ELECTRON COOLING PERFORMANCE AT IMP FACILITY[*]

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Abstract

The ion beam of ^{58}Ni^{19+} with the energy of 6.39MeV/u was accumulated in the main ring of HIRFL-CSR with the help of electron cooling. The related angle between ion and electron beams in the horizontal and vertical planes was intentionally created by the steering coils in the cooling section after maximized the accumulated ion beam in the ring. The radial electron intensity distribution was changed by the ratio of potentials of grid electrode and anode of the electron gun, the different electron beam profiles were formed from solid to hollow in the experiments. In these conditions, the maximum accumulated ion beam intensity in the 10 seconds was measured, the lifetime of ion beam was measured, simultaneously the momentum spread of the ion beam varying with particle number was measured during the ion beam decay, furthermore, and the power coefficient was derived from these data. In additional, the momentum spread in the case of constant particle number was plotted with the angle and electron beam profile. The oscillation and shift of the central frequency of the ion beam were observed during the experiments. The upgrade and improvement in the CSRm cooler and the progress in the CSRe cooler were presented. These results were useful to attempt the crystal beam forming investigation in the CSR.

MAIN WORKS IN CSR

- ^{209}Bi^{36+} Accumulation and Acceleration in CSRm
- Experiments related to cancer therapy [1]
- Patients treatment
- Mass measurement [2]
- Prophase Experiments on recombination [3]

Accumulation and acceleration of ^{209}Bi^{36+}

A new superconducting ECR ion source SECRAL developed by IMP has started operation to provide high intensity heavier ion beam. ^{209}Bi^{36+} delivered by the SECRAL was accelerated by smaller cyclotron SFC to 1.877 MeV/u and then injected into CSRm. The average pulse intensity was about 1.8 μA in the injection line. The average pulse particle number of ^{209}Bi^{36+} was about 7.3×10^{6} in one standard multi-turn injection. With the help of electron cooling of partially hollow electron beam, 4.4×10^{7} particles were accumulated in the ring after 67 times injection in 10 seconds, and 1.3×10^{7} particles were accelerated to the final energy of 170 MeV/u. The DCCT signal of ^{209}Bi^{36+} beam was displayed in Fig. 1 during accumulation and acceleration with the help of electron cooling.

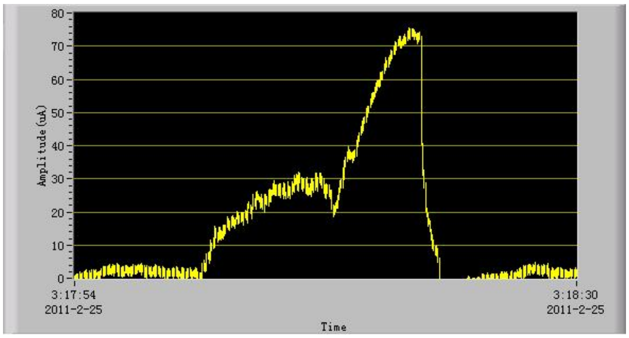

Figure 1: DCCT signal of ^{209}Bi^{36+} beam accumulation and acceleration with the help of electron cooling, 1.87MeV/u -170MeV/u.

BEAM ACCUMULATION IN CSR

The main function of electron cooler in CSRm was heavy ion beam accumulation. The accumulation efficiency was related with a lot of parameters of storage ring and electron cooler, such as the work-point setting, closed-orbit, electron density, and angle between electron beam and ion beam. At the beginning, the electron beam alignment was done to maximize the accumulated ion beam intensity. This setting was defined as "0" angle. The related angle between ion and electron beams in the horizontal and vertical planes was intentionally created by the steering coils in the cooling section after maximized the accumulated ion beam in the ring in the case of fixed storage ring parameters setting and electron beam parameters. After ion beam accumulation, the ion beam intensity and longitudinal signal were recorded by the DCCT monitor and Schottky probe during the ion beam decayed, and the maximal accumulated ion beam intensity in the 10 seconds interval was derived from the DCCT signal. The dependence of the ion beam intensity on the related horizontal and vertical angle was presented in the Fig. 2a and 2b. The angle between ion and electron beams reflected the temperature of electron in the system. In the case of the fixed electron beam current, ion encountered different electron temperature. The temperature influenced the cooling force and cooling time. The cooling force varying as the angle was reported in the reference [4]. The cooling force approached to maximal value in the perfect alignment between ion and electron beams, and the cooling time was minimal. One can see the maximal accumulated ion beam intensity was obtained near the zero angles in both panes. Another main parameters was the electron beam profile, the radial electron intensity distribution was changed by the ratio of potentials of grid electrode and anode of the electron gun, in this sense, and the different electron beam profiles were

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NICA PROJECT AT JINR

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Abstract

The project of Nuclotron-based Ion Collider fAcility NICA/MPD (MultiPurpose Detector) under development at JINR (Dubna) is presented. The general goals of the project are providing of colliding beams for experimental studies of both hot and dense strongly interacting baryonic matter and spin physics (in collisions of polarized protons and deuterons). The first program requires providing of heavy ion collisions in the energy range of $\sqrt{s_{NN}} = 4\div11$ Gev at average luminosity of $L = 1\cdot10^{27}$ cm$^{-2}\cdot$s^{-1} for ^{197}Au^{79+} nuclei. The polarized beams mode is proposed to be used in energy range of $\sqrt{s_{NN}} = 12\div27$ Gev (protons at luminosity of $L \geq 1\cdot10^{30}$ cm$^{-2}\cdot$s^{-1}. The key issue of the Project is application of cooling methods – stochastic and electron ones. The report contains description of the facility scheme and characteristics in heavy ion operation mode, status and plans of the project development.

NUCLOTRON-M & NICA PROJECT

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) [1] is a new accelerator complex (Fig. 1) being constructed at JINR. It is aimed to provide collider experiments with:

- heavy ions ^{197}Au^{79+} at $\sqrt{s_{NN}} = 4\div11$ GeV ($1\div4.5$ GeV/u ion kinetic energy) at average luminosity of $1\cdot10^{27}$ cm$^{-2}\cdot$s^{-1} (at $\sqrt{s_{NN}} =$ 9 GeV);
- light-heavy ions colliding beams of the same energy range and luminosity;
- polarized beams of protons $\sqrt{s} = 12\div27$ GeV ($5\div12.6$ GeV kinetic energy) and deuterons $\sqrt{s_{NN}} = 4\div13.8$ GeV ($2\div5.9$ GeV/u ion kinetic energy) at average luminosity $\geq 1\cdot10^{30}$ cm$^{-2}\cdot$s^{-1}.

The proposed facility consists of the following elements (Fig. 1):

– "*Old*" *injector* (pos. 1): set of light ion sources including source of polarized protons and deuterons and Alvarez-type linac LU-20*);

– "*New*" *injector* (pos. 2, under construction): ESIS-type ion source that provides ^{197}Au^{32+} ions of the intensity of $2\cdot10^{9}$ ions per pulse of about 7 μs duration at repetition rate up to 50 Hz and linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at A/q ≤ 8 up to the energy of 6 MeV/u at efficiency not less than 80 %.

– *Booster-synchrotron* housed inside Synchrophasotron yoke (pos. 3). The Booster (pos. 4) has superconducting (SC) magnetic system that provides maximum magnetic rigidity of 25 T·m at the ring circumference of 215 m. It is equipped with electron cooling system that allows to provide cooling of the ion beam in the energy range from injection energy up to 100 MeV/u. The maximum energy of ^{197}Au^{32+} ions accelerated in the Booster is of 600 MeV/u. Stripping foil placed in the transfer line from the Booster to the Nuclotron allows to provide the stripping efficiency at the maximum Booster energy not less than 80 %.

– *Nuclotron* – SC proton synchrotron (pos. 5) has maximum magnetic rigidity of 45 T·m and the circumference of 251.52 m provides the acceleration of completely stripped ^{197}Au^{79+} ions up to the experiment energy in energy range of $1\div4.5$ GeV/u and protons up to maximum energy of 12.6 GeV.

– *Transfer line* (pos. 6) transports the particles from Nuclotron to Collider rings.

– *Two SC collider rings* (pos. 8) of racetrack shape have maximum magnetic rigidity of 45 T·m and the circumference of about 400 m. The maximum field of SC dipole magnets is 1.8 T. For luminosity preservation an electron and stochastic cooling systems will be constructed.

– *Two detectors* – MultiPurpose Detector (*MPD*, pos. 9) and Spin Physics Detector (*SPD*, pos. 10) are located in opposite straight sections of the racetrack rings.

– *Two transfer lines* transport particle beams extracted from Booster (pos. 11) and Nuclotron (pos. 12) to the new research area, where fixed target experiments both basic and applied character will be placed.

The NICA parameters (Table below) allow us to reach the goals of the project formulated above.

One of NICA accelerators – Nuclotron is used presently for fixed target experiments on extracted beams (Fig. 1, pos. 7).

This program is planned to be developed further and will be complementary to that one to be performed at Collider in heavy ions beam mode operation. The program includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology and applied research.

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CURRENT PLANS FOR BEAM COOLING AT FAIR

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Abstract

The accelerators of the international FAIR project are designed to provide stable heavy ion beams, rare isotope beams and antiprotons with high intensity and high beam quality. Beam cooling is indispensable to improve the beam quality of secondary beams produced by bombardment of thick targets. The goals of the project as well as the methods to achieve high intensity and high quality secondary beams will be described. Due to budget constraints the project realization is planned in a staged scenario. The main accelerator systems in the first project stage to provide cooled beams will be the Collector Ring for pre-cooling of secondary beams and the High Energy Storage Ring for experiments with stored cooled antiprotons.

INTRODUCTION

The international FAIR project will provide heavy ion and proton primary beams over a large range of energies [1]. These beams serve four basic physics programs, research with high energy antiprotons, studies of compressed baryonic matter, nuclear structure and related astrophysics, and atomic and plasma physics and their applications. The use of beam cooling is foreseen for highly charged primary heavy ion beams, for rare isotope beams from the new large acceptance separator SuperFRS and for antiproton beams produced in a dedicated antiproton source with a target and a separator section. A number of storage rings was conceived for various purposes, such as pre-cooling of the hot secondary beams immediately after the production target, for accumulation of the pre-cooled secondary beams and finally storage rings equipped with powerful cooling systems which allow the use of high quality cooled beams in high precision and high luminosity experiments with internal targets [2]. Another option will be the deceleration of cooled secondary beams for experiments at low energy and even after further deceleration in linear decelerators, nearly to rest, for which beam cooling is indispensable. For these purposes mainly four storage rings were designed, the Collector Ring (CR) for the pre-cooling of antiprotons and rare isotopes, the accumulator ring RESR for the accumulation of high intensity antiproton beams by a dedicated stochastic cooling system, the New Experimental Storage Ring (NESR) as a storage ring for internal experiments with heavy ions and rare isotopes and deceleration of cooled beams of ions and antiprotons, and the High Energy Storage Ring (HESR) for experiments with cooled antiprotons using internal hydrogen targets. These storage rings together with the other new accelerator facilities of the FAIR project were documented in technical design reports [3].

After a revision of the project cost, it was decided that the project will be constructed in a staged manner. The first stage of the project, called Modularized Start Version (MSV), is conceived such that it can serve all four basic pillars of the physics program of FAIR. Due to the limited money available for the first part of the FAIR project, however, the accumulator ring RESR and the ion storage ring NESR had to be postponed to a later stage of the FAIR project and will not be constructed in the frame of the MSV. As a compensation of the lack of stored ion beams in the MSV of FAIR it was decided that the operation of the existing ESR storage ring will be continued.

FAIR ACCELERATORS OF THE MODULARIZED START VERSION

The MSV is based on the existing linear accelerator UNILAC for heavy ions serving as injector into the existing heavy ion synchrotron SIS18. An extended upgrade program is under way to improve the performance of these injector machines and towards increased intensities and acceleration with higher ramp rate. The MSV now comprises the following new accelerator facilities. A new 70 MeV proton linac as injector in front of the synchrotron SIS18 will provide the high intensity proton beam required for the production of antiprotons, it can fill SIS18 up to the space charge limit. The new synchrotron SIS100 uses the SIS18 as injector for high intensity proton and heavy ion beams. The maximum magnetic rigidity of 100 Tm allows either acceleration to higher energy or the acceleration of low charge states, which provides higher beam intensity as no additional stripping stage in front of SIS18 is needed, thus avoiding the reduction of intensity associated with the use of the stripper foil. The SIS100 design is based on superferric magnets allowing fast 4 T/s ramping of the magnetic field which is needed to provide high average beam intensities [4]. The 1080 m circumference ring tunnel of SIS100 will be prepared for the later installation of an additional 300 Tm superconducting synchrotron for the acceleration of heavy ions to correspondingly higher energy or for use as a stretcher ring for slow extraction of 100 Tm beams accelerated in SIS100.

After SIS100 two stations for the production of secondary beams will be constructed. The SuperFRS has a target for the production of rare isotope beams by projectile fragmentation followed by a large acceptance super-

STATUS OF THE 2 MEV ELECTRON COOLER FOR COSY / HESR

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Abstract

The 2 MeV electron cooling system for COSY-Jülich is being built to boost the luminosity in presence of strong heating effects of high-density internal targets in the entire energy range. The 2 MeV cooler is also well suited in the start up phase of the High Energy Storage Ring (HESR) at FAIR in Darmstadt. It can be used for beam cooling at injection energy and for testing new features of the high energy electron cooler for HESR. The design and construction of the cooler is accomplished in cooperation with the Budker Institute of Nuclear Physics in Novosibirsk, Russia. The infrastructure necessary for the operation of the cooler in the COSY ring (radiation shielding, cabling, water cooling etc.) is established. The electron beam commissioning at BINP Novosibirsk started in May of 2011. First results are reported. Final commissioning at COSY-Jülich is planned for the end of 2011.

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 momentum spread in antiproton beam, which must be better than 10^{-4}. To obtain such a momentum spread cooling time in the range of 0.1- 10 s 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 longitudinal and transverse cooling which 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.

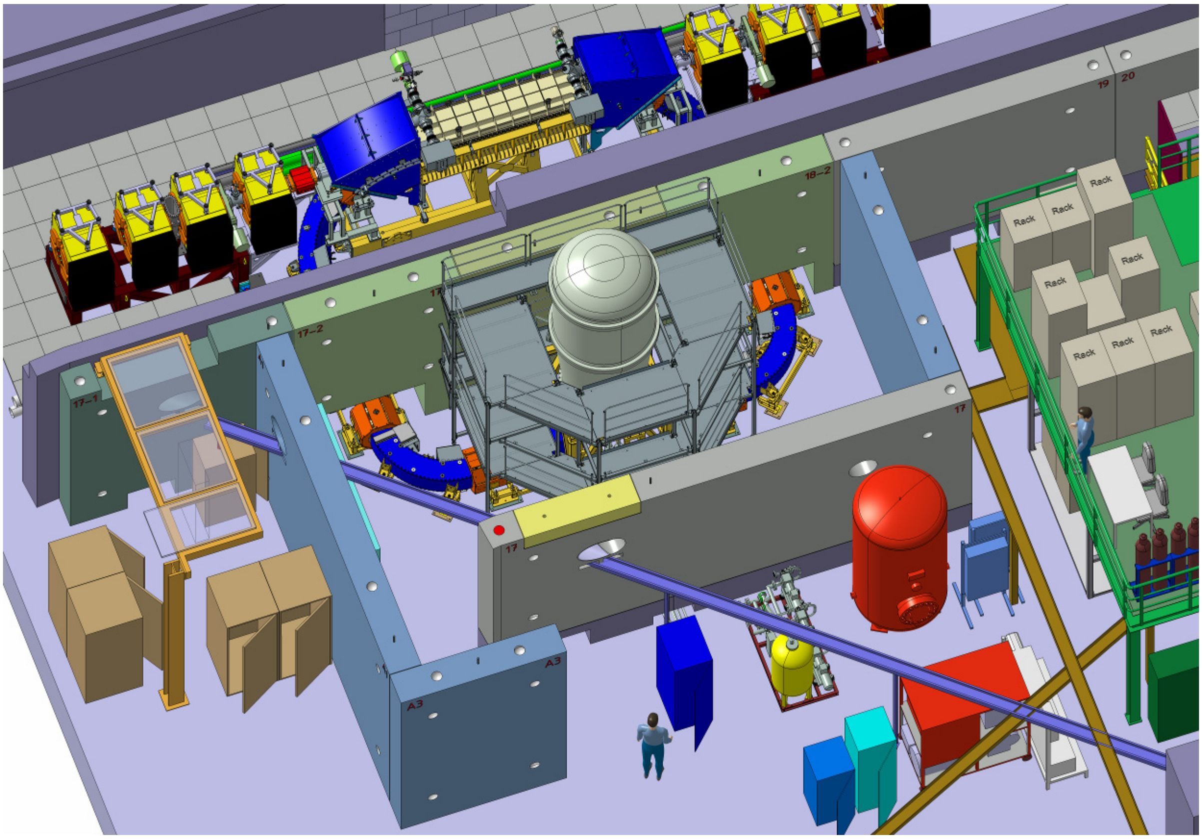

Figure 1: A 3D model of the 2 MeV electron cooler to be installed in COSY.

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RECENT STATUS OF BEAM COOLING AT S-LSR*

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Abstract

At S-LSR in ICR, Kyoto University, electron cooling of 7 MeV protons has been applied. A relative velocity sweep scheme reduced the cooling time from 30.4 s to 1.7 s for the initial momentum spread of 1 %. One dimensional ordering by electron cooling was also realized at a proton number of approximately 2000, resulting in 2K and 11 K in the longitudinal and the horizontal directions, respectively. With the combination of electron cooling and phase rotation techniques a very short bunch length of ~3 ns was realized, which should be used for bio-medical irradiation. For multi-dimensional laser cooling of $^{24}\mathrm{Mg}^+$ ions, synchro-betatron coupling has been applied for a bunched ion beam. The realized beam temperatures are 24K and ~200 K for the longitudinal and horizontal directions, respectively at resonance, while the corresponding values are 15K and ~600 K, respectively at the off resonance condition.

INTRODUCTION

A small laser equipped storage ring (S-LSR) was constructed at ICR, Kyoto University, in order to investigate acceleration of hot laser-produced ion beams. The ion beams produced by laser plasma interaction has a large energy spread. The capability of efficient electron cooling of these hot proton beams by a relative velocity sweep was investigated at S-LSR. S-LSR is also oriented for the beam cooling research to realize ultra low beam temperature. For this purpose, the S-LSR lattice was designed with a rather large super symmetry of 6 to satisfy the so called maintenance condition [1]. With deflection elements composed of magnetic and electric fields, a dispersion less lattice can be realized [2]. In Fig.1 the S-LSR is shown together with other accelerators in our accelerator building. The main parameters of S-LSR are listed up in table 1 and the layout of S-LSR with its injectors is shown in Fig. 2.

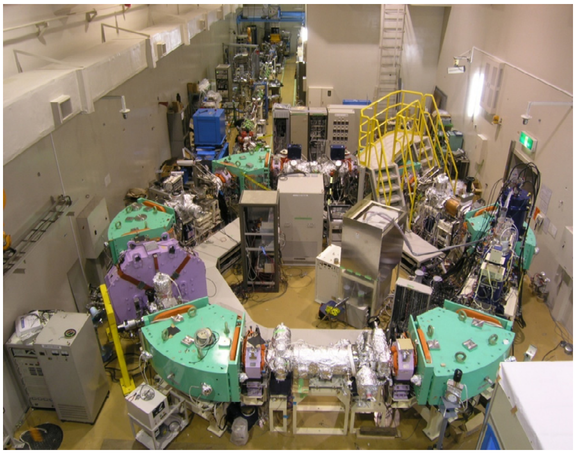

Figure 2. Photograph of S-LSR and its injector.

Up to now, we have applied electron cooling to a 7 MeV proton beam to realize one dimensional ordering [3]. "Synchrotron-betatron coupling " [4], was applied for the laser cooling experiments using 40 keV $^{24}\mathrm{Mg}^+$ ions, where the beams, however, still have a rather hot transverse temperatures.

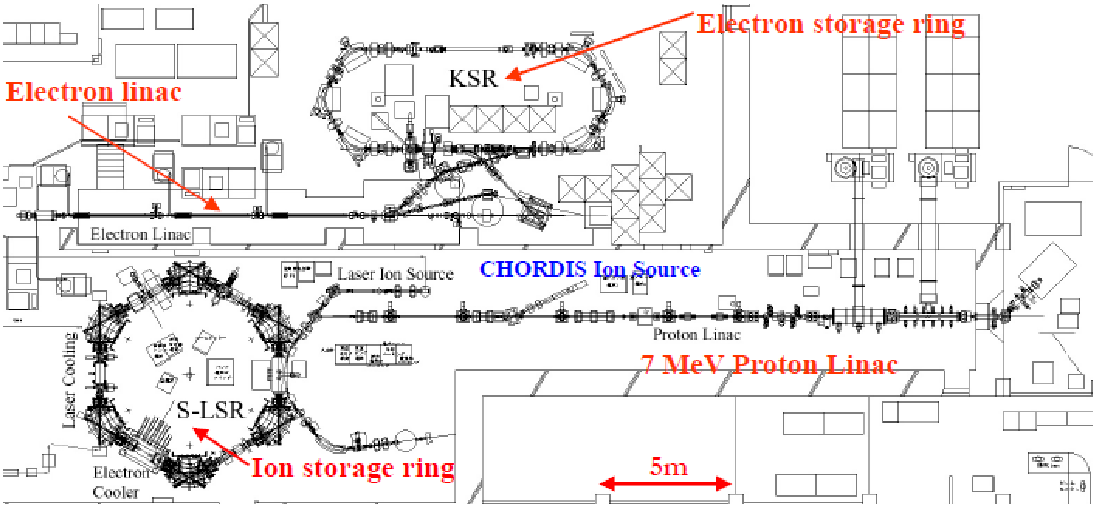

Figure 1. Layout of S-LSR located in the accelerator building together with other accelerators.

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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 experiments with colliding heavy ions up to Au for experimental study of hot and dense strongly interacting baryonic matter and search for possible signs of the mixed phase and critical endpoint in the centre-of-mass energy range $\sqrt{S_{NN}}$ = 4-11 GeV. Beam cooling systems are proposed for elements of the NICA project. The Booster synchrotron will be equipped with an electron cooling system. Two beam cooling systems – stochastic and electron will be used in the collider rings. Parameters of cooling systems, proposed scenario of operation and peculiarities of their design intended to achieve required average luminosity of the order of $10^{27}cm^{-2}s^{-1}$at high energies are presented in this report.

INTRODUCTION

The goal of the NICA project [1] is construction at JINR of the new accelerator facility that consists of:

- cryogenic ESIS ion source “KRION” with 6T solenoid;
- source of polarized protons and deuterons;
- the existing linac LU-20 (energy up to 5 MeV/u);
- a new heavy ion linear accelerator (3 MeV/u);
- a new 600 MeV/u Booster-synchrotron;
- modernized heavy ion synchrotron Nuclotron (4,5 GeV/u maximal kinetic energy for ions with Z/A = 1/3);
- two new superconducting rings of the collider;

The facility will have to provide ion-ion (1÷ 4.5 GeV/u), ion-proton collisions and collisions of polarized pp (5 ÷ 12.6 GeV) and dd (2 ÷ 5.8 GeV/u) beams. The Booster will be equipped with a slow extraction system to provide medicine, biological and other applied researches.

The collider will have two interaction points. The Multi Purpose Detector (MPD) in the first IP, and the second IP is used for the Spin Physics Detector (SPD).

Collider will be operated at fixed energy without acceleration of 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 is to provide collider experiment with heavy ions like Au, Pb, or U at average luminosity above $1\cdot10^{27}$ $cm^{-2}\cdot s^{-1}$ in the maximal wide energy range up to 4,5 GeV/u. Therefore in this report it is discussed heavy ion mode of the facility operation only, and $^{197}Au^{79+}$ 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.

ELECTRON COOLING SYSTEM FOR BOOSTER. OPERATION MODES.

The maximum design ion energy of 4.5 GeV/u can be achieved at 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). 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 not less than 80%.

The Booster is equipped with room-temperature electron cooling system that allows to provide efficient cooling of the ions in the energy range from injection energy up to 100 MeV/u (Fig.1). Electron cooling at injection energy 3 MeV/u is required to accumulate intense beam especially if multiple injection is used. Such mode will be required also for storing highly charged ion states (for example Au^{65+} ions) or polarized ions (for example $\uparrow H^-$ atoms) with high intensity. Beam cooling at higher energies (up to 100 MeV/u) could be useful to achieve special beam parameters required by fixed target experiments on the extracted beam from Booster.

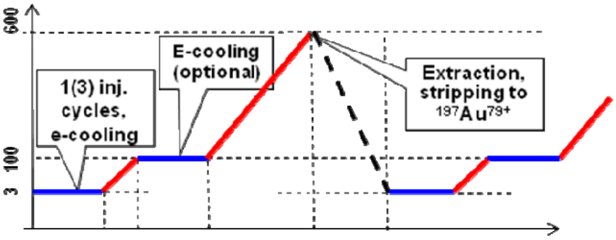

Figure 1: Booster cycle diagram (Y-axis: energy, MeV/u)

The magnetic system of the Booster is superconducting. Its design is based on the experience of construction of the Nuclotron SC magnetic system [3]. Parameters of the Booster cooler are typical for conventional electron cooling systems. Design of the cooler had been performed by JINR and its construction is planned to be done in collaboration with Budker INP.

Main goal of the cooling of heavy ion beam at 100 MeV/u energy could be decreasing its longitudinal emittance to the value required for effective injection and acceleration in the Nuclotron before injection into the collider. Transverse beam emittance has to be stabilized at relatively large value to avoid space charge limitations in the Nuclotron and collider rings. Simulations of such a regime of the cooler operation performed with Betacool code showed that during 1 second of the cooling one can decrease the longitudinal beam emittance by about 3 times at practically constant transverse emittance.

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ULTIMATE PERFORMANCE OF RELATIVISTIC ELECTRON COOLING AT FERMILAB*

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Abstract

Fermilab's Recycler ring employs a 4.3 MeV, 0.1A DC electron beam to cool antiprotons for accumulation and preparation of bunches for the Tevatron collider. The most important features that distinguish the Recycler cooler from other existing electron coolers are its relativistic energy, a low longitudinal magnetic field in the cooling section, ~100 G, and lumped focusing in the electron beam lines. The paper summarizes the experience of designing, commissioning, and optimizing the performance of this unique machine.

INTRODUCTION

An electron cooler was envisioned as an important part of the Recycler ring [1]. The main cooler parameters (Table 1) were chosen to satisfy the Recycler goals: store antiprotons coming from the Accumulator, prepare bunches for Tevatron shots, and "recycle" particles left over from Tevatron stores. Because of the longitudinal injection scheme of the Recycler, the main emphasis was made on longitudinal cooling. Note that later changes, most notably the decision not to "recycle" antiprotons from the Tevatron and the lower than predicted emittances of the bunches coming from the Accumulator, relaxed the operational requirements for the cooler.

Table 1: Parameters of the cooler

Parameter	Unit	Design	Operation
Electron energy	MeV	4.33	4.33
Beam current, DC	A	0.5	0.1
Magnetic field in the cooling section	G	100-200	105
Beam radius in the cooling section	mm	~5	~2
Pressure	nTorr	1	0.3
Total length of the beam line	m	90	90

As soon as the electron beam could be reliably sustained in 2005, relativistic electron cooling was demonstrated [2] and within days was put into operation. Since then, electron cooling significantly contributed to a several-fold increase of the Tevatron luminosity until the end of operation in October 2011.

In this paper, we discuss the choice of the cooler's scheme and its implementation, describe the setup and cooling measurement procedures, and present the ultimate results .

CHOICE OF THE SCHEME

The scenario of using the Recycler electron cooler [3] assumed typical cooling times of tens of minutes. Estimations showed that at a reasonable electron current (~0.5A) it could be achieved without using the benefits of a strong magnetic field in the cooling section. Such "non-magnetized" approach was a clear deviation from the tested way of building coolers, creating serious questions about the stability of the electron beam transport and ability to provide low transverse electron velocities in the cooling section. On the other hand, estimations of the budget available and time needed to develop an "all-magnetized" version of the cooler and contribute to Fermilab's Run II showed that it was not realistic.

Nevertheless, simply leaving a lumped focusing in the cooling section to counteract the electron beam's space charge looked dangerous because of beam interactions with the residual ions background and with the vacuum chamber walls [4]. However, it was realized that it is theoretically possible to transport an electron beam from one solenoid to another through a lumped-focusing section without excitation of additional angles with the appropriate choice of optics for this section [5]. As a result, a novel scheme was chosen where the electron gun and the cooling section are both immersed in a longitudinal magnetic field but the beam focusing in between is provided by separate solenoidal lenses.

Applicability of such scheme is critically dependent on the magnetic flux in the cooling section. When a beam with no transverse velocities inside a solenoid exits into a free space, conservation of the canonical angular momentum results in a coherent angular rotation of the beam. In the paraxial ray equation, it is equivalent to the addition of an effective normalized emittance [5]

$$\varepsilon_{B,eff} = \frac{e\Phi}{2\pi m_e c^2}, \qquad (1)$$

where $\Phi = B_{CS} R_{CS}^2$ is the magnetic flux through the beam cross section in the solenoid, e and m_e are the electron charge and mass, and c is the speed of light. As in the case with a real emittance, the beam transport with lumped focusing is possible only if this emittance is low enough. For example, a transport channel for $\gamma = 10$ with a typical beam radius of ~1 cm and the beta-function of ~1 m to bring the beam into a cooling section at the radius of R_{CS} ~ 1 cm limits the solenoid magnetic field to ~300G. To use lumped focusing during acceleration (i.e. at lower γ), the magnetic flux had to be decreased in comparison with this example by limiting both the beam size and the magnetic field strength in the cooling section down to R_{CS} = 2 - 4 mm and B_{CS} =100 – 200 G.

Because of the large (reactive) beam power required in the cooling section, ~1 MW, using the energy recovery

THE FIRST COMMISSION RESULTS OF THE HIGH VOLTAGE MAGNETIZED COOLER FOR COSY

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Abstract

The electron cooler of a 2 MEV for COSY storage ring FZJ is assembling in BINP. The cooling section is designed on the classic scheme of low energy coolers like cooler CSRm, CSRe, LEIR that was produced in BINP before. The electron beam is transported inside the longitudinal magnetic field along whole trajectory from an electron gun to a collector. This optic scheme is stimulated by the wide range of the working energies 0.1(0.025)-2 MeV. The electrostatic accelerator consists of 34 individual unify section. Each section contains two HV power supply (plus/minus 30 kV) and power supply of the magnetic coils. The electrical power to each section is provided by the cascade transformer. The cascade transformer is the set of the transformer connected in series with isolating winding. This paper describes the status of the electron cooling assembling processing;

INTRODUCTION

New generation of the accelerators for study nuclear physics at range of relativistic physics 1-8 Gev/u requires very powerful cooling to obtain high luminosity. For example the experiments with 15 GeV antiproton for investigation of meson resonances on PANDA detector require an internal hydrogen target with effective thickness 4×10^{15} hydrogen atoms per cm^2 and 10^{10} – 10^{11} antiprotons circulating in HESR. In this case the peak luminosities ranging from 2×10^{31} to 2×10^{32} cm^{-2}s^{-1} are achievable. These experiments provide to observe 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 on such target (for antiprotons with energy 4 GeV) will be about $(dp/dt)/p = 4\cdot10^{-6}$ s^{-1} and heating rate of momentum spread by fluctuation of ionization losses will be near $(dp^2/dt)/p^2 = 2\cdot10^{-9}$ s^{-1}. Easy to see that to obtain momentum spread 10^{-5} – 10^{-4} we need cooling time at range

$$\tau_{cool} = 2(dp/p)^2/(dp^2/dt/p^2) = 0.1 \div 10 \text{ s.}$$

The electron cooler with energy 4.34 MeV at RECYCLER (FNAL) [1] has cooling time near 1 hour. New cooler for COSY should have few order magnitude more powerful cooling that required new technical solutions. The basic idea of this cooler is to use high magnetic field along all orbit of the electron beam from the electron gun to the electron collector. At this case we have chance to have high enough the electron beam density at cooling section with low effective temperature. For example the electron beam density $2*10^8$ cm^{-3} (beam diameter 6 mm and current 1.5 A) magnetized with longitudinal magnetic field 2 kG will have at beam reference system drift velocity $2.7*10^6$ cm/sec. This velocity lets (at principle) to have cooling time near 0.1 sec for the beam with low angular spread $\Delta p_\perp / p = 10^{-5}$.

The basic idea of the design 2 MeV electron cooler for COSY ring is to test main features of the 4-8 MeV electron cooler for HESR GSI. The step at the energy of electron beam from 200-300 keV today to 8 MeV for HESR looks too large. The new technical solution should be tested at smaller step for example 2 MeV cooler for COSY. The design of the electron cooler for existing synchrotron COSY give additional limitation by existing building (upper points for lifting crane hook 7 m) and existing free space for cooler 6390 mm.

The structure of the 2 MeV cooler for COSY is shown in Fig. 1.

MAGNETIC SYSTEM

The optics of 8 MeV cooler for COSY is designed close to the classical low-energy coolers. The motion of the electron beam is magnetized (or close to magnetized conditions) along whole trajectory from a gun to a collector. This decision is stimulated by requirement to operate in the wide energy range from 25 keV to 2 MeV. So, the longitudinal field has maximum value with compare to the transverse component of the magnetic fields.

The magnetic system of the cooler consists of the coils of gum and collector, accelerating/decelerating tubes, transport channels from high-voltage tank to the cooling section, cooling section and transport channel of the return way. The transport channels contains the six 90 degree bend toroidal magnets, two matching sections between high-voltage tank and transport channel, two matching section between transport channel and cooling section and six straight section for technological purpose.

THE ADVANCE TECHNOLOGY EXTRACTION FOR THERAPY IONS BEAM FROM CARBON STORAGE RING WITH ELECTRON COOLING

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Abstract

The electron cooling because of increasing the 6D phase space density of ion beams is the path for development compact accelerator ions beam therapy. The aperture magnets for the main synchrotron, the transport lines and the moveable ion gantry can be decreased very fundamentally. The systems for the extraction ions will operate with the smaller aperture and the low fields that improves reliability of dose control. The first experiments made at Landzow Institute of Modern Physics with cooling carbon beam on the energy 200 and 400 MeV/u increased enthusiasm of authors this report at these sort therapy systems.

INTRODUCTION

At Institute Modern Physics the electron cooling systems was install at the main ring CSRm and at experimental ring CSRe. In the treatment phase the stripping injection of carbon beam with few repeated cycles accumulation by e-cooling (7 MeV/u) to insure the current and stability of slow-extracted carbon beam with energy range 150 to 250 MeV/u [1]. But using the electron cooling directly at the energy treatment will open high perspective for shrinking the ion beam diameters. The reasons connected with the space charge limitation of the intensive ion beam. The transverse beam emittance limited so called the tune shift at the range of values $\delta\nu \le 0.1-0.2$ as follow from equation:

$$\varepsilon_{\perp} = \frac{r_i N_i g}{2\pi\delta\nu\beta^2\gamma^3}, \quad (1)$$

with the classical ion radius $r_i = (Z_i e)^2 / M_i c^2$, the relativistic quantities β, γ, g is the bunch factor or the ratio the peak current of the ion beam to average current. As was showed at many experiments the electron cooling [2,3] effectively cooled the ions beam up to this limits and increasing energy will inverse proportional decrease the ion beam emittance. The carbon beam on energy 7 MeV/u at the storage ring with betafunction 20m and intensity $N_i = 10^{10}$ have the ion beam diameter (for $\delta\nu = 0.1$) 2 cm but on 400 MeV/u only 2 mm..

ELECTRON COOLING RESULTS OF THE CARBON BEAM IN CSRE

For illustration we can used results the first electron cooling experiments with 400 MeV/u the carbon ion beam in CSRe. After injection from CSRm ring the ion beam cooled as show fig. 1 at the momentum spread.

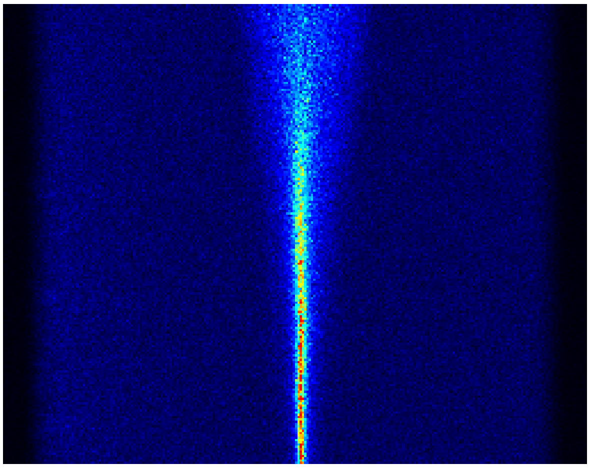

Fig. 1. The signal of Schottky signal after new injection.

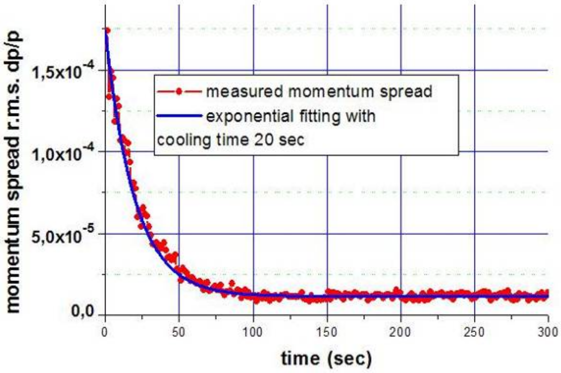

Fig. 2. The momentum spread at process electron cooling versus time.

The experiments with cooling the bunch beam (with RF on) demonstrated that the cooling was continued up to the compensations the RF field the own space charge field. At this case the longitudinal shape of the ion beam bunch are close to parabolic but the longitudinal potential well becomes very flat. There is correspond low synchrotron frequency for individual ions and the momentum spread demonstrated its self as the small tails near edges of the ion bunch. This phenomena was the subject of PD theses dissertation S.Negaitsev many years ago. At this regime the momentum spread at many times less estimation from the bunch length according single particle oscillation at RF field. This phenomena's interesting for using at ion-ion colliders but increased problems for stochastic cooling the bunches beam.

The same shrinking the transverse the ion beam size was measured with scanning the ion beam aperture with moveable collimator.

RADIATIVE RECOMBINATION OF HEAVY BARE NUCLEI AND IONS IN ELECTRON COOLING SYSTEM

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Abstract

An overview of experimental data of radiative recombination (RR) rate of nuclei (from helium to uranium) and various intermediate charge states of ions in electron coolers is presented at the report.

The fit of RR rates energy dependence the electron energy shift is found (formula (1) below). This dependence is significantly different from that one presented in theoretical works of H. Kramers and R. Schuch. It was found also the dependence of bare nuclei RR rates on transverse temperature as $T_\perp^{-0.95}$ that differs with theoretical result obtained by M. Bell and J. Bell.

Analysis of the experimental data for cooled heavy ions in intermediate charge state shows a RR critical dependence on the ion charge state (electron configuration of ion shells). Particularly, for some charge states RR rate increases essentially having a resonant character.

The estimations of RR rate losses of the Au^{32+}, Au^{33+}, Au^{50+}, Au^{51+} ion beams in the electron cooler of the Booster is presented. The limitation of Au^{79+} ions lifetime by RR process in the electron cooler of the Collider NICA is analyzed and measures of its increasing are considered.

INTRODUCTION

Application of the electron cooling of heavy ions to the Booster and the Collider of the NICA accelerator facility is necessary to obtain the project luminosity [1]. However, according to the theoretical models [2]-[4] RR can significantly affect the beam losses in the Booster and the Collider NICA. Therefore an experimental verification of theoretical formulae validity is of a great importance. Such a verification has been performed on the basis of the experimental works results [5]-[16].

THE BARE NUCLEI EXPERIMENTAL DATA ANALYSIS

The experimental data of RR rate dependence on the electron energy shift ΔE (relatively to optimal electron energy value) in different electron coolers for different nuclei U^{92+} [5], Bi^{83+} [6], Ar^{18+} [7], Cl^{17+} [8], Si^{14+} [9], Ne^{10+} [10], N^{7+} [9], C^{6+} [11] and He^{2+} [9] can be fitted (Fig. 1 a, b) with the following formula:

$$\nu_{Z\to Z-1}^{\text{Fitted}}\left(\Delta E\right) = a_1 \cdot Z^2 \cdot \left(\frac{\Delta E + b_1}{\text{Ry}}\right)^{-3/8}. \qquad (1)$$

Here $\nu_{Z\to Z-1}^{\text{Fitted}}(\Delta E)$ is RR rate fit in cm^3/s; ΔE is electron energy shift from its optimal value in the particle rest frame (PRF); $a_1=2.8\cdot10^{-13}$ cm^3/s and $b_2=2\cdot10^{-4}$ eV are the fit parameters; Ry=13.6 eV is the Rydberg constant. In all figures below the fit is shown with black dot line.

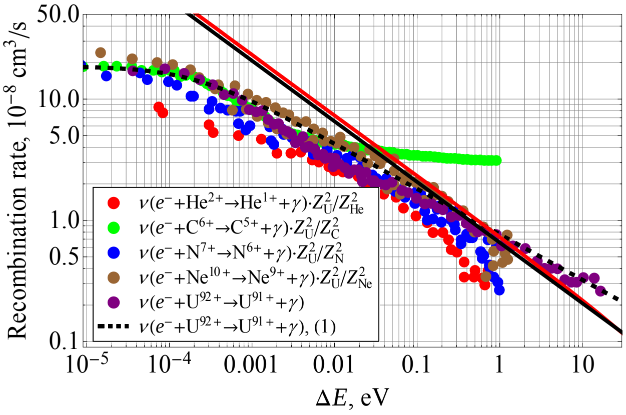

Figure 1 a. Experimental values of RR rates in 10^{-8} cm^3/s for bare nuclei: U^{92+} [5], Ne^{10+} [10], N^{7+} [9], C^{6+} [11] and He^{2+} [9] (in dots) and theoretical dependences by Kramers [2] (red line) and Schuch [3] (black line); the black dot line is the fit with formula (1).

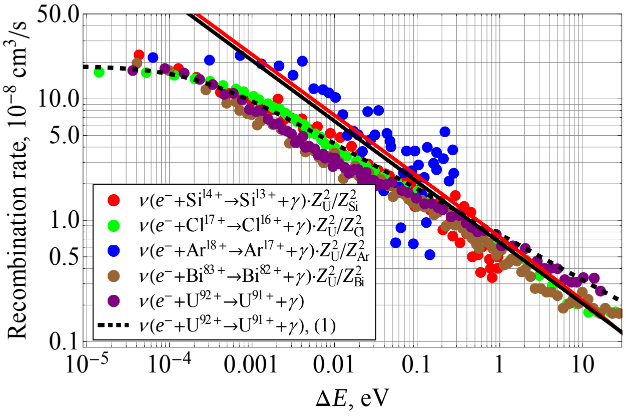

Figure 1 b. Experimental RR rates in 10^{-8} cm^3/s of bare nuclei U^{92+} [5], Bi^{83+} [6], Ar^{18+} [7], Cl^{17+} [8] and Si^{14+} [9] (in dots) and theoretical dependences by Kramers [2] (red line) and Schuch [3] (black line); the black dot line is the fit with formula (1).

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NUMERICAL INVESTIGATION OF STOCHASTIC COOLING AT NICA COLLIDER

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Abstract

At the heavy ion collider NICA promoted at the Dubna, JINR, the stochastic cooling will play the crucial roles to manipulate the beam. The primary goal is to prevent the IBS diffusion effects to keep the high luminosity during the experimental cycle. The other purpose is to accumulate the beam intensity up to several times 1e10 from the injector Nuclotron with use of barrier bucket method. With this method, the short bunch formation is not necessary in the Nuclotron, and is transferred to the collider as a long bunch condition. After the BB accumulation the coasting beam is adiabatically bunched with the help of RF field and the stochastic cooling. In the present paper the detailed simulation results are presented for the above three process mainly longitudinal freedom.

INTRODUCTION

The low energy heavy ion collider is proposed at the JINRwhich aims to achieve the 1-4.5 GeV/u (kinetic energy) gold beam head-on collision with the luminosity 1e27/cm2/sec. [1] The number of bunches in the collider is ~24 and each bunch should contain the ion number of ~5e9/bunch, depending upon the operation energy. Thus totally around 1e11 ions should be accumulated in the collider ring. The injector for the collider is planned to use the existing superconducting heavy ion synchrotron, Nuclotron which provides the beam 1-4.5 GeV/u with the intensity of 1e8-1e9/cycle, the cycle time of 10 sec. The bunch length of the beam from the Nuclotron is around 1/3 of the circumference, 300 nsec. [2]

The main task of the beam cooling is to realize the beam parameters required for the experiment, beam accumulation and the short bunch formation and keep their qualities during the experimental cycle.

In the present scenario, the beam is transferred to the collider without the manipulation of short bunch formation in the Nuclotron which allows us much easier operation of the Nuclotron. The long bunch beam is transferred in the longitudinal injection area which is provided by the barrier voltages, and is accumulated with the assistance of stochastic cooling, for low energy operation, say below 2 GeV/u, the electron cooling will be used.

Thus accumulated high intensity heavy ion beam in the collider is the coasting beam condition, and then the large voltage RF field is applied adiabatically as well as the stochastic cooling. The beam is gradually bunched to the required rms bunch length for the collision experiment, 2ns (rms). The bunch length is the equilibrium condition of the RF filed, stochastic cooling force and the Intra Beam Scattering (IBS) force.

In the present simulation work, the RF field (barrier or normal RF), IBS heating effects and the cooling force are taken into account. The space charge repulsion force is not included which might be significant effects at the low energy, high intensity and short bunch condition. This subject will be treated in the future work.

Table 1 Basic parameters of NICA collider

Ion species	197Au79+	Transverse Emittance	1.0 Pi mm.mrad
Operation energy	1-4.5 GeV/u	Momentum spread	1.0-1.5e-3
Circumference	503.04 m	Beat function at colliding point	0.35 m
Number of ions/bunch	3e8-5e9	Expected luminosity	3e27/cm2/sec
Number of bunch/ring	24	Bunch length (rms)	0.6 m
Injector	Nuclotron	Injected intensity	1e9/cycle
Emittance	0.5 Pi mm.mrad	Momentum spread (rms)	3e-4
Bunch length	300 nsec		

LATTICE AND IBS GROWTH RATE

The Intra Beam Scattering (IBS) effects are critical diffusion factor for the low energy high charge state ion collider. The growth rate is numerically calculated with use of the formula by Martini including the lattice function in Fig. 1. The lattice structure is the race-track shape with two long straight sections for the colliding experiments and the arc section, basically being composed of the FODO structure. The IBS growth rate can be analytically obtained for the high energy, much higher than the transition energy, and for the lattice structure with only normal lattice. The present lattice is a complicated structure and the IBS growth rate has to be numerically analyzed.

The bunched \beam IBS growth rates of the energy 4.5 GeV/u with 6e9/bunch and 1 GeV/u with 3e8/bunch are given in Fig. 2. The typical growth rates for 4.5 GeV/u are 3.65e-3 (momentum spread), 4.86e-4 (horizontal beam size) and -6.1e-5 for the vertical beam size. For 1.0 GeV/u, they are -7.95e-5, 3.86e-3 and 6.03e-3, respectively.

SIMULATIONS OF STOCHASTIC COOLING OF ANTIPROTONS IN THE COLLECTOR RING CR

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Abstract

The Collector Ring at FAIR will be equipped with pertinent stochastic cooling systems in order to achieve fast cooling of the hot secondary beams, antiprotons and rare isotopes, thus profiting from the repetition rate of the SIS100 synchrotron. Detailed simulations of the system performance are needed for optimization as well as input for the users of the CR pre-coooled beams, e.g. HESR. We presently focus on the antiproton cooling in the band 1-2 GHz. After a comprehensive overview, results from Fokker-Planck simulations with the CERN code of the momentum cooling of antiprotons will be presented. The performance of the betatron cooling of antiprotons, which has to proceed simultaneously with the momentum cooling, was calculated separately by means of an analytical model. First results and their implications will be discussed, including an outlook to future simulation work.

INTRODUCTION

The main purpose of the Collector Ring (CR) within the FAIR project [1] is the fast reduction of the phase space occupied by the hot secondary beams. The latter are antiprotons at 3 GeV and rare isotope beams (RIBs) at 740 MeV/u, coming from the production targets in a very short ($\approx$ 50 ns) bunch. At injection into the CR, they have the largest momentum spread and fill the transverse aperture. After bunch rotation and adiabatic debunching their momentum spread is reduced, whereas the transverse emittances remain unchanged. The reduced δp/p is a prerequisite for stochastic cooling. Otherwise, the effect of undesired mixing (see below) would exclude particles at the tails of the momentum distribution from being cooled. In order to meet the requirements of maximum production rate the CR stochastic cooling system has to strongly reduce all 3 phase subspaces, within 9 s for the antiprotons (with the option of 5 s after future upgrade) and 1 s for the highly charged RIBs (Table 1). The recent scenario according to which, in the first phase of the FAIR project, the pre-cooled antiprotons from the CR will be accumulated in the HESR instead of the RESR calls for 20% lower (if possible) final emittances and momentum spread than those in Table 1 in order to match the very small acceptances of the HESR [2].

Table 1: Requirements for the CR stochastic cooling

Antiprotons, 3 GeV, 10^8 ions		
	δp/p (rms)	$\epsilon_{h,v}$ (rms) π mm mrad
Before cooling	0.35 %	45
After cooling	0.05 %	1.25
Phase space reduction	9×10^3	
Cooling down time	$\leq$9 s	
Cycle time	10 s	
Rare isotopes, 740 MeV/u, 10^9 ions		
	δp/p (rms)	$\epsilon_{h,v}$ (rms) π mm mrad
Before cooling	0.2 %	45
After cooling	0.025 %	0.125
Phase space reduction	1×10^6	
Cooling down time	$\leq$1 s	
Cycle time	1.5 s	

The CR lattice is governed by the demands from stochastic cooling: (i) flexibility in setting different transition energy values for antiprotons and RIBs to reach an optimal compromise for the mixing parameters of the stochastic cooling, as explained below, (ii) accommodation of pickups and kickers in regions of appropriate dispersion, (iii) control of the horizontal and vertical betatron phase advance between pickups and kickers of the transverse stochastic cooling systems, (iv) reducing chromaticity over the whole momentum range.

OVERVIEW OF THE CR STOCHASTIC COOLING SYSTEM

Design criteria

In a simplified model, one can write the stochastic cooling rate, e.g. for transverse emittance, as

$$\frac{1}{\tau_\perp} = \frac{2W}{N}\left[2gB|\sin(\mu_{pk})| - g^2(M+U)\right], \qquad (1)$$

where W is the system bandwidth, N is the number of particles in the beam, g is the system gain, U is the ratio of power densities of the system thermal noise to the Schottky signal. For transverse cooling the CR lattice satisfies the condition of proper betatron phase advance $\sin(\mu_{pk}) \approx \pm 1$ between pickup and kicker. The undesired mixing parameter B (mixing between pickup and kicker) can be written in the form $B = \cos(m_c\phi_u)$, where m_c is the central harmonic in the band and $\phi_u = -2\pi\chi_{pk}\eta_{pk}\delta p/p$. At the beginning of cooling i.e. for the maximum total (2σ) momentum spread $m_c\phi_u \leq \pi/2$, otherwise the cooling force changes sign i.e. heats up the beam. Here, $\chi_{pk} = (s_k - s_p)/C$ is the ratio of the path from pickup to kicker to the closed orbit circumference C, η_{pk} is the lo-

STOCHASTIC COOLING PROJECT AT THE EXPERIMENTAL STORAGE RING, CSRE AT IMP *

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Abstract

Stochastic cooling at the experimental Cooler Storage Ring, CSRe [1] at the Institute of Modern Physics (IMP) in China, will be used mainly for the experiments with radioactive fragment beams. RI beams arrive from the fragment separator with emittance of 20-50 π mm. mrad and momentum spread *δp/p* of ± 0.5~1.0 %. The electron cooler, which is running now at the CSRe, is not able to cool down this hot beam rapidly enough. Stochastic cooling is effective for these RI beams to reduce the emittance to less than 5 π mm.mrad and of *δp/p* = 5e-4 within 2-20 sec. After stochastic pre-cooling, electron cooling will further cool down the emittance and momentum spread within several seconds. The paper gives the design of the stochastic cooling system and the simulation results. A recently developed forward traveling wave structure is presented as well as the measured results of a test model.

INTRODUCTION

CSRe ring has the circumference of 128.801 m with the layout in Fig.1. A combination of stochastic precooling and subsequent electron cooling is needed to get overall cooling times of the order of 10 seconds for injected secondary heavy ion beams and beams cooled by electron cooling to equilibrium phase space density. The development of a stochastic cooling system is very useful for performing competitive experiments with secondary rare isotope beams. Example of the setup of the stochastic cooling system is illustrated in the figure. It is planned to cool RI beam energies between 300 MeV/u and 400 MeV/u. As no straight section is available for the installation of pickups and kickers for the stochastic cooling and they have to be installed in the C type bending magnet chambers. The aperture of the bending vacuum tube is 236 mm *74 mm thus the useful aperture is 220 mm * 70 mm. The space at two sides in vertical direction can be increased to 4-5 mm if the electrodes are not placed in the middle. So the space is very limited inside it, especially in vertical direction, and the feedthrough is an issue. Thus the size and the number of pickups/kickers are severely limited.

For present operation mode which stochastic cooling will be used, internal-target mode with γ_{tr} = 2.457 and normal mode with γ_{tr} = 2.629, the frequency will be very low with large momentum dispersion of +/- 0.5~1.0 % which causes the slow cooling. A new optical mode at γ_t = 1.86 is developed which allows for an upper limit of the usable stochastic cooling bandwidth at about 1 GHz (of course the high frequency requires the microwave propagation attenuation in CSRe). At this optical mode the stochastic cooling system can be arranged in figure 1, sharing one pickup tank for the whole cooling system. The twiss parameters and the phase advance are shown in table 1. As this optical mode is never operated, the systematic simulation and experimental studies, such as optical optimization and beam acceptance measurement, will be performed in future.

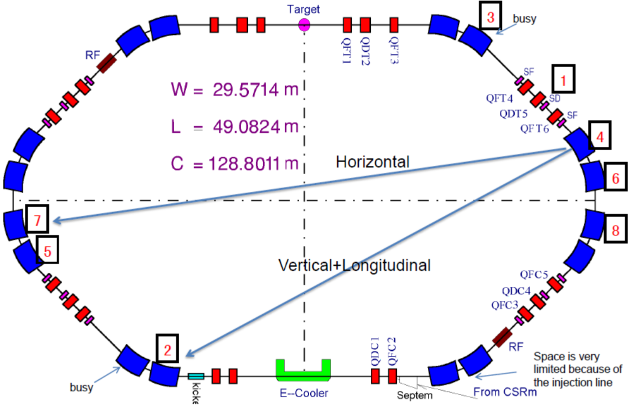

Figure 1 Typical layout of stochastic cooling pickup and kicker system

Table 1 Twiss parameters at pick-up/kicker position

	Horizontal		Vertical+Momentum	
	Pickup	Kicker	Pickup	Kicker
β_x（m）	19.9-14.3	6.6-7.6	19.9-14.3	16.8-11.9
β_y（m）	12.9-13.7	6.7-9.4	12.9-13.7	10.6-9.6
D_x（m）	9.3-7.5	6.0-6.1	9.3-7.5	0-0.4
θ	76^0		78^0	
L(m)	67		49	

PICK-UP/KICKER STRUCTURE

A novel type of perforated travelling wave pick-up/kicker structure is developed which was originally proposed by F.Caspers at CERN in 1998 [2]，shown in Fig.2. The unit cell length is 12 mm and the thickness of the electrode metal foil amounts to 0.4 mm. The electrode which is following the bending vacuum chamber inside the dipole magnet is 87 mm wide and 1 m long. The distance between the electrode and the ground is 3 mm. The characteristic impedance is 17 ohm and it can be raised if the distance between the electrode to ground is increased， but in our case it is limited. A large number

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HELICAL COOLING CHANNEL DEVELOPMENTS*

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Abstract

Several beam phase space manipulation and cooling stages are required to provide the extraordinary reduction of emittances required for an energy-frontier muon collider. From the pion production target, the pions and their decay muons must be collected into RF bunches, rotated in phase space to reduce momentum spread, cooled in 6 dimensions by 6 orders of magnitude, cooled in each transverse plane by another order of magnitude, and accelerated and matched to the RF system used to accelerate the muons to the final collider energy. Many of these stages have Helical Cooling Channel (HCC) [1] solutions based on superimposed solenoid, helical dipole, and helical quadrupole magnetic fields. The HCC was invented to achieve efficient ionization cooling with continuous emittance exchange. We first describe the essential HCC equations and describe how they can be applied for longitudinal and transverse emittance matching. We then describe simulations of HCC segments with a continuous gaseous hydrogen energy absorber suitable for basic 6d cooling as well as new results of related pressurized RF cavity beam tests. We then describe a new and creative application of the theory and use of the HCC that has been developed for Parametric-resonance Ionization Cooling (PIC), and the phase space matching needed for transitions between various cooling channel subsystems

INTRODUCTION

Considerable progress has been made in developing promising subsystems for muon beam cooling channels to provide the extraordinary reduction of emittances required for an energy-frontier muon collider. A high-performance front end from the target to the cooling systems has been designed and simulated [2], and many advances in theory, simulation codes, and hardware development have been achieved, especially regarding the 6d HCC described below. However, the HCC theory is not necessarily restricted to channels having solenoid fields. For example, the Twin Helix [3], which is also described below, does not possess a solenoid field component. The HCC theory and its extensions can describe a wide variety of beam dynamics and is thus well suited to provide the platform from which matching sections can be designed. We now review the theory of the HCC and examine how it can be used for emittance matching between cooling segments that have been independently developed.

Basic Helical Cooling Channel

In the HCC, a solenoid field is augmented with a transverse helical field that provides a constant dispersion along the channel as necessary for the emittance exchange that allows longitudinal cooling. The Hamiltonian that describes motion in this magnetic configuration is easily solved by a transform into the frame of the rotating helical magnet, where it is seen that the addition of a helical quadrupole field provides beam stability over a very large acceptance.

The helical dipole magnet creates an outward radial force due to the longitudinal momentum of the particle while the solenoid magnet creates an inward radial force due to the transverse momentum of the particle:

$$F_{h-dipole} \approx p_z \times b; \quad b \equiv B_\perp; \qquad F_{solenoid} \approx -p_\perp \times B; \quad B \equiv B_z\,,$$

where B is the field of the solenoid, the axis of which defines the z axis and b is the field of the transverse helical dipole. By moving to the rotating frame of the helical fields, a time- and z-independent Hamiltonian can be formed to derive the beam stability and cooling behaviour [1]. The motion of particles around the equilibrium orbit is shown schematically in Figure 1.

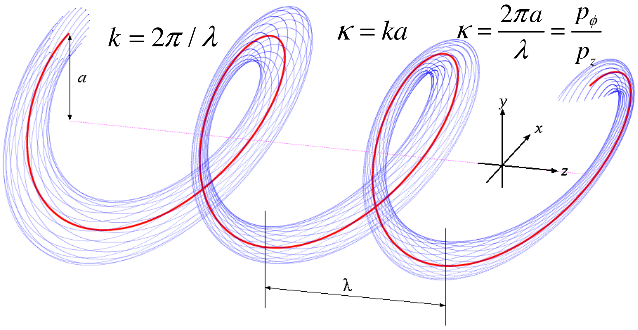

Figure 1: Schematic of beam motion in a HCC.

The equilibrium orbit shown in red follows the equation that is the Hamiltonian solution:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa} b\right] \tag{1}$$

The dispersion factor $\hat{D}$ can be expressed in terms of the field components B, b, and the transverse magnetic field radial gradient $\partial b/\partial a$ on the particle's orbit:

$$\hat{D} = \frac{p}{a}\frac{da}{dp} = \left(\frac{a}{p}\frac{dp}{da}\right)^{-1}; \qquad \hat{D}^{-1} = \frac{\kappa^2 + (1-\kappa^2)q}{1+\kappa^2} + g; \qquad g \equiv \frac{-(1+\kappa^2)^{3/2}}{pk^2}\frac{\partial b}{\partial a}\,,$$

where g is the effective field index at the periodic orbit.

The magnetic field ratio on the equilibrium trajectory satisfies the condition

$$\frac{b}{B} = \frac{\kappa}{1+\kappa^2}\left(1 - \frac{k}{k_c}\right) = \frac{\kappa}{1+\kappa^2}\left(\frac{q}{q+1}\right), \text{ where } q \equiv \frac{k_c}{k} - 1\,.$$

For stability, the following condition has to be satisfied

$$0 \;<\; G \equiv (q-g)\hat{D}^{-1} \;<\; R^2 \equiv \frac{1}{4}\left(1 + \frac{q^2}{1+\kappa^2}\right)^2. \tag{2}$$

Use of a continuous homogeneous absorber takes advantage of a positive dispersion along the entire cooling

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MICE STEP I: FIRST MEASUREMENT OF EMITTANCE WITH PARTICLE PHYSICS DETECTORS

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On Behalf of the MICE Collaboration

Abstract

The muon ionization cooling experiment (MICE) is a strategic R&D project intending to demonstrate the only practical solution to prepare high brilliance beams necessary for a neutrino factory or muon colliders. MICE is under development at the Rutherford Appleton Laboratory (UK). It comprises a dedicated beam line to generate a range of input emittance and momentum, with time-of-flight and Cherenkov detectors to ensure a pure muon beam. The emittance of the incoming beam is measured in the upstream magnetic spectrometer with a scintillating fiber tracker. A cooling cell will then follow, alternating energy loss in liquid hydrogen absorbers and RF acceleration. A second spectrometer identical to the first and a second muon identification system measure the outgoing emittance. In the 2010 run the beam and most detectors have been fully commissioned and a first measurement of the emittance of a beam with particle physics (time-of-flight) detectors has been performed. The analysis of these data is presented here. The next steps of more precise measurements, of emittance and emittance reduction (cooling), that will follow in 2011 and later, are also outlined.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) collaboration is building a lattice cell of the cooling channel [1] of Neutrino Factory of Neutrino Factory Feasibility Study-II [2] at a muon beam line at the ISIS proton accelerator at the Rutherford Appleton Laboratory in the UK. In order to demonstrate cooling over a range of emittances and momenta, the beam line must generate several matched beams with different optical parameters at TOF1.

The normalized root mean square (RMS) emittance in 6 dimensions is defined as

$$\epsilon_{rms} = \frac{1}{m_\mu}\sqrt{|V|},$$

$|V|$ is the determinant of the 6×6 covariance matrix of the phase space vector $\vec{U} = (\vec{x}, \vec{p})$, where $\vec{x} = (x, y, t)$ and $\vec{p} = (p_x, p_y, E)$. All these 6 variables will be measured in spectrometers before and after cooling cell on a particle-by-particle basis and then bunched to up to 10^6 particles for emittance calculation. The beam before colling channel can be measured by timing detectors. Data from TOF0 and T0F1 were used already to analyze the performance of the existing MICE muon beam line.

Technique

Data from timing detectors TOF0 and T0F1 are used to analyze the performance of the MICE muon beam line (Figure 1). Both detectors are composed of two orthogonally oriented planes of scintillator slabs read out at each end by photomultiplier tubes, and measure time. with resolution st = 50 ps [3]. Particle species is determined by measuring the time of flight between TOF0 and TOF1. Longitudinal momentum may then be reconstructed using an iterative method.

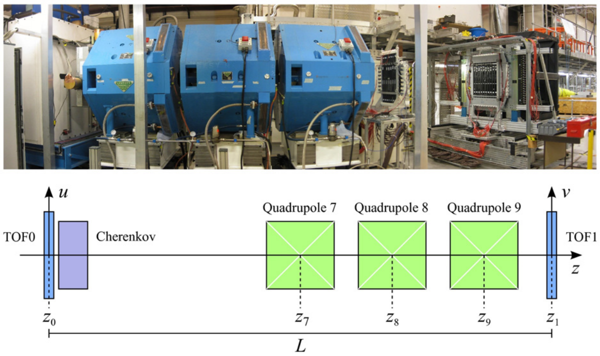

Figure 1: The MICE time of flight system.

The average momentum between the TOFs is given by

$$p(s,t) = \frac{m_0 s/t}{\sqrt{1 - s^2/(ct)^2}},$$

where the path length $s = L + \delta$ is reconstructed by tracking (Figure 2) the particle's trace-space vectors $(x, dx/dz)$ and $(y, dt/dz)$ through the beam line, and integrating the path length through each section. The initial trace space vector at TOF0 can be transported to TOF1 by a transfer matrix $(x_1, x_1') = M(x_0, x_0')$ defined by quadrupole parameters. Since the TOFs provide a measurement of (x_0, x_1) and that det M = 1 for linear transformation, it is possible to find the angles $x' = dx/dz$ and $y' = dy/dz$ needed for path length calculation:

$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}$$

A set of beam line optics configurations have been generated and corresponding beam parameter measured by TOF system. All variables measured in data have been compared with simulation.

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PROGRESS IN THE CONSTRUCTION OF THE MICE COOLING CHANNEL

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Abstract

The international Muon Ionization Cooling Experiment (MICE), sited at Rutherford Appleton Laboratory in the UK, aims to build and test one cell of a realistic ionization cooling channel lattice. This comprises three AbsorberFocus-Coil (AFC) modules and two RF-Coupling-Coil (RFCC) modules; both are technically challenging. The Focus Coils are dual-coil superconducting solenoids, in close proximity, wound on a common mandrel. Each pair of coils is run in series, but can be configured with the coil polarities the same (solenoid mode) or opposite (gradient mode). At the center of each FC there is a 20-L liquid-hydrogen absorber, operating at about 14 K, to serve as the energy loss medium for the ionization cooling process. The longitudinal beam momentum is restored in the RFCC modules, each of which houses four 201.25-MHz RF cavities whose irises are closed with 42-cm diameter thin Be windows. To contain the muon beam, each RFCC module also has a 1.4-m diameter superconducting coupling solenoid surrounding the cavities. Both types of magnet are cooled with multiple 2-stage cryo-coolers, each delivering 1.5 W of cooling at 4 K. Designs for all components are complete and fabrication is under way. Descriptions of the various components, design requirements, and construction status is described.

INTRODUCTION

Neutrino Factory [1] (Figure 1) based on muon storage ring is the ultimate tool for studies of neutrino physics [2]. It is also a first step towards a muon collider. One of the challenges posed is the control of the large emittances possessed by muons produced from pion decay at the proton driver target. Ionization cooling is a proposed mechanism to reduce this on a suitably short timescale. It has never been demonstrated in practice but has been shown by simulation and design studies to be an important factor both for the performance and for the cost of a Neutrino Factory.

The MICE collaboration has designed an experiment [3] in which a section of cooling channel is exposed to a muon beam, which would demonstrate and explore this technique for the first time in practice. It is proposed to install MICE at the ISIS facility [4], at Rutherford Appleton Laboratory (RAL).

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

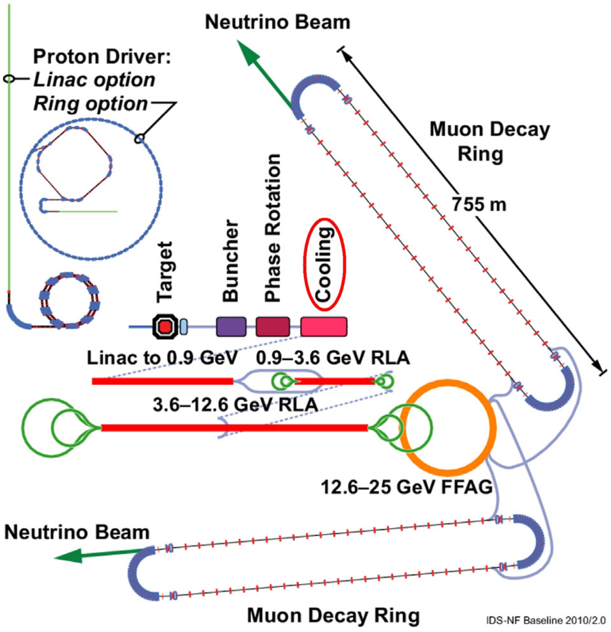

Figure 1: Neutrino Factory baseline scheme.

Ionization Cooling

The principle of ionization cooling relies on the cooling rate formula, expressing the emittance variation in a medium with thickness X $(g \cdot cm^2)$ due to ionization(cooling) and multiple scattering(heating):

$$\frac{d\epsilon_n}{dX} = -\frac{\epsilon_n}{\beta^2 E_\mu}\left\langle\frac{dE_\mu}{dX}\right\rangle + \frac{\beta_t (0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0} \quad (1)$$

where ϵ_n is the normalized 4D emittance of the beam, β_t is the betatron function, and β is the velocity of the particle. The ideal cooling channel should produce the lowest possible emittance:

$$\epsilon_{eq} = \frac{\beta_t (0.014GeV)^2}{2\beta m_\mu X_0}\left\langle\frac{dE_\mu}{dX}\right\rangle^{-1} \quad (2)$$

Hence, the goal is to minimize the β_t and maximize $X_0\langle\frac{dE_\mu}{dX}\rangle$. Therefore liquid hydrogen has been chosen for the first realization of the absorber of a cooling channel.

Due to the short muon lifetime (2.2 μs), ionization cooling must be used. The cooling of the transverse phase-space coordinates of a muon beam can be accomplished

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METHODS FOR OPTIMIZATION OF THE DYNAMICS OF THE STORAGE OF POSITRONS IN THE SURKO TRAP*

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Abstract

Surko traps are used successfully, example, for the accumulation of positrons and antiprotons in the experiments on the generation of antihydrogen atoms the ALPHA/CERN. The report presents methods for optimizing the dynamics of the storage of positrons in the Surko trap based on experimental studies on the trap the facility LEPTA/JINR and theoretical estimates of the accumulation and dynamics of particles with technique "Rotating Wall".

INTRODUCTION

Open Penning-Malmberg trap successfully used in the generation of antihydrogen experiments ALPHA [1]. For the accumulation and compression of charged plasma of positrons and antiprotons before injection into the central part of the trap with magnetic mirrors, restraint produced atoms of antimatter, the method of rotating electric field (RW-«rotating wall") [2]. Stabilizing and compressive action of RW-field was first discovered in experiments on the accumulation of ions Mg+ [3]. Then the method used in the experiments with electron [4] and positron bunches [5]. In our experiments on the LEPTA [6,7], whose ultimate goal is to generate a directed flow of atoms of orthopositronium, we investigated the accumulation of positrons before introducing them into the storage ring. It was found that an increase in the lifetime and the number of accumulated particles of the bunch requires highly monochromatic flux of positrons from the sources. A study of instabilities of a non-neutral plasma in the trap, limiting the lifetime and the number of particles accumulated a bunch of positrons [8].

EXPERIMENTS

We represent the results of our experiments on the accumulation of electron and positron plasma in the trap Surko.

Experiments setup

Our facility is the trap open Penning-Malmberg type in the form of the hollow cylinder. Confinement of non-neutral plasma in the transverse direction with respect to the axis of the trap is carried out by the longitudinal of magnetic field magnetic field produced by solenoids. In the longitudinal direction of the storage plasma electrostatic potential for blocking electrodes. One-third of the storage region by the accumulation of the split RW-electrodes, giving the opportunity to include in the accumulation of rotating in the transverse direction the RW electric field. Typical values for our the trap are shown in Table 1:

Table 1: The typical parameters of the our the trap

Parameters	**Value**	**Comments**
E_ω, V/cm	0.05	RW electric field
f_{RW}, kHz	600	Frequency RW-field
n_e, cm^{-3}	$10^7 \div 10^8$	Density of storage particle
ω_p, c^{-1}	$3.5 \cdot 10^7 \div 2 \cdot 10^8$	Plasma frequency
B, Gauss	1200	Longitudinal of magnetic field
ω_B, c^{-1}	$2 \cdot 10^{10}$	Cyclotron frequency
p_{N2} , Torr	$2 \cdot 10^{-6}$	Buffer gas pressure (in storage region)
R_T , cm	10	Radius of transverse plan electrode in the trap (in storage region)
L_T, cm	48	Length of the electrodes in the trap (in storage region)
R , cm	~1÷ 2	Radius of transverse plan the storage bunch
L , cm	~40	Length of the storage bunch

Inside the trap creates a vacuum base. To capture the particles in the trap from a buffer gas (nitrogen) is used. The role of the buffer gas will be discussed further on. To trap a series of experiments were conducted with both electrons and positrons with. Here we can distinguish experiments:

- by measuring the collector current for damp the bunch collector,
- on photographing the dump discharge in the bunch to bunch phosphor screen,
- to measure the signal from the photomultiplier tube at the positron annihilation bunch.

Storage of the electrons. Results of experiments with the collector

Measurements of the collector current can determine the number of storage particles. Performing these measurements at fixed times, we define the dependence of the accumulated particles from the accumulation time. To clarify the role of the rotating field, we carried out experiments on and off the field during accumulation. The results are shown in Fig. 1. Accumulation occurred at found us the optimal parameters: buffer gas pressure, the

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ENHANCING TRAPPABLE ANTIPROTON POPULATIONS THROUGH AN INDUCTION UNIT FOLLOWED BY FRICTIONAL COOLING

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Abstract

The antiproton decelerator (AD) at CERN currently delivers antiprotons for antimatter trapping experiments. The AD slows the antiprotons down to ~ 5 MeV. This energy is currently too high for direct trapping, and foils are used to slow down the antiprotons to energies which can then be trapped. This is an inefficient process. CERN is developing a new machine (ELENA) for further deceleration to ~ 100 keV, using a decelerating ring with elecron cooling. We describe a frictional cooling scheme that can serve to provide significantly improved trapping efficiency, either directly from the AD or using a standard deceleration mechanism (induction linac or RFQ), in a short time scale and at reasonable cost, which could serve in the interim until ELENA is ready for operation. Simulations provide a preliminary assessment of the concept's strengths and limitations, and highlight important areas for experimental studies. We show that the frictional cooling scheme can provide a similar energy spectrum to that of ELENA, but with higher transverse angles.

INTRODUCTION

Sources of low energy antiprotons are in increasing demand for for various experimental initiatives, including direct measurements of charge-to-mass ratios and production and trapping of antihydrogen, and eventually may lead to measurements of trapped neutral antimatter that test the Weak Equivalence Principle and CPT invariance [1, 2, 3].

The primary source of low energy antiprotons remains the Antiproton Decelerator (AD) at CERN. Experiments typically suffer from low capture efficiency, because the antiprotons exit the AD at energies around 5.3 MeV, far above achievable electrostatic trap depths. To trap the antiprotons, the beam is first sent through a degrading foil which slows the particles on average but leads to large particle losses and energy spread due to straggling effects, so only a small fraction of the antiproton source are trapped.

To improve trapping efficiencies, the Extra Low ENergy Antiproton (ELENA) upgrade [4, 5, 6] to the AD has been proposed, which would use a post-decelerator and ring-based electron cooling to provide a source of 100 keV antiprotons while maintaining high phase space density. Other laboratories are also proposing low energy antiproton deceleration and cooling rings, such as the Facility for Antiproton and Ion Research (FLAIR) [7] at GSI.

Here we propose a simple scheme for longitudinal slowing and cooling of the antiproton beam delivered by the AD, utilizing an optional deceleration section which could be an induction linac or RF quadrupole (RFQ), followed by a degrading foil and finally frictional cooling. The frictional cooling stage consists of a series of thin carbon foils separated by re-accelerating electrostatic gradients. Such a scheme is not as effective as ELENA will be, but is an adequate and available option for antiproton experiments. Longitudinal losses should be comparable to that of ELENA, but there may be significant transverse losses even with large solenoidal fields for focusing the beam.

After providing a brief overview of our cooling concept, we present preliminary results from Monte Carlo simulations, suggesting that frictional cooling can enhance the population of trapped antiprotons by a factor of 10 or more. Potentially, a factor of 100 gain can be achieved if the frictional cooling is augmented by using an RFQ. We conclude with a discussion of advantages and limitations of the scheme, and of future directions for study.

OVERVIEW OF FRICTIONAL COOLING FOR ANTIPROTONS

Frictional cooling has been proposed and studied theoretically and experimentally in the context of muons [8, 9, 10]. For antiprotons, frictional cooling might be used to compensate for the large mismatch between the average kinetic energy of the antiproton beam exiting the AD and the kinetic energy of particles that can be trapped (several MeV versus several keV). To compress its energy spread, each antiproton bunch is passed through a series of thin foils separated by electrostatic potential differences that reaccelerate the beam, as shown schematically in Figure 1. For antiprotons with kinetic energy below ~ 90 keV, higher energy particles lose more energy in each foil, so this design causes particles to converge to an equilibrium energy (this is analogous to "terminal velocity" for falling objects in air). Transverse angles reach an equilibrium of order of a fraction of a radian, and solenoidal fields are used to minimize growth in transverse spot size.

Because the stopping power starts to decrease for kinetic energies above ~ 90 keV, the maximum energy acceptance of the frictional cooling section is limited to the energy, typically around 400 keV, where the stopping power drops back down to match that of the equilibrium energy. Thus a degrading foil [11] must still be used, whose thickness is comparable to the range of the incident antiprotons. If the incident antiprotons have an energy of ~ 5 MeV, straggling

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ION KINETICS IN THE ULTRA-LOW ENERGY ELECTROSTATIC STORAGE RING (USR)

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Abstract

The Ultra-low energy Storage Ring (USR) at the Facility for Low-energy Antiproton and Ion Research (FLAIR) will provide cooled beams of antiprotons in the energy range between 300 keV down to 20 keV and possibly less. A large variety of the envisaged experiments including in-ring collision experiments with a reaction microscope require a comprehensive study of the long term beam dynamics processes in the ring.

Detailed investigations into the ion kinetics under consideration of the effects from electron cooling and multiple scattering of the beam on a supersonic gas jet target have been carried out using the BETACOOL code.

The life time, equilibrium momentum spread and equilibrium lateral spread during collisions with this internal gas jet target were estimated. The results from simulations were benchmarked against experimental data of beam losses in the ELISA storage ring. In addition, the results from experiments at the TSR ring where a 93 keV/u beam CF^+ ions has been shrunk to extremely small dimensions have been reproduced.

Based on these simulations, conditions for stable ring operation with extremely low emittance beam are presented. Finally, results from studies into the interaction of ions with a gas jet target at very low energies are summarized.

INTRODUCTION

The next-generation antiproton facility at GSI, the Facility for Antiproton and Ion Research (FAIR), will not only provide future users with antiprotons in the high energy range, but it is also intended to include a dedicated research program for ultra-low energy antiproton research, realized with the FLAIR project [1]. Low-energy antiprotons are the ideal and perhaps the only tool to study in detail correlated quantum dynamics of few-electron systems in the femto- and sub-femtosecond time regime [2]. Within the FLAIR Facility the Ultra-low energy Storage Ring (USR) operates in the variable energy range from 300 keV down to 20 keV and possibly to even lower energies [3,4]. The USR will enable, for the first time, access to kinematically complete antiproton-induced rearrangement and fragmentation measurements. The USR, presently being developed in the QUASAR group [5], is comprised of electrostatic ion optics elements and studies into the long term beam dynamics and ion kinetics are of crucial importance for the performance of the envisaged experiments.

BENCHMARKING OF EXPERIMENT

For benchmarking purposes, the ELISA electrostatic ring, successfully in operation since the late 90s and dedicated to atomic physics studies [6], has been chosen. In the original ring design spherical deflectors had been used to provide equal focusing in both the horizontal and vertical plane but were later on substituted by cylinder deflectors [7]. Systematic experimental studies showed strong limitations on the maximum storable beam current and reduced beam life time at higher beam intensities. The nature of these effects was not fully understood [8].

We studied transition processes, i.e. growth rates of beam emittance and momentum spread, as well as equilibrium conditions in ELISA by simulating the rms parameters of the evolution of the ion distribution function with time. For this purpose the BETACOOL code was applied [9,10]. In this study, the beam parameters summarized in table 1 were used. BETACOOL allows choosing and switching between different effects and in this particular investigation only heating processes were used: Intra-Beam Scattering (IBS), small angle multiple scattering of the circulating ions on the residual gas atoms, energy straggling and ion losses on the ring acceptance. It was found that beam losses caused by single large angle scattering are negligible at a vacuum level $2\cdot10^{-11}$ Torr, even at such a low beam energy. The limited life time of O^- ions due to the electron detachment by collision with the residual gas

Table 1: BETACOOL beam parameters of ELISA.

Ion	**O^{16}**	**Mg^{24}**
Charge	–1	+1
Ion energy, keV	22	18.4
Initial beam intensities	$5\cdot10^5 \div 1.6\cdot10^7$	$2.7\cdot10^7$
Ring circumference, m	7.616	7.616
Initial hor/vert ε, π mm mrad (σ)	1 / 1	0.7/0.35
Initial full ε, π mm mrad (3σ)	6 / 6	4 /2
Ring acceptance ESD-cyl, π mm mrad	10	10
Ring acceptance ESD-sph, π mm mrad	6	6
Initial RMS momentum spread, $\Delta p/p$	10^{-3}	10^{-4}
Equilibrium momentum spread, $\Delta p/p$	$4\cdot10^{-3}$	
Electron detachment life time of O^-, sec	26	--
Life time of O^- at 22 keV, sec	~ 12	

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CLOSED ORBIT CORRECTION IN 2 MEV ELECTRON COOLER SECTION AT COSY-JUELICH

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Abstract

A 2 MeV magnetized electron cooling system will be installed at COSY in order to boost the luminosity for future high density internal target experiments. For an effective electron cooling, the ion beam and electron beam have to overlap coaxially, demanding a perfect orbit correction in the cooler region. Due to the U-shaped arrangement of the toroid magnets the ion beam orbit distortion is anti-symmetric in horizontal plane. With two steerers at each side of cooler the ion beam can be made coaxial in the cooler without disturbing the region outside the cooler. The distortion caused by the bending coils in the toroids is symmetric in the vertical plane. Also here a local correction is suggested for correction. Using the magnetic field data measured at BINP we calculated the orbit distortion of ion beam at injection energy and investigated the schemes for orbit corrections.

INTRODUCTION

Considering the requests of high luminosity for future COSY internal target experiments, a magnetized electron cooling system up to 2 MeV was suggested to be tested and operated at COSY [1]. This device has been developed together with the Budker Institute in Novosibirsk and will be installed in COSY at the end of 2011. Basically, a strong longitudinal magnetic field is used to guide the electron beam and to magnetize the electrons. The vertical field components in the toroids cause a severe horizontal deflection of the ion beam which has to be corrected by a set of steerers around the cooler. The principles of correction schemes have been described in various articles, e.g. in [2] and [3]. Two horizontal dipole correctors already installed in the toroids and regular steerers around form a fully compensated bump on each side of cooler. A weaker but not negligible orbit distortion in the vertical plane is caused by the bending coils in the toroids which serve to compensate the centrifugal force of the electrons related to the toroid radius. Also here fully compensated bumps are considered.

MAGNETIC FIELD DISTRIBUTION

The magnetic field map of the 2 MeV cooler produced by the cooling section drift solenoid, the toroids and the bending coils in the toroids have been measured at BINP [4]. The dipole correctors are connected in series with the toroids using the same power supply. Additional small coils mounted in the dipole correctors [5] will be used for a fine adjustment of the horizontal and vertical steering angle. The map (see Fig. 1) of magnetic field along the ion beam orbit has been measured with typical operational parameters.

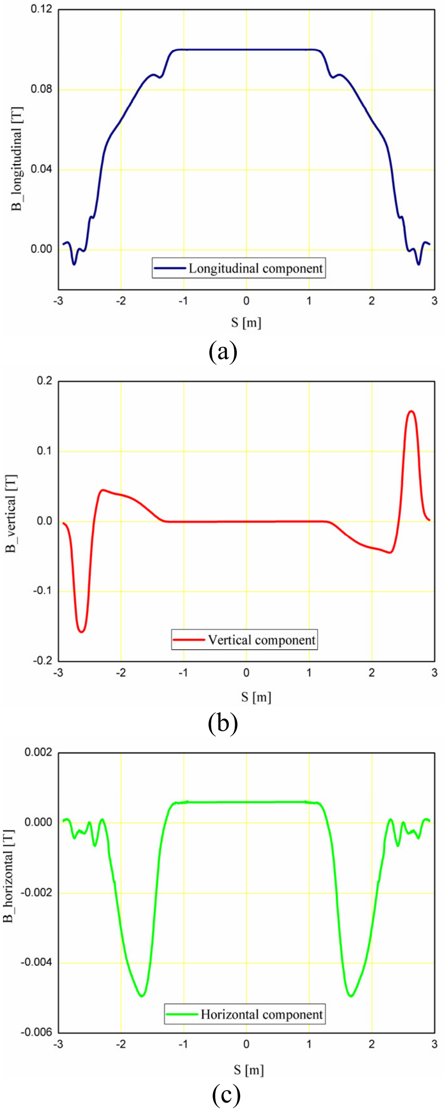

Figure 1: The magnetic field along the ion trajectory in cooler. From top down are shown the longitudinal, vertical and horizontal components. The current value of power supply is 175 A for the solenoid, 500 A for the toroids and the dipole correctors, 200 A for the bending coils. These parameters are half of design value.

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SIMULATION OF HIGH-ENERGY ELECTRON COOLING AT COSY WITH BETACOOL PROGRAM

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Abstract

A 2 MeV electron cooling device will be installed at COSY in order to boost the luminosity for future high density internal target experiments, e.g. WASA pellet target experiments. The magnetized electron cooling technique is used to compensate the energy loss and emittance growth due to beam-target interaction. In this article, a numerical simulation of electron cooling process was performed with BETACOOL program. The cooling time is calculated for variant electron cooling parameters. The intrabeam scattering (IBS) and pellet target effect are essential for prediction of equilibrium beam parameters. The influence of the pellet target on the beam parameters is demonstrated.

INTRODUCTION

As the requests of high luminosity for future COSY pellet target experiments, an electron cooling system up to 2MeV was suggested to operate at COSY [1]. This device has been developed together with the Budker Institute in Novosibirsk and will be installed in COSY at the end of this year. The magnetized electron cooling technical solution is used to obtain a powerful 6-dimensional phase cooling.

A simulation study of the beam dynamics at COSY taking into account electron cooling in combination with pellet target and intrabeam scattering effects was performed with BETACOOL program. The BETACOOL program developed by JINR electron cooling group is oriented to simulation of the ion beam dynamics in a storage ring in the presence of cooling and heating effects [2]. To simulate the short scale luminosity variation in pellet target experiments, an additional algorithm has been implemented into BETACOOL program recently [3].

In this paper, the cooling time dependences on electron cooler parameters are calculated with RMS dynamics algorithm method. The suggestion for cooler optimization is obtained from the calculation. The momentum distribution of proton beam at equilibrium between electron, IBS and pellet target is simulated with model beam algorithm method. The Landau distribution caused by beam-target interaction is discussed with different cooling efficiency. In the end of this paper, the short-scale and long-scale luminosities for proposed pellet target experiments are analyzed. The main parameters required in simulation are listed in table 1. The lattice structure of zero-dispersion at target point is used in simulation.

Table 1: The main parameters of simulation

Proton beam parameters	
ion kinetic	2.0 GeV proton beam
Initial emittance (x/y)	0.2 / 0.2 pi*mm*mrad
Initial momentum spread (dp/p)	$2.0*10^{-4}$
Particle number	$2.0*10^{10}$
Electron cooler parameters	
Electron beam radius	5.0 mm
Magnetic field in cooling section	0.2 T
Cooler length	2.69 m
Electron beam current	2.0 A
Electron temperature (trans / longi.)	$1.0 / 1.0*10^{-4}$ eV
Magnetic field misalignment	$2.0*10^{-5}$
Beta function at cooler (hori / vert)	5.5 / 4.5 m
Pellet target parameters	
Effective target thickness	$2.0*10^{15}$ atoms/cm^2
Pellet flux radius	2.5 mm
Pellet velocity	80 m/s
Pellet radius	0.03 mm
Rate of pellet generation	8.0 kHz

OPTIMIZATION OF COOLER

Electron cooling is a fast process to compress the phase space of charged particle beam in storage ring with low temperature electron beam [4]. The phase space is shrinking up to the equilibrium between electron cooling and heating effects. In order to estimate the electron cooling efficiency, the cooling time dependences were calculated with RMS dynamics algorithm in BETACOOL program.

The RMS dynamics algorithm is a simplified model that all effects are described by cooling or heating rates. The rates can be calculated with different models. In this calculation, the Parkhomchuk empirical cooling force formula is applied for magnetized electron cooling process [5]. The Martini's model is used for IBS effect calculation and the pellet target effect is presented in the form related to kick of the ion momentum [6]. The initial parameters of proton beam are listed in table.1.The horizontal (or longitudinal) cooling time was defined as

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ELECTRON GUN WITH VARIABLE BEAM PROFILE FOR COSY COOLER

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Abstract

Electron gun with variable beam profile is used on COSY 2 MeV cooler to optimize the cooling process. Further development of the gun is achieved with the help of the four-sector control electrode that provides some new features. Combined with BPMs it gives the possibility of the electron beam shape estimation. Application of the gun for stochastic cooling is also discussed in the article.

INTRODUCTION

The electron gun design is based on the slightly changed gun previously used for CSRe,CSRm [1] and LEIR coolers. The only difference is the four-sector control electrode (fig.1) with separate feeding of all sectors via additional feedthroughs. This small change, nevertheless, opens a new possibility for non-axially modulation of the electron beam profile, which could be used in some applications. Combined with BPMs this feature of the gun provides beam shape monitoring when it passes transport channels.

One more perspective is to use the gun as 3D kicker.

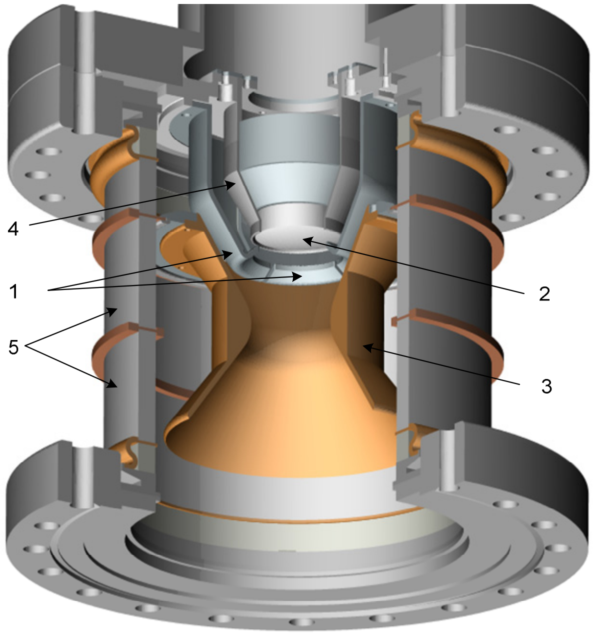

Fig.1 The sketch of the electron gun for COSY 2 MeV cooler.

1 – four-sector control electrode, 2 – oxide cathode,
3 – anode, 4 – cathode housing, 5 – ceramics.

Since the electron gun of the COSY cooler is embedded in longitudinal magnetic field, its characteristics depend on field strength. Emissive ability of oxide cathode (2) is about 0.5 A/cm^2, so the maximum possible current is about 3A for 29 mm cathode diameter. Another important characteristic of the gun is the electron transverse temperature, which entirely determines cooling process. One of the tasks for cooler's electron guns design is keeping the transverse temperature as low as possible. On the other hand the electron current density should be increased to provide high efficiency of electron cooling at high energies. Following results of simulations (fig.2), made with UltraSAM code [3], specify the electron beam parameters depending on anode voltage and magnetic field strength.

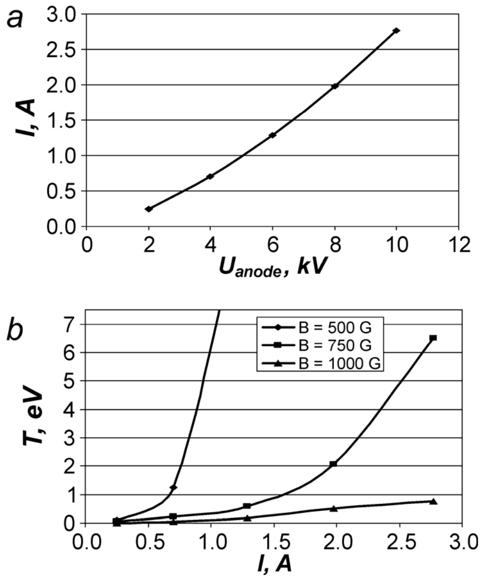

Fig 2: Current (a) and transversal temperature (b) of homogeneous electron beam.

With the current increase the transversal temperature grows also (Fig. 2b). For COSY cooler electron gun 3A current is achievable with few electron-volts transverse temperature at 600 G longitudinal magnetic field and about 10kV anode voltage.

BEAM PROFILE SIMULATIONS AND MEASUREMENTS

Specification of the electron gun characteristics is very important for further electron cooler operation. Every time when a design of the gun is changed it should be tested before installation on the cooler. For this purpose special test bench was constructed at BINP to perform all

ELECTRON COLLECTOR FOR 2 MEV ELECTRON COOLER FOR COSY

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Abstract

New electron collector for 2 MeV electron cooler for COSY ring is presented. In electron coolers efficiency of collector is important for high voltage power supply. In 2 MeV cooler for COSY it is also important from the point of view of radiation safety because secondary electrons, reflected from the collector go back to accelerating tube. Besides radiation effect it can cause problems with vacuum and electric strength. The collector presented in the article is supplemented with Wien filter which allows increase efficiency of the system by deflection secondary electron flux in crossed transverse electric and magnetic fields. Results of calculation and experimental results achieved on special test bench are presented.

INTRODUCTION

Bad efficiency of recuperation in electron cooling systems results in higher current of lost of full energy electrons. It needs higher power of high voltage source that can be difficult technical task. Also electrons reflected from the collector and accelerated in accelerating tube are source of radiation because they hit a wall of vacuum chamber on full energy. Besides the problems, related with the radiation safety, the radiation can cause problems in reaching good vacuum conditions and decrease electric strength of the cooler. In previous coolers produced in BINP for IMP (China) and CERN the efficiency was improved with the help of special electrostatic bending plates installed in the toroid parts of the coolers [1]. Electrons reflected from collector move from collector to gun solenoid and then back to collector where they can be absorbed. These plates allow to increase efficiency of cooler recuperation from 10^{-3} to 10^{-6}. But in 2 MeV cooler for COSY shape of the magnetic system and high energy of electrons make using of such method very complicated. In this case one should improve collector's efficiency.

In the 2 MeV electron cooler for COSY new construction of collector was proposed. From calculations, its efficiency is about 10^{-3} that is not enough for the high voltage cooler, where maximum electron current is 3 A. In order to increase efficiency of recuperation a Wien filter was installed before the collector for suppression of secondary electron flux reflected from the collector

COLLECTOR

The collector design is shown in Fig. 1. The electron beam coming from the Wien filter (1), passes through collector electrode (2) and suppressor (3) and enters inside the collector (4). Due to magnetic shield (8) and coil (9) with opposite current the beam expands and deposits on cooled collector surface (5). To provide effective pumping from the collector there is a hole with small ion pump (6). To avoid electron flux into this hole in its center a thin electrode is placed.

Adjusting current in coil (9) one can improve collector efficiency by closing in the collector electrons reflected form its surface. Moreover it allows achieve more uniform distribution of electron flux on inner surface of the collector without causing local overheating and to cool the collector more effectively.

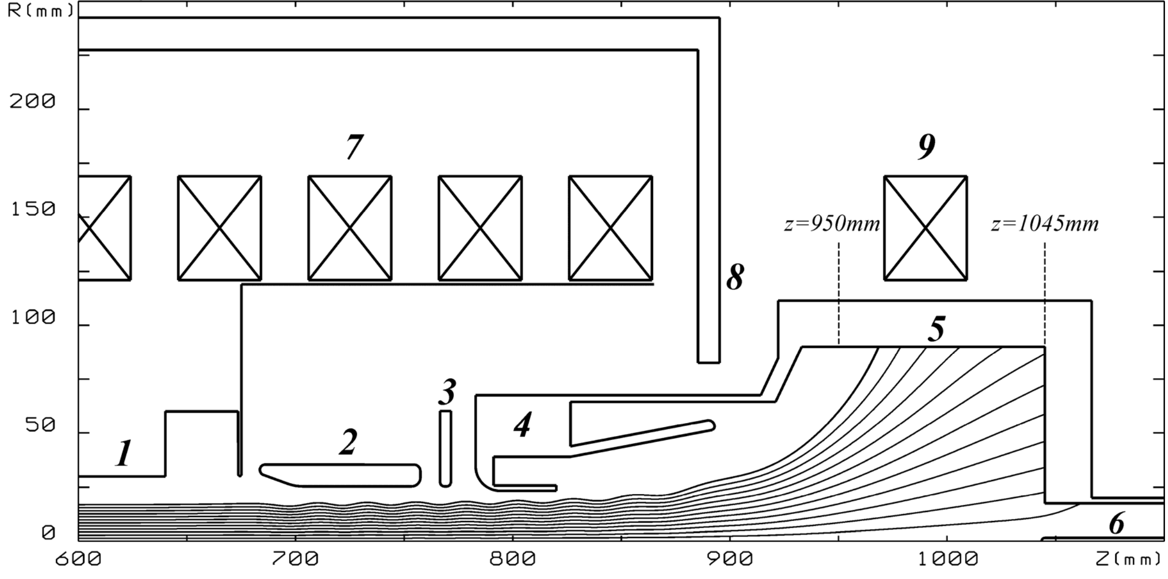

Figure 1: Collector design.

SYSTEM FOR MEASUREMENT OF MAGNETIC FIELD LINE STRAIGHTNESS IN SOLENOID OF ELECTRON COOLER FOR COSY

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Abstract

Construction of measurement system is presented. The system is based on special magnetic sensor (compass) with a mirror attached to the compass needle. The needle with the mirror are suspended on gimbal suspension and can rotate in two directions. Measuring reflected laser beam deflection one can measure field line straightness with accuracy up to 10^{-6} rad. The compass is installed inside vacuum volume of the cooling section on special carriage that moves on rail along the section via special tape. To calibrate the compass special test bench was made. The calibration procedure allows to determine and to diminish compass inaccuracy appeared during manufacture and assembling. Results of calibration of the compass on the test bench are presented.

INTRODUCTION

Straightness of magnetic field line in cooling section is very important for electron cooling as it increases effective velocity of electrons. For high energy electron cooling it is especially important as the influence increases with energy $V_T=\gamma V\theta$, where γ – relativistic factor, V – longitudinal velocity of an electron, θ – angle of field line deflection.

Experience with production of electron coolers shows that straightness of magnetic field line degrades with time. Because of this a new device which allows to measure straightness with period of several months without disassembling of vacuum chamber is needed. For 2 MeV cooler for COSY it was proposed to install measuring system based on magnetic compass inside the vacuum chamber of cooling section and toroids. Similar system was used on electron cooler for NAP-M storage ring [1].

The transverse components of the magnetic field of coil can be determined by the magnitude of deviation from the axis of magnetosensitive element of sensor. If it is rigidly connected with the mirror, the angle of deviation can be determined from the shift of the light spot produced by a beam from an external source, reflected by the mirror. Returning a spot in the starting position by the influence of compensating magnetic field from an external source, the magnitude of corresponding component of field of tested solenoid (i.e. misalignment of field line at that point) can be determined.

In the first experiments on determination of the quality of magnetic field in INP [1], an optical automatic autocollimator was used as the measuring system, in which the angle of deflection was determined by the mechanical adjustment of the light in the instrument. As the magnetic sensor it was used a construction composed of the mirror, laid down in the gimbal suspension with jewels from clock as the bearing supports, and of steel rod penetrating the mirror axis. In a magnetic field of a solenoid with magnitude of about 1 kG field inhomogeneity about 10^{-5} radian was determined. The sensitivity was limited mainly by friction at the nodes of motion in the optical components of the collimator during the rearrangement of its optics.

In 2000, in the BINP a measurement system for a prototype of electron cooling system for the Tevatron (Fermilab, USA) was designed [2]. For operating magnetic field of 50-100 G sensitivity of previous devices was not enough, therefore the measuring system was modernized.

The mirror was fixed on the end of a light frame along which axis a magnet (cylinder of material NdFeB) was inserted. At another end a nonmagnetic counterbalance was attached. With the help of wire, fixed at the center of gravity, the sensor node was suspended in the center of a hollow cylindrical carriage, which had compensating circuits. The carriage was moved along the bottom of a narrow chamber and was stabilized by two strings, stretched along the pipe.

Electronic circuit contained a low power semiconductor red laser as light source, four quadrant photodiode, source of compensating current and the feedback loop, allowing return reflected from the mirror compass beam to the starting position for fixing the value of the compensation current.

This scheme with no significant changes was used in future for setting up solenoids of produced at the BINP coolers for IMP (Landzhou, China) and for CERN. Only constructions of compasses were improved.

Such constructions of compasses are highly sensitive due to the absence of nodes with the mechanical friction. But they can not be used in the COSY because of limited strength of thin metal suspension wires. This can result in break of the wire especially on curved parts of magnetic system. Such situations are inevitable since the compass need to be removed from a region with homogeneous field to release accelerator's aperture. Increasing the strength of wire by increasing its thickness is also limited because of rapid growth of the elastic forces. Significantly more durable fishing line is not a vacuum material and it does not allow heating to even 100 degrees.

For these reasons for 2 MeV COSY cooler a design (already described above) with setting the magnet to the mirror in a gimbal suspension was chosen (fig. 1).

LEPTA PROJECT: TOWARDS POSITRONS

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Abstract

The project of the Low Energy Positron Toroidal Accumulator (LEPTA) is under development at JINR. The LEPTA facility is a small positron storage ring equipped with the electron coolin system. The project positron energy is of 2 – 10 keV. The main goal of the facility is to generate an intense flux of positronium atoms – the bound state of electron and positron.

Storage ring of LEPTA facility was commissioned in September 2004 and was under development up to now. The positron injector has been constructed in 2005 ÷ 2010, and beam transfer channel – in 2011. By the end of August 2011 experiments on electron and positron injection into the ring have been started. The recent results are presented here.

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.

Vacuum system improvements

In old design the distance between kicker plates was off 32 mm that limited the aperture. New kicker design allows us to increase aperture up to 120 mm.

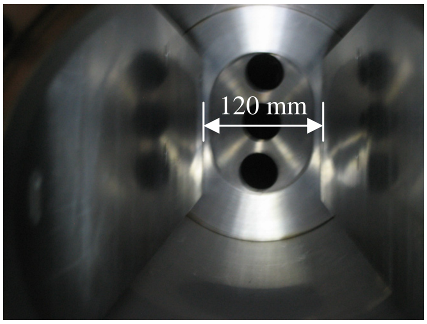

Figure 1: The new kicker

Testing after upgrading

Typical life time dependence on electron energy, τ_e(Ee), has two slopes (Fig.2). The left one, where τ_e increases with Ee, is defined by electron scattering on residual gas. The right slope, descending with Ee, relates to violation of electron motion adiabaticity on inhomogeneities of solenoid magnetic field.

The curves 1 and 2 were obtained in 2005, whereas the curves 3, 4 and the point 5 have been measured in June 2008. The curve 6 was measured in August 2009, after all modifications of the ring described above. One can see significant increase of the electron life time. Of the main importance is the increase of the life time (comparing with the values of the year 2005, 2008) in the energy range above 4 keV by 6÷10 times. It proves the necessity of a further improvement of the solenoid field homogeneity. The point 7 (2011) is result of the regime optimization and vacuum improvement.

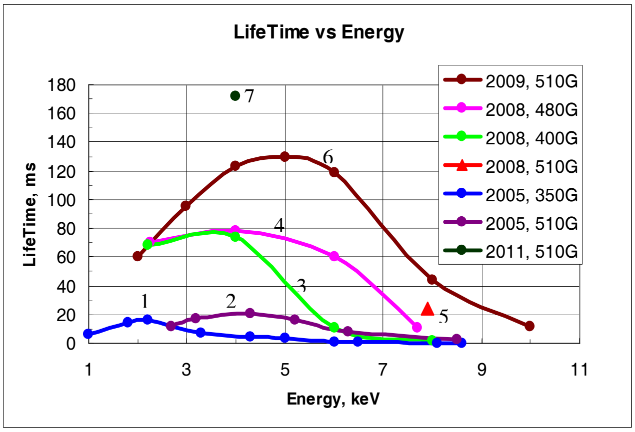

Figure 2: LifeTime vs electron energy.

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MAGNETIC SYSTEM OF ELECTRON COOLER FOR COSY

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Abstract

The magnetic system for the COSY cooler is presented. Electron beam energy range is wide (24keV-2MeV), typical bend's radii of electrons track are near to 1 m, typical magnetic fields are 0.5 – 2kG. Transport channels with guiding magnetic fields for motion of electrons from high voltage terminal of cascade transformer into cooling section and their return for recuperation under such conditions are discussed. Results of Hall sensors measurements are compared with corresponding computations. Also some steps were taken for improvement of the magnetic field lines straightness in the cooling section.

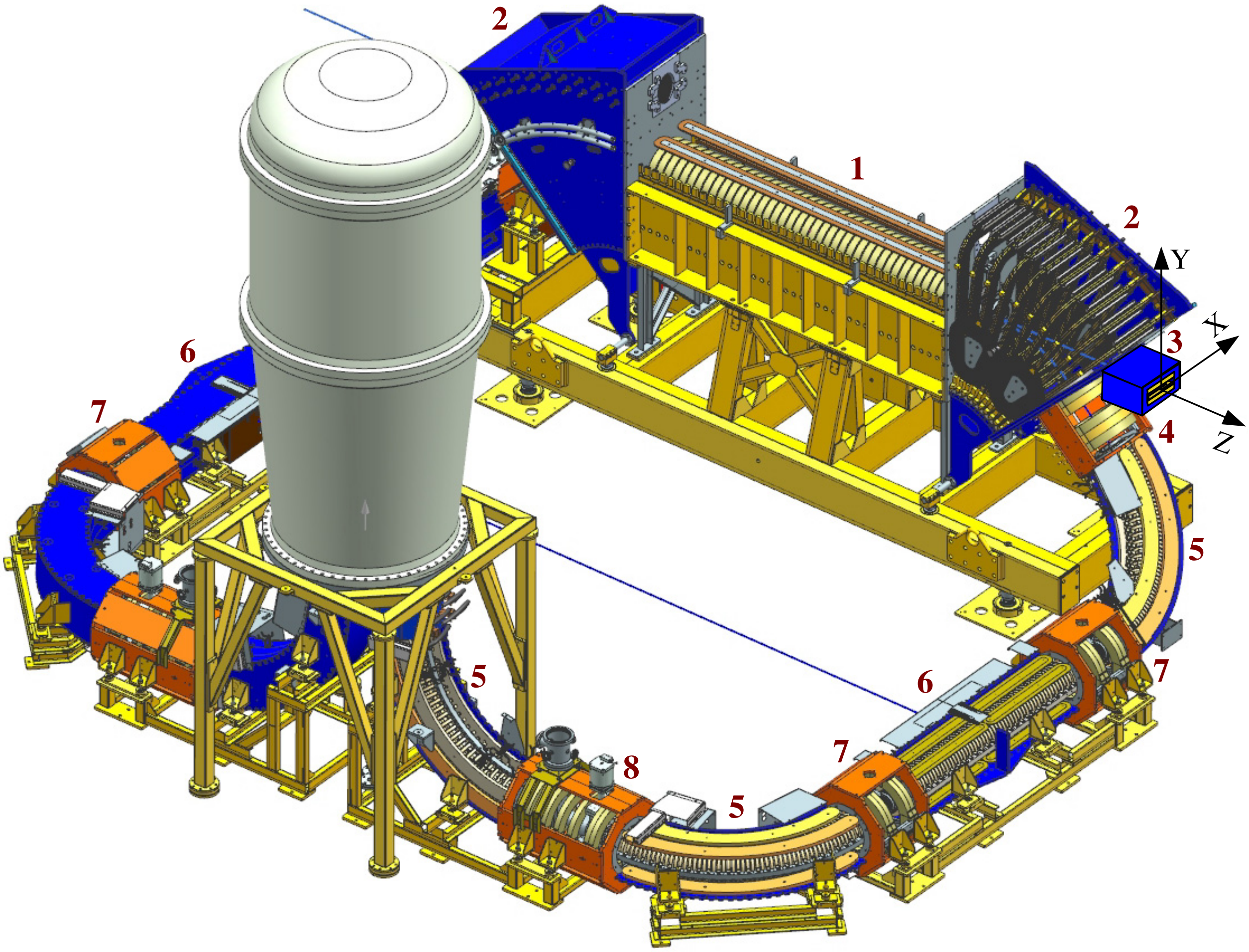

Figure 1: Cooler magnetic system layout: 1 – solenoid and transverse correctors of cooling section, 2 – toroidal and bending coils of 45° toroid, 3 – dipole corrector, 4 – two coil groups of matching section, 5 – toroidal and bending coils of 90° bend, 6 – solenoid and transverse correctors, 7 – coils of short transition section, 8 – coils of long transition section, 9 – coil group of matching section.

DESCRIPTION

Solenoid consists of 40 pancake moveble coils [1]. Half the coils have right-handed winding, the rest – left-handed winding. Interleaving of such coils minimize field inhomogeneities which arise at commutation of coils. Since cooling by magnetized electrons is used, high straightness of the magnetic field line is required: $\Delta B_{\perp} / B = \theta < 10^{-5}$. Coils are installed on ball bearings for adequate correction of position. Magnetic field is aligned by tilting or slewing the coils. Necessary displacements of control screws were found by mathematical treatment of previous compass measurements [2]. Displacements of ~0.01mm were needed in final stage. In addition magnetized electron beam may be tilted by horizontal and vertical correctors

SUPERCONDUCTING SHIELD FOR SOLENOID OF ELECTRON COOLING SYSTEM

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Abstract

The homogeneity of the magnetic field in the straight solenoid of the electron cooling system is the very important task. The superconducting solenoids are planned for electron cooling systems of collider rings of NICA project [1]. To reach the necessary homogeneity in the straight section the superconducting shield was proposed. The design of the superconducting shield, experimental and numerical investigation of the field homogeneity in the solenoid with the superconducting shield are presented.

INTRODUCTION

Special properties of superconducting materials (Meissner Effect, high current) permits to use these materials for magnetic field screening in different facilities, for example: chambers with magnetic vacuum, current limiters, and tomography. For maximum current density 5×105 A/cm2 the magnetic field difference on the thin superconducting layer with the thickness about 20 µm can reach a value up to 1000 G. The using of the NbTi superconducting shield for the increasing of the field homogeneity was investigated in the different works [2, 3].

The aim of these investigations is the problem of the field homogeneity in the straight section of the electron cooling system. The price of the straight solenoid with field homogeneity up to value ΔB/B=10-5 [1] is very high. When the length of the high precision solenoid is 10 m and more than the solenoid is divided on a few sections. This situation leads to the field unhomogeneity between solenoid sections. The using of the superconducting shield can resolve this problem.

For the investigation of the high homogeneity magnetic field in large volumes the experiments with superconducting shields which are placed inside superconducting solenoid were done in Laboratory of High Energy Physics (JINR, Dubna, Russia). The design of the superconducting shield is a multilayer close-coiled winding from the superconducting foil. This article presents the comparison of experimental and numerical results which were done with standard simulation programs and original program code.

EXPERIMENTS WITH SHORT SOLENOID

Laboratory of High Energy Physics JINR has a large experience in the production of superconducting systems [4]. In first experiment the existing superconducting solenoid with length 150 mm, outer diameter 130 mm and inner diameter 100 mm was used. The superconducting shield was made from the NbTi foil with thickness 150 µm and width 138 mm. The shield was wind on the tube with diameter 78 mm and has 5 layers which have a close-coiled shape and are divided by the isolator paper.

The dependence of the magnetic field homogeneity on different solenoid currents is presented on Fig.1. Initially measurements were done without the superconducting shield then with the shield for the same values of solenoid currents. The field measurements were made with the Hole probe along the solenoid axis with step 5 mm. A sensitivity of the Hole probe was 73 mV/T.

The using of the superconducting solenoid leads to the increasing of the field range with high homogeneity even in the short solenoid (Fig.1). At the same time the value of magnetic field decreases in the solenoid center and increases on the edge. The size of the field range with high homogeneity has a dependence on the absolute value of the magnetic field: the higher field value the smaller range size. This behavior can be explained by the saturation of the superconducting shield. The efficiency of the shield is decreasing when the current in the foil reach the critical value.

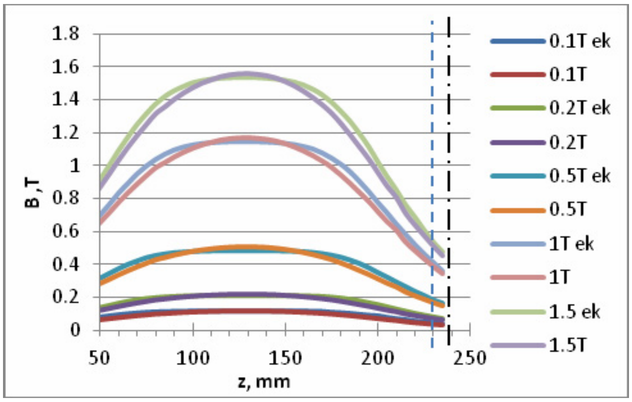

Figure 1: The dependence of magnetic field (arbitrary units) on the longitudinal coordinate for different values of the magnetic field B = 0.1, 0.2, 0.5, 1, 1.5 T) with the superconducting shield (ek) and without it. Vertical lines correspond to boundaries of the solenoid and shield.

EXPERIMENTS WITH HIGH HOMOGENEITY FIELD

For further investigation of the influence of the superconducting shield on the field homogeneity the solenoid with large ratio of the length and diameter was

OPTICAL ELECTRON BEAM DIAGNOSTICS FOR RELATIVISTIC ELECTRON COOLING DEVICES

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Abstract

For the cooling of proton and ion beams a well established overlap between cooling beam and circulating beam is needed. The new relativistic electron cooling devices, like the one proposed for the High Energy Storage Ring (HESR) at FAIR, have special demands on the diagnostics which can be used to characterize the cooling beam. Due to high voltage breakdowns they only allow a very small beam loss so non-invasive beam diagnostic methods are necessary. A system based on beam induced fluorescence (BIF) was installed at the 100 keV test setup at the Mainzer Mikrotron (MAMI). First results of the measured photon yield as a function of beam current and residual gas pressure will be presented. In addition a Thomson scattering experiment is planned at the same test setup. This method enables the measurement of other observables of the cooling beam like the electron beam energy or the electron temperature. The design of the experiment as well as the challenges will be discussed.

INTRODUCTION

The cooling beam and the cooled beam have to overlap and propagate with the same velocity to ensure a small cooling time. This matching is done by optimizing the H^0-signal. In this case the protons of the cooled beam are recombining with the electrons of the cooling beam. The resulting Hydrogen Atoms are neutral they are not deflected by magnetic fields and can be detected after the next bending magnet. This technique is only applicable for protons and positive ions. For the cooling of antiprotons as it is planned in the (HESR) [1] there is no H^0-signal which could indicate a good cooling rate. Because of this special beam diagnostics of the cooling beam are necessary. The diagnostic has to be be non destructive because of the high beam power. It should also not affect the magnetic field flatness of the solenoids inside the cooling section.

There are already several non destructive beam diagnostic methods established. They are used in different accelerators like a scintillation profile monitor [2], [3] or the Laser wire scanner at the synchrotron source PETRA III [4]. These methods can be adapted for the use in relativistic electron cooling devices.

BEAM INDUCED FLUORESCENCE

For protons and ions beam profile measurement based on beam induced fluorescence is a common technique [5]. The idea is to image the fluorescing residual gas on a photo detector with a spatial resolution as shown in Fig. 1. There are different types of detectors available, like multi channel plates (MCP), multichannel photo multiplier or intensified ccd (ICCD) cameras.

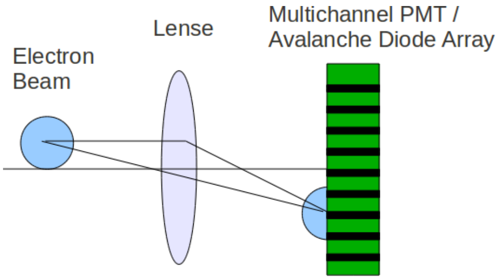

Figure 1: Principle of scintillation profile monitor

The production of the scintillation light depends on the residual gas pressure, the beam current and the composition of the residual gas. Different gases show different excitation spectra and consequential have different fluorescence spectra. But they are also differing in the intensity of the scintillation light.

For electrons and protons with the same velocity the ionization energy loss is very similar. They amount to $4.4\,MeVcm^2/g$ and $4.3\,MeVcm^2/g$ respectively for $\beta = 0.55$ in N_2. This should lead to a corresponding light output. From the energy loss and the photo production coefficient from [6] we can therefore estimate the fluorescence rates for electrons in nitrogen gas. For our detection device which has a solid angle $\Omega = 3.1 \cdot 10^{-2}$ sr and a detector efficiency of 0.3 we expect a count rate of 10^4 Hz/cm of longitudinal beam extension at a pressure of 10^{-6} mbar and a $100\,\mu A$ beam.

To test this assumption a special vacuum chamber has been designed (Fig. 2) and has been installed at the polarized test source (PKAT) [7] at the Mainzer Mikrotron (MAMI). In this source a NEA-GaAs [8] photo cathode is used which requires 10^{-11} mbar for stable operation. Therefore this chamber together with additional turbo molecular pumps acts as a differential pumping stage. This allows local pressure bumps up to 10^{-5} mbar while maintaining the UHV condition at the cathode. The main purpose of this experiment is to gain understanding of the different background sources which degrade the signal to noise ratio for the optical beam diagnostics.

The chamber is equipped with a silica window which is transparent down to 200 nm. This allows to image the transverse beam profile by transmitting the UV parts of the spectral lines of N_2. With the leak valve the residual gas

ELECTRON COOLER FOR NICA COLLIDER

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Abstract

The electron cooling system at electron energy up to 2.5 Mev for the NICA collider is under design at JINR. The electron cooler is developed according to the available world practice of similar systems manufacturing. The main peculiarity of the electron cooler for the NICA collider is using of two cooling electron beams (one electron beam per each ring of the collider) that never has been done before. The acceleration and deceleration of the electron beams is produced by common high-voltage generator. The conceptual design of the electron cooling system has been developed. The cooler consist of three tanks. Two of them contain acceleration/deceleration tubes and are immersed in the copper ("warm") solenoids. The third one contains HV generator, which design is based on voltage multiplying scheme.

CONCEPTUAL DESIGN OF THE COOLER

The electron cooler (Fig. 1) consists of three tanks filled with SF6 gas under pressure of 8 at. The tanks 1 and 3 contain acceleration tube and electron gun for one of the electron beam and deceleration tube and electron collector for another one. The tank 2 houses the HV generator.

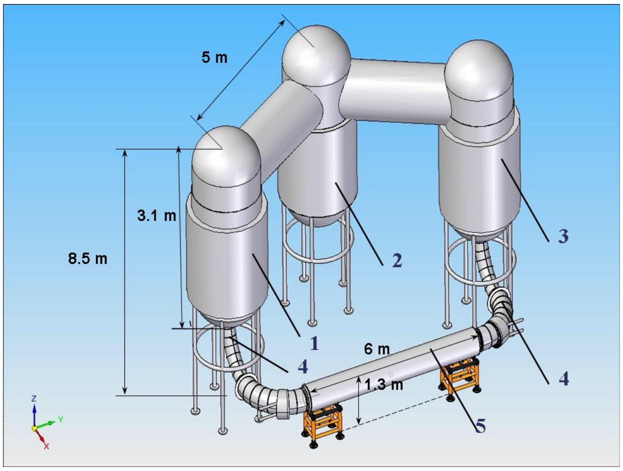

Fig.1. General view of the electron cooler. 1, 3 – tanks with electron gun and acceleration tube and deceleration tube + collector for electron beam of opposite direction,
2 – tank with HV generator, 4 – beam transportation solenoids, 5- electron cooling section.

The magnetic field is formed by a set of straight and toroidal solenoids. The solenoids forming the magnetic field in the region of acceleration/deceleration tubes are placed outside of the tanks that resolve the problem of HV insulation.

Table 1. Cooler parameters

Electron energy, MeV	0.5 ÷ 2.5
Electron beam current , A	0.1 ÷ 1,0
Beam diameter, cm	1,0
solenoid magnetic field, T	0.1 ÷ 0.2
HV PS current, mA	1
Collector PS, kW	2×2
HV PS stability, ΔU/U	1×10^{-4}
SF_6 gas pressure, at	5 ÷ 8

ELECTRON BEAM GENERATION AND ENERGY RECUPERATION

Both acceleration and deceleration systems consist of three main subsystems (Fig. 2): acceleration vacuum tube with electron gun or collector mounted on the upper end of the tube, high pressure tank, solenoid forming longitudinal magnetic field. Acceleration vacuum tube with electron gun or collector mounted on the upper end of the tube. Electron gun design (Fig.3) has three main elements: cathode with the Pierce electrode, control (steering) electrode, anode connected with first (upper) flange of acceleration tube. Electron collector (Fig.3) consists of three elements as well: collector anode connected with upper flange of deceleration tube, suppressor ("repeller") electrode, electron collecting vessel. The last one is cooled by water circulating at high potential. The design and construction of collector cooling system is in progress.

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THE STOCHASTIC COOLING SYSTEM OF HESR

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Abstract

The HESR is the High Energy Storage Ring (1.5 - 15 GeV/c) for antiprotons at the FAIR facility (Facility for Antiprotons and Ion Research) in Darmstadt (GSI). Stochastic cooling in the HESR is necessary not only during the experiments to fulfill the beam requirements, but also during the accumulation due to the postponed RESR. Extensive simulations and prototype measurements have been carried out to optimize the HESR stochastic-cooling system with the new slot-ring couplers. The system design is now in the final construction phase for the mechanical tank layout and all active RF-components. First results of the optical notch-filter with automated frequency control and the 4-6 GHz slot-ring couplers will be presented.

Stochastic cooling tanks

The main system of the HESR [1] stochastic cooling (SC) system [2] will operate in the frequency range from 2-4 GHz. In total, 5 SC-tanks will be installed, each tank housing 64 slot coupler rings and each ring is coupled out by eight electrodes [3]. Two tanks will be used as pickups, each cryogenically cooled by two cold heads on top of the tank. Support bars and rings connect the combiner-boards with the second stage of the cryo-pumps. Thus the lowest temperature of about 20 K will be found at the Wilkinson resistors which are the main noise sources.

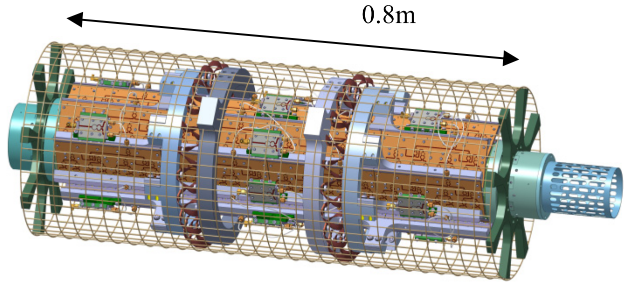

Fig. 1: Inner part of one pickup tank with combiner-boards and support bars for the cryogenic connections.

Each pickup will be used to detect the signals of all three cooling planes (horizontal, vertical and longitudinal). The 16:1 combiners join the electrodes in beam direction, while the 2:1 combiners join neighboring electrode-rows to get the upper, lower, right and left signals for the transverse cooling. These combiners are designed as heat trap for the heat flow coming from the RF lines. The inner part of one pickup tank including all combiner-boards is shown in Fig.1. The design phase of the pickup tanks including the x-y support to adjust the inner structure according to the beam centre is now in the final stage and production can start in 2012.

The kicker-tank layout will be similar to the pickup-tank layout except that no cryogenic cooling system will be installed and the electrode combination within the tank and thus the number of feed troughs will be adjusted according to the RF power needed for the new accumulation scheme [4, 5]. Here three tanks will be installed, one for each cooling direction. Nevertheless all tanks will be fully installed to ensure that each tank can be used for any cooling plane. This gives a good compromise to meet the necessary phase advance at the different foreseen optics. During the accumulation all tanks will be used for longitudinal cooling, where a higher RF power is needed. A relay-matrix will be used to switch between the different operation modes. This concept provides an installed RF power of about 250 W for each transverse cooling direction (horizontal/vertical) at each tank, or 500 W per tank when used for longitudinal cooling.

RF components outside the tanks

The combined power of the pairs of 16 electrodes in beam direction are coaxially fed through the vacuum envelope and put in 32 low-noise octave-band pre-amplifiers. These commercial available amplifiers will gain around 20 dB and will work outside the tank at ambient temperature. The compact design of this highly integrated amplifier minimized the fabrication tolerances. Nevertheless each amplifier will be measured and paired to reduce amplitude and phase errors of the corresponding channels. The 16:1 combiner has been optimized for a best signal combination at injection energy (ß = 0.96). Combiner losses at higher energies are negligible while at the lowest HESR energy a loss of 2.5 dB is still tolerable (Fig. 2).

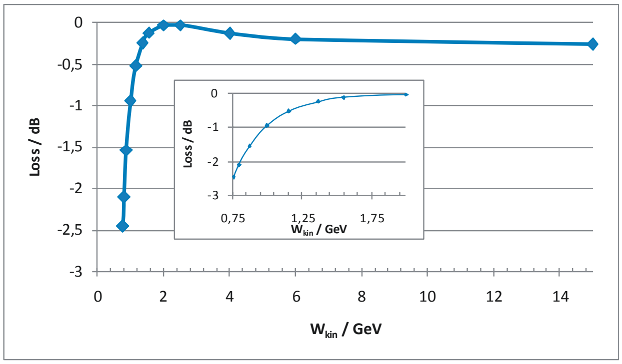

Fig. 2: Losses of the 16:1 combiner at different energies. The shown losses are upper limits occurring at 4 GHz.

The pre-amplified signals will be combined in further 3 layers (Fig. 3). Hereby, switchable delay lines are required to compensate for the energy-dependent beam drift time. The delay lines will be switched in steps of 10 mm of electrical length at the first layer (PV1) and 20 mm at the further layers (PV2, PV4). Each programmable delay-line includes a Wilkinson coupler which combines the two input signals after the switching stage. A

AN IMPROVED FORWARD TRAVELLING WAVE STRUCTURE DESIGN FOR STOCHASTIC COOLING AT EXPERIMENTAL COOLER STORAGE RING (CSRE), AT THE INSTITUTE OF MODERN PHYSICS (IMP) IN CHINA*

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Abstract

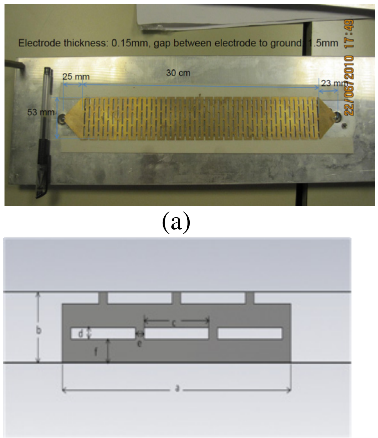
An improved forward travelling wave (TW) structure as the pick-up/kicker is designed for the stochastic cooling to match the field wave's (phase) velocity to that of the beam. The theoretical analysis is performed together with the simulations of the propagation characteristics. Using CST Microwave Studio (CST MWS), the simulated results, including phase velocity, characteristics impedance, and distributions of the longitudinal fields, are implemented and compared with the experimented results. The improved forward TW structure can be satisfied the requirements of stochastic cooling project at CSRe, which the phase velocity is closed to 0.70 (matching the desired beam energy of 400 MeV/u) and the characteristics impedance is 17 ohm.

INTRODUCTION

At the experimental cooler storage Ring, CSRe at the Institute of Modern Physics (IMP) in China, the electron cooler is already equipped and is successfully operated [1]. For the Radio Isotope beam experiment planned at the CSRe, the injected beam emittance will be 20–50 π mm. mrad and the momentum spread △p/p will be +/- 0.5 ~ 1.0 %. The pre-cooling of stochastic cooling is quite effective for these RI beam to reduce the emittance to less than 5π mm. mrad and △p/p of 0.05 % within 2 – 20 sec. which is dependent upon the injected RI particle numbers. The energy range of RI beam is expected from 300 MeV/u to 500 MeV/u. The frequency range of the stochastic cooling system is determined as roughly from 0.2 to 0.7 GHz. The structure of pick-up /kicker should have a matched phase velocity, the high coupling impedance and a simple structure to be constructed and installed in the storage ring. In the present CSRe case, the pick-up/kicker should be installed in the bending magnet chamber. The size and the number of pick-up/kicker are severely limited. In this paper, an improved forward travelling wave (TW) structure, based on the electrode designed by Fritz Caspers, as the pick-up/kicker will be shown.

MODEL OF A FORWARD TRAVELLING WAVE ELECTRODE

A photo and an equivalent representation of the forward TW structure is shown in Fig. 1. This multi-slot strip-line structure was designed by Fritz Caspers and produced at CERN in 1998 for tests of the concept [2]. In contrast to the conventional travelling wave structures as pick-up/kicker, such as Flatin type slotted transmission line [3] and McGinnis type slotted wave guide structure [4] , this structure is very broadband, operating from low frequencies upwards as a forward coupler. We need a structure for the installations in the bending magnet, which has a large bandwidth, which works for the required beta and does not need many feedthroughs and has no significant aperture reduction. Thus this multi-slot strip-line electrode is full of interest to us. As shown in Fig. 1(b), the reduction in phase velocity is a function of slot length *c*, slot width *d*, electrode thickness, and the spacing between the electrode to ground. From the measurement and simulated results it is evident that up to 1.5 GHz this structure has a very low phase dispersion.



(a)

(b)

Figure 1: (a) The multi-slot strip-line electrode. The total number of cells in this example is 25. (b) An equivalent representation of this structure (*a*=53mm, *b*=12mm, *c*=15mm, *d*=2mm, *e*=2mm, *f*=4mm).

Longitude electric field distribution

A quarter cell (of 12mm length in vertical beam direction) model used by CST MWS is shown in Fig. 2(a). The xz axis and the y = 35 mm planes are magnetic symmetry planes. The beam moves vertically in the z-direction at x=0 and y = 34 mm. There are strong E_x fields in the cell mid-plane off the cell centre shown in Fig. 2. There is good agreement with HFSS cell simulations done at CERN as show in Fig. 2 (b).

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SIMULATION STUDY OF BARRIER BUCKET ACCUMULATION WITH STOCHASTIC COOLING AT GSI ESR

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Abstract

The beam accumulation experiments with use of barrier bucket cavity and stochastic cooling system was performed at the ESR, GSI. Two methods of barrier voltage operation, moving barrier and fixed barrier cases were tried, and for the moving barrier case the electron cooling was additionally employed as well as the stochastic cooling. In the present paper, the beam accumulation processes are simulated with particle tracking code where the cooling force (stochastic and electron cooling), the diffusion force and the barrier voltage force are included as well as the IBS diffusion effects. The simulation results are well in agreement with the experimental results.

INTRODUCTION

In the original concept of the FAIR project, the function of 3 GeV antiproton accumulation is planned in the RESR ring where the stochastic stacking method is planned. However, the RESR was postponed due to the budgetary limitation as the 2nd phase project. Then, a strong demand of the beam accumulation directly from the Collector Ring to the High Energy Storage Ring (HESR) urgently occurred. The barrier bucket accumulation method using the barrier voltage system assisted by the stochastic cooling was proposed as a most promising way. [1, 2]

The concept of beam accumulation with barrier bucket system with beam cooling was already tried in 2007 at the GSI, ESR where the heavy ion beam 40Ar18+, 60 MeV/u was injected into ESR from SIS 18. The experiment was successfully achieved to demonstrate the possibility of beam stacking with BB system assisted by electron cooling. The electron cooling is effective for the low energy and high charge state ions while in the HESR 3 GeV antiproton beam has to be accumulated. In this case the stochastic cooling is exclusively a main cooling means.

To verify the principle of BB accumulation with stochastic cooling, the Proof Of Principle (POP) experiment was performed at ESR, GSI where both the stochastic cooling and electron cooling are available. The experimental results are presented in the accompanied paper in this conference [3]. In the present report the simulation results of BB accumulation are presented and compared to the experimental results to bench-mark the simulation code.

STOCHASTIC COOLING AT THE ESR

In Table 1 the main parameters for experiment and simulation are tabulated.

Table 1: Parameters of Stochastic Cooling at ESR

Ion species	40Ar18+	Energy	0.4 GeV/u
Ring Circumference	108.36 m	Revolution Period	500 nsec
Number of ions/shot	5e6/shot	Dp/p (rms) of Injected beam	5.0e-4
Bunch length of injected beam	150 nsec (simulation) 60 nsec (exp., cut by kicker)	Ring slipping factor	0.309
TOF from PU to Kicker	0.253e-6 sec	Dispersion at PU & Kicker	4.0 m
Band width	0.9-1.7 GHz	Number of PU &Kicker	8
PU Impedance	50 Ohm	System gain	90-130 dB
Atmospheric temperature	300 K	Noise temperature	40 K

The typical momentum cooling process with this stochastic cooling system is analyzed with the Fokker-Planck code as given in Fig. 1 with 1e6 particles.

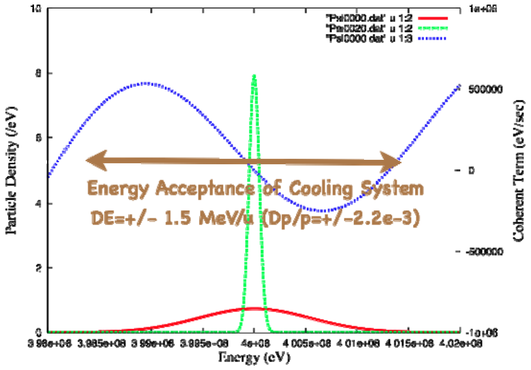

Fig. 1 The evolution of momentum cooling process analyzed with Fokker-Planck code. Red: Initial particle distribution, Green: Particle distribution after 20 sec. Blue: The coherent term of the cooling system. Gold line with arrow: Energy acceptance of the cooling system. Particle number is 5e6 and the cooling system gain is 120 dB.

DEMONSTRATION OF LONGITUDINAL STACKING IN THE ESR WITH BARRIER BUCKETS AND STOCHASTIC COOLING

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Abstract

Fast longitudinal beam accumulation has been demonstrated in the ESR at GSI with an $^{40}\mathrm{Ar}^{18+}$ beam coming from the synchrotron SIS18 at 400 MeV/u. Continuous application of stochastic cooling in all three phase space directions merged the stack with the newly injected bunch. Longitudinal beam compression was achieved either by using short barrier bucket rf pulses or by successive injections onto the unstable fixed point of the rf bucket at h=1. This recent experiment in the ESR provides the proof of principle for the longitudinal stacking of antiprotons in the FAIR project. It is planned to accumulate pre-cooled antiprotons in the HESR, injected from the CR.

INTRODUCTION

One of the four pillars of the physics program at FAIR [1] is based on a high production rate of antiprotons for hadron physics with high energy antiprotons, but also on the availability of low energy antiprotons. For optimum production rate it was proposed to have a system of collector and accumulator ring after the antiproton production target in order to have fast collection, stochastic precooling and accumulation of the hot antiprotons emerging from the target. After the accumulator ring the cooled antiprotons then could be sent either to a high energy storage ring (HESR) for experiments with stored antiprotons or to another storage ring (NESR) which constitutes the first stage of deceleration to lowest energy. Due to funding limitations, it was decided to start the FAIR project with high energy antiprotons at reduced intensity.

The first stage antiproton production concept of FAIR now comprises the following ingredients. A high intensity 70 MeV proton beam from a new linac will be injected into the existing synchrotron SIS18 which boosts it to 4 GeV. The new 100 Tm synchrotron SIS100 will accelerate the protons to 29 GeV. The ramping cycle can be as short as 2.5 s, but as the antiproton production rate is limited by the stochastic pre-cooling a repetition cycle of 10 s is foreseen, with an option to upgrade to a 5 s cycle. A single short ($\approx$50 ns) bunch of up to 2×10^{13} protons will be extracted towards a nickel target for antiproton production followed by a magnetic horn to focus the divergent antiproton bunch. A magnetic separator selects 3 GeV antiprotons which are subsequently transported to the large acceptance collector ring CR [2]. Bunch rotation and debunching transforms the short bunch into a nearly coasting beam with a reduced momentum spread. Stochastic cooling is applied to reduce the longitudinal momentum spread and both transverse emittances. In contrast to the old scheme with a dedicated accumulator ring, the cooled antiprotons will be transferred directly to the high energy storage ring HESR [3], which in the new scheme also serves as accumulator ring.

The HESR cannot support a traditional accumulation system which is based on a ring with large momentum acceptance. The HESR has a momentum acceptance of $\Delta p/p = \pm 0.25\%$ which is less than twice the momentum spread of the bunch from the CR. On the other hand, the circumference of the HESR is more than double the circumference of the CR. Therefore, a longitudinal accumulation scheme is much more favorable. In addition, the HESR is equipped with a stochastic cooling system and a barrier bucket rf system, thus no significant additional investment is required [4]. It is clear, however, that accumulation in the HESR will reduce the luminosity for experiments with stored antiprotons. A similar scheme for the accumulation of high intensity heavy ion beams is proposed in the frame of the NICA project [5]. At Fermilab, barrier buckets (BB) are being used in many beam manipulations, in particular in combination with stochastic cooling [6]. Efficient antiproton accumulation using the h=1 rf system and stochastic cooling was first demonstrated in ICE [7].

As the usefulness of stochastic cooling in combination with BB is not obvious due to increased coherent signals originating from the time structure of the beam, a proof of principle experiment was proposed. This requires the availability of injected bunches in the receiving storage ring with fast kicker injection, a stochastic cooling system and a BB rf system. All these requirements are met by the ESR [8] storage ring at GSI with the synchrotron SIS18 as injector. Similar accumulation experiments in combination with electron cooling have been performed before [9]. From these experiments two serious limitations are well known. Firstly, the timing of the injection kicker of the ESR is very critical, in particular because of the small ring circumference and the resulting relatively short revolution time. Secondly, the ESR is not equipped with a dedicated BB system, the modified ESR acceleration cavity can provide a maximum voltage of 120 V in the BB mode. Nevertheless, with these known limitations the ESR is useful to study the accu-

THE NONLINEAR TRANSFORMATION OF AN IONS BEAM IN THE PLASMA LENS*

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Abstract

The plasma lens can carry out not only sharp focusing of ions beam. At those stages at which the magnetic field is nonlinear, formation of other interesting configurations of beams is possible. Plasma lens provides formation of hollow beams of ions. Application of the several plasma lenses allow to get a conic and a cylindrical beams. The plasma lens can be used for obtaining a beams with homogeneous spatial distribution. Calculations and measurements were performed for a C^{+6} and Fe^{+26} beams of 200-300 MeV/a.u.m. energy. The obtained results and analysis are reported.

INTRODUCTION

The ion beam focusing in the plasma lens is carried out as shown in Fig.1. The discharge current produces an azimuthal magnetic field. The ions are injected along the lens axis, and the radial Lorentz force focuses the ion beam [1].

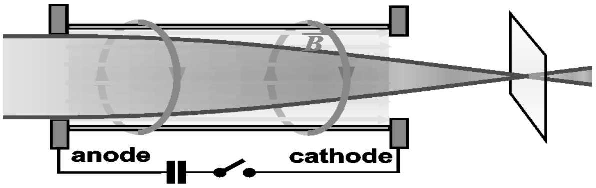

Figure 1: Ion focusing in a plasma lens.

Table 1: Features of discharge current generator

Short pulse mode	
Switch (2 pcs) Discharge current pulse duration Max discharge current	Thyratron TDI1-150/25 T = 5 µs at C = 25 µF I = 200 kA at T = 5 µs
Long pulse mode	
Switch (2 pcs) Discharge current pulse duration Max. discharge current	ThyratronTDI1-200k/25H T = 20 µs at C = 160 µF I = 400 kA at T = 20 µs

In the current generator (Table 1) cold-hollow cathode thyratrons (pseudospark switches) TDI1-200k/25H [2] are employed to form a stable discharge with peak current up to 250 kA. TDI-thyratrons in plasma lens generator avails to operate in a mode of long energy-intensive pulse. The time sweep of the luminosity of the plasma and the discharge current for short pulse mode and long pulse mode are shown on Fig. 2 and 3.

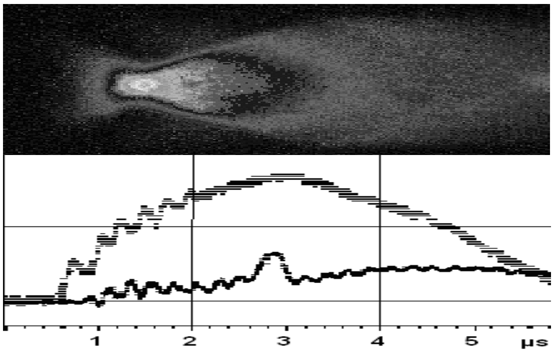

Figure 2: Time scanning of a discharge luminescence and a discharge and beam currents for short pulse mode.

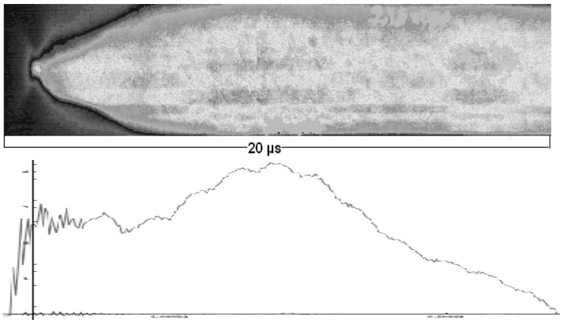

Figure 3: Time scanning of the discharge luminescence and current for long pulse mode.

Hamped shape of the long current due to the fact that part of the capacity (25 µF) have low self-inductance. The focusing properties of plasma lenses depend on the current density distribution along the radius of the plasma discharge. The current distribution across the tube changes significantly during the discharge. Therefore, plasma lens, in general, is nonlinear. Uniform current distribution exists for a limited time, so the plasma lens, as a device for sharp focusing, operates for about 1 µs or less. As a non-linear focusing device, the plasma lens can be used to produce beams of special shape. The researches were conducted on the follows parameters: the discharge tube radius R = 1 cm and its length L = 10 cm,

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DECELERATION OF CARBON IONS AT THE HEAVY ION STORAGE RING TSR

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Abstract

To evaluate the beam quality obtained after deceleration of ^{12}C^{6+} ions at the heavy ion Test Storage Ring (TSR), considering the possible sources of beam heating is important. In our experiments at the TSR, we inject ^{12}C^{6+} ions at 73.3 MeV and decelerate them to 9.7 MeV in a cycle that includes two steps in which beam cooling is applied. In this study we discuss the influences of intrabeam scattering (IBS) on the circulating ions during deceleration. We additionally present results on the deceleration efficiency and lifetime measurements of ^{12}C^{6+} ions in the energy range 9.7 - 73.3 MeV .

INTRODUCTION

The heavy ion storage ring TSR, at the Max-Planck-Institut für Kernphysik (MPIK) in Heidelberg, operates for accelerator, atomic and molecular physics experiments. The storage ring has a circumference of 55.42 m, and it receives heavy ions from a 12 MV tandem van-de-Graaff and a normal conducting RF linac combination. Light positive ions and negative ions with mass to charge ratio $\frac{A}{|q|} \leq 9$ are provided by a high current injector. At TSR the experiments mainly performed at the injection energy. In addition, the widely tunable range of the RF resonator enables the possibility to accelerate and decelerate ions. To ramp the magnetic fields at TSR, Digital-Analog Converter(DAC) and DSP driven synthesizer cards developed by MPIK. The generated functions to ramp the magnetics can be calculated from the rigidity by assesing the measured saturation effects of the TSR magnets. With some minor additional corrections to the calculated dipole magnets ramp and one quadrupole family ramp, decelerating a ^{12}C^{6+} ion beam from 73.3 MeV to 9.7 MeV, corresponding to a rigidity decrease from 0.71 Tm to 0.26 Tm is possible. In the deceleration process, an increase of bunch length, momentum spread and beam emittance occurs. To avoid beam loss during deceleration due to these effects, electron pre-cooling of the injected bunched ion beam is necessary.

INTRABEAM SCATTERING EFFECTS DURING DECELERATION

To decelerate a heavy ion beam, cooling at the injection energy is required, resulting in a dense ion beam such that IBS effects must be considered. Immediately before starting the deceleration cycle, electron cooling is switched off and the ion beam sizes increase due to IBS. The blow up rate of a bunched beam due to IBS can be expressed by [1]:

$$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = c_i \cdot \frac{Z^4}{A^2}\frac{N}{\beta^3}\frac{1}{\epsilon_x \epsilon_y \Delta p/p \cdot h \cdot l_{eff}}, \tag{1}$$

where i (i=x,y,$\frac{\Delta p}{p}$) corresponds to the horizontal, vertical and longitudinal coordinates of the beam. N is the number of ions with charge state Z, mass A, and velocity β. The number of bunches in the storage ring is h and l_{eff} is the effective bunch length. c_i are lattice dependent functions which depend slightly on the ion energy. The horizontal emittance and vertical emittance scales are computed as $\epsilon_x \propto \sigma_x^2$, $\epsilon_y \propto \sigma_y^2$, where σ_x and σ_y are the horizontal and vertical beam widths, respectively. If in the IBS process σ_x, σ_y, and the momentum spread $\Delta p/p$, l_{eff} are proportional to each other as in $\epsilon_x \epsilon_y l_{eff} \Delta p/p \propto \sigma_i^6$, we obtain three uncoupled differential equations for all three degrees of freedom [2] [3]:

$$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = \frac{D_i}{\sigma_i^\gamma}. \tag{2}$$

In simplified IBS model γ=6 [3] for a bunched ion beam and the heating term:

$$D_i \propto c_i \frac{Z^4}{A^2}\frac{1}{\beta^3}\frac{N}{h}. \tag{3}$$

If the velocity of circulating the ion beam is not changed the solution of equation 2 is given by:

$$\sigma_i(t) = (\sigma_{i,0}^\gamma + \gamma D_i t)^{\frac{1}{\gamma}}, \tag{4}$$

where $\sigma_{i,0}$ is the initial beam width. In figure 1, the measured horizontal beam width of a ^{12}C^{6+} bunched ion beam at the injection energy of 73.3 MeV is shown as a function of time. For bunching, a resonator voltage of 186 V was applied. By fitting the experimental data, we obtained $\bar{\gamma} = 5.9$, which is approximately close to the theoretical value of $\gamma = 6$. As shown in figure 1, the horizontal profile can be described well with simplified IBS model if the ion beam velocity is constant. To investigate the velocity dependence of IBS we make the following ansatz for the heating term:

$$D_i(t) = \frac{\tilde{D}_i}{\beta^\kappa(t)}, \tag{5}$$

where κ=3. In the deceleration cycle the ion velocity is changed linearly:

$$\beta(t) = \beta_0 + \alpha t, \tag{6}$$