON COOLING R&D FOR THE MUON COLLIDER - A 5 YEAR PLAN FOR THE US *

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Abstract

The Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task Force have recently submitted a proposal to the US Department of Energy Office of High Energy Physics to deliver a Design Feasibility Study for a Muon Collider after a 5 year R&D program. This paper presents a brief physics motivation for and the description of a Muon Collider facility and then discusses in some detail the technical components of the proposal with respect to the muon ionization cooling R&D needed for an Energy-Frontier, high luminosity Muon Collider.

INTRODUCTION

The physics potential of a high-energy lepton collider has captured the imagination of the high energy physics community. Understanding the mechanism behind mass generation and electroweak symmetry breaking, searching for, and perhaps discovering, supersymmetric particles and confirming their supersymmetric nature, and hunting for signs of extra space-time dimensions and quantum gravity, constitute some of the major physics goals of any new lepton collider. In addition, making precision measurements of standard model processes will open windows on physics at energy scales beyond our direct reach. Sensitivity to the unexpected is, of course, of fundamental importance. The Muon Collider (MC) provides a possible realization of a multi-TeV lepton collider, and hence a way to explore new territory beyond the reach of present colliders. A muon accelerator facility also presents the opportunity to explore new physics within in a number of programs.

A schematic that shows the evolution of a muon accelerator complex which ultimately reaches a multi-TeV Muon Collider [1] is shown schematically in Fig. 1. The front-end of the facility provides an intense muon source that can perhaps support both an energy-frontier Muon Collider and a Neutrino Factory (NF). The muon source is designed to deliver $O(10^{21})$ low energy muons per year within the acceptance of the accelerator system, and consists of (*i*) a multi-MW proton source delivering a multi-GeV proton beam onto a liquid Mercury pion production target, (*ii*) a high-field target solenoid that radially confines the secondary charged pions, (*iii*) a long solenoidal channel in which the pions decay to produce positive and negative muons, (*iv*) a system of RF cavities in a solenoidal channel that capture the muons in bunches and reduce their energy spread (phase rotation), and (*v*) a muon ionization cooling channel that reduces the transverse phase space occupied by the beam by a factor of a few in each transverse direction. At this point the beam will fit within the acceptance of an accelerator for a Neutrino Factory. However, to obtain sufficient luminosity, a Muon Collider requires a great deal more muon cooling. In particular, the 6D phase-space must be reduced by $O(10^6)$, which requires a longer and more complex cooling channel. Finally after the cooling channel, the muons are accelerated to the desired energy and injected into a decay (NF) or storage ring (MC). In a Neutrino Factory the ring has long straight sections in which the neutrino beam is formed by the decaying muons. In a Muon Collider, positive and negative muons are injected in opposite directions and collide for about 1000 turns before the luminosity becomes marginalized due to the muon decays.

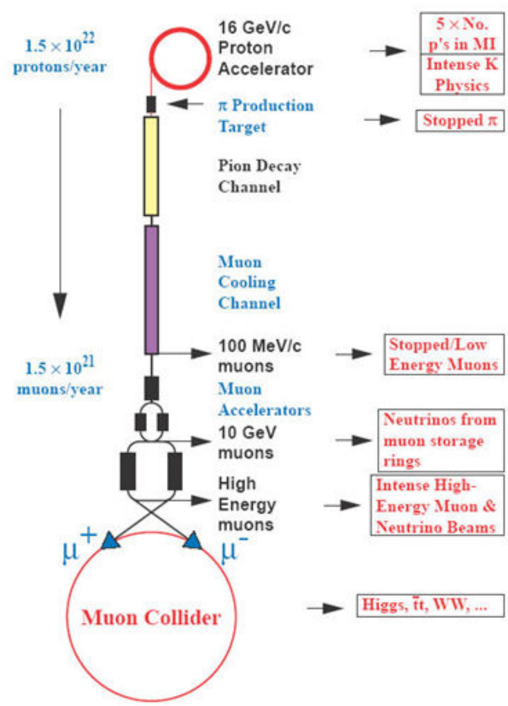

Figure 1: Schematic of muon acceleration complex.

6 D COOLING FOR THE MUON COLLIDER

Overview

Intense 6D cooling for the Muon Collider is not yet under experimental study, but is being modeled, studied with theoretical and computation tools and an

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ENHANCED OPTICAL COOLING OF MUON BEAMS

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Abstract

The possibility of the Enhanced Optical Cooling (EOC) of muon beams in storage rings is investigated.

INTRODUCTION

Muon in motion has a lifetime $\tau_\mu = \tau_{\mu,0}\gamma$, where $\tau_{\mu,0} \cong 2.2\mu\, s$ is the muon lifetime at rest, $\gamma = \varepsilon / m_{\mu,0}c^2$, ε stands for muon energy. During this time, muons can develop $N_\mu\big|_{\gamma>>1} = \tau_\mu c / C \cong 297\overline{B}(T)$ revolutions in a storage ring having the orbit circumference C and average magnetic field strength $\overline{B}$. Damping time of the muon beam in a storage ring must be much smaller than the muon decay time: $\tau < \tau_\mu$. This is the most severe limitation on the muon cooling in storage rings. Enhanced (fast) Optical Cooling methods must be used in this case.

Below we investigate the possibility of muon cooling in a storage ring using version 1, section 3 of EOC [1].

COOLING SCHEME

Stochastic cooling (SC) and optical stochastic cooling (OSC) of particle beams in rings were considered in [2] - [4]. Our scheme is close to the OSC one. It includes a storage ring, pickup and kicker undulators installed in straight sections of the ring, an optical system which includes an optical filter, an optical parametric amplifier (OPA) [1]. It also includes a procedure and adequate hardware for selection of undulator radiation (UR) wavelets (URW) emitted by particles in the pickup undulator. This selection is arranged by means of a screen installed at the image plane of the optical system connecting the pickup and kicker undulators.

Maximal rate of energy loss for a particle in the combined fields of one helical kicker undulator and URW amplified in OPA is

$$P^{\max}_{loss} = -eE^{cl}_w L_u \beta_{\perp m} f\, \Phi(N^{cl}_{ph})\sqrt{\alpha_{ampl}} \quad \text{or}$$

$$P^{\max}_{loss} = \frac{2\sqrt{2}\pi e^2 \gamma f\, K^2 \sqrt{M}\,\Phi(N^{cl}_{ph})\sqrt{\alpha_{ampl}}}{(1+K^2)^{3/2}\sigma_w}, \qquad (1)$$

where $E^{cl}_w = \sqrt{2} r_\mu \gamma^2 \sqrt{\overline{B^2}} / (1+K^2)^{3/2}\sqrt{M}\sigma_w$ is the electric field strength related to the first harmonic of the undulator radiation emitted by a particle in the pickup undulator within the frequency band $\Delta\omega/\omega = 1/2M$ calculated in the framework of the classical electrodynamics (CED), $K = e\sqrt{\overline{B^2}}\lambda_u / 2\pi m_\mu c^2$, $\sqrt{\overline{B^2}}$ is the undulator r.m.s. magnetic field strength, $\beta_{\perp m} = K/\gamma$, $\Phi(N^{cl}_{ph})|_{N^{cl}_{ph}<1} = \sqrt{N^{cl}_{ph}}$, $N^{cl}_{ph} = \pi\alpha K^2 / (1+K^2)$ is the number of photons emitted by one particle in the URW, M is the number of the undulator periods, $L_u = M\lambda_u$, λ_u is the undulator period, α_{ampl} is the gain in OPA, f is the revolution frequency, σ_w is the waist size of the URW. Function $\Phi(N^{cl}_{ph})$ takes into account the quantum nature of the particle emission of the electromagnetic radiation. It radiates on average one photon per $1/N^{cl}_{ph}$ pass throw pickup undulator in the photon energy interval $\Delta(\hbar\omega)/\hbar\omega = 1/2M$ near the maximum photon energy $\hbar\omega_{\max}$. Contrary, in this case the electric field strength and the stimulated energy transfer in the kicker undulator are only $1/\sqrt{N^{cl}_{ph}}$ times bigger than the ones calculated in the framework of CED.

We suggested that the density of the energy in the URW emitted by a particle, is approximated by Gaussian distribution with a waist size $\sigma_w > \sigma^\mu_{x,\,z}$, $\sigma_{w,c}$ within the length $2M\lambda_{1\min}$, where $\sigma^\mu_{x,\,z}$, are the transverse beam dimensions; a value $\sigma_{w,c} = \sqrt{L_u \lambda_{1\min}/8\pi}$ is the waist size corresponding to $Z_R = L_u/2$; the Rayleigh length $Z_R = 4\pi\sigma^2_w / \lambda_{1\min}$, $\lambda_{1\min} = \lambda_1|_{\theta=0}$, $\lambda_1 = \lambda_u(1+K^2+\vartheta^2)/2\gamma^2$ is the wavelength of the first harmonic of the UR emitted at the angle θ, counted between the vector of particle average velocity in the undulator and the direction to the observation point, $\vartheta = \gamma\theta$.

The damping times for the particle beam in the longitudinal and transverse planes are [1]

$$\tau_\varepsilon = \frac{6\sigma_{\varepsilon,0}}{P^{\max}_{loss}\cdot N_k} = \frac{3\sqrt{2}(1+K^2)^{3/2}T\sigma_w\sigma_{\varepsilon,0}}{2\pi r_e mc^2\gamma K^2\sqrt{M}\,\Phi(N^{cl}_{ph})N_k\sqrt{\alpha_{ampl}}},$$

$$\tau_x = \tau_\varepsilon \frac{\sigma_{x,0}}{\sigma_{x_\eta,0}}, \qquad (2)$$

where $\sigma_{\varepsilon,0}$ is the initial energy spread of the particle beam, $\sigma_{x_\eta,0} = \eta_{x,k}\beta^{-2}(\sigma_{\varepsilon,0}/\varepsilon_s)$, $\sigma_{x,0} = \sqrt{\beta_{x,k}\in_x}$ are the initial radial beam sizes in kicker undulator determined by the energy spread and the spread of betatron amplitudes, $\eta_{x,\,k}$, $\beta_{x,k}$ are the ring dispersion and beta functions at the kicker undulator, $\in_{x,0}$ is the initial radial emittance of the beam, N_k is the number of kicker undulators, $T = 1/f$, the product $r_e m_e c^2 = e^2$ of the electron radius and mass are introduced for the convenience. Note, that the damping time for the transverse direction is proportional to $\beta_{x,\,k}/\eta_{x,\,k}$. Factor 6 in (2) takes into account a

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FRICTIONAL COOLING DEMONSTRATION AT MPP

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Abstract

Frictional Cooling holds promise for delivering beams with a very narrow energy spread. At the Max Planck Institute for Physics (MPP), a demonstration experiment based on this scheme will soon take data. In this paper, the experimental setup and the Monte-Carlo simulation results based on Geant4 are described. The use of frictional cooling as an efficient scheme for producing a low energy muon beam is also simulated yielding a beam with mean energy of 3 keV and an RMS of ~300 eV with an efficiency significantly improved from the current scheme.

FRICTIONAL COOLING

The idea of Frictional Cooling is to bring charged particles into a kinetic energy range where the faster particles lose more energy per distance traveled than slower ones [1]. This is done by passing the beam through a gas. Fig. 1 shows the stopping power for μ^+ in Helium as a function of kinetic energy. For kinetic energies below 10 keV, the stopping power increases with increasing energy. Applying

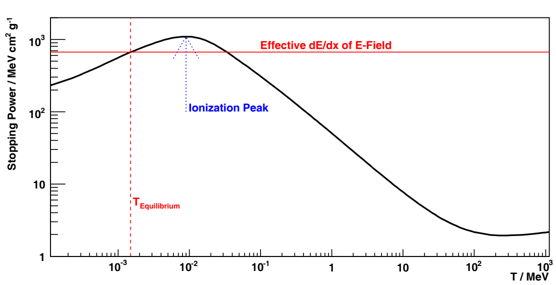

Figure 1: Stopping power of μ^+ in Helium (scaled from the NIST data [2] for protons).

an electric field to restore kinetic energy in the longitudinal direction will bring the particles to an equilibrium energy: particles with kinetic energies less than the equilibrium energy are accelerated because they gain more energy from the electric field than they lose to the gas. Particles with kinetic energies greater than the equilibrium energy are decelerated because they lose more energy than they gain. Thus the phase space is reduced. Additionally, since energy is restored only in the longitudinal direction, the beam divergence is reduced, cooling the beam in the transverse direction.

In this energy regime, energy is lost through excitations, elastic scattering on nuclei and charge exchange interactions. Multiple scattering places a lower limit on the emittance achievable by the two cooling effects described above. The cooled beam has an energy spread of ~ 300 eV, which can be preserved during reacceleration, yielding high energy beams with small relative momentum spreads.

EXPERIMENTAL DEMONSTRATION AT MPP

The Frictional Cooling Demonstration (FCD) experiment at MPP is undertaking verification of the principal behind frictional cooling using protons, which are stable and more easily produced than muons.

Experiment Setup

We have constructed a basic cooling cell consisting of a Helium gas cell and a 10 cm long accelerating grid (Fig. 2). The aim of the experiment is to verify that protons starting from rest are accelerated up to an equilibrium energy. The proton source produces protons at rest at one end of accelerating grid. A Silicon Drift Detector (SDD) at the other end of the grid measures the energy of the protons.

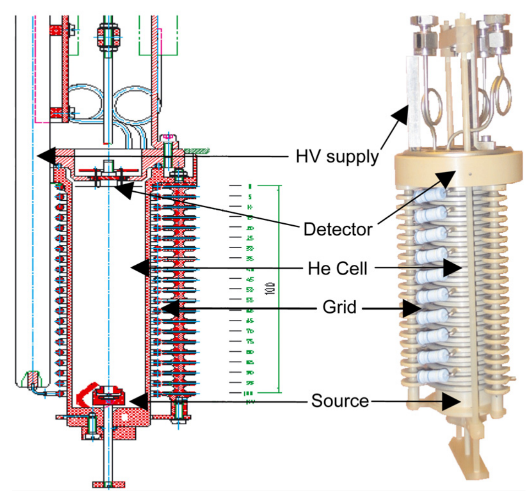

Figure 2: FCD experimental setup.

The Helium gas cell is a PEEK cylinder with two feedthroughs for flowing gas in and out. The flow rate is controled by an electronic valve to maintain a constant gas pressure in the cell. Both the detector and the source are inside the cell, so no windows are required.

The gas cell is mounted inside the accelerating grid. The grid consists of 21 metal rings connected in series by 64 MΩ resistors.The detector-side ring is grounded, and

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SIX-DIMENSIONAL COOLING SIMULATIONS FOR THE MUON COLLIDER*

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Abstract

The two cooling channels based on the RFOFO ring concept are considered and simulated. One of them is the RFOFO helix, also known as the Guggenheim. The helical shape of the channel resolves the injection and extraction issues as well as the absorber overheating issue. The issue of the RF breakdown in the magnetic field is addressed in the so-called open cavity cooling channel lattice with magnetic coils in the irises of the RF cavities. The details of the tracking studies of both channels are presented and compared to the performance of the original RFOFO cooling ring design.

RFOFO COOLING RING

In a Muon Collider design the muon beam 6D phase space volume must be reduced several orders of magnitude in order to be able to further accelerate it. Ionization cooling is currently the only feasible option for cooling the beam within the muon lifetime ($\tau_0 = 2.19\ \mu$s). The RFOFO ring [1, 2] is one of the feasible options currently under active investigation along with other designs [3, 4, 5]. The RFOFO ring provides a significant reduction in the six-dimensional emittance in a small number of turns with a relatively low particle loss factor. 6D cooling is achieved by employing the concept of emittance exchange. When a dispersive beam passes through a wedge absorber in such a way that higher momentum particles pass through more material, both the longitudinal and the transverse emittances are reduced. However, the design of the injection and extraction channels and kickers is very challenging for the RFOFO, and the ring could not be used as is, because the bunch train is too long to fit in the ring. Both problems would be removed in the RFOFO helix, also known as the Guggenheim channel [6]. In addition, using the helix solves another important issue, namely, the overheating in the absorbers.

The main parameters of the original RFOFO design are summarized in Table 1 and compared to the parameters of the Guggenheim channel. The layout of the RFOFO ring is shown in Fig. 1. The results of particle tracking through the RFOFO channel in the code G4Beamline [7] are used as the point of reference while comparing the RFOFO and Guggenheim channel efficiencies.

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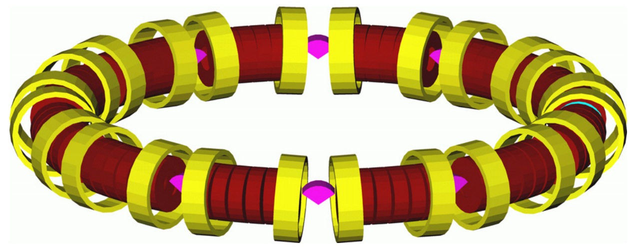

Figure 1: RFOFO ring layout. Yellow—tilted magnetic coils with alternating currents to provide necessary bending and focusing, and generate dispersion, purple—wedge absorbers for cooling and emittance exchange, brown—RF cavities for restoring the longitudinal component of the momentum.

Table 1: Parameters of the RFOFO Ring Compared to the Guggenheim Helix

		RFOFO	Guggenheim
RF frequency	[MHz]	201.25	201.25
RF gradient	[MV/m]	12.835	12.621
Maximum axial field	[T]	2.77	2.80
Pitch	[m]	0.00	3.00
Pitch angle	[deg]	0.00	5.22
Circumference	[m]	33.00	32.86
Radius	[m]	5.252	5.230
Coil tilt (wrt orbit)	[deg]	3.04	3.04
Average momentum	[MeV/c]	220	220
Reference momentum	[MeV/c]	201	201
Absorber angle	[deg]	110	110
Absorber vertical offset	[cm]	9.5	9.5
Absorber axial length	[cm]	27.13	27.13

GUGGENHEIM HELIX

The layout of the Guggenheim channel to a large extent repeats the one of the RFOFO ring, except for the three meters of separation between the layers of the helix. As a result, the circumference of the helix has to be slightly smaller than that of the ring to keep the arclength of one revolution intact.

Figure 2 shows the 5-turn layout which has been simulated. Along with the unshielded case with all the magnetic coils of all layers contributing to the magnetic field guiding muons, another scheme has been considered, with shielding between individual layers. Both layouts include safety windows around absorbers and Be windows in the RF cavities.

The simulation details can be found in [6]. Here we show only the six-dimensional emittance reduction (see Fig. 3), and the transmission (see Fig. 4) as functions of the num-

COMPENSATION OF MEAN ENERGY LOSS DUE TO AN INTERNAL TARGET BY APPLICATION OF A BARRIER BUCKET AND STOCHASTIC MOMENTUM COOLING AT COSY

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Abstract

The High Energy Storage Ring (HESR) of the future International Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt will be built as an antiproton 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. Theoretical investigations have demonstrated that the strong mean energy loss due to an internal target can not be compensated by cooling alone. A barrier bucket cavity can be used for mean energy loss compensation while cooling will reduce the momentum spread. Experimental results at COSY to compensate the large mean energy loss induced by an internal pellet target similar to that being used by the PANDA experiment at the HESR with a barrier bucket cavity (BB) will be presented. Experimental cooling results using the Time-Of-Flight (TOF) method are shown in comparison with Filter cooling. TOF cooling is found to be very effective to cool the momentum spread prior to Filter cooling. Main focus of attention is the presentation of the experimental results.

HESR BEAM REQUIREMENTS

The High-Energy Storage Ring (HESR) [1] of the future International Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt will be built as an antiproton cooler ring in the momentum range from 1.5 to 15 GeV/c. Two operational modes will be available for the users. A pellet target with a thickness of $4 \cdot 10^{15}$ atoms cm^{-2} provides the high luminosity mode (HL) with 10^{11} antiprotons yielding the required luminosity $2 \cdot 10^{32}$ cm^{-2} s^{-1}. The HL-mode has to be prepared in the whole energy range and beam cooling is needed to particularly compensate beam heating by the beam-target interaction. Much higher requirements have to be fulfilled in the high resolution mode (HR) with 10^{10} antiprotons. The same target thickness yields here the luminosity $2 \cdot 10^{31}$ cm^{-2} s^{-1}. This mode is requested up to 8.9 GeV/c with an rms-relative momentum spread down to about $4 \cdot 10^{-5}$.

Both, transverse and longitudinal cooling is foreseen at the HESR. Transverse cooling is mainly applied to compensate a transverse beam blow up due to the beam-target interaction. The highest demands are made on longitudinal cooling, especially in the HR-mode. To fulfil this goal the bandwidth of the cooling system will be increased from (2 – 4) GHz to (2 – 6) GHz in the final stage. High sensitive pickup/kicker structures are being developed and tested at COSY [2]. The filter cooling technique [3] is applied for longitudinal cooling in the momentum range above 3.8 GeV/c. Below 3.8 GeV/c the Time-Of-Flight momentum (TOF-) cooling technique [4] will be used.

MOMENTUM COOLING METHODS

In the Filter cooling method a pickup in sum mode measures the beam current and the discrimination of particles with different momentum deviations is obtained by inserting a notch filter in the signal path before it drives a kicker in sum mode. The advantage of this method is that Schottky particle noise is substantially suppressed in the centre of the particle momentum distribution. A severe restriction in the practical cooling bandwidth comes from mixing between pickup and kicker. Large mixing from pickup to kicker will reduce the maximum momentum spread that can be cooled for a given upper cooling frequency without particle losses. Strong unwanted mixing from pickup to kicker especially prevents filter cooling below 3.8 GeV/c in the HL-mode. In the low momentum range 1.5 GeV/c up to 3.8 GeV/c TOF cooling is therefore envisaged. In this method the filter in the cooling chain is removed and the signal transit time from pickup to kicker is adjusted to the time-of-flight of a particle with nominal momentum. Mixing from pickup to kicker can now be used to discriminate between particles of different momenta. This method attains a larger cooling acceptance which is especially preferable for the HL-mode. Larger initial momenta can thus be cooled without particles losses. The main disadvantage of this method is however that due to the absence of the notch filter strong particle noise diffusion occurs in the distribution centre. The gain of the cooling system should be then reduced to avoid too much Schottky heating in the center of the distribution. Beam equilibrium values are consequently larger as for filter cooling.

MOMENTUM COOLING EXPERIMENTS

At COSY momentum as well as transverse cooling is available. The system consists of two bands. Band I covers the frequency range (1 – 1.8) GHz and band II the range (1.8 – 3) GHz. The pickup and kicker electrode bars are movable to achieve a maximum in sensitivity. In these experiments only momentum cooling in band II is considered. The proton beam was accelerated to 2.6 GeV/c. To avoid transition crossing during acceleration the optics in the arcs is manipulated so that the transition energy is shifted upwards. When the flat top momentum is reached the acceleration rf-cavity is switched off and the optics is changed again so that now

PARTICLE ACCUMULATION USING BARRIER BUCKET RF SYSTEM

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Abstract

Using of the RF burrier bucket system for the accumulation process was proposed for a few accelerator projects (FAIR, NICA). This rather new idea can bring new advantages to the accelerator physics. The principle possibility of this accumulation method with moving and stationary barrier bucket in the presence of the electron cooling was successfully demonstrated in the ESR storage ring last year. The article presents results of the numerical simulation and comparison with the experimental data. The aim of this work is an investigation of the accumulation process and optimization of the parameters of the cooling and barrier bucket systems. The numerical simulation of the accumulation process with barrier bucket systems for the ESR and NESR storage rings was done with BETACOOL code.

INTRODUCTION

One of the main goals of barrier buckets application at the New Experimental Storage Ring (NESR) of the FAIR project is to reach the high intensity of RIBs required by the internal experiments in the NESR and in particular by the electron-ion collider [1]. It is planned to stack the RIBs longitudinally at injection energy i.e. in the range 100-740 MeV/u. The stacking will be supported by electron cooling.

The Nuclotron-based Ion Collider fAcility (NICA) is a new accelerator complex being constructed at JINR aimed to provide collider experiments with heavy ions in the energy range from 1 to 4.5 GeV/u. To provide designed average luminosity of the order of 10^{27}cm^{-2}s^{-1} one needs to store in each ring of the collider of about $2\cdot10^{10}$ ions [2]. Injection chain of the collider permits to accelerate a single heavy ion bunch at intensity of the order of 10^9 particles. More attractive scheme of the beam storage in the collider ring relates to barrier buckets application and stacking under support by stochastic cooling system.

Presently two general schemes of the particle accumulation are discussed: with moving or with fixed barrier RF bucket.

In the scheme with moving barrier RF bucket (which is effectively used, for instance, in Fermilab's Recycler) the ion bunch is injected in the longitudinal gap prepared by two 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 or stochastic 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.

In the fixed barrier bucket scheme, one prepares a stationary (fixed in phase) voltage distribution consisting of two barrier pulses of opposite sign. The resulting stretched rf potential separates the longitudinal phase space into a stable and an unstable region. After injection onto the unstable region (potential maximum), the particles circulate along all phases and cooling application leads to their capture in the stable region of the phase space (potential well). After some time of the beam cooling the unstable region is free for a next injection without losing of the stored beam.

In an ideal case the maximum intensity of the stored beam is limited by intrabeam scattering (IBS) process. In equilibrium between IBS and cooling the stack momentum spread increases with increase of the stored particle number. When the momentum spread becomes to be larger than the barrier height the particles from the stack can penetrate into the injection region where they are killed by injection kicker pulse. The stacking efficiency depends on relation between injection repetition period and cooling time. In the real life the stacking efficiency can be seriously restricted by quality of the injection kicker pulse and imperfection of the barrier voltage pulse shape.

To investigate the stacking efficiency of the storage process both schemes (with moving and fixed barrier buckets) were experimentally tested at ESR with electron cooling of the ion beam [3]. The experimental results were used for benchmarking of computer codes developed for design of new storage rings. One of them, dedicated to simulation of the particle accumulation with barrier RF bucket at FAIR rings was developed in [4]. To compare predictions of different models new algorithms were implemented into BETACOOL program also [5]. In this article we discuss the results of the BETACOOL simulations.

PARTICLE ACCUMULATION WITH FIXED BARRIER BUCKET

Experiments with fixed burrier buckets were performed at beam and cooler parameters listed in the Table 1. Electron beam current was varied from 150 to 300 mA, injection repetition period t_{inj} was 3, 5 or 8 s. The revolution period of about 700 ns was separated by two sinusoidal burrier pulses into a stable region of duration of about 100 ns and unstable one, where the injection was taking place. For simplicity, the stacking process was simulated in BETACOOL with rectangular shape of the barrier pulses shown in Fig. 1 by red line.

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STATUS OF THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT*

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Abstract

Muon ionization cooling provides the only practical solution to prepare high brilliance beams necessary for a neutrino factory or muon colliders. The **m**uon **i**onization **c**ooling **e**xperiment (MICE) is currently under development at the Rutherford Appleton Laboratory in UK. The experiment comprises a dedicated beam line to generate a range of input emittance and momentum of a muon beam, with time-of-flight and Cherenkov detectors to ensure a pure muon beam. A first measurement of emittance is performed in the upstream magnetic spectrometer with a scintillating fiber tracker. A cooling section will then follow, alternating energy loss in liquid hydrogen and RF acceleration. A second spectrometer identical to the first one and a particle identification system provide a measurement of the outgoing emittance. In September 2009, it is expected that the beam and some detectors will be in the final commissioning phase and the time of the first measurement of input beam emittance only months away. The plan of steps of measurements of emittance and cooling that will follow in the rest of 2009 and later.

INTRODUCTION

Neutrino **f**actory (NF) and **m**uon **c**ollider (MC) offer high potential physics opportunities, but both NF and MC are difficult to build. Muon beams are produced with very large six-dimensional emittance and have short lifetime (~ 2.2 micro-second at rest). One of the main challenges is how to effectively manipulate intense muon beams, in particular to reduce the transverse emittance of the muon beams, namely cooling. Ionization cooling is considered to be the only practical cooling scheme for muons. No one has ever demonstrated the muon ionization cooling yet. MICE is such a demonstration experiment where a section of real ionization cooling channel hardware (based on the US Feasibility Study-II design) will be built and tested. The experiment is currently under construction at the Rutherford Appleton Laboratory (RAL) in UK [1]. The experiment comprises a dedicated beam line to generate a range of input emittance and momentum of a muon beam, with time-of-flight and Cherenkov detectors to ensure a pure muon beam. The emittance of the incoming muon beam will be measured in the upstream magnetic spectrometer with a scintillating fiber tracker. A cooling section will then follow. The cooling section consists of three liquid hydrogen absorbers and eight 201-MHz normal conducting RF cavities surrounded by two superconducting solenoid magnets. Muon beams lose energies in the liquid hydrogen absorber and gain longitudinal energies only from RF cavities, therefore a net reduction in transverse emittance. A second spectrometer that is identical to the first one and a particle identification system provide a measurement of the outgoing emittance. Figure 1A & 1B show an engineering model of the MICE experiment setup and the ionization cooling channel.

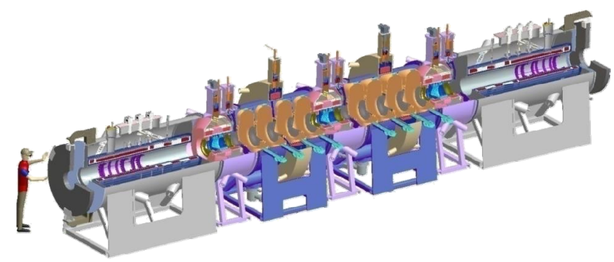

Figure 1A: MICE experiment layout: two spectrometer solenoids with particle ID and timing for emittance measurement and a section of cooling channel in between.

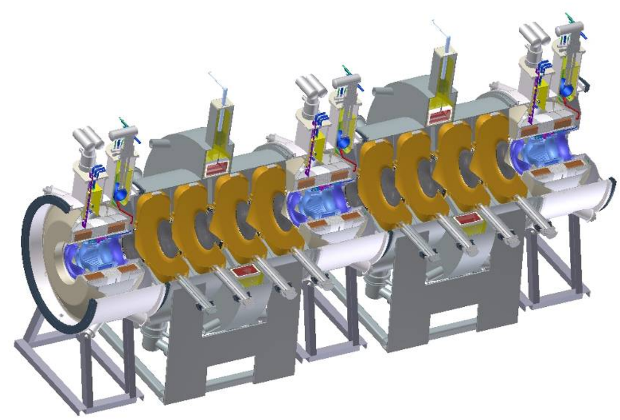

Figure 1B: MICE cooling channel consists of three liquid hydrogen absorbers (blue) and eight 201-MHz normal conducting RF cavities (yellow) surrounded by five superconducting solenoid magnets.

The aim of MICE is to measure ~ 10% cooling of 140 - 240 MeV/c muons with a measurement precision of $\Delta\varepsilon/\varepsilon$ of 10^{-3}. In addition, it is also necessary to explore and demonstrate that we can design, engineer and fabricate the hardware needed for MICE and place them in a muon beam and measure their performance. Moreover, MICE will help to validate design tools (simulation codes) we have developed and check agreements with the experiment.

MICE collaboration has over 150 collaborators from Belgium, Bulgaria, China, Holland, Italy, Japan,

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STUDY OF COLLECTIVE EFFECT IN IONIZATION COOLING *

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Abstract

As a charged particle passes through a non-gaseous medium, it polarizes the medium and induces wake fields behind it. The interaction with wake fields perturbs the stopping power for the beam particles that follow. The perturbation strongly depends on the densities of both the incident beam and the medium. To understand this collective effect, detailed studies have been carried out. Both analytic and simulation results are obtained and compared.

INTRODUCTION

The study of the physics of a charged particle passing through a non-gaseous medium is of long history [1, 2, 3]. For a single particle, if its momentum is high enough, it will lose energy through both ionization process and density effect. The latter has been systematically studied. For a beam consisting of a large number of particles, the interaction among the beam particles should also be taken into account in order to describe the process correctly.

Essentially, the density effect is introduced by the polarization of the medium. The electric fields from the polarized medium molecules generate wake fields behind the incident particle, which perturb the motion of the beam particles following. If the particle density of the beam is high enough, the wake will enhance the stopping power for beam particles, and may possibly increase the rate of ionization cooling.

In this article, we derive the expressions for the wake electric field introduced by a single incident charged particle and its perturbation on the stopping power. This is extended to a two-particle system and a multi-particle system with various distributions. The comparison with simulations is next demonstrated. Finally, the damping mechanism on the wake is discussed, and its effect on the stopping-power enhancement is found to be important.

WAKE ELECTRIC FIELD

First, let us focus on a single particle of charge e moving with velocity v in the z direction, where $-e$ is the electron charge. The particle is at longitudinal position $z = z_1$ at time $t = 0$. Cylindrical coordinates are used with $\vec{\rho}$ denoting the transverse directions. The scalar potential generated by both the incident particle and polarized medium in the Coulomb gauge is given by

$$\phi(\vec{r},t) = \frac{e}{\pi v}\int d\omega \int \frac{\kappa d\kappa J_0(\kappa\rho)}{\kappa^2+\omega^2/v^2}\frac{e^{i\frac{\omega}{v}(z-z_1-vt)}}{\varepsilon(k^2,\omega)}, \qquad (1)$$

where J_0 is the Bessel function. The wave number vector is denoted by $\vec{k} = (\vec{\kappa}, k_z)$ and the frequency by ω. In the above, the integration over k_z and $\vec{\kappa}\cdot\vec{\rho}$ have already been carried out. The polarization of the medium is described by the dielectric constant, which in a dispersive medium takes the form

$$\varepsilon(k^2,\omega) = 1-\omega_p^2\sum_j \frac{f_j}{\omega^2-\omega_j^2+i\omega\Gamma_j}, \qquad (2)$$

where f_j is the fraction of bound electrons that oscillate with the bound frequency ω_j and damping rate $\frac{1}{2}\Gamma_j$, with $\sum_j f_j = 1$. In the above, $\omega_p = \sqrt{4\pi n_e e^2/m_e}$ is the plasma frequency, where m_e is the electron mass and n_e the electron density. We make the assertion that ω_p is much larger than the bound frequencies and damping rates.[1] Then $\frac{1}{2}\Gamma_j$ can be replaced by the infinitesimal positive number ϵ, leading to

$$\frac{1}{\varepsilon} = \frac{\omega^2}{(\omega+i\epsilon)^2-\omega_p^2} = \frac{\omega^2}{(\omega-\omega_p+i\epsilon)(\omega+\omega_p+i\epsilon)}. \qquad (3)$$

Contour integration over ω can now be performed giving

$$\phi(\vec{r},t) = e\int d\kappa \frac{\kappa^2 J_0(\kappa\rho)}{\kappa^2+\omega_p^2/v^2}e^{-\kappa|z-z_1-vt|} + \frac{2e\omega_p}{v}\int d\kappa\frac{\kappa J_0(\kappa\rho)}{\kappa^2+\omega_p^2/v^2}\sin\frac{\omega_p}{v}(z-z_1-vt)\theta(z_1+vt-z). \qquad (4)$$

The limits of integration are from $\kappa = 0$ to

$$\kappa = \frac{\omega_p}{v}\sqrt{x_m^2-1} \quad \text{with} \quad x_m = \frac{2\gamma m_e v^2}{\hbar\omega_p}, \qquad (5)$$

which corresponds to the maximal momentum transfer in a collision. In the above, $\gamma = 1/\sqrt{1-v^2/c^2}$, c is the velocity of light, and $\hbar$ is the reduced Planck constant. The second term in Eq. (4) is the potential coming from the polarization of the medium, and the first term is the *medium-modified self-field* of the incident charged particle. The longitudinal and transverse electric fields derived from the second term vanish in front of the particle and are therefore the wake fields. Behind the particle, they take the form:

$$E_z^w(\vec{r},t) = -\frac{2e\omega_p^2}{v^2}\int d\kappa\frac{\kappa J_0(\kappa\rho)}{\kappa^2+\omega_p^2/v^2}\cos\frac{\omega_p(z-z_1-vt)}{v},$$
$$E_\rho^w(\vec{r},t) = +\frac{2e\omega_p^2}{v^2}\int d\kappa\frac{\kappa^2 J_1(\kappa\rho)}{\kappa^2+\omega_p^2/v^2}\sin\frac{\omega_p(z-z_1-vt)}{v}. \qquad (6)$$

Evaluating at the particle location ($z = z_1 + vt$, $\rho = 0$), we obtain the longitudinal field on axis,

$$E_z^w = -\frac{2e\omega_p^2}{v^2}\ln x_m. \qquad (7)$$

* Work supported by USDOE Grant DE FG0292ER40747 and USDOE STTR Grant DE FG02 08ER86281.

[1] We believe the bound frequencies are one order of magnitude smaller than ω_p in liquid hydrogen.

DEVELOPMENT OF HELICAL COOLING CHANNELS FOR MUON COLLIDERS

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Abstract

The biggest technical challenge problem for muon colliders is to cool of the six-dimensional (6D) muon beam phase sufficiently within the muons' short lifetime to permit acceleration. The Helical Cooling Channel (HCC) has been proposed as a means to obtain exceptional cooling performance in a short channel length. A number of experimental, design and simulation studies of the HCC have been completed recently. Results and current activities for the HCC are presented.

INTRODUCTION

The P5 committee compiled a road map for future facilities for high-energy physics (HEP) in May, 2008 [1]. According to their road map, muon colliders will be an appropriate long-term project for HEP community if progress is made on the necessary breakthrough technologies. Muons are an attractive for acceleration in future colliders because 1) muons emit no synchrotron radiation in circular accelerators even at TeV energies, whereas it severely limits the energies of circular electron-positron accelerators, and requires linear accelerators that are much larger than muon colliders, and 2) muon colliders have much less beamsstrahlung than electron-positron colliders, which results in better energy resolution, 3) muons have no internal structure, whereas that is a drawback in proton-proton and other hadron colliders. On the other hand, there are some challenges to make muon colliders. First, muons must be accelerated to high energy within their short lifetime. Half of the muons decay weakly into electron (positron) and anti-neutrino (neutrino) within 2.2 μs at rest. Second, rapid 6D muon beam phase space cooling is required to make practical muon colliders. Muons are generated in a pion decay channel. Without phase space cooling the initial muon beam phase space is too large to be accepted in a conventional RF accelerator system. A compact muon accelerating and cooling system is an essential requirement. Because high gradient RF is preferred for quick acceleration, SRF cavities are the most feasible solution for muon acceleration. To this end, the beam phase space needs to be cooled down to levels that are acceptable by the SRF system.

The most effective method of muon beam phase space cooling is by ionization cooling. 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. However, this process only makes 4D phase space cooling, called transverse cooling. Recently, a novel 6D phase space cooling channel based on ionization cooling called a helical cooling channel (HCC) was proposed [2]. It consists of a helical dipole and solenoid magnetic components to make a helical beam path as shown in Figure 1. The dense hydrogen gas is homogeneously filled in the beam path. In a helical dipole magnet, a high (low) momentum muon passes with longer (shorter) path length. As a result, the momentum distribution after the magnet with a continuous cooling absorber becomes uniform. This process is called emittance exchange. A helical quadrupole component is required to stabilize the beam phase space. To compensate for energy loss, a continuous RF acceleration field is needed. A high pressurizing hydrogen gas filled RF (HPRF) cavity can be used a homogeneous cooling absorber and a continuous acceleration at the same time. The HPRF cavity has been successfully tested and investigated for the cooling applications [3]. Integrating the HPRF cavity into the HCC is a major issue. The HCC is the most compact type of cooling channel of the various types of cooling channel.

In this paper, we discuss the latest results of 6D cooling simulation studies of the HCC. Then, we discuss the beam elements in the HCC. This study will lead to the question of how to incorporate the RF system into a compact helical cooling magnet.

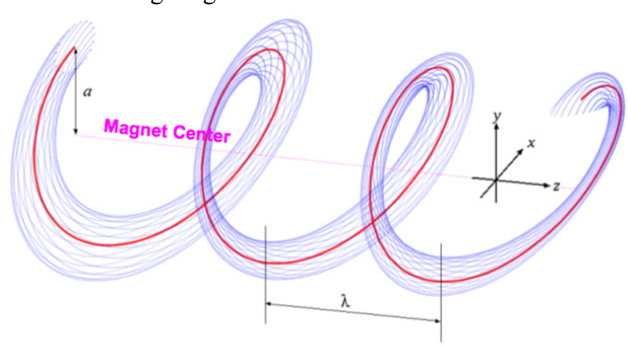

Figure 1: Helical particle tracking in the HCC. The red line indicates the trajectory of the reference design particle and the blue lines are the beam envelope. The particle track has a position offset from magnet center ("*a*" in picture). λ is a helical period.

HCC SIMULATION

From past HCC simulation studies, we noticed that an HCC with a lower RF frequency channel has larger longitudinal phase space stability [4]. The most plausible reason is because the momentum slip factor is not well

STATUS AND CHALLENGES IN BEAM CRYSTALLIZATION*

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Abstract

During the past several decades, beam crystallization has been studied both theoretically and experimentally. Theoretical investigations have been numerical, mainly using computer modeling based on the method of molecular dynamics (MD), and analytical, based on phonon theory. Experimental investigations involve both ion storage rings and ion traps using both electron and laser beam cooling. Topics of interests include crystal stability in various accelerator lattices and under different beam conditions, colliding crystalline beams, crystalline beam formation in shear-free ring lattices with both magnets and electrodes, experimental simulation of alternating-gradient conditions with an ion trap, tapered cooling and coupled cooling, and beam dynamics at different temperature regime as the beam is cooled from high to low temperature. In this paper, we first review theoretical approaches and major conclusions pertaining to beam crystallization. Then, we analyze conditions and methods of the various major experiments. Finally, we discuss, both theoretically and experimentally, some improvements, open questions, and challenges in beam crystallization.

INTRODUCTION

Beam crystallization has been a topic of interests since first evidence of experimental anomaly was observed on an electron-cooled proton beam at the storage ring NAP-M [1]. Since then, strong space-charge dominated phenomena and one-dimensional (1-D) ordering states were reported with both proton and heavier ions at storage rings ASTRID [2], TSR [3], CRYRING [4], ESR [5], and S-LSR [6]. Electron and laser beam cooling methods were used in attaining such states. On the other hand, attempts to achieve beam ordering beyond 1-D have not been successful, unlike the situation with ion traps where multi-dimensional crystalline structures were attained [7].

Theoretically, two main approaches were pursued: for the low-temperature regime, the molecular dynamics (MD) method was used to predict the ground-state structure [8–11] and the low-temperature dynamics [11–13]; for the intermediate temperature, high density regime the more conventional beam dynamics methods including envelope-equation resonance analysis [14, 15], space-charge particle-in-cell simulations, and intra-beam scattering analysis.

To attain an ordered state, effective beam cooling is needed to overcome beam heating caused by coherent resonance crossing and intra-beam scattering. Furthermore, the cooling force must conform to the dispersive nature of a crystalline ground state in a storage ring for 3-D structures. Experimentally, electron cooling has been used at NAP-M [1], ESR [4], CRYRING [5], and S-LSR [6] to cool beams of protons and heavier ions in all three directions, successfully reaching 1-D ordered states. With laser cooling, which has been used at ASTRID [2] and TSR [3], the beam can be cooled to ultra-low temperature in the beam rest frame in the longitudinal direction along the beam motion. However, to effectively reduce the transverse beam temperature methods like resonance coupling needs to be adopted [16]. With either cooling approach, the ideal "tapered cooling" effect is yet to be realized to move beyond 1-D ordering towards forming high-density crystalline structures in an actual storage ring.

CRYSTALLIZATION CONDITIONS

There are several necessary conditions for the formation of high-density, 3-D crystalline beams in storage rings.

Ground State Existence Condition

The storage ring is alternating-gradient (AG) focusing operating below the transition energy, γ_T,

$$\gamma < \gamma_T \tag{1}$$

where γ is the Lorentz factor of the beam. This condition is due to the criterion of stable kinematic motion under Coulomb interaction when particles are subject to bending in a storage ring [11].

Phonon Spectrum and Resonance Condition

The bare transverse phase advances per lattice period need to be less than 90°, i.e.,

$$\nu_{x,y} < \frac{N_{\rm sp}}{4} \tag{2}$$

where ν_x and ν_y are the bare horizontal and vertical tunes, and $N_{\rm sp}$ is the lattice super-periodicity of the storage ring. Note that the lattice elements consists of every device that

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THE EVOLUTION OF THE PHASE SPACE DENSITY OF PARTICLE BEAMS IN EXTERNAL FIELDS

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Abstract

In this paper the evolution of the phase space density of particle beams in external fields is presented proceeding from the continuity equation in the six-dimensional (6D) phase space (μ-space). Such a way the Robinson theorem, which includes the Liouville theorem as a special case, was proved in a more simple and consistent alternative way valid for arbitrary external fields, averaged fields of the beam (self-generated electromagnetic fields except intrabeam scattering) and arbitrary frictional forces (linear, nonlinear). It includes particle accelerators as a special case. The limits of the applicability of the Robinson theorem in case of cooling of excited ions having a finite living time are presented.

INTRODUCTION

In 1958 K.W.Robinson derived at once the sum of damping rates (decrements) of three particle oscillation modes in circular accelerators in the relativistic case [1]. He did an expansion of the power of frictional forces over the particle energy for the private case of radiative reaction force. That is why his final formulae do not include the term with the derivative of the power. Later, A.A.Kolomensky derived the formulae in the general form for the relativistic case and applied it to the ionization cooling [2]. He calculated separately damping rates for three directions in the curvilinear coordinate system and then took their sum.

In order to derive damping increment, K.W.Robinson evaluated the determinant of the transfer matrix of the infinitesimal element of length of a particle orbit. The determinant determines the evolution of a 6D phase space volume of the beam or its density along the trajectory. P.Csonka for this purpose evaluated the infinitesimal 6D phase space volume as well and used some additional conditions to prove the theorem [3]. H.Wiedemann in the textbook [4] presented the proof of the theorem following Robinson's idea but keeping the derivative of the power losses over the energy. Now the theorem in the particle accelerator community is named by Robinson theorem or Robinson's damping criterion.

EVOLUTION OF PARTICLE BEAM DENSITY IN THE EXTERNAL ELECTROMAGNETIC FIELDS

Let us proceed from the continuity (Liouville's) equation in the 6D phase space coordinate-momentum $(\vec{r},\vec{p})$:

$$\frac{d\rho}{dt}+\rho\, div\,\vec{v}=0\,. \qquad (1)$$

Here components of the 6D velocity $\vec{v}=(\vec{v}_r,\vec{v}_p)$ are $\dot{x},\dot{y},\dot{z},\dot{p}_x,\dot{p}_y,\dot{p}_z$, where $\dot{r}_i=dr_i/dt$, $\dot{p}_i=dp_i/dt$. The equation (1) or equivalent equation $\partial\rho/\partial t+div\,(\rho\vec{v})=0$ expresses the number of particles conservation law. In our case the form of the equation (1) is preferable as it presents the total derivation of the density in the coordinate system moving with the beam. It can be presented in the integral form $\rho=\rho_0\exp[-\int div(\vec{v})dt]$, where ρ_0 is the initial phase space density.

The divergence $div\,\vec{v}=div_r\vec{v}_r+div_p\vec{v}_p$, $div_r\vec{v}_r=0$ as the velocity $\vec{v}_r=c\vec{p}/\sqrt{p^2+m^2c^2}$ does not depend on spatial coordinates (r_i, p_i are independent variables). The value $\vec{v}_p=\dot{\vec{p}}=\dot{\vec{p}}_H+\dot{\vec{p}}_{Fr}=\vec{F}_H+\vec{F}_{Fr}$ is the force acting upon the particle. The conservative force $\vec{F}_H=e\vec{E}(\vec{r},t)+(e/c)[\vec{v}\,\vec{H}(\vec{r},t)]$ is determined by external fields and the fields of the particle beam ($div_p\vec{F}_H=0$), while $\vec{F}_{Fr}$ is the frictional force. That is why $div_p\vec{v}_p=div_p\vec{F}_{Fr}$, and the equation (1) can be presented in the integral form $\rho=\rho_0\exp[-\int div_p\vec{F}_{Fr}dt]$.

The frictional force can be written in the form $\vec{F}_{Fr}=-\chi_{Fr}(\vec{r},p,t)\cdot\vec{n}$, where $p=|\vec{p}|$, $\vec{n}=\vec{p}/p$, $\chi_{Fr}(\vec{r},p,t)$ is the frictional coefficient. In this case $div_p\vec{F}_{Fr}=-\chi_{Fr}div_p\vec{n}-\vec{n}\cdot grad_p\chi_{Fr}=-2\chi_{Fr}/p-\partial\chi_{Fr}/\partial p$. We took into account, that $div_p\vec{n}=2/p$ and $\vec{n}\cdot grad_p\chi_{Fr}(\vec{r},p,t)=(\partial\chi_{Fr}/\partial p)=v_r(\partial\chi_{Fr}/\partial\varepsilon)$, where $\varepsilon=\sqrt{p^2c^2+m^2c^4}$ is the energy of the particle.

The frictional power $P_{Fr}=\vec{F}_{Fr}\cdot\vec{v}_r=\chi_{Fr}(\vec{r},p,t)\cdot\vec{n}\cdot\vec{v}_r=c\,\beta\cdot\chi_{Fr}(\vec{r},p,t)$, where $\beta=v_r/c$. It follows that $\chi_{Fr}=P_{Fr}(\vec{r},p,t)/c\beta$, and the equation (1) become

$$\rho=\rho_0\exp[-\int\alpha_{6D}(\vec{r},p,t)\,dt]\,, \qquad (2)$$

where $\alpha_{6D}(\vec{r},p,t)=-div_p\vec{F}_{Fr}=2\chi_{Fr}/p+\partial\chi_{Fr}/\partial p$ or:

$$\alpha_{6D}(\vec{r},\varepsilon,t)=(1+\frac{1}{\beta^2})\frac{P_{Fr}(\vec{r},\varepsilon,t)}{\varepsilon}+\frac{\partial P_{Fr}(\vec{r},\varepsilon,t)}{\partial\varepsilon}.$$

The integral (2) along a trajectory of a particle is the solution of the equation (1). According to (2), the 6D rate of the beam density change is determined by the frictional

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WEDGE ABSORBER SIMULATIONS FOR THE MUON IONISATION COOLING EXPERIMENT

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Abstract

In the Muon Ionisation Cooling Experiment (MICE), muons are cooled by ionisation cooling. Muons are passed through material, reducing the total momentum of the beam. This results in a decrease in transverse emittance and a slight increase in longitudinal emittance, but overall reduction of 6D beam emittance.

In emittance exchange, a dispersive beam is passed through wedge-shaped absorbers. Muons with higher energy pass through more material, resulting in a reduction in longitudinal emittance as well as transverse emittance. Emittance exchange is a vital technology for a Muon Collider and may be of use for a Neutrino Factory.

In this paper, we show that even in the straight solenoidal lattice of MICE, emittance exchange can be demonstrated. In order to achieve this, a muon beam is passed through a wedge shaped absorber; the input beam distribution must be carefully selected to accomodate strong non-linear effects due to chromatic aberrations in the solenoid lattice, which we achieve using a polynomial weighting function to select beam moments.

EMITTANCE EXCHANGE IN THE MUON IONISATION COOLING EXPERIMENT

Ionisation cooling is achieved in the Muon Ionisation Cooling Experiment (MICE) [1] baseline by the placement of absorbing material in the beamline. The absorbing material removes beam momentum, which is replaced only in the longitudinal direction by RF cavities, resulting in a net reduction of emittance. Low-Z materials must be used as absorbers together with carefully designed beam optics. This minimises the effects of multiple Coulomb scattering, which tend to reduce the cooling effect. Overall, transverse emittance is reduced to some equilibrium point while longitudinal emittance stays the same or increases slightly due to stochastic processes in the energy loss.

In this note we consider using MICE to observe a phenomenon known as emittance exchange. In emittance exchange a dispersive beam is passed through a wedge-shaped absorber. Muons with higher energy pass through more material and experience greater momentum loss. In this way the longitudinal emittance of the beam can be reduced either in addition to, or even instead of transverse emittance reduction. Emittance exchange is vital to a Muon Collider and has been considered as an upgrade option to the Neutrino Factory. Ring coolers [2], Helical coolers [3] and Guggenheim coolers [4] have been proposed to perform emittance exchange and longitudinal cooling using a simple wedge or a truncated wedge.

In MICE muons will be passed one-by-one through a short section of ionisation cooling equipment and the six-dimensional phase space vector of each muon will be measured to high precision, enabling the measurement of reduction in 2D, 4D and 6D emittance due to ionisation cooling. The position and momentum of individual muons is determined by high resolution scintillating fibre spectrometers before and after the cooling apparatus. Fast time-of-flight counters measure time-of-flight between the upstream and downstream spectrometers, which together with the spectrometers enables reconstruction of the full 6D phase space vector of individual muons. Rejection of beam impurity before the cooling channel will be achieved using a pair of time-of-flight counters together with a threshold Cherenkov counter. After the cooling channel decay electrons will be identified using the time-of-flight through the experiment together with an Electron-Muon-Ranger.

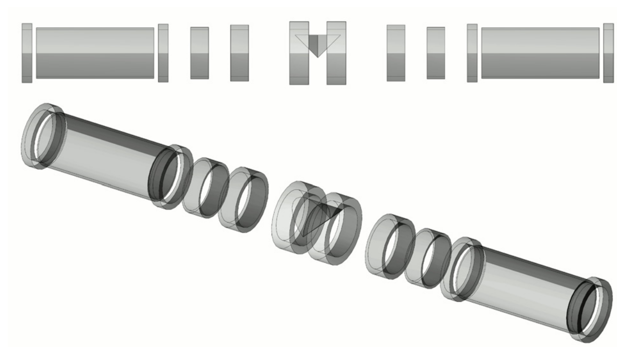

Figure 1: The geometry as simulated in G4MICE code: side and 3D view. The wedge absorber and coils are shown. The total length of the Step IV layout is just over 7.5 m, inner radius of the coils is 258 mm. A steel, cylindrical beam pipe with a 232 mm aperture was also included in simulations but is not shown in these figures.

Wedge Geometry

We study the use of a simple wedge-shaped absorber in a straight solenoid channel. The geometry considered is shown in Figure 1. The case considered here is MICE Step IV, where MICE is operated in a mode without RF cavities. RF cavities will be added to MICE at a later stage, but

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STATUS OF THE FAIR PROJECT*

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Abstract

The acceleration of high intensity primary beams and the preparation of high quality secondary beams are the main goals of the accelerators of the FAIR project. Primary beams are either heavy ions used for the production of rare isotope beams or protons which are converted to antiprotons. Various cooling systems are planned which allow the preparation of the secondary beams for high precision experiments. The system of accelerators which has been recently documented in a set of technical design reports is passing through a final review. This report gives an overview of the FAIR accelerators and the status of the design of various systems and components.

INTRODUCTION

Acceleration of high intensity primary beams and their conversion to secondary beams is the main mission of the proposed Facility for Antiproton and Ion Research (FAIR) [1]. The existing GSI accelerator system with the UNILAC linear accelerator and the heavy ion synchrotron SIS18 will serve as injector complex for the new synchrotron SIS100. Two production targets, one for antiproton production using a primary proton beam and one for rare isotope production by fragmentation or fission of heavy ions, in combination with subsequent magnetic separators, will provide the secondary beams. In a complex of storage rings the secondary beams will be prepared for the users. Beam cooling will be crucial to prepare high quality secondary beams. Stochastic cooling will provide pre-cooling of the hot secondary beams, for antiprotons it is also employed in beam accumulation. Electron cooling is mainly a tool to perform experiments with high quality stored beams. Moreover, it is also employed in the accumulation of rare isotopes and in the deceleration of ions and antiprotons in order to increase the efficiency of these manipulations. Details of the new accelerators of the FAIR project were documented in technical design reports which are the basis for further planning of the accelerators and the general machine concepts [2].

UPGRADE OF THE EXISTING FACILITY

The main activity at the existing GSI accelerator facility is devoted to the improvement of the machines for high intensity operation. The low energy part of the UNILAC is being modified in order to increase the transverse acceptance and therefore to accelerate beams with larger efficiency. This is achieved by installation of new electrodes in the RFQ and new matching sections between RFQ and DTL section. The goal is the acceleration of beam intensities for the heaviest ions which are sufficient to fill the synchrotron SIS18 up to the space charge limit. Installation of new power converters in the linear accelerator as well as the recent addition of a large acceptance charge state separator between linear accelerator and synchrotron will significantly improve the performance with intense heavy ion beams.

The upgrade of SIS18 comprises various aspects. The problem of the dynamic vacuum has attracted high attention. The increase of the residual gas pressure during high intensity operation with low charge states at the SIS18 injection energy of 11.4 MeV/u is counteracted by various measures. Amongst others the pumping speed was increased by NEG coating of vacuum chambers, additional collimators for localized and defined beam loss at surfaces designed with special orientation and low desorption materials were installed. Various technical modifications will allow an increase of the ramping rate of SIS18 to 10 T/s which is beneficial with respect to high average intensity and which will reduce the losses in the residual gas during injection and acceleration. A new connection to the power mains has been installed. Some weak corrector magnet power converters are being replaced, an additional acceleration cavity operating at $h = 2$ will allow faster acceleration. A dedicated machine development program with beam dynamics investigations and hardware improvements is aiming at filling the synchrotron SIS18 with heavy ion beams up to the space charge limit.

NEW SYNCHROTRONS

It is planned to install two new synchrotrons with a circumference of 1083 m in a common tunnel. They can be either used for the acceleration of highest intensity beams of relatively low charge states, e.g. U^{28+} from SIS18 without any stripping between UNILAC and SIS18 or for acceleration to highest energies at the expense of intensity due to unavoidable losses in the stripper foil.

SIS100

For the achievement of high average intensities SIS100 is designed as a fast ramping synchrotron with a magnetic bending power of 100 Tm using super-ferric magnets [3]. With a maximum ramp rate of 4 T/s it can provide 5×10^{11} U^{28+} ions at 2.7 GeV/u every 1.5 s. With the same cycle time 2×10^{13} protons can be accelerated to 29 GeV.

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TEVATRON ELECTRON LENS AND IT'S APPLICATIONS*

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Abstract

The Tevatron Electron Lenses (TELs) are designed for the purpose of the Beam-beam tuneshift compensation. Now they are the vital parts of the Tevatron. In this report, their daily operations and beam study results are presented. Their possible future applications are discussed as well.

INTRODUCTION

Fermilab's Tevatron is a 980 GeV particle collider ring in which tightly focused beams of protons and antiprotons collide in two dedicated interaction points (IPs). Both beams share the same beam pipe and magnet aperture by placing the beams on separated helical orbits everywhere except the main IPs using high-voltage (HV) electrostatic separators. However, the effects due to electromagnetic beam-beam interactions at the main IPs together with long-range interactions between separated beams limit the collider performance, reducing the luminosity integral per store (period of continuous collisions) by 10-30%[1]. The long-range effects which (besides being nonlinear) vary from bunch to bunch are particularly hard to treat. To compensate these beam-beam effects, the electron lenses were proposed [2] and installed at the Tevatron [3]. An electron lens employs space-charge force of a low-energy beam of electrons that collides with the high-energy bunches over an extended length L_e. Such a lens can be used for linear and nonlinear force compensation depending on electron current-density distribution $j_e(r)$ and on the ratio of the electron beam radius a_e to the rms size σ of the high-energy beam at the location of the lens. The electron transverse current profile (and thus the radial dependence of electromagnetic (EM) forces due to electron space-charge) can easily be changed for different applications. The electron-beam current can be adjusted between individual bunches, equalizing the bunch-to-bunch differences and optimizing the performance of all bunches in a multi-bunch collider by using fast high voltage modulator [6].

A shift of the betatron frequency (tune) of high-energy particles due to EM interaction with electrons is a commonly used "figure of merit" for an electron lens. A perfectly steered round electron beam with current density distribution $j_e(r)$, will shift the betatron tunes $Q_{x,y}$ of small amplitude high-energy (anti-)protons by [2]:

$$dQ_{x,y} = \pm \frac{\beta_{x,y} L_e r_p}{2\gamma ec} \cdot j_e \cdot \left(\frac{1 \mp \beta_e}{\beta_e} \right) \qquad (1),$$

where the sign reflects focusing for protons and defocusing for antiprotons, $\beta_e = v_e/c$ is the electron beam velocity, $\beta_{x,y}$ are the beta-functions at the location of the lens, L_e denotes the effective interaction length between the electron beam and the protons or antiprotons, $r_p = e^2/mc^2 = 1.53 \times 10^{-18}$ m is the classical proton radius, and $\gamma_p = 1044$ the relativistic Lorentz factor for 980GeV protons.

TEVATRON ELECTRON LENSES

Both Tevatron Electron Lenses (TELs) direct their beam against the antiproton flow. The TELs operate at up to 10kV electron energy and can shift the betatron tune by as much as $dQ_{x,y}^{max} \approx 0.008$ [4] depending on the type of the electron gun design. The layout of the Tevatron Electron Lens 2 (TEL2) is shown below. TEL2 is installed in the Tevatron at the location where β_x/β_y=68m/150m whereas TEL1 is installed at the different location where β_x/β_y=104m/29m. The design difference between the two lenses is that the TEL1 bending section has a 90° angle between the gun solenoid and the main solenoid while this angle is about 57° in TEL2.

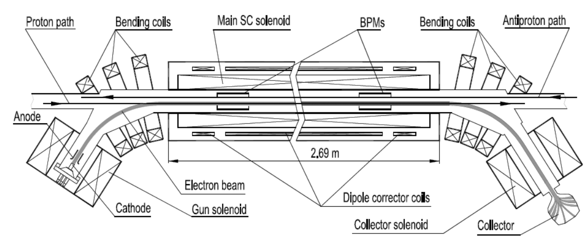

Figure 1: TEL2 layout.

The designed and measured electron beam profiles are flattop, smooth edge flattop (SEFT) and Gaussian, which are shown below:

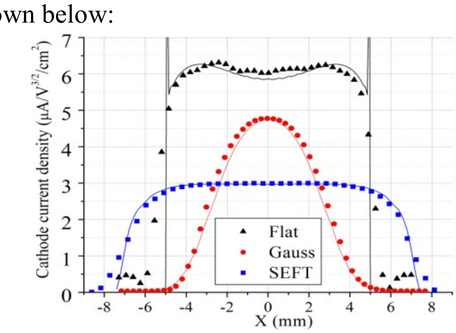

Figure 2: Three profiles of the electron current density at the electron gun cathode: black, flattop profile; red, Gaussian profile; blue, SEFT profile. Symbols represent the measured data and the solid lines are simulation results. All data are scaled to refer to an anode–cathode voltage of 10 kV.

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COOLING FORCE MEASUREMENTS WITH VARIABLE PROFILE ELECTRON BEAM AT HIRFL-CSR *

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Abstract

Two electron coolers have been operated at HIRFL-CSR for fast phase space cooling of heavy ion beams. The variable profile electron beam can be produced by these coolers. This should be one of the solutions for electron heating problems. In order to demonstrate the particularity of variable profile electron beam cooling, the longitudinal cooling force has been measured by electron energy-step method. In this paper, the measurement results were presented. It's clear that the cooling force is function of the electron beam density at ion orbit for variable profile electron beam. Moreover, parameter dependence on the alignment angles between the ion and electron beam was investigated.

INTRODUCTION

HIRFL-CSR is a new heavy ion cooling-storage-ring in IMP [1]. It consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC and SSC are used as injectors. The heavy ions were accumulated in CSRm with the help of electron cooling at injection energy, then, accelerated and extracted to CSRe for nuclear and atomic physical experiments. Two electron coolers were installed at CSRm and CSRe respectively.

Electron cooling is a well-established method to improve the phase space quality of ion beams in storage rings [2]. However, the ultra cooled ion beam leads to the formation of a core with extremely high density and gets lost easy. This sort of phenomena has been found at CELSIUS and COSY called electron heating. Using variable profile electron beam is one of the possible solutions for this problem. The variable profile electron beam is adopted in the electron coolers installed at HIRFL-CSR for first time.

The most important characteristics of the electron cooler are the attainable values of the cooling force as well as the dependencies of the cooling force on electron parameters. The electron coolers at HIRFL-CSR offer the opportunity to study cooling force with variable profile electron beam. The longitudinal cooling force was measured by the electron energy-step method with the aid of Schottky spectra system.

ELECTRON COOLERS AT HIRFL-CSR

The 35keV electron cooler was installed at CSRm for beam accumulation and the 300keV electron cooler was installed at CSRe for improving the luminosity even with strong heating effects of internal targets. The main parameters are listed in table 1.

The electron beam is generated in a gun which is immersed in a longitudinal magnetic field. With the help of a 2kV power supply connected between the cathode and grid electrode one can produce the negative electric field at the cathode edge thereby suppressing the emission of electrons at this place. By varying the potential of gird it is possible to obtain the electron beam with parabolic, flat or hollow profile, which is shown in fig 1.

Table 1: Parameters of the E-cooler at HIRFL-CSR

Parameters	CSRm	CSRe
Maximum electron energy [keV]	35	300
Maximum electron current [A]	3.0	3.0
Cathode diameter [mm]	29.0	25.0
Maximum magnetic field in gun section [T]	0.24	0.5
Maximum magnetic field in cooling section [T]	0.15	0.15
Magnetic expansion factor	1 - 4	1-10
Effective cooling section length [m]	3.4	3.4
Parallelism of cooling solenoid field	10^{-5}	10^{-5}
Maximum potential between the cathode and grid electrode [kV]	2.0	2.0
Maximum potential between the cathode and anode electrode [kV]	5.0	5.0

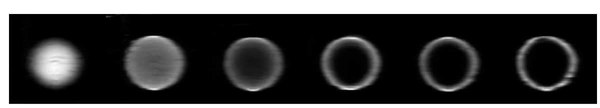

Figure 1: Electron beam profiles at grid potential U_{grid}=0V, 100V, 200V, 350V, 400V and 600V, the anode potential U_{anode}=500V.

LONGITUDINAL COOLING FORCE MEASUREMENT TECHNIQUE

The electron energy-step [3] method is one of the straightforward techniques for measuring the longitudinal cooling force. After the ion beam was cooled to equilibrium, the electron energy was changed rapidly by changing the cathode potential, creating a well defined velocity difference between ions and electrons. The ions will be accelerated or decelerated toward the new electron velocity. The acceleration is determined via Schottky spectra from the change in revolution frequency per unit time. The longitudinal cooling force at each time can be calculated in accordance with the relation

MODIFICATIONS OF CRYRING FOR TRANSFER TO FAIR

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Abstract

FLAIR will be the next-generation facility for physics with low-energy antiprotons, providing antiprotons at energies from tens of MeV down to rest. Also highly charged ions at very low energies will be available at FLAIR. A key component of the FLAIR facility will be the Low-energy Storage Ring LSR which will decelerate antiprotons from 30 MeV to 300 keV. The LSR will consist of the present CRYRING at the Manne Siegbahn Laboratory, which is being modified mainly with respect to injection and extraction, to allow injection of 30 MeV antiprotons and to provide it with both fast (single-turn) and slow (resonant) extraction at a variable energy. We here describe some aspects of the design of these modifications.

FLAIR AND CRYRING

FLAIR [1,2], the Facility for Low-energy Antiproton and Ion Research at FAIR [3], is expected to become the next-generation facility for physics with low-energy antiprotons, providing the world's highest fluxes of antiprotons at energies from tens of MeV down to rest. It will also offer unique possibilities for physics with highly charged ions at very low energies.

FLAIR will obtain beams of already decelerated antiprotons and ions from the NESR ring. The particles will then be further decelerated in one magnetic deceleration ring, the Low-energy Storage Ring LSR, which will be the modified CRYRING, and in one electrostatic ring, the Ultralow-energy Storage Ring USR, such that antiprotons can be delivered to experiments at a kinetic energy of only 20 keV. Also ions can be decelerated to low energies, limited in many cases by the increasing rate of recombination in collisions with residual-gas atoms as the energy is reduced, and by the consequent rapid reduction of the lifetime of stored beams of highly charged ions at low energies. Furthermore, antiprotons and ions can be decelerated by HITRAP for other experiments at very low energies or sent directly to experiments from the NESR or the LSR.

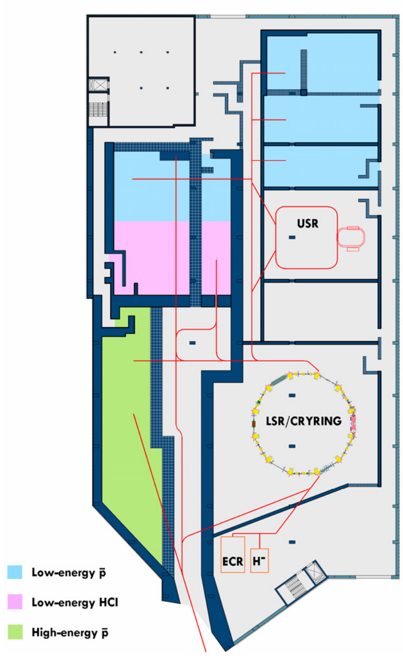

Figure 1: Proposed layout of the FLAIR hall.

The perhaps most important new feature at FLAIR, as compared to the Antiproton Decelerator, AD, at CERN, is that antiprotons will be phase-space cooled at lower energies during the deceleration process. The high production rate of antiprotons at FAIR, similar to that at CERN at the time of proton–antiproton collisions in the SPS but much higher than today's rate at CERN, can thus be combined with beams that have the smallest possible emittance and results in unprecedented beam intensities at low energies. Another difference is that the AD does not have the slow extraction that will be available at FLAIR.

A preliminary layout of the FLAIR hall is seen in fig. 1. Antiprotons will be delivered from NESR to the LSR at a kinetic energy of 30 MeV. In the LSR, the antiprotons can be decelerated down to 300 keV, or possibly somewhat lower if this is desirable. At 300 keV, the antiprotons are extracted to the electrostatic Ultralow-energy Storage Ring, USR, for further deceleration down to, at minimum, 20 keV. At that energy the particles can be trapped electrostatically and brought to rest by lowering the trap potential to zero. The LSR will, however, not be limited to extraction at the lowest energy, but antiprotons can be extracted at any energy between 30 MeV and 300 keV. For example, antiprotons will be delivered to HITRAP at 4.2 MeV.

Ions will be injected into the LSR at the same magnetic rigidity $B\rho$ of 0.80 Tm as 30 MeV antiprotons have, or at an energy of 30 Z^2/A^2 MeV/u, where Z is the charge state of the ion and A is its mass number. The ions can be decelerated and extracted over the same range of rigidities as the antiprotons, although the lowest limit may in practice be determined by the beam lifetime as already mentioned.

LSR will consist of the present CRYRING at the Manne Siegbahn Laboratory. This is a 1.44 Tm synchrotron and storage ring with 52 m circumference. CRYRING's properties closely match those required by the LSR as has been discussed earlier [4], and in that paper it was also shown that CRYRING already as it looks today is able to decelerate protons from 30 MeV to 300 keV with intensities close to the space-charge limit

THE VERSATILE NESR STORAGE RING WITH POWERFUL ELECTRON COOLING

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Abstract

The large-acceptance New Experimental Storage Ring (NESR) at FAIR has two main operation modes: storage of ion beams for internal experiments and deceleration of highly charged ions and antiprotons before transfer to a low-energy area. The heavy ion beams can be stable or rare isotopes selected in a magnetic separator. Antiprotons come at 3 GeV from the production target, they are stochastically pre-cooled and accumulated in a dedicated complex. The NESR operation relies on a performant electron cooler designed for up to 500 keV electron energy, 2 A electron current and with the option of magnetic expansion/compression. Electron cooling provides highest phase-space density of the stored beams and compensates beam diffusion during deceleration, so that high efficiency can be reached. For low-abundant isotopes, it also supports the longitudinal RF-accumulation, e.g. by means of barrier bucket pulses. For short-lived isotopes the cooling and deceleration time is optimized to a few seconds. Selected results of beam dynamics studies and benchmarking experiments from the existing ESR are presented in connection with the requirements of the users.

INTRODUCTION

The NESR of the FAIR project [1, 2] will store highly charged radioactive and stable ion beams for internal experiments and decelerate ions and antiprotons for transfer to the low-energy experimental facility FLAIR. The beams stored in the NESR are provided from various sources. Stable ions can be injected at magnetic rigidity up to 13 Tm, energy and charge state are chosen according to their availability after acceleration in the synchrotrons SIS18 or SIS100. Secondary rare isotope beams (RIBs) emerge from a production target and are selected in the magnetic separator SuperFRS. There are two ways of injecting RIBs into the NESR. The first is to inject a short bunch directly from the SuperFRS. The second, ensuring a better injected beam quality, makes use of stochastic pre-cooling in the CR. Then, in the RESR, beams can be optionally fast decelerated and transferred to the NESR. Antiprotons at 3 GeV will be injected from the RESR, where they are accumulated after pre-cooling in the CR.

OPERATION MODES

The operation modes and experimental performance in the NESR rely on the availability of powerful beam cooling and dedicated RF systems. An electron cooling system is installed in one of the four straight sections (Fig. 1). It covers the full energy range (740-4 MeV/u) for ions and

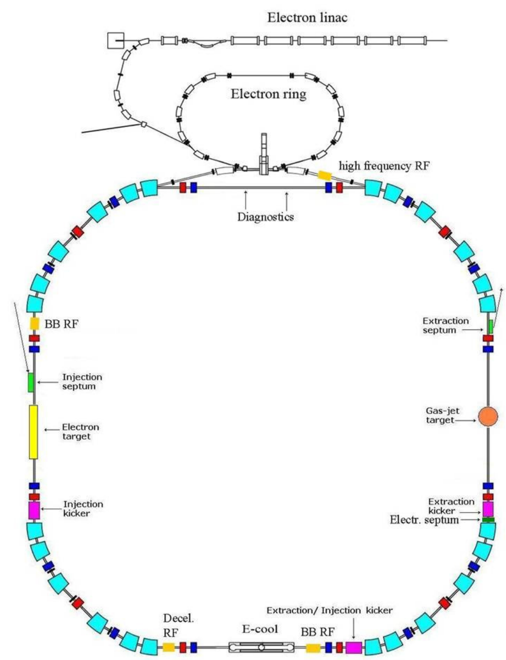

Figure 1: Layout of the NESR with experimental insertions.

allows for intermediate cooling in the range 800-30 MeV during the deceleration of antiprotons. It provides highest phase space density of the stored beams for the experiments and compensates the diffusion of the beams during deceleration. This ensures high efficiency and small losses during the deceleration cycle. For experiments with short-lived isotopes, the cooling time and the time of deceleration can be optimized to a few seconds. In addition, electron cooling will vitally support all RF manipulations: (i) the longitudinal accumulation at injection energy of RIBs produced at low abundancies, (ii) (re)bunching of the beams before each deceleration ramp, (iii) bunching at lowest energy for beam transfer to FLAIR and (iv) the generation of very short bunches in order to achieve maximum luminosity in the electron-ion collider mode. Three different RF systems are foreseen. A ferrite-filled RF cavity is responsible for bunching and decelerating the stored beams by successively changing the harmonic number. A broadband barrier bucket (BB) system is used for longitudinal compression of RIBs at injection energy and for the preparation of a single low-energy bunch for FLAIR. A high harmonics RF cavity produces short ion bunches for the electron-ion collider.

ULTRA-LOW ENERGY ELECTRON COOLER FOR THE HEIDELBERG CSR

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Abstract

As a part of the low energy electrostatic Cryogenic ion Storage Ring (CSR) an ultra-low energy electron cooler is under construction at the MPIK in Heidelberg. The cooler shares the basic CSR ultra-high-vacuum and 2 K cryogenic concept and uses a magnet system installed inside of the CSR isolation vacuum for the electron confinement. Cold electron beams will be provided for both phase space cooling of 300 keV stored ions and for recombination merged beam experiments with typical electron energies of 1-20 eV. A cryogenic photocathode electron source, developed for the Heidelberg Test Storage Ring, is used to achieve the beam quality required for electron cooling at such low energies. A new electron-ion merging scheme together with a decelerating electron optics suitable for both low energy electrons and slow ions will be applied. The production of high-quality electron beams of sub eV energies was studied at the TSR photocathode electron target.

INTRODUCTION

The Heidelberg CSR (see Fig. 1) is an electrostatic ring to be built at the Institute, with no mass limitation and with the capability of storing 20-300 keV ions. The circumference of the ring is about 35 m and it is designed to have a large ring acceptance of about 100 mm mrad.

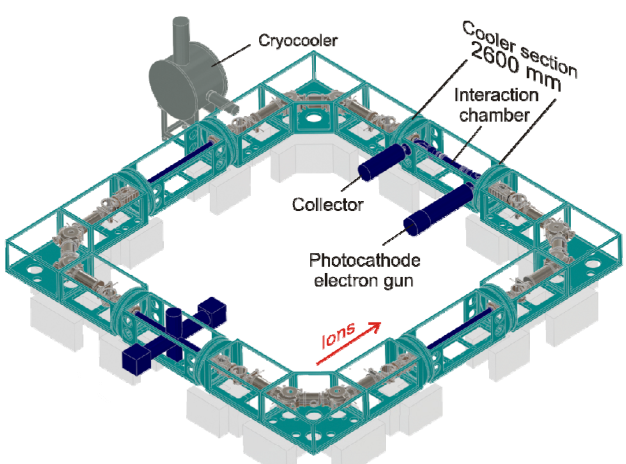

Figure 1: Schematic view of the CSR showing the electron cooler.

The key feature of the ring is the possibility of phase-space cooling of heavy, 100-200 a.m.u., molecular ions. To provide both phase space cooling with a velocity matched electron beam and cold electrons for merged beam recombination experiments, the CSR will be equipped with a dedicated ultra-low-energy electron cooler/target. The ring optics gives us the range of cooling energies we are interested in. The upper limit is given by 300 keV protons and corresponds to 163 eV electrons. For heavier single-charged ions the cooling energy decreases linearly as $1/M_i$ with M_i the ion mass, and corresponds to about 0.8 eV for M_i=200 a.m.u.; the typical electron cooling is foreseen to be a few eV. It is very difficult to cool these slow molecular ions because of the heavy mass and the low density of the electron beam, limited by the gun perveance. Thus, the lowest boundary is defined by the electron beam properties, including electron beam temperature and density.

The cooler will fit in one of the straight 2.6 m long experimental sections (see Fig. 1) and share the basic mechanical and cryogenic concept of the CSR with a two-level vacuum system. The first level is an isolation vacuum protecting the cryogenic environment from convection heat transfer and reducing radiation heat flux by thermal shields and by multilayer thermal isolation [1]. The second one is the 2K cryo-pumped beam vacuum volume at 10^{-13} mbar room temperature density equivalent pressure. The heat emission for the electron cooler has to be minimized and it should withstand bakeout up to 200-300^0 C. The magnetic electron optics of the cooler installed inside of the isolation vacuum has to be compatible with the electrostatic ring optics.

The CSR basic mechanical concept has been tested at the large scale 3-m long cryogenic electrostatic ion trap (Cryogenic Trap for Fast ion beams - CTF) that has been built as a part of the CSR project in 2007-2008. The CTF brought us practical knowledge about design and operation of large-scale cryogenic devices and proved our ability to achieve and measure vacuum with only 1000 rest gas particles per cubic centimetre specified for the CSR [1,2].

In this paper we discuss in more detail the results of numerical simulations, the mechanical and cryogenic concept of the cooler, and recent experiments on ultra-low energy electron beams [3], we have performed at the TSR e-target [4] with the same electron source and at energies we plan to use at the CSR.

NUMERICAL ANALYSIS OF LOW-INTENSITY SCHOTTKY SPECTRA RECORDED AS TIME SERIES

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Abstract

Schottky spectra of extremely well cooled low-intensity ion beams suffer from a low signal-to-noise ratio. Their digital post-processing is neither well prescribed nor trivial. The paper presents a comparison of the use of Hanning windows with overlapping samples on one hand, and of multitaper analysis, on the other hand. It is shown that the area under the Schottky peak is better defined if the multitaper method is used.

INTRODUCTION

Modern Spectrum spectrum analyzers nowadays usually offer several types of measurements. One of these measurement modes records the digitized data in the time domain after down conversion of the central frequency, as well as digital and analog filtering in a predetermined frequency span which is directly coupled to the sampling frequency. The digital data consist of in-phase and quadrature (IQ) components which are stored on disk. Because the data are stored without any gap in the time domain it is possible to analyze data packages of any desired size.

This article describes a set of first results which were gained with an RSA3303B analyzer from Tektronix. Two types of data evaluation are presented:

1. Evaluation using the classical averaging method with overlapping averages using a cosine (von Hann or Hanning) window.
2. Evaluation using the more advanced multitaper method.

MATHEMATICAL MODELLING OF SCHOTTKY SPECTRA

Single Particle Signal

The classical picture of Schottky spectra of coasting beams assumes a beam of N particles with constant revolution frequecies ω_n (or revolution periods $T_n = 2\pi/\omega_n$) which are positioned azimuthally in a random fashion. In order to take account of this position, one assumes a time lag τ_n, $0 \leq \tau_n < T_n$ for each particle. Any interaction among the particles or with other particles (internal gas jet target, cooling of any kind etc.) is neglected.

In the limit of an infitite number of passages through the Schottky probe, the Fourier transform of the resulting signal of each particle can be written

$$\tilde{U}(\Omega) = \frac{Z_L Q e \omega}{2} \sum_{m=-\infty}^{+\infty} S(\Omega) e^{-i\Omega\tau_n} \delta(\Omega - m\omega_n) \quad (1)$$

where $S(\Omega)$ is the Fourier transform of the sensitivity $s(t)$. The spectrum has peaks at every harmonic of the revolution frequency. As the phases $\omega_n \tau_n$ are random, one has to describe somehow its statictical properties.

Schottky Spectrum

The 'process' $U(t)$ is characterized by its autocorrelation function

$$R(t, \tau) = \langle U(t + \tau/2) U(t - \tau/2) \rangle \quad (2)$$

where $< \cdots >$ denotes a sample average. If the process $U(t)$ is stationary, then R is independent of t, i.e. $R(t, \tau) = R(\tau)$. The Fourier $S(\Omega)$ transform of $R(\tau)$ is then called the power spectrum of U. If the unit of U is volts, then $S(\Omega)$ has the unit V^2s. In the case of the Schottky spectrum, it is given by

$$S(\Omega) = \frac{N(Qe)^2}{m} \Psi(\Omega/m) \quad (3)$$

where $\Psi(\omega)$ is the revolution frequency distribution, assuming that there is no Schottky band overlap. It is assumed that $\Psi(\omega)$ is normalized to one.

Due to its statistical origin, the power spectrum can only be *estimated* from a single measurement.

ANALOG SIGNAL PROCESSING

Figure 1 shows how the analog signal from the Schottky pick-up is processed. The mixer can be modeled mathematically as a multiplier with the input signal U_i

$$U_n(t) \propto \cos(\omega_n t + \phi_n) = \cos((\omega_{\mathrm{LO}} + \delta\omega_n) t + \phi_n) \quad (4)$$

and the local oscillator (LO) signal

$$U_{\mathrm{LO}} \propto \cos(\omega_{\mathrm{LO}} t) \quad (5)$$

yielding signals at $\omega_i \pm \omega_{\mathrm{LO}}$. If this is done by using first the LO frequency directly and secondly after a 90 degree phase shift, one gets the in-phase (I) and quadrature phase (Q) low-frequency signals

$$U_I \propto \cos(\delta\omega_n t - \phi_n) \quad (6)$$

$$U_Q \propto \sin(\delta\omega_n t - \phi_n) \quad (7)$$

If both signals are available, one can decide which parts of the low frequency signal arise from rf components at either $\omega_{\mathrm{LO}} + \delta\omega_n$ or $\omega_{\mathrm{LO}} - \delta\omega_n$. This can be done either by using another 90 degree shift of the quadrature signal and adding or subtracting this signal from the in phase signal (image reject mixer) or by digitizing both signals and treat them numerically as a complex number $U_I + iU_Q$. After a digital Fourier transform (DFT) one gets different components below and above zero frequency.

EFFECTIVE LUMINOSITY SIMULATION FOR PANDA EXPERIMENT AT FAIR

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Abstract

In last years at GSI (Germany) the new accelerator complex project FAIR is being realized. One of the most important goals of this project is caring out an experiment with internal target PANDA [1]. One of ways to achieve the design luminosity value is to use a pellet target. However, such target is coming up with the short-scale luminosity variation. Peak to mean luminosity ratio can reach a big value unacceptable for detectors. If a detector is overloaded its count rate is not proportional to the luminosity, but depends on electronics design. In this case one can define so called "effective luminosity" as a ratio of the detector count rate to cross-section of the reaction.

Dependencies of the effective luminosity on the pellet target parameters for PANDA experiment simulated using BETACOOL code [2] are presented in this article.

INTRODUCTION

A numerical simulation of the experiment with a pellet target is connected to two different time-scale processes. The first one is the short-time process, which describes luminosity variations while one pellet is crossing the beam. This process can be about a few tenths microseconds long. The long-time process of the beam parameter evolution (particle number, transverse and longitudinal profiles) are defined by the beam losses and equilibrium between target heating and electron cooling. Characteristic time of this process can be of a few minutes or even hours.

The long-time process simulation is the general goal of the BETACOOL program. In the case of a pellet target simulation the algorithm is based on assumption that during one step of the integration over the time a large number of the pellets cross the beam. In the frame of the PANDA collaboration an additional algorithm was developed and implemented into the BETACOOL. It calculates luminosity time dependencies at the time scale sufficiently shorter then time that takes a pellet to get through the beam.

For benchmarking of the BETACOOL algorithms, results of experiment with the pellet target WASA at the COSY storage ring were used. During the COSY run from June 21 to July 5 2008 a luminosity value and different beam parameters were recorded as functions of time. Modeling of the experiment using the BETACOOL program showed a good agreement with the recorded data [3].

This article presents results of the PANDA experiment simulations using the developed algorithms.

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DESCRIPTION OF THE ALGORITHM

In the process of the long-time BETACOOL algorithm working, profiles of the antiproton beam are saved to hard disk drive at each step of integration over the time. Typically the integration step is of the order of a few seconds. The beam profile (horizontal or vertical) is a normalized particle density distribution along the corresponding co-ordinate. The beam profiles are calculated from array of model particles by averaging over their betatron oscillations. The new short-time algorithm generates a flux of pellets and propagates the pellet flux through the antiproton beam. When the pellet flux crosses the beam the profiles are considered to be constant on each integration step. The integration step of this algorithm is about 1 μs. At every step of the algorithm the density of the particles in the current pellet position is calculated for every pellet using the beam profiles.

Initially the short-time algorithm generates a pellet array. The pellets from the array are located in a long cylinder which has radius equal to the pellet flux radius. The cylinder height is chosen in accordance with the pellet vertical velocity in order to have required time of the simulation. For instance, the cylinder of 1 m of the height (see Fig. 1, the vertical position of the pellet is indicated as a "longitudinal distance" inside the cylinder) at the pellet velocity of 60 m/s (typical value for the pellet target) the pellet array will cross the antiproton beam during about 15 ms. Across the cylinder the pellets are distributed uniformly. Along the cylinder the pellets distributed in accordance with mean distance between pellets in vertical direction with a given dispersion.

After generation of the pellet array the algorithm propagates this array through the antiproton beam in the vertical direction from top to bottom with given step over time.

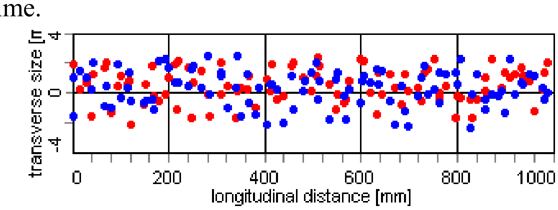

Figure 1: The pellet distribution along the flux: red – horizontal coordinate, blue – vertical.

During the propagation a "weight" value P_{xy}, which is proportional to the antiproton areal density in the pellet position, for each pellet is calculated. The pellet "weight" is evaluated as a product of the horizontal and vertical beam profile magnitudes in the pellet position:

PROTOTYPE PICK-UP MODULE FOR CR STOCHASTIC COOLING AT FAIR*

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Abstract

The performance of the collector ring (CR) of the FAIR project will strongly depend on a stochastic cooling system which is designed for fast pre-cooling of rare isotope and antiproton beams injected at different velocities. A prototype of the cryogenic movable pick-up module has been built. It consists of four circuit boards on an aluminum body and includes two times eight slotline electrodes, combiners and test electronics. It has been optimized for high sensitivity and flat frequency response. Measurements of the electric near-field over frequency and position will be presented.

INTRODUCTION

The collector ring (CR) will be a storage ring in the FAIR project at GSI which has three different operating modes.

The first mode is stochastic cooling of rare isotope beams. The rare isotope beams have a velocity of 0.83*c*. After bunch rotation and adiabatic debunching, they will be cooled down from ε_{xy} = 200 mm·mrad and $\delta p/p$ = 0.4% (2σ) to ε_{xy} = 0.5 mm·mrad and $\delta p/p$ = 0.05% within 2 s.

The second mode is stochastic cooling of antiproton beams with a velocity of 0.97*c*. After bunch rotation and adiabatic debunching, they will be cooled down from 240 mm·mrad and 0.7% to 5 mm·mrad and 0.1% within 10 s. Due to the low charge, this is the most demanding mode for the stochastic cooling system.

The last mode uses an isochronous optical setting for nuclear mass measurements of very short-lived nuclei. In this mode, no stochastic cooling will be used.

In the CR, four pick-up and three kicker tanks are foreseen. Three pick-up tanks will be placed in straight sections without dispersion for horizontal, vertical, and longitudinal cooling. Each of this pick-up tanks will be equipped with eight movable, cryogenic pick-up modules described in this paper. A fourth pick-up tank is foreseen for Palmer cooling of rare isotope beams. This one will be located in an arc with high dispersion. It will use the same slotline electrodes in a different arrangement. The three kicker tanks, foreseen in straight sections without dispersion will use the same slotline electrode board and a similar module body, but a different power splitter board.

SLOTLINE PICK-UP MODULE

To meet the requirements for large bandwidth, high signal to noise ratio and large aperture, a planar slotline electrode has been developed [1]. The stochastic cooling system for the CR is designed for a band from 1 GHz to 2 GHz. A pick-up module consists of a milled aluminum (Al) body, two alumina (Al_2O_3) pick-up boards, two combiner boards, and a lot of small electrical and mechanical parts. Figure 1 shows the aluminum body with one pick-up and one combiner board. Each module will be mounted with a steel tube to a linear motor drive outside the vacuum. It will be individually movable to any distance between 10 mm and 70 mm from beam axis. Two times four of such modules will be mounted in one cryogenic tank. This will allow us to have a large, non-uniform aperture along the tank for the incoming hot beams and a small aperture with high sensitivity for the cooled beam [2].

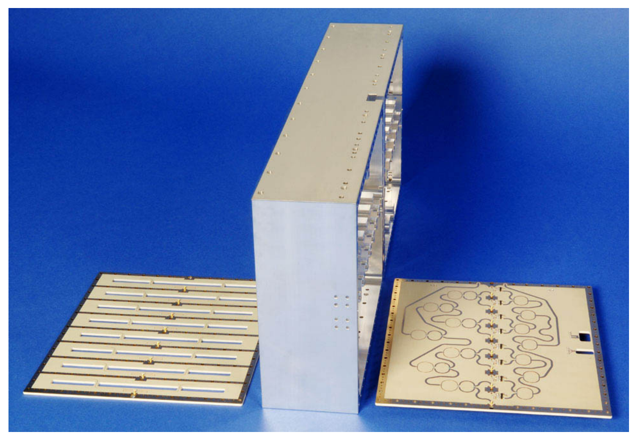

Figure 1: Main components of the pick-up module.

Each pick-up board (Fig. 2, top, left) consists of eight slotline electrodes. Each electrode consist of a slotline perpendicular to the beam and a microstrip circuit on the rear side of the Al_2O_3 board. The mirror currents of the charged particles induce traveling waves in both directions of the slotline. At approximately $\lambda/4$ 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 optimized to get large signals and a flat frequency response in magnitude and phase [3]. The two signals are coupled out to microstrip lines and are combined in the first stage 100 Ω to 50 Ω Wilkinson combiner. For the wanted signal, this combiner could also be replaced by a simple parallel connection, but it helps to damp unwanted modes in the pick-up system.

Behind the first combiner, the signal goes through a coaxial line in the module body (Fig. 2, bottom) to the combiner board or an optional low noise amplifier. The slotline electrode with the first combiner stage have a high reflection factor. An amplifier at this position would see its own

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CALCULATIONS OF ELECTRON BEAM MOTION IN ELECTRON COOLING SYSTEM FOR COSY

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Abstract

Results of calculations of electron beam motion in cooler for COSY (Juelich, Germany) are shown. The aim of the calculations is to study excitation of the beam galloping due to magnetic and electric field ripples, imperfection of bending field in toroids, transverse electric field in the end of accelerating tube etc. Dependences of the beam temperature on different parameters of magnetic and electrostatic systems are presented. Methods of correction of electron beam motion in order to decrease its transverse velocity are shown.

INTRODUCTION

In low energy electron coolers temperature (transverse velocity) of electron beam is not very important parameter because motion of electrons is adiabatic along full length of coolers from electron gun to collector and there is no significant excitation of transverse velocity. But in electron cooling systems for high energy, longitudinal Larmor length for electrons is high. Because of this, motion is not adiabatic and strong excitation of transverse temperature of the beam in possible. In such case investigation of electron motion in order to prevent strong increasing of electron transverse temperature is important task.

There are several one-particle effects which can increase transverse temperature of electron during the flight in magnetic field of the electron cooler:

1) magnetic field ripples,
2) electric field ripples,
3) excitation on transverse electric field in the end of the acceleration tube,
4) excitation on transverse magnetic field in transition between different values of magnetic field,
5) entry and leaving from bending parts.

In linear approximation, transverse beam motion in the system can be divided to for modes. First one is transverse shift of the beam relatively the reference line of the system without transverse velocity. Second one is dipole mode, in which all electrons of the beam with the same longitudinal coordinate move in transverse direction synchronously in the same direction, i.e. centre of mass of the beam moves, but there is no motion of electrons relatively the centre of mass. Third mode is synchronous motion of electrons relatively the centre of mass, but centre of mass doesn't move. In literature such motion is called galloping. And the fourth mode appears in systems where quadruple component of transverse magnetic field exists. This mode changes transverse profile of the beam by compressing it in one direction and stretching in perpendicular direction.

In systems with axial symmetry only galloping (third mode) can exist. Since in points 1-4 from the list above we suppose axial symmetry, only galloping can be excited there. In point 5 excitation of all modes is possible.

Influence of quadruple component on the temperature of the beam is very weak and it can be adjusted by field index in bends of the cooler. According to this, we need only two different types of additional correctors: dipoles and axial lenses, for correction of beam motion.

ELECTRON COOLER FOR COSY

Electron cooler for COSY (Juelich, Germany) is constructed to work in wide range of operating electron energy: 25 keV (injection) – 2 MeV (maximum energy for the ring) [1]. Magnetic field in cooling section is 2 kG. Cooling time ~10 sec.

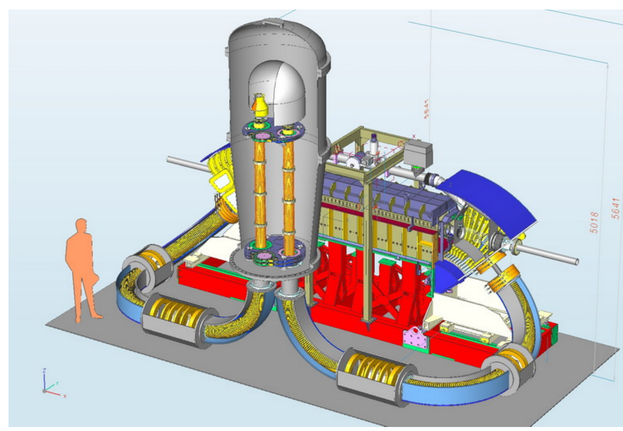

Figure 1: Electron cooler for COSY.

Strict requirements on size of the cooler, forces us to make its shape so complicated (fig. 1). In such shape acceleration and deceleration tubes are placed in one high voltage vessel. Length of acceleration tubes is 2 m. Along full trajectory from gun to collector electrons move in longitudinal magnetic field.

Magnetic system of high voltage vessel consists of two sets of identical coils, producing longitudinal magnetic field in acceleration and deceleration tubes. Transport line between high voltage vessel and cooling section consists of three 90° bends, one 45° toroid, two straight sections for technical purposes and two sections with variable profile of magnetic field for minimization of excitation of transverse motion in transition between different values of magnetic field. Cooling section consists of special coils with possibility to adjust straightness of magnetic force line by rotating each coil independently [2]. Bending field in 90° bends (82 G for 2 MeV electrons) is made with special coils (fig. 2). Each bend includes 4 coils. We are

SIMULATION STUDY OF SIMULTANEOUS USE OF STOCHASTIC COOLING AND ELECTRON COOLING WITH INTERNAL TARGET AT COSY AND HESR

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Abstract

The small momentum spread of proton or anti-proton beam has to be realized and kept in the storage ring during the experiment with dense internal target such as pellet target. The stochastic cooling alone cannot compensate the mean energy loss by the internal target, and the barrier bucket cavity will help this energy loss. In addition the further small momentum spread can be realized with use of electron cooling. In the present study, the simulation results on the simultaneous use of stochastic cooling and electron cooling at COSY and HESR are presented.

INTRODUCTION

A stochastic cooling is useful tool to cool a hot beam with smaller number of beam particles even in the high kinetic energy regime. While an electron cooling is useful for lower energy and cold beam, and has also advantage for effective cooling even in the large number of beam ions.

In HESR of FAIR project [1] a large number of antiprotons with high kinetic energy should be stored in the storage ring. The small momentum spread of anti-proton beam has to be realized and kept in the storage ring during the experiment with dense internal target such as pellet target.

In this study, we propose the simultaneous use of the stochastic cooling and electron cooling. The stochastic cooling can collect the protons or anti-protons with large momentum spread into the central energy regime, in addition the further small momentum spread can be realized with use of electron cooling.

SIMULATION MODEL

A Fokker-Planck equation is often used as an investigation tool in the stochastic momentum cooling process. The simplified Fokker-Planck equation for a model of a stochastic momentum cooling is given by [2]

$$\frac{\partial \Psi}{\partial t} + \frac{\partial}{\partial E}\left(F\Psi - D\frac{\partial \Psi}{\partial E}\right) = 0, \qquad (1)$$

where $\Psi \equiv \Psi(E,t) \equiv dN/dE$ is the particle distribution function, $F \equiv F(E)$ is the coefficient for the cooling force, and $D \equiv D(\Psi(E),t)$ is the coefficient for the diffusion process.

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The coherent and incoherent terms in the Fokker-Planck equation mean the cooling force and the diffusion process, respectively. The terms are derived by the electrical characteristics of the feedback system for the stochastic cooling [3]. Also the coherent term coefficient includes the electron cooling force as

$$F = F_{scool} + F_{ecool}, \qquad (2)$$

where F_{scool} is the cooling force due to the stochastic cooler and F_{ecool} is the cooling force caused by the electron cooler. For the calculation model of the electron cooling drag force, we carry out the Parkhomchuk empirical formula [4].

In this study, we simulate numerically the particle distribution during the cooling process using the Fokker-Planck equation solver [5] based on a constrained interpolation profile (CIP) method with a rational function [6].

Table 1 shows the parameters for COSY simulation [7] including the electron cooler option [8].

Table 2 shows the parameters for HESR simulation [1].

NUMERICAL SIMULATION RESULTS

COSY

Figure 1 shows the energy spread history during the cooling in COSY parameters. Here the energy spread σ is calculated by

$$\sigma^2(t) = \frac{1}{N}\int_{-\infty}^{\infty} E^2 \Psi(E,t)\, dE, \qquad (3)$$

where N is the total particle number in the ring.

As shown in Fig. 1, the energy spread can be improved well by the stochastic cooling in the case without the internal target. In the case with the internal target, the stochastic cooling does not compensate the energy loss, and the energy spread increases. When the electron cooling is simultaneously applied with the stochastic cooling, the energy spread can be improved until 500 sec in the case with the internal target. However even if in cooperation of the electron cooling of 0.25 A, the energy loss due to the internal target is not compensated in the later stage.

HESR

Figure 2 shows the particle distributions as a function of energy during the stochastic cooling in HESR at each cooling time. The anti-protons can be collected into the

IMPLEMENTATION OF LONGITUDINAL DYNAMICS WITH BARRIER RF IN BETACOOL AND COMPARISON TO ESME

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Abstract

The barrier bucket RF system is successfully used on Recycler storage ring at Fermilab. The special program code ESME [1] was used for numerical simulation of longitudinal phase space manipulations. This program helps optimizing the various regimes of operation in the Recycler and increasing the luminosity in the colliding experiments. Electron and stochastic cooling increases the phase space density in all degrees of freedom. In the case of a small phase space volume the intrabeam scattering introduces coupling between the transverse and longitudinal temperatures of the antiproton beam. For numerical simulations of the cooling processes at the Recycler, a new model of the barrier buckets was implemented in the BETACOOL code [2]. The comparison between ESME and BETACOOL codes for a stationary and moving barrier buckets is presented.

This article also includes an application of the barrier bucket numerical model for simulation of the luminosity distribution for RHIC colliding experiments. These simulations take into account the specific longitudinal distribution of the bunch and the vertex size of the detector.

BARRIER BUCKET MODELS IN THE BETACOOL PROGRAMM

Currently, the BETACOOL code has three algorithms that describes the synchrotron motion of the particles and which can be used for the simulation of the barrier bucket (BB) models. The first algorithm solves the standard equations of motion in the longitudinal phase space(s-s_0, $\delta=\Delta p/p$). The equations are:

$$\begin{cases} \dfrac{d(s-s_0)}{dt} = |\eta|\beta c\delta \\ \dfrac{d\delta}{dt} = -\dfrac{ZeV(t)}{Cp_0} \end{cases} \qquad (1)$$

where βc is the ion velocity, η is the ring off-momentum factor, Ze – the particle charge, $V(t)$ – the dependence of RF voltage on time, C – the ring circumference and p_0 – the momentum of the particles.

In the context of this algorithm the longitudinal motion any arbitrary RF voltage shape can be simulated. However, the problem of this algorithm is the calculation time because the integration step should be much smaller than the synchrotron period.

To avoid this problem, the analytical solution of the longitudinal motion between two square barrier buckets was introduced. In this case, the integration step can be independent on the synchrotron period. When the ion passes through the cavity gap at voltage $\pm V_0$ it gains (losses) an equal amount of energy ZeV_0, i.e.

$$\frac{d(\Delta E)}{dt} = \pm\frac{ZeV_0}{T_0} \qquad (2)$$

where ΔE is the energy deviation from the synchronous one, T_0 – the revolution period. The ion trajectory in the longitudinal phase space (t-t_0, ΔE) inside the bucket can be written in the following form:

$$(\Delta E)^2 = \begin{cases} A_E^2, \quad if\,|t-t_0| \le T_2/2 \\ A_E^2 - \left(|t-t_0| - \dfrac{T_2}{2}\right)\dfrac{2\beta^2 E_0 ZeV_0}{T_0|\eta|}, \\ \qquad if\, T_2/2 \le |t-t_0| \le (T_2/2)+T_1 \end{cases} \qquad (3)$$

where A_E is the maximum energy deviation from the synchronous energy E_0, V_0 is the voltage height, T_1 is the pulse width, T_2 is the gap duration. The phase space trajectory is composed of a straight line in the RF gap region and a parabola in the square RF wave region

The analytical model has static potentials for the barrier bucket with a rectangular shape which is resolved analytically in the longitudinal phase space. However, using of the analytical model is very difficult for the case of a moving bucket with an arbitrary shape.

A numerical model of the RF bucket is implemented in the BETACOOL code where the motion of one particle through each barrier is calculated independently. After crossing of the barrier the particle energy can increase (Fig.1a), decrease (Fig.1b) or the particle can be reflected by the barrier (Fig.1c).

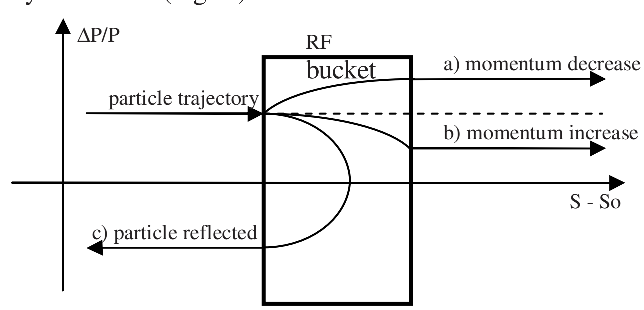

Figure 1: Particle trajectories trough a RF barrier in longitudinal phase space.

For the description of the individual synchrotron motion of each particle one can use a series of the barriers and numerical integration over the longitudinal phase

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ADVANCE IN THE LEPTA PROJECT*

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Abstract

The Low Energy Positron Toroidal Accumulator (LEPTA) at JINR is close to be commissioned with circulating positron beam. The LEPTA facility is a small positron storage ring equipped with the electron cooling system and positron injector. The maximum positron energy is of 10 keV. The main goal of the project is generation of intensive flux of Positronium (Ps) atoms - the bound state of electron and positron, and setting up experiments on Ps in-flight. The report presents an advance in the project: up-grade of LEPTA ring magnetic system, status of the construction of positron transfer channel, and the electron cooling system, first results of low energy positron beam formation with ^{22}Na radioactive positron source of radioactivity of 25 mCi.

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]. First experience of the LEPTA operation demonstrated main advantage of the focusing system with longitudinal magnetic field: long life-time of the circulating beam of low energy electrons. At average pressure in the ring of 10^{-8} Torr the life-time of 4 keV electron beam of about 20 ms was achieved that is by 2 orders of magnitude longer than in usual strong focusing system. However, experiments showed a decrease of the beam life-time at increase of electron 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 inhomogeneity and resonant behaviors of the focusing system.

Magnetic and Vacuum System Improvements

During March-May 2009 new measurements of the longitudinal magnetic field at solenoids connections were performed. According to the measurement results water cooled correction coils have been fabricated and mounted. As result, the inhomogeneity has been decreased down to $\Delta B/B \leq 0{,}02$ (Fig.1).

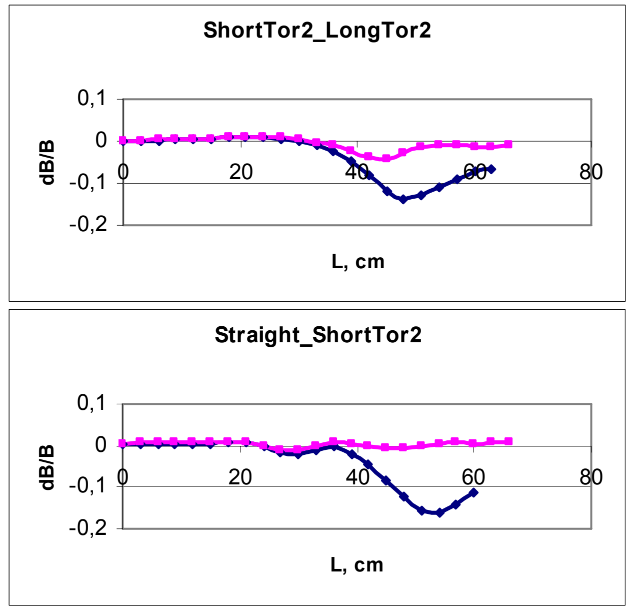

Figure 1: Magnetic field distribution along the toroidal solenoid axis.

The new water cooled helical quadrupole lens was designed and fabricated (Fig.2) that allowed us to improve significantly the vacuum conditions in the straight section.

Figure 2: The water cooled helical qudrupole.

To improve vacuum condition the evaporating titanium getter pumps manufactured at Budker INP have been mounted at the entrance and the exit of the straight section (Fig.3). First run of the pumps showed the average pressure decrease down to $5{\cdot}10^{-9}$ Tor at least.

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MUON COOLING IN A RACETRACK FFAG USING SUPERFLUID HELIUM WEDGE ABSORBERS

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Abstract

A fixed field alternating gradient (FFAG) lattice with racetrack-shape has been proposed to cool muon beams. The ring has straight sections with FFAG magnets. Wedge absorbers using superfluid helium and RF cavities are installed to the straight section. This paper describes the first result of simulation study and R&D status of the superfluid helium wedge absorber.

INTRODUCTION

The 6D-emittance reduction of a muon beam is essential for future neutrino factories and muon colliders. Ionization cooling was proposed to achieve a quick muon cooling, since the muon lifetime is 2.2 s in its rest frame. The emittance reduction in the muon ionization cooling is achieved by repeated channels of an absorber and an RF cavity [1]. In order to demonstrate this cooling method, the MICE is in preparation at Rutherford Appleton Laboratory (RAL) [2]. A long muon cooling channel is necessary to achieve a required emittance reduction for a neutrino factory and a muon collider. Such channels need a high cost of construction. A cooling section using a ring (ring cooler) would be more cost-effective than that consists of straight channels, since a number of RF and absorbers would be reduced. Some designs for the ring cooler have been proposed [3]. These designs, however, have some issues must be solved: injection/extraction and its kicker system, effects of windows for absorbers and RFs.

The study in this paper is the first attempt to design a ring cooler using the following ideas:

- racetrack FFAG ring and
- superfluid helium wedge absorbers.

The racetrack FFAG can be realized by new ideas of a straight beamline consists of FFAG type magnets, which was proposed recently by Y. Mori and S. Machida, *et.al.* [7]. These ideas bring new possibilities to design of the scaling type FFAGs such as dispersion suppressing section in a FFAG ring and an enough space to install devices for kicker systems. New ideas with the racetrack FFAG are actively discussed for example in the PRISM task force [4] and FFAG workshops [5]. FFAG as a muon ring cooler is not well studied yet. Papers by H. Schönauer report the study on ionization cooling in Japan's FFAG-based neutrino facility [6]. However, there is no other papers on the muon ionization cooling in FFAGs.

A typical absorber material proposed in the muon cooling channels is liquid hydrogen, since it has the lowest multiple scattering due to its lowest Z and sufficient ionization loss. Since the liquid hydrogen is an explosive material, its mechanical and engineering design and cooling of the liquid hydrogen are very finicky [8]. On the other hand, helium has no explosion risk and the second lowest Z of any materials. For the superfluid helium, there are more advantages as the absorber material: a lower pressure than the liquid hydrogen and a high thermal conductivity. All of these properties would make the absorber design easier than that with the liquid hydrogen. A thinner absorber window can be used, and a cooling system for the absorber material can be simpler, for instance.

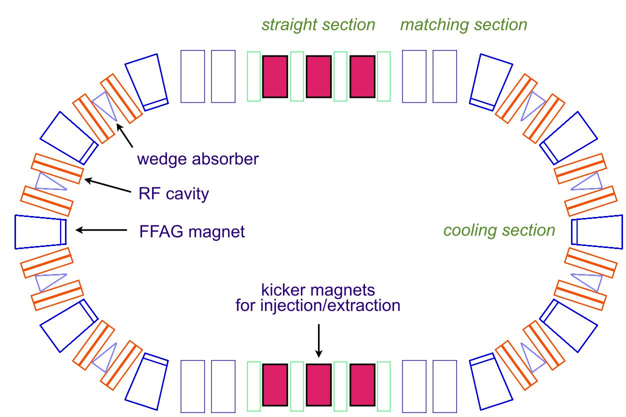

Figure 1: Concept of the muon ring cooler with a racetrack FFAG.

CONCEPT OF RACETRACK FFAG COOLER

Figure 1 illustrates a concept of the muon ring cooler with a racetrack FFAG. The ring is designed as a scaling type FFAG, since it can achieve a large transverse acceptance and a large momentum acceptance simultaneously. The ring consists of three sections: arc sections for the cooling, which has RF cavities and wedge absorbers; straight sections, which have an enough space to install kicker magnets for injection and extraction; and matching sections between the arc section and the straight section.

Zero-chromaticity and large momentum dispersion in a

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COOLING STACKING EXPERIMENTS AT HIMAC

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Abstract

^{11}C beam acceleration has been studied in order to form and verify a three-dimensional irradiation field for cancer radiotherapy at HIMAC. In the project, the ^{11}C beam is generated in the ion source and injected to HIMAC synchrotron. The cooling stacking technique plays an important role because of the low intensity of ^{11}C (several 10^7 /injection). The numerical target of the stored ^{11}C is 10^9 in the ring, which is a sufficient number to irradiate a single slice in the 3D scanning irradiation method. We have preceded the cooling stacking experiments using ^{12}C. The issues of the cooling stacking at HIMAC are the cooling time and the coherent instability. The cooling time becomes 2 sec after the improvements of the ion trapping. The coherent instability can be suppressed by the digital beam feedback system. The stacking of 8×10^9 particles is achieved with the feedback.

INTRODUCTION

Since 1994, the carbon beam treatment has been continued at the Heavy Ion Medical Accelerator in Chiba (HIMAC) [1]. The total number of patients reaches more than 4000. Based on the experience of the treatment, we have constructed the new facility for the further therapeutic developments [2]. The research subjects are the fast 3D scanning system toward the adaptive therapy and a gantry system for the intensity modulated carbon therapy. Another future subject is the radioactive beam irradiation such as ^{11}C in order to confirm the dose distribution directly.

Figure 1 (a) shows the treatment plan for head phantom by the carbon beam irradiation [3]. The irradiation shape is concave. Figure 1 (b) shows the PET-CT image after 1 Gy irradiation of ^{12}C. The positron emitter is created along the beam track and the image shows the irradiation area. But it is difficult to compare it with the treatment plan quantitatively. On the other hand, Fig. 1 (c) shows the PET-CT image after 1 Gy irradiation of ^{11}C, which is the positron emitter beam. It was carried out in the secondary beam line at HIMAC. The image clearly shows the stop point of the ^{11}C beam. It is possible to compare with the treatment plan without model calculation. The event rate of PET is also higher than the ^{12}C irradiation. However, the fragment reaction is used for the present ^{11}C irradiation at HIMAC and the beam rate is less than 10^7 pps. It is too low for the normal treatment, because the particle number of 10^{10} is necessary even by the scanning irradiation.

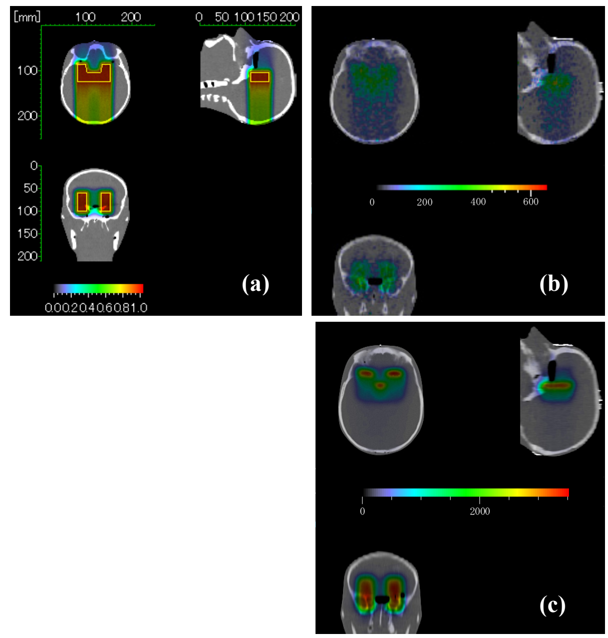

Figure 1: Dose distribution of the treatment planning for head phantom (a) and the measured image by PET-CT after the beam irradiation of ^{12}C , 1 Gy (b) and ^{11}C , 1 Gy (c) [3].

In order to increase the ^{11}C beam intensity for the treatment, we are planning to use the direct ^{11}C beam acceleration scheme from ion source to synchrotron [4]. Figure 2 shows the schematic diagram of the system. It is the application of the drug generation technique for PET. The separation of ^{11}C is carried out with liquid Ar using the difference of the melting point. The separation efficiency is around 50 % [4]. The atoms of ^{11}C are provided to ECR ion source.

Although the sufficient numbers of ^{11}C atoms are generated by the proton beam irradiation, the number of the injected ^{11}C to the synchrotron is rather limited due to the low efficiency of the compression and the ionization processes. The expected number of ^{11}C is less than 10^8 per one injection. Typically, the 10^{10} particles are necessary for the treatment but the ^{11}C particles are sufficient for one slice irradiation by the 3D scanning method. If we can irradiate a slice with the single injection, the non-uniformity of the dose distribution can be avoided. We

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APPLICATION OF BPM IN HIRFL-CSR ELECTRON COOLER

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Abstract

In order to measure the positions of ion beam and electron beam at the same time, two sets of capacitive cylinder beam position monitors were installed in the two ends of electron cooling section. The NI-5105 (8 channel High-Density Digitizer) was adopted as main data acquisition and the data was processed by the special code of LabView. With the help of these systems, the positions of electron beam and ion beam were measured during the process of accumulation and acceleration in CSRm. The movement of cooling force was observed in the case of different relative position (angle) in CSRe.

INTRODUCTION

CSR is a double cooler-storage-ring with a main ring (CSRm) and an experimental ring (CSRe). Two electron coolers located in the long straight sections of CSRm and CSRe.

In CSRm e-cooling is used for the beam accumulation. In CSRe e-cooling is used to compensate the growth of beam emittance during internal-target experiments or to provide high-quality beams for the high-resolution mass measurements of nuclei. For the two e-coolers, the hollow e-beam can be obtained to partially solve the problem due to space charge effect of recombination between the ions and the e-beam.[1]

The parameters of CSR coolers are listed in Table 1.

Table 1: Parameters of CSR Coolers

Parameters	CSRm	CSRe
Energy Ion [MeV/u]	10-50	25-500
E [keV]	4-35	10-300
Ion beam momentum spread	$\pm1.5\times10^{-3}$	$\pm1.5\times10^{-3}$
Ion beam divergences [mrad]	4.7, 1.3	2.0, 1.4
Ion beam emittance [π·mm·mrad]	150, 20	30, 30
e-beam radius at cooling section [cm]	2.9	2.9
Magnetic expansion factor	1- 4	1- 10
Length of cooling section [m]	4.0	4.0
Effective cooling section length [m]	3.4	3.4
β at cooling section [m]	10.0,17.0	12.5, 16.0
Parallelity of cooling solenoid field	$\leq1\times10^{-4}$	$\leq1\times10^{-4}$
Electron loss rate	$\leq3\times10^{-4}$	$\leq3\times10^{-4}$
HVPS stability	$\pm1\times10^{-5}$	$\pm1\times10^{-5}$
Electron beam current [A]	3 (1.0A@5.5keV)	

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BPM SYSTEM

The basic principle of electron cooling requires the ion beam is parallel with the electron beam. In order to measure the positions of ion beam and electron beam at the same time, a beam position measurement system was developed for the HIRFL-CSR electron cooling device, which is consist of some capacitive cylinder linear-cut probes, a NI-5105 (8 channel High-Density Digitizer) and some PET-amplifier (AM-4A-000110-11030N).

Due to the electron beam is direct current, this monitor can not get the signal, and the electron beam was modulated by an external 3MHz signal. The system was illustrated in Fig.1.

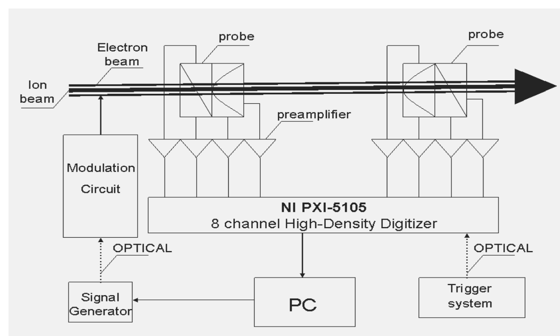

Figure 1: Layout of BPM system for HIRFL-CSR COOLER.

Probes were made of cylinder stainless steel, which specs are 80mm (length), 100mm (radius) and 1mm (thickness). They are sensitive and linearizing due to their induction and linear-cut configuration. Signal processing system consisted of preamplifiers and high-density digitizer. Preamplifier is PET P/N AM-4A-000110-11030N, which specs are 1MHz-1000MHz (BW), 54dB (gain) and 50Ω (input\output impedance). High-Density Digitizer is NI 12-bits and 8-channel PXI-5105, which specs are 60MS/s (sampling rate), 60MHz (BW), $150mV_{pp}$-$30V_{pp}$ (input voltage range) and 50Ω\1MΩ (input impedance).

The electron beam was modulated by an external 3MHz signal in electron gun-side. In order to prevent electromagnetic interference resulted from high voltage device, the external modulation signal was converted to optical signals and transmitted to the modulator module via fiber.[2]

The signals picked up by probes were magnified by independent preamplifiers. The data was processed by the special code of LabView. The both beam position were derived from the picking up signals of electrodes with the help of FFT method. The positions of electron and ion

STUDY ON THE OXIDE CATHODE FOR HIRFL-CSR ELECTRON COOLER

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Abstract

The oxide cathode is still wildly used in vacuum electronic devices as electron sources. With the ongoing development of electronic devices, the requirements for the emission characteristics of the cathode have to be enhanced to suit the new applications. It is a promising research direction improving the emission characteristics of the cathode at a low operating temperature and simple manufacture technology.

This paper studied the manufacture technology and properties of the oxide cathode and its emission mechanism. Then a new type of oxide cathode is developed and tested for its emission properties and lifetime. Its emission characteristic is better than that of the conventional oxide cathode. Part of properties of the cathode used in HIRFL-CSR Electron cooler is tested. The results show that the new oxide cathode is suitable to the electron cooler applications.

Keywords: Electron cool, Oxide cathode, Emission current

INTRODUCTION

The oxide cathode is a cathode coated BaSrCa(CO_3) on the surface of Ni base or W filament. When heated it in vacuum, the BaSrCa(CO_3) is decomposed into BaSrCaO, and Ba is produced when BaO reacted with the activators like Si and Mg in the Ni base, which make the cathode emit electrons. The oxide cathode has been developed more than 100 years. It is widely applied in electric light source, transmitter-receiver tube, grid control tubes, CRTs, space TWTs, high power klystrons[1,2,3,4] and electron cooler[5,6] because of its low operating temperature, large pulse emission current density, simple manufacture technology and low cost. However, the application of the oxide cathode is restricted in dc and wide pulse, high duty ratio pc emission tube because of its coating resistance and the interface layer resistance produced during the cathode operating process. For many years, worldwide scholars have programed a great deal of research to solve this problem.

In 1986, Saito[7] developed the rare-earth doped oxide cathode, doping 0.12-0.20% rare-earth oxide (Sc_2O_3 or Y_2O_3) in the coating of the conventional oxide cathode. The emission capability and lifetime of the rare-earth oxide cathode exceed that of the conventional oxide cathode because of its high coating electrical conductivity with the free Sc released by $BaSc_2O_4$'s reaction with the oxide in the coating. In the 1970's, a new type of oxide cathode has been developed in IECAS[8]. With the low coating resistance and little interface layer resistance, the cathode has high reliability, large current and long lifetime and has been applied to high power klystrons, long lifetime satellite TWTs and some special devices.

This paper analyzed the material composition of the oxide Cathode for HIRFL-CSR Electron cooler, and the emission characteristic such as dc, pc and the lifetime of this cathode is compared with that of the new oxide cathode developed by us through diode testing. The result shows that the lifetime and reliability of the electron gun for HIRFL-CSR electron cooler can be improved.

THE CATHODE STRUCTURE IN ELECTRON COOLER

The main parameters of the cathode: the convex radius of the cathode is 48mm, the diameter is Φ30mm, the Ni sponge is sintered on the cathode surface and its diameter is 28mm, a layer carbonates is sprayed on the Ni sponge. This kind of cathode is Ni sponge oxide cathode. The Ni sponge oxide cathode has ever been used in gird-control emission tube with 3% duty ratio in our insititute, but it was not succeed. However, this gird-control emission tube using the new oxide cathode operated successfully with 4～6% duty ratio in radar.

ELECTRON EMISSION PHYSICAL PROCESSES OF THE CATHODE

The Conventional Oxide Cathode

The basic structure of the conventional oxide cathode is shown in figure1. The process of the electron emission of the oxide cathode is following three steps:

A.By heating, the carbonate on the Ni base decomposes into oxide:

$$(BaSrCa)CO_3 \rightarrow (BaSrCa)O + CO_2\uparrow$$

B.The activator (Si, Mg, W) in the Ni base diffuses to cathode's surface which reacts with the BaSrCaO and produces excess Ba:

$$BaO+Si \rightarrow SiO_2+Ba$$
$$BaO+W \rightarrow WO_3+Ba$$

C. The excess Ba diffuses to the surface of the （BaSrCa）O grain and is activated by SrO, then releases two electrons and emit vacuum through micro-ostium in the coating. The excess Ba loses two electrons and becomes Ba^{++} which needs obtaining electron and keeps its electric charge balance. At the same time, the interface layer ($BaSiO_3$) is produced by the reaction between SiO_2 to BaO:

$$BaO+SiO_2 \rightarrow BaSiO_3$$

DESIGN OF STOCHASTIC COOLING SYSTEM AT HIRFL-CSRe *

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Abstract

In the CSRm synchrotron, the beam is accelerated to energies of 500-1000 MeV/u. It can be fast extracted at energies of 200-700 MeV/u to produce radioactive ion beams (RIBs) or high Z beams at the target in the beam line. The secondary beams can be stored in the CSRe ring for internal-target experiments or β decay measurements. The secondary beams are very hot. Electron cooling to such beams would take several minutes, which is too long for experiments with short-lived ions. Stochastic cooling is very efficient for such hot beams. The large phase space after injection will be reduced to values which are well-suited for the subsequent e-cooling.

We report here the proposal and primary design of the stochastic cooling system at CSRe. The simulation results of the Palmer cooling and bunch rotation will be presented.

INTRODUCTION

HIRFL-CSR [1], a heavy ion synchrotron and cooler-storage ring system in Lanzhou, consists of a main synchrotron ring (CSRm) and an experimental storage 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 the HIRFL with energies of 7-25MeV/u are injected into the CSRm. Electron cooling supports the accumulation at injection energy. The beams are accelerated and extracted slowly at energies of 500-1000MeV/u for external-target experiments, or fast extracted at energies of 200-700MeV/u to produce RIBs or high Z beams at an external production target for rare isotope beams. These beams are stored or decelerated in the CSRe for internal-target experiments or high precision spectroscopy with beam cooling. The radioactive fragments emerging from the target occupy a large transverse and longitudinal phase space which would lead to the e-cooling times of several minutes. This is too long for the experiments with rare isotope beams of short lifetime. Stochastic cooling at the CSRe would be very efficient to cool such hot beams and it will be used mainly for pre-cooling of RIBs. It is planned to reduce the momentum spread of ±1% and the horizontal and vertical emittances of 30 π mm mrad to the values which are well-suited for the subsequent e-cooling. The beam energy for stochastic cooling will be in the range of 350-500MeV/u.

CSRE RING

The layout of CSRe ring is shown in Fig. 1. It has a race-track shape and consists of two quasi-symmetric parts. One is the internal target part and another is the e-cooler part. Each part is a symmetric system and consists of two identical arc sections. Each arc consists of four dipoles, two quadruple triplets or one triplet and one doublet. Two long dispersion free straight sections house the internal target and the e-cooler. The major parameters of the CSRe are listed in table 1.

Table 1 Major parameters of CSRe

	CSRe
Circumference (m)	128.80
Ion species	Stable nuclei: C~U, RIB(A<238)
Max. energy (MeV/u)	600 (C^{6+}), 400 (U^{90+})
Intensity (Particles)	$10^{3\sim9}$
$B\rho_{max}$ (Tm)	8.40
B_{max} (T)	1.4
Ramping rate (T/s)	0.01~0.4
E-cooler Ion energy (MeV/u) Length (m)	 25~400 4.0
RF system Harmonic number f_{min}/f_{max} (MHz) Voltages (n × kV)	Capture 1 0.5 / 2.0 2 × 10.0
Vacuum pressure (mbar)	6.0×10^{-11}

In CSRe three lattice modes are adopted for different requirements. The first one is the internal-target mode with small β-amplitude at the target point, large transverse acceptance (A_h=150πmm mrad, A_v=75πmm mrad) and γ_{tr} = 2.457 for internal-target experiments. The second one is the normal mode with a large momentum acceptance of $\Delta P/P$ = 2.6% and γ_{tr} = 2.629 used for high-precision mass spectroscopy. The third one is the isochronous mode with a small transition γ_{tr} that equals the energy γ of beam in order to measure the mass of those short-life-time RIB. Figure 2 and Figure 3 show the distribution of the β-functions and the dispersions for those modes.

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ELECTRON COOLING FOR THE THERAPY ACCELERATOR COMPLEX

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Abstract

Institute of Nuclear Physics (BINP, Novosibirsk) is engaged in R&D of the new therapy accelerator system based on the electron cooling. The electron cooling is used for the ion beam accumulation in process of repeated multi turn injection into the main ring from the fast cycling booster synchrotron. After acceleration of the carbon ions up to 200-400 MeV/u the electron cooling is used for shrinking the beam emittance to minimal value and for further extraction and distribution of small fractions of the ion beam according to the irradiation program. The extraction systems base on the electron cooling is discussed in the report. The computer simulation results are in a good agreement with the experimental data of the electron cooling of the carbon ion beam with energy 400 MeV/u obtained resently during the CSRe commissioning (May 2009).

INTRODUCTION

Heavy ion beam therapy is one of the most advanced and effective cancer treatments. It is more accurate, caused less damage to healthy tissue and has a higher cure rate in comparison with conventional kinds of radiotherapy with x-ray. Traditional therapy systems with carbon ion beam consist of following parts: ion source, linear accelerator up to 30 MeV/u, synchrotron for ions acceleration up to the energy of 100-400 MeV/u and irradiation channels including (in most radiotherapy centers) the gantry system intended for irradiation a tumor from different directions [1]. The application of the achievements of the ion beam cooling science to this therapy system can fundamentally improve the characteristic of beams used for therapy. If we discuss just adding the electron cooling to existing system [2] it looks like additional cost about 2 M$ to the existing equipment with total price about 70-100 M$. But new system based on the electron cooling from the very beginning (from stage of design) opens many unique possibilities unachievable for conventional systems namely:

1. Accumulation primary ion beams by means of repeating injection that relieves requirements on injection system.
2. Possibility to accumulate secondary positrons emitting nuclei that can be used for precise diagnostic of the radiation dose distribution in and around a tumor with the help of standard PET apparatus.
3. After acceleration with further cooling the ion beam has very small emitance that allow the extraction system to be less powerful and has failure-free operation
4. Possibility of the precise beam extraction by a recombination.

These advantages make it possible to construct therapy system more reliable and cheaper. According to a contract with Chinese company BINP works on development of the project for carbon therapy. But after the economic crisis begun the project got strong problems with financing. Initial construction of prototype of elements and calculation of the cooling process showed high level perspectives. This year experiments with cooling 400 MeV/u carbon ions at CSRe demonstrate very interesting results.

PRIMARY BEAM ACCUMULATION

Injector comprises the ion sources, tandem accelerator, the fast-cycling booster synchrotron and low energy beam transport lines. A multi-turn injection from the tandem accelerator into the booster synchrotron is performed in a horizontal plane. The booster synchrotron accelerates protons up the maximum energy of 250 MeV and the carbon ions $^{12}C^{+4}$ up to 430 MeV/u. The booster circumference is of 27 m, repetition rate is 10 Hz. The maximal energy of booster synchrotron is 30 MeV/u which is optimal for accumulation the carbon ions in the main synchrotron with period 0.1 sec. After injection into the main synchrotron, the ion beam is stored, cooled and accelerated up to the energy required for therapy then extracted into the high energy beam transport system. The ion beam is stored during 10 booster cycles with electron cooling.

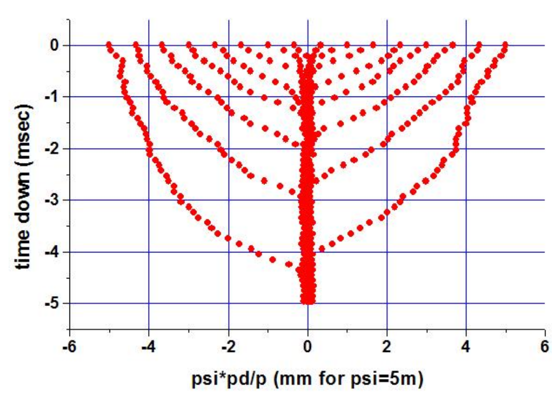

Figure 1: The computer simulation of initially injected beam cooling (momentum): electron current 0.5 A, electron energy 16 kV, time range arrow is shown from up to down in milliseconds.

Radioactive Isotopes Accumulation

The electron cooling can be used for an accumulation of radioactive nuclei which could be useful for cancer

COMMISSIONING OF ELECTRON COOLING IN CSRe*

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Abstract

The 400MeV/u $^{12}C^{6+}$ ion beam was successfully cooled by the intensive electron beam near 1 Ampere in CSRe. The momentum cooling time was estimated near 15 seconds. The cooling force was measured in the cases of different electron beam profiles, and the different angles between ion beam and electron beam. The lifetime of ion beam in CSRe was over 80 hours. The dispersion in the cooling section was confirmed as positive close to zero. The beam sizes before cooling and after cooling were measured by the moving screen. The beam diameter after cooling was about 1 millimeter. The bunch length was measured with the help of BPM signals. The diffusion was studied in the absent of electron beam.

INSTRUCTION

HIRFL-CSR[1] 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: Lattice Parameters of CSRe

Lattice Parameter	Value
Transition gamma	$\gamma_{tr} = 2.629$
Betatron Tune	Q_x / Q_y=2.53/2.57
Max. Betatron amplitude	$\beta_x / \beta_y = 17.6/8.2$m(Dipole) $\beta_x / \beta_y = 30.9/22.3$m(Quadruple)
Max. Dispersion	D_x=6.5m(Dipole β_x=13m) D_x=7.8m(Quadruple β_x=16m)
Injection section	β_x=30.4m, D_x=0m(Septum) β_x=30.9m, D_x=0m(Quadruple)
Electron cooling section	$\beta_x / \beta_y = 12.5/16.0$m, D_x=0
Internal target	$\beta_x / \beta_y = 5.4/1.5$m, D_x=0
RF station	$\beta_x / \beta_y = 4.0/8.4$m, D_x=4.5m

* supported by the central government of China

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CSRe is a 128.8m circumference cooler storage ring with sixteen 22.5 degree C-type bending dipole magnets. The maximum Betatron functions are 30.9m and 22.3m in horizontal and vertical respectively. The maximum dispersion is 7.8m, and the dispersion at injection point is zero, the Betatron function is 30.4m in the Septum. The Betatron functions at electron cooler are 12.5m and 16m in the two transverse directions respectively, the dispersion is near zero here. The tunes are about 2.53 and 2.57, the transition gamma is 2.629, and the transverse acceptance of CSRe is about 150πmmmrad, and the longitudinal one is $\pm 5\times10^{-3}$.

Accelerated ion beam from the CSRm through the radioactive beam separator line with the length of 100m was injected into the CSRe. Generally the CSRe operated with the DC mode. A gas jet internal target was installed in the opposite side of electron cooler.

Table 2: Parameters of the CSRe Electron Cooler

Maximum electron energy	300 keV
Maximum electron current	3A
Gun perveance	29 μP
Cathode diameter	29mm
Current collection efficiency	≥99.99%
Maximum magnetic field in gun section	0.5T
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	$\leq 3\times10^{-11}$mbar

The electron cooling device plays an important role in HIRFL-CSR experimental ring for the heavy ion beam. Continuous electron cooling is applied to the stored ion beam for the compensation of the heating by various scattering. The most important is the ability to cool ion beams to highest quality for physics experiments with stored highly charged ions. 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 2. It was reported in many conferences[2],[3],[4],[5],[7]The previous commissioning results have been given in the COOL05-P02[6] and COOL07-TUM1I02[8]

STATUS OF THE 2 MEV ELECTRON COOLER FOR COSY JUELICH

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Abstract

The design and construction of the 2 MeV electron cooling system for COSY-Juelich is proposed to further boost the luminosity in presence of strong heating effects of high-density internal targets. In addition the 2 MeV electron cooler is an important step towards the high energy electron cooler for the High Energy Storage Ring (HESR) in the FAIR project. The design of the 2 MeV electron cooler will be accomplished in cooperation with the Budker Institute of Nuclear Physics in Novosibirsk, Russia. A newly developed prototype of the high voltage (HV) section, consisting of a gas turbine, magnet coils and HV generator was successfully tested. Special emphasis is given to voltage stability which must be better than 10^{-4}. First experiments with three HV sections, installed in a pressure vessel filled with SF_6 gas are reported.

INTRODUCTION

The new generation of particle accelerators operating in the energy range of 1-8 GeV/u for nuclear physics experiments requires very powerful beam cooling to obtain high luminosity. For example, the investigation of meson resonances with PANDA detector requires an internal hydrogen target with effective thickness 4×10^{15} atoms per cm^2 and $10^{10} – 10^{11}$ antiprotons at 15 GeV circulating in the HESR. In this case the peak luminosities ranging from 2×10^{31} to 2×10^{32} cm^{-2}s^{-1} are achievable. These experiments allow to study meson resonances in proton-antiproton annihilations. Resolution of the experiments is limited only by momentum spread in antiproton beam, which must be better than 10^{-4}.

The average momentum losses dp/pdt on such a target (for 4 GeV antiprotons) will be about $4\cdot10^{-6}$s^{-1} and the heating rate of momentum spread by fluctuation of ionization losses will be near $dp^2/p^2dt = 2\times10^{-9}$s^{-1} To obtain momentum spread of $10^{-5} – 10^{-4}$ cooling time in the range $\tau_{cool} = 2(dp/p)^2/(dp^2/dt/p^2) = 0.1 \div 10s$ is needed. The 4 MeV electron cooler at the RECYCLER ring (FNAL) [1] achieves cooling time about 1 hour. The new cooler for COSY should provide a few orders of magnitude more powerful cooling that requires new technical solutions. The basic idea of this cooler is to use high magnetic field along the orbit of the electron beam from the electron gun to the electron collector. In this case high enough electron beam density at low effective temperature can be achieved in the cooling section. For example the electron beam density of 2×10^8 cm^{-3} (6 mm beam diameter and 1.5 A of current) magnetized with longitudinal magnetic field of 2 kG will have 2.7×10^6 cm/s drift velocity in the beam reference frame. This velocity allows (in principle) to have cooling time near 0.1 s for the low angular spread ($\Delta p_\perp / p = 10^{-5}$) beam.

BASIC DESIGN FEATURES

The basic parameters for the COSY cooler are listed in Table 1. The restrictions are given by the space available in the COSY ring. The height is limited to 7 m by the building.

Table 1: Basic Parameters and Requirements

COSY 2 MeV Electron Cooler	Parameter
Energy Range	0.025 ... 2 MeV
High Voltage Stability	$< 10^{-4}$
Electron Current	0.1 ... 3 A
Electron Beam Diameter	10 ... 30 mm
Length of Cooling Section	2-3 m
Toroid Radius	1.25 m
Magnetic Field (cooling section)	0.5 ... 2 kG
Vacuum at Cooler	10^{-8} ... 10^{-9} mbar
Available Overall Length	6 m
Maximum Height	7 m
COSY Beam Axis above Ground	1.8 m

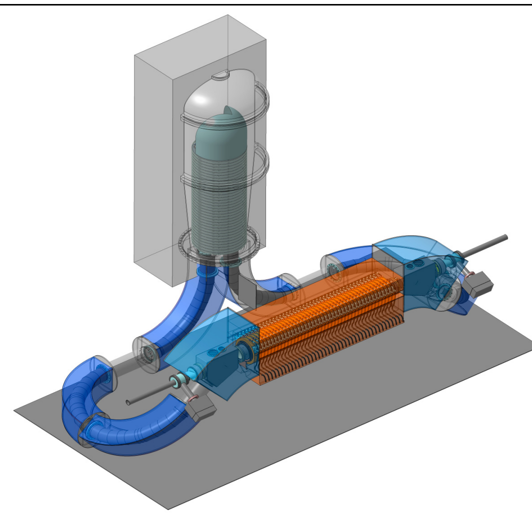

Figure 1: Layout of the 2 MeV electron cooler for COSY.

In Fig. 1 the layout of the COSY 2 MeV cooler is shown. The cooler HV terminal is installed inside the pressure vessel filled with SF_6 gas. The main features of the cooler are:

1. The design of the cooling section solenoid is similar to the ones of CSR (IMP) and LEIR (CERN) coolers designed by BINP [2,3]. However, for the 2 MeV cooler the requirement on the straightness of magnetic field lines is so high ($\Delta\theta < 10^{-5}$) that a system for monitoring the magnetic field lines in vacuum becomes necessary.

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ELECTRON COOLING FOR ELECTRON-ION COLLIDER AT JLAB*

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Abstract

A critical component of a conceptual design of a high luminosity electron-ion collider at JLab is an electron cooling facility which consists of a 10 mA, 33 MeV energy recovery linac and a circulator ring. A fast kicker has been conceptually designed for switching electron bunches between the linac and the circulator ring. To alleviate space charge impact on cooling, we developed a concept of *helical* electron cooling in which the cooled ion beam has a large round size but a low 4D emittance by matching the *circular eigenmodes* of the ion ring with solenoid in the cooling section. The collider luminosity could be restored by transforming the round ion beam to a flat one in the collision area. In this paper, design parameters of this cooling facility and a scenario of forming and cooling of the ion beam will be presented.

INTRODUCTION

The CEBAF recirculating SRF linac, currently under an energy doubling upgrade, will provide up to 12 GeV polarized CW electron beam with 3x499 MHz bunch repetition rates and excellent beam quality for fixed target nuclear science programs at JLab. The upgraded CEBAF will also open a great opportunity for a high luminosity electron-ion collider (ELIC) which can be achieved by adding an ion complex. [1] Such a collider could provide collisions between polarized electrons and polarized light ions or non-polarized heavy ions in a wide center-of-mass (CM) energy range, delivering a luminosity up to 10^{35} $cm^{-2}s^{-1}$. Electron cooling (EC) is essential both during the process of forming high intensity ion beams as well as at a collision mode for maintaining good beam quality. A conceptual design of the ELIC electron cooler was first reported in a previous paper of the same workshop series. [2] Here we will present an update of the design and also discuss several key technology R&D issues required for realizing this design.

ELECTRON-ION COLLIDER AT JLAB

JLab has been engaged in conceptual design of ELIC for nearly a decade. After several major design iterations, the latest ELIC design, as shown in Figure 1, focuses on a low-to-medium energy collider with CM energy up to 52 GeV. [3] There are three vertically stacked figure-8 shape storage rings, namely, the electron ring and two ion rings for low (up to 12 GeV/c) or medium (up to 60 GeV/c) momentum per proton respectively, in a small tunnel (red line in Fig.1a) of approximately 640 m, and crossed at four collision points as shown in Fig. 1b. Two large figure-8 rings (the grey line in Fig.1a) are for future upgrade to a high energy collider. Table 1 summarizes the design parameters for the low to medium energy ELIC.

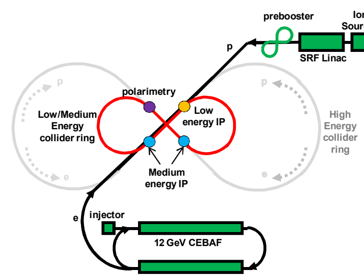

Figure 1a. Schematic drawing of a ring-ring electron collider based on CEBAF at JLab.

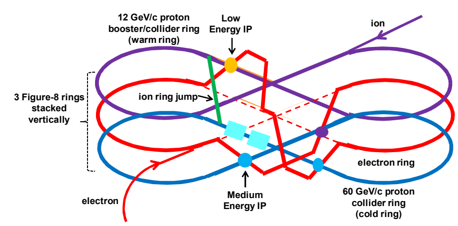

Figure 1b. Three figure-8 shape storage rings for electron, low and medium energy ions are stacked vertically and crossed at four collision points.

Table 1. ELIC main parameters

Beam energy	GeV	60/5	60/3	12/3
Collision frequency	MHz	499		
Beam current	A	0.6/2.3	1.1/6	0.5/2.3
Particles/bunch	10^{10}	0.7/2.9	0.86/4.8	0.47/2.3
Energy spread	10^{-4}	~3		
RMS bunch length	mm	5	5	50
Hori. emit., norm.	mm	0.56/85	0.8/75	0.2/80
Verti. emitt, norm	mm	0.11/17	0.16/15	0.18/80
Hori. beta-star	mm	25	25	5
Verti. beta-star	mm	5		
Verti. b-b tune shift		.01/.03	.015/.08	.015/.013
Laslett tune shift		0.1	0.054	0.1
Peak lumi./IP, 10^{34}	$cm^{-2}s^{-1}$	1.9	4	0.6

The ELIC high luminosity concept is based on the following design features: very high bunch collision rate (0.5 GHz), large beam-beam parameters, and very small bunch spot sizes at collision points. The very small β_y^* value (~5 mm) requires a very short ion bunch (~5 mm RMS) which is achievable due to not only electron cooling but also a relatively small bunch charge, a fraction of 10^{10} protons per bunch, compared to typical super bunches (of 10^{12} protons or more) with much longer bunch lengths (10 cm RMS or larger) in all existing hadron colliders.

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STATUS OF HIRFL-CSR PROJECT*

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Abstract

The HIRFL-CSR project is a national mega project of China, which concentrates on heavy ion synchrotrons and cooling storage rings. It is finished recently. The present commissioning results, testing experiments and new development are introduced in this paper. The future improvement of the machine is also discussed in this paper.

INTRODUCTION

The HIRFL-CSR project consists of CSRm (main synchrotron), RIBLL2 (RIB production and transfer line), CSRe(experimental storage ring) and experimental terminals (see Fig. 1). Its injector is a two cyclotrons complex. Its total budget is around 27 million euro. The main parameters are listed in Table 1.

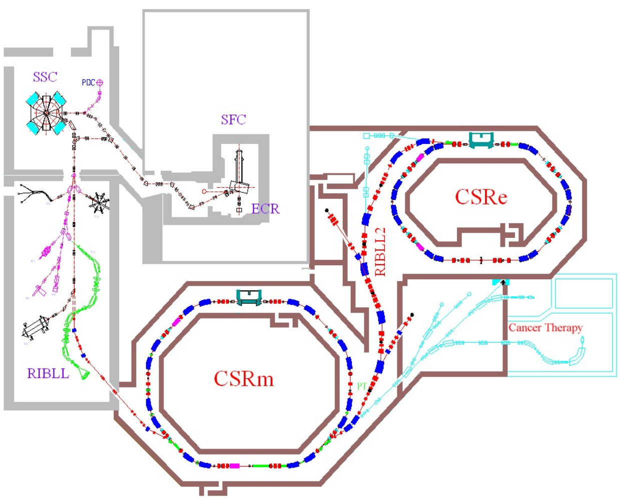

Figure 1: Layout of HIRFL-CSR.

The project starts in Apr. 2000 and gets the first stored beam in CSRm in Jan. 2006. By end of 2007, the commission and official tests are done successfully.

Up to now, several species of beam are commissioned at CSR, including Carbon, Argon, Krypton and Xeon. The intensity of them reached 7×10^9, 4×10^8, 1×10^8 and 1×10^8 pps respectively. The energy of Carbon and Argon reached 1AGeV, which surpassed the designed magnet rigidity value 10.64Tm. The Carbon, Argon and Krypton beams are injected into CSRe, and two mass measurement experiments are done with Argon and Krypton beams.

The slow extraction is realized for CSRm, it's the first step towards external target experiments and cancer therapy study.

Table 1: Major Parameters of CSR

	CSRm	CSRe
Ion species	Carbon~Uranium	Carbon~Uranium
Magnet rigidity	0.7~11.5Tm	0.6~9Tm
Max. Energy	$^{12}C^{6+}$-1000MeV/u $^{238}U^{72+}$-460MeV/u	$^{12}C^{6+}$-700MeV/u $^{238}U^{91+}$-460Mev/u
Beam intensity	$^{12}C^{6+}$- 7×10^9ppp $^{129}Xe^{27+}$-1×10^8ppp	$^{12}C^{6+}$- 7×10^9ppp $^{129}Xe^{27+}$-1×10^8ppp
Emittance	~1π mm mrad	~1π mm mrad
Tunes	3.63/2.62	2.53/2.58
e-cooler energy	35keV (50MeV/u)	300keV (400MeV/u)
Vacuum Pressure	$<6\times10^{-11}$mbar	$<6\times10^{-11}$mbar
RF cavity	0.24~1.7MHz 7kV	0.5~2MHz 2×10kV
Injection	Multi-turn Charge exchange	Single turn
Extraction	Fast Slow(RF KO)	-

COMMISSIONING AND OPERATION

At beginning of 2005, the commission of CSRm started. The first beam passed CSRm in Feb. 2005. During 2005, a lot of work was done to improve the beam diagnosis system, power supply system and local control system. The first stored beam was obtained by charge stripping injection (CSI) method in Jan. 2006(Fig. 2).

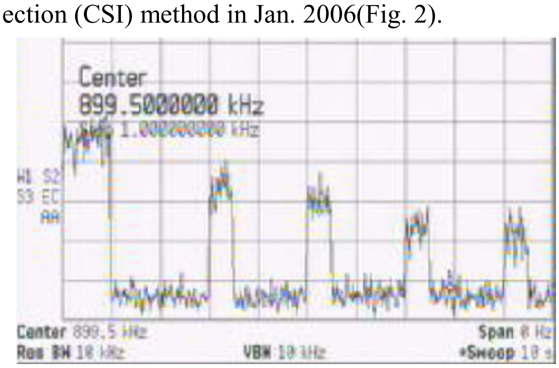

Figure 2: The first stored beam observed by periodical RF capture and release.

Later, the remote control system, the beam current monitor, and tune measurement were available. The magnet field measurement data is investigated and

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