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NICA SYNCHROTRONS AND THEIR COOLING SYSTEMS

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) is under construction at JINR. The NICA goal is to provide of colliding beams for studies of hot and dense strongly interacting baryonic matter and spin physics. The ion mode accelerator facility of the NICA Collider consists of the following accelerators: The new operating Heavy Ion Linac (HILAC) with RFQ and IH DTL sections at energy 3.2 MeV/u, new operating superconducting Booster synchrotron at energy up 600 MeV/u, operating superconducting synchrotron Nuclotron for the gold ion energy 3.9 GeV/u and two Collider storage rings with two interaction points. There is the electron cooling system in the Booster synchrotron, the Collider has electron and stochastic cooling systems. The status of the NICA acceleration complex and its cooling systems is presented. The application of the cooling systems to the operation of the NICA accelerators – the Booster and the Nuclotron are discussed.

NICA INJECTION COMPLEX

The NICA accelerator complex [1,2] is constructed and commissioned at JINR. NICA experiments will be aimed at searching of the mixed phase of baryonic matter and studying the nature of the nucleon/particle spin. The new NICA accelerator complex will permit implementing experiments in the following modes: with the Nuclotron ion beams extracted to a fixed target; with colliding ion beams in the Collider; with colliding ion-proton beams; with colliding beams of polarized protons and deuterons. The main elements of the NICA complex are an injection complex, which includes a set of ion sources and two linear accelerators, the superconducting operating Booster, the superconducting operating synchrotron Nuclotron, a Collider composed of two superconducting rings with two beam interaction points, a Multi-Purpose Detector (MPD) and a Spin Physics Detector (SPD) and the beam transfer lines.

The heavy ion injection chain consists from electron string ion source, the laser ion source, the plasma ion source, the operating HILAC, the transfer line HILAC-Booster, the superconducting operating synchrotron Booster, the transfer line Booster-Nuclotron and the operating superconducting synchrotron Nuclotron.

The HILAC constructed by the JINR-Bevatech collaboration is under exploitation since 2016. It is aimed to accelerate the heavy ions injected from KRION-6T, a superconducting electron-string heavy ion source. At the present time KRION-6T produces 5×10^{8} $^{197}Au^{31+}$ and 2×10^{8} $^{209}Bi^{27+}$ ions per pulse.

Especially for the test of the Booster [3] the plasma source generating a single component He^{1+} beam was created. The efficiency of the beam transportation through second and third IH sections was 78.5%. The maximal ion $^{4}He^{1+}$ beam current at HILAC entrance during first Booster runs corresponds to the project value of 10 mA. During second Booster run the $^{4}He^{1+}$and $^{56}Fe^{14+}$ ions produced in the plasma and the laser ion sources were accelerated in HILAC and injected in Booster.

The transfer line from HILAC to Booster [1] consists of 2 dipole magnets, 7 quadrupole lenses, 6 stirrer magnets, debuncher, collimator, vacuum and diagnostic equipment. The assembling of transfer line was done in 2020. The achieved efficiency of the beam transportation during first Booster beam run was of 90% at the beam current at the HILAC exit of 4 mA, this value was sufficient for the first experiments.

The Booster [1-3] (Fig. 1) is a superconducting synchrotron intended for accelerating heavy ions to an energy of 600 MeV/u. The magnetic structure of the Booster with a 211-m-long circumference is mounted inside the yoke of the Synchrophasotron magnet.

Figure 1: Booster ring inside Synchrophasatron yoke.

The main goals of the Booster are accumulation of $2\cdot10^{9}$ $^{197}Au^{31+}$ ions, acceleration of the heavy ions up to the energy 578 MeV/u required for effective stripping, and forming of the required beam emittance with the electron cooling system. The Booster has a four-fold symmetry lattice with DFO periodic cells. Each quadrant of the Booster has ten dipole magnets, six focusing and six defocusing quadrupole lenses, and multipole corrector magnets. All Booster dipole magnets and quadrupole lenses were fabricated and tested at JINR.

The beam injection system of the Booster consists of an electrostatic septum and three pulsed electric kickers.

The Booster RF system designed and constructed by Budker Institute of Nuclear Physics (BINP), Siberian Branch, Russian Academy of Sciences, provides 10 kV of

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ELEMENTS OF HIGH VOLTAGE ELECTRON COOLING SYSTEM FOR NICA COLLIDER

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Abstract

Beam cooling plays a key role in the project of the NICA collider. In order to achieve needed luminosity it is important to provide effective cooling during beam accumulation and during experiment. For this purpose, the ring will be equipped with both electron and stochastic cooling systems. The article describes construction of the electron cooler and status of its production by Budker INP.

INTRODUCTION

The collider ring will be the main element of the future NICA complex (JINR, Russia), where experiments with colliding ion beams in the energy range 1÷4.5 GeV/u will be provided in order to investigate properties of dense baryonic matter at extreme values of temperature and density with planned luminosity 10^{27} cm^{-2}s^{-1}. In order to achieve such luminosity the collider ring will be equipped with two cooling systems: stochastic and electron. The systems will provide increase of beam intensity during accumulation and decrease bunch length and emittance during experiments. The electron cooling system for the NICA collider now is under construction in the Budker Institute of Nuclear Physics (Novosibirsk, Russia).

In order to provide electron cooling in full range of ion energy the electron cooling system must produce electron beam with energy up to 2.5 MeV. Experience, achieved during experiments on the high voltage electron cooling system of the COSY synchrotron [1] and results of operation of electron cooler of the Recycler ring [2] in Fermilab (USA) show, that for effective cooling it is enough to have electron beam with current about 1 A.

Main parameters of the system are shown in Table 1.

Table 1: Electron Cooling System Parameters

Parameter	Value
Electron energy	0.2 ÷ 2.5 MeV
Energy stability	$<10^{-4}$
Electron current	0.1 ÷ 1 A
Cooling section length	6 m
Magnetic field in the cooling section	0.5 ÷ 2 kG
Vacuum presure	10^{-11} mbar

SYSTEM OVERVIEW

Figure 1 shows 3-d layout of the NICA high voltage electron cooling system. The construction is based on high voltage electron cooling system for the COSY synchrotron. In order to cool both ion beams simultaneously, the system consists of two independent coolers. Every cooler contains independent high voltage system, cooling section and transport channels.

Electron beam, emitted by electron gun, is accelerated by electrostatic tube to working energy and moves (through transport cannel) to the cooling section, where it interacts with ion beam. After the cooling section electrons move back to high voltage system where they are decelerated and absorbed by collector surface. On whole trajectory from gun to collector electron beam moves in longitudinal magnetic field, which provides transverse focusing of the beam.

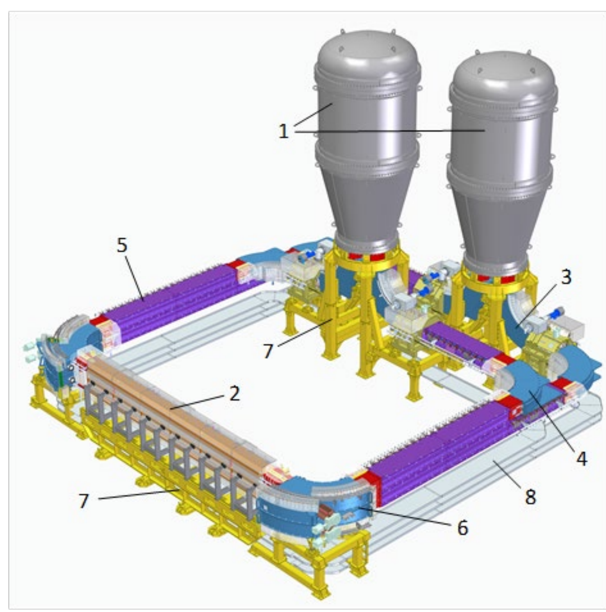

Figure 1: 3D model of the electron cooling system for the NICA collider. 1 – high-voltage vessels, 2 – cooling section, 3 – vertical bend, 4 – horizontal bends, 5 – linear sections, 6 – toroid magnet, 7 – supports, 8 – cable channels.

Figure 2 shows construction of the high voltage system. Its main parts are high voltage column (which generates accelerating voltage and provides electron acceleration to working energy) and high voltage terminal (which contains

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DEVELOPMENT OF ELECTRON COOLER COMPONENTS FOR HIAF ACCELERATOR*

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Abstract

The High Intensity heavy-ion Accelerator Facility (HIAF) is under constructed at IMP in China, which is used to provide high intensity heavy ion beam pulse. A 450 keV electron cooler was proposed to boost the luminosity of high-density internal targets experiment in the spectrometer ring (SRing) at HIAF. The cooler is designed based on changes of the 300 keV cooler at IMP, which was made by BINP in 2004. In this paper, experimental testing results of the prototypes of the coils, the electron gun and the collector are reported. The technical challenges and solutions on the 450 keV high voltage system are discussed.

INTRODUCTION

The High Intensity heavy-ion Accelerator Facility (HIAF) is a new accelerator under construction at the Institute of Modern Physics (IMP) in China [1]. It is designed to provide intense primary heavy ion beams for nuclear and atomic physics. The facility consists mainly of a superconducting electron-cyclotron-resonance (SECR) ion source, a continuous wave (CW) superconducting ion linac (iLinac), a booster synchrotron (BRing) and a high precision spectrometer ring (SRing). A fragment separator (HFRS) is also used as a beam line to connect BRing and SRing. Six experimental terminals will be built in phase-I at HIAF. The layout of the HIAF accelerator was shown in Fig. 1. The main parameters are listed in Table 1.

The construction of the HIAF project was started officially in December 23rd, 2018. Up to now, roughly 50% of civil construction is finished. The first component of SECR is planned to equip in the tunnel in the middle of 2022. The first beam will be accelerated at BRing in the middle of 2025. A Day-one experiment is proposed before the end of 2025.

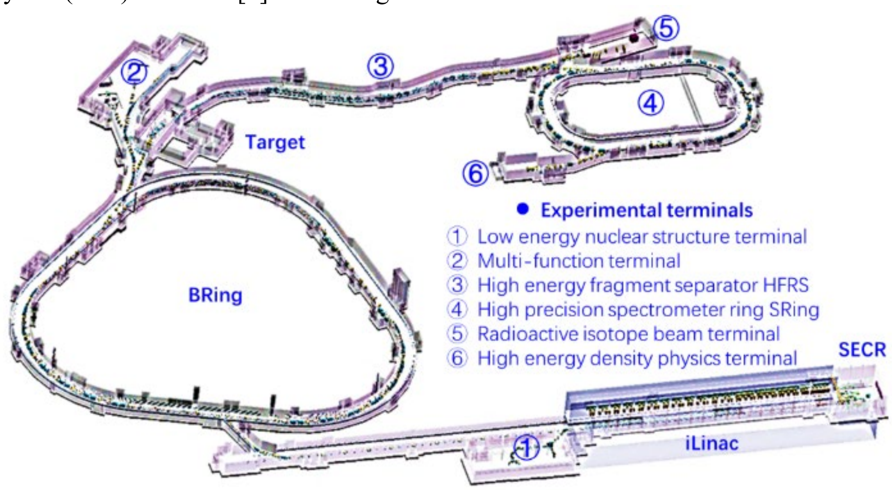

Figure 1: Layout of the HIAF project.

Table 1: Main Parameters of the HIAF Accelerators.

	SECR	iLinac	Bring	HFRS	SRing
Length / circumference (m)	---	114	569	192	277
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Max. magnetic rigidity (Tm)	---	---	34	25	15
Max. beam intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	10^{11}ppp (U^{35+})		10^{10}ppp (U^{92+})
Operation mode	DC	CW or pulse	fast ramping (12T/s, 3Hz)	Momentum-resolution 1100	DC or deceleration
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	40/40, 1.5%, normal mode

SRing is a versatile storage ring employed in nuclear and atomic experiments with stored stable or radioactive ion beams. Especially, the highly-charged stable ions can be used either at the injection energies or at lower energies

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ELECTRON COOLING WITH SPACE-CHARGE DOMINATED PROTON BEAMS AT IOTA

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Abstract

We describe a new electron cooler being developed for 2.5 MeV protons at the Integrable Optics Test Accelerator (IOTA), which is a highly re-configurable storage ring at Fermilab. This system would enable the study of magnetized electron cooling in the presence of intense space-charge with transverse tune shifts approaching -0.5 as well as highly non-linear focusing optics in the IOTA ring. We present an overview of the design, simulations and hardware to be used for this project.

INTRODUCTION

The creation and stability of high-intensity hadron beams is very important to future projects such as heavy-ion facilities [1–3], Electron-Ion Colliders [4], etc. Electron cooling provides a well-established method of attaining high equilibrium beam intensities and have been demonstrated for a wide range of ion energies from $\gamma \sim 1.00011$ [5] up to $\gamma \approx 9.5$ [6]. The maximum intensity of ion beams achieved through electron cooling is limited by the additional heating processes of Intra-Beam Scattering (IBS) and resonance-driven transverse heating due to space-charge tune shifts. [7] In practice, the transverse size of the ion beam decreases under the influence of electron cooling until the betatron tune shift reaches a maximum value of 0.1-0.2. [8, 9] Studying the influence of ion space-charge forces on electron cooling at the high-intensity limit requires the development of a novel test platform and associated theoretical models.

The Integrable Optics Test Accelerator (IOTA) is a re-configurable 40 m storage ring built at Fermilab which acts as a test facility dedicated to research on intense beams including the areas of Non-linear Integrable Optics (NIO), beam cooling, space-charge, instabilities and more. [10, 11] It can circulate both electrons up to 150 MeV and protons with a kinetic energy of 2.5 MeV ($pc \approx 70$ MeV). The proton beam energy is limited by the existing injector RFQ. In this contribution, we discuss the design of the electron cooler which we will operate with 2.5 MeV protons as a part of our electron-lens research program. [12] Besides enabling experiments on non-linear integrable optics by reducing energy spread and improving the lifetime of the beam by compensating for transverse emittance growth, the primary motivation of research with this cooler is to study the effect of space-charge forces in the regime of large transverse incoherent tune shift of $\Delta\nu_{x,y} \approx -0.5$ and compare with theoretical models. In addition, we are also planning experiments which uses electron cooling as a knob to study the interplay between space-charge and instabilities [13] and also control the phase space distribution in order to facilitate the realization of NIO in the presence of space-charge forces.

In the next section, we detail the operation parameters of IOTA with protons and describe the electron cooler setup. Then we discuss a novel simulation model which includes electron cooling with transverse space-charge. In the last section, we summarize our results and present future plans.

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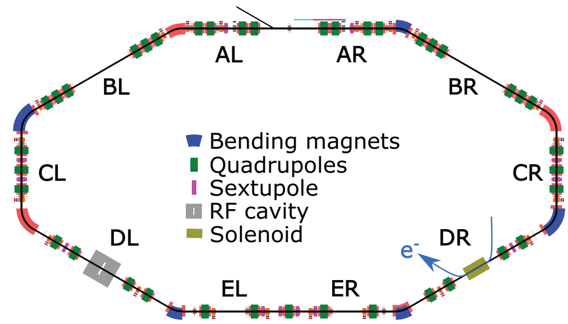

Figure 1: Layout of the Integrable Optics Test Accelerator (IOTA) at Fermilab. The machine is divided into multiple sections named AR (A right), BR (B right) and so on through AL (A left). The blue arrow represents the path of the electrons in the cooler.

ELECTRON COOLER SETUP

Figure 1 shows the layout of IOTA along with the planned location of the electron cooler. Protons with a kinetic energy of 2.5 MeV from the injector (not shown) enter into the ring in the A section, circulate clockwise and co-propagate with electrons in the DR section. Besides the coasting beam mode, an rf cavity operating at the 4th harmonic of the revolution frequency, placed in the DL section is used for bunched beam operation. In addition, non-linear magnets can be placed in the straight sections BL and BR to perform experiments on NIO. While the optics of the ring will be optimized for individual experiments, Table 1 shows some general parameters of operation with electron cooling. At the maximum design current corresponding to a vertical tune shift of -0.5, emittance growth times due to IBS are typically less than 10 seconds, thus limiting beam lifetime and constraining the experiments which

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RECOMMISSIONING OF THE CERN AD STOCHASTIC COOLING SYSTEM IN 2021 AFTER LONG SHUTDOWN 2

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Abstract

The power amplifier system of the Stochastic Cooling System of the Anti-proton Decelerator (AD) at CERN, installed on top of the shielding blocks of the AD ring, was completely dismantled during the long shutdown 2 (LS2) at the end of the 2018 run in order to gain access to the accelerator for magnet consolidation. At start-up, this required finding and verifying the correct electrical delays for all 48 power amplifiers feeding the two kickers, by means of beam transfer functions for the two cooling plateaus at 3.57 GeV/c and 2 GeV/c. We describe the methods used for the setting up and the results of the optimization for the cooling in all three planes, longitudinal, horizontal and vertical. An experimental set-up has been put into operation for automatic monitoring and correction of the notch position of the longitudinal cooling at 3.57 GeV/c with optical delay lines. We also comment on the lessons learnt during the recommissioning including the repair work for a vacuum leak in the water cooling circuits of the kicker following bake-out and the verification of the internal loads by RF reflectometry.

INTRODUCTION

In the CERN Anti-proton Decelerator (AD) anti-protons are routinely decelerated since 1999 and distributed to experiments located in the same hall as the AD machine [1]. The AD machine itself is covered for radiation shielding purposes by concrete blocks leaving only limited space for access to equipment inside the ring. In case a bulky element in the ring needs to be shifted or exchanged concrete blocks covering the AD ring have to be removed so that the equipment can be accessed by the overhead crane. The CERN Long Shutdown 2 (LS2) from 2019 to 2020 saw a number of interventions for consolidation in AD and for connection of beam transfer lines between ELENA and the newly installed experiments. Notably the change of a magnet in between the two kicker tanks of the stochastic cooling system and the installation of the extraction line from ELENA (LNE00) necessitated the temporary dismantling of the stochastic cooling power amplifier system.

RECAP OF STOCHASTIC COOLING PICK-UPS AND KICKERS

The stochastic cooling system in AD comprises four elements in the ring: horizontal pick-up UHM 3107 and horizontal kicker KHM 0307, and vertical pick-up UVM 3207 with vertical kicker KVM 0407 [2]. The longitudinal cooling is using the same pick-ups and kickers in their common mode combining both signals from the horizontal and vertical pick-ups and splitting on the back-end the signal to feed both the horizontal and vertical kickers.

The basic element in these pick-ups and kickers is a rectangular short electrode of a length of 33 mm (in beam direction) and width of 46 mm. A total of 48 of these small electrodes are lined up on a rail with a gap of 10.85 mm to form what is called a "super-electrode" with a total active length of 2093.95 mm. The individual electrodes are grouped in 12 sets of four electrodes (Figure 1). For the kicker, each set is fed by a single 100 W power amplifier connected to a dedicated RF vacuum feedthrough on the tank.

Figure 1: Set of four electrodes (length of support 175.4 mm) powered by a single amplifier (see text).

Within the set of four electrodes the power is distributed through a 2:1 splitter of Wilkenson type, but without matching resistor, mounted on the rail inside the vacuum tank. Power is then applied to two pairs of adjacent electrodes connected in series and proper terminations ensure that the lack of resistor in the power splitter does not result in adverse reflections. Electrical delays match the time of flight to give a maximum of the shut impedance at the beam momentum the structure was originally optimized for (3.57 GeV/c). Power is dissipated in 12 RF loads mounted on the side of the rail opposing the beam. Damping of higher order and propagating modes in the structure is achieved by ferrite tiles attached to two rails in the plane perpendicular to the electrodes.

The rails supporting the electrodes can be moved, however this movement is no longer used for the case of the kickers since LS1 (2014) and the mechanism has been blocked in the position giving the maximum acceptance for the beam. In addition to reducing the operational complexity, the suppression of the kicker movement also renders the performance less sensitive to beam position as the region of homogeneous field is larger with jaws open. Additionally, final smaller

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ELECTRON COOLER OF THE NICA BOOSTER AND ITS APPLICATIONS

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Abstract

The report presents the results obtained during the commissioning the Electron Cooling System (ECS) of the Booster, the first in the chain of three synchrotrons of the NICA accelerator complex. The work was performed with a circulating ion beams $^{4}He^{1+}$ and $^{56}Fe^{14+}$ at ion injection energy of 3.2 MeV/u. In the first experiment (December 2020) with a circulating $^{4}He^{1+}$ ion beam, the effect of reducing the lifetime of the circulating ions was observed when the velocities of the cooling electrons and the cooled ions coincide. In second experiment (September 2021) the effect of electron cooling of $^{56}Fe^{14+}$ ion beam was registered both for longitudinal and transverse degrees of freedom using Schottky noise spectrometer and ionization profilometer.

INTRODUCTION

The main tasks of the Booster synchrotron of heavy ions are the accumulation of gold ions or other low-charged heavy ions and their acceleration to the maximum energy 578 MeV/u for gold ions, which is sufficient for their subsequent stripping to the state of bare nuclei. The application of electron cooling in a Booster at ion energy up to 65 MeV/u makes it possible to significantly reduce the 6D emittance of the beam.

NICA BOOSTER ELECTRON COOLING SYSTEM (ECS)

The Booster ECS (Fig. 1) was constructed according to the classical scheme proposed and implemented in 1970 in the Institute of Nuclear Physics (Novosibirsk) [1]. Its present version is significantly developed by the team of V. V. Parkhomchuk in the same Institute named after the founder academician G.I.Budker. In electron cooling set-up, an electron beam passes from the cathode of the electron gun to the collector in a uniform longitudinal magnetic field. In the ECS, the homogeneity of the magnetic field of this solenoid is made at the level of $3{\cdot}10^{-5}$ (straightness of the magnetic field line) that provides the design value of the cooling time. The energy of the ECS electrons variates in this range from 1.0 to 50.0 keV. The main Booster ECS parameters are shown in the Table 1.

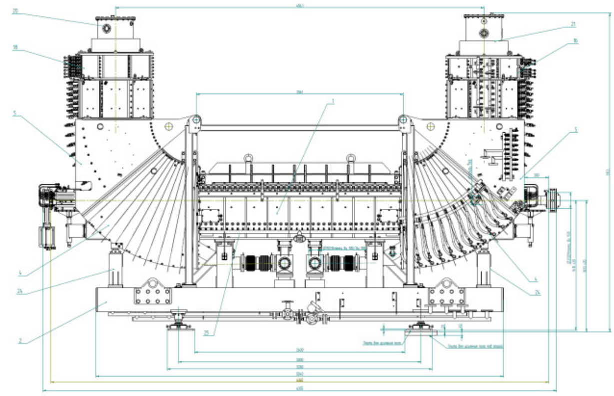

Figure 1: The Booster ECS scheme.

Table 1: The main Booster Electron Cooling System Parameters

Parameter	Value
Electron energy E, keV	≤ 1
Accuracy of energy adjustment and its stability, ΔE/E	$\leq 1{\cdot}10^{-5}$
Beam current stability, ΔI/I	$\leq 1{\cdot}10^{-4}$
Electron beam loss current, δI/I	$\leq 3{\cdot}10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, ΔB/B	≤ 3·10-5 on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	≤ 0.3
Correction of the ion orbit at the input and output of ECS	offset, mm ≤ 1,0 angular deviation, mrad ≤ 1,0

FIRST ION ELECTRON COOLING EXPERIMENT

During the first Booster session in December 2020, an experiment was conducted to commission the ECS with a circulating $^{4}He^{1+}$ helium ion beam with an energy of 3.2 MeV/u (injection energy into the Booster) (Table 2). In this experiment the only diagnostic devices that allowed observing the cooling effect were used: a parametric current transformer (PCT) measuring ion beam current and the A. A. Baldin ionization profilometer [2], that was operated in summing mode the counting rate of all the MCP channels

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SCALABLE HV-MODULES FOR A MAGNETIZED RELATIVISTIC ELECTRON COOLER

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Abstract

At HIM in Mainz the test setup for the magnetized relativistic cooler is progressing. The first 600 kV module at 1:1 scale for the HESR-cooler has been installed in its pressure tank. Our goal is to show the scalability of the approach aiming at stacking 13 modules in the final version at HESR. Plans for the near future are reported. Ideas for converting the prototype into an experimental facility are presented.

INTRODUCTION

Research at Helmholtz Institute Mainz (HIM) is aiming to resolve technical challenges that are related to high energy electron cooling, in particular connected to a possible relativistic magnetized electron cooler for the High Energy Storage Ring HESR at FAIR. An electron kinetic energy of almost 8 MeV would be required, which exceeds the voltage of the Jülich cooler [1] considerably, which is currently the cooler with the largest voltage and magnetized beam. In cooperation with BINP we have proposed a modular concept based on high voltage platforms, each delivering a potential of 600 kV. The floating electric power is provided by 5 kW turbo-generators which supply the solenoids and auxiliary devices such as electron source, collector or vacuum pumps. A first module was built by BINP and delivered to Mainz in 2018 [2]. These modules are intended to be 1:1 scale size prototypes for the HESR-cooler. A second module is currently under production at BINP and could be delivered during the first half of 2022.

During the last almost two years, our work was seriously hampered by the COVID-19 pandemic because of extended lockdowns. Nevertheless, some progress was achieved which we report in the next paragraph, including a description of the new pressure vessel and an improved concept for closed cycle operation of the turbo-generators. The main purpose of the ongoing work is to demonstrate the reliability of the power generation approach and the scalability of the stages.

HV TANK

The existing module was tested with turbine-based power generation. During these tests, high voltage (HV) was limited because of the absence of a pressure tank. This tank was ordered in 2019 and delivery took place in spring 21. The tank consists of three parts (see Fig. 1 and Fig. 2).

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Figure 1: Lower part of HV tank at HIM with first platform installed. Inner diameter of tank is 4 meter.

In the bottom of the lower part, the feedthroughs for the gas supplies and for outgoing/ingoing beam are located. A manhole will allow maintenance once the device is fully assembled. Additional ports for filling with insulating gas are foreseen, the vessel is designed for a pressure of 10 bar and has been subject to the usual safety tests by the authorities. The gas filling is planned with nitrogen, the same gas will be used to drive the turbines. About 6 bar pressure of the insulating gas is sufficient to operate with two platforms at an acceleration voltage of 1.2 MV [2]. First HV tests under pressure are foreseen in 2022.

Figure 2: "Big-Blue-Bubble" HV tank with still open flanges.

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OBSERVATION OF BEAM INDUCED FLUORESCENCE (BIF) AT THE ELECTRON COOLER TEST BENCH AT HELMHOLTZ-INSTITUT MAINZ (HIM)*

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Abstract

Further wavelength-resolved studies of the beam-induced fluorescence have been made at the electron cooler test bench at Helmholtz-Institut Mainz (HIM). As a new feature a low-noise, cooled sCMOS-camera was utilized. Beam current dependence of the fluorescence has been recorded. Data evaluation is imminent and options for further experiments will be discussed.

ELECTRON COOLER TEST BENCH AT HIM

An electron cooler test bench including components from TSL (Uppsala) and BINP (Novosibirsk) is operated at Helmholtz-Institut Mainz (HIM) with $U_{\text{Source}} = 18\,\text{kV}$, $U_{\text{Collector}} = 3\,\text{kV}$ and $I = 0.55\,\text{A}$ (Fig. 1). The beam pipe vacuum meets UHV conditions, i.e. in this case $p \approx 3 \times 10^{-10}$ mbar when the electron beam is switched on. A detailed description of our apparatus and efficiency measurements of its energy-recovering-setup can be found in [1]. An upgrade to the electron source, made to suppress penning discharges around the Pierce electrode for solenoid fields that are strong enough to allow higher extraction voltages ($U_{\text{Source}} \approx 30\,\text{kV}$) and therefore beam currents ($I \approx 1$ A), is described in [2].

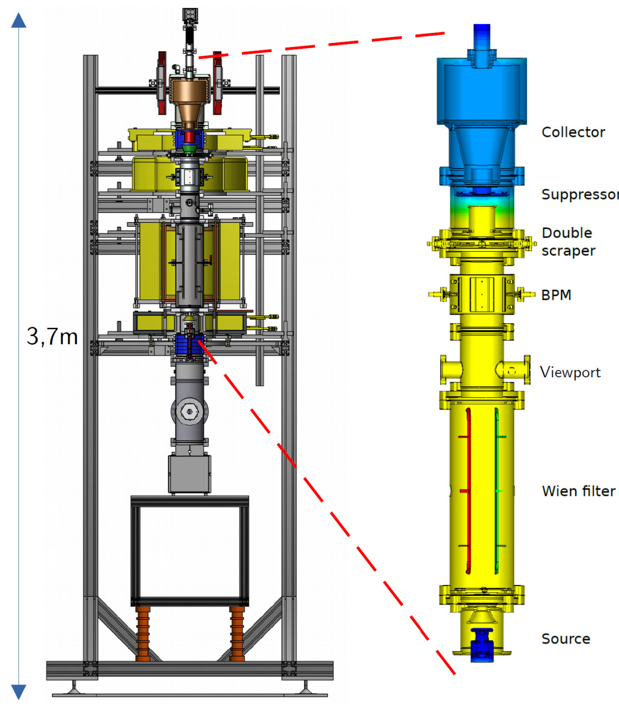

Figure 1: Schematic sketch of the electron cooler test bench at HIM.

PHOTON MEASUREMENTS

Early Measurements

During early photon measurements with an optical setup a signal was found at the location of the electron beam. The setup consisted of a photomultiplier tube (PMT), a slit and lens, both motorized and a set of optical bandpass filters (center wavelengths $\lambda = 400 - 650$ nm in $\Delta\lambda = 50$ nm steps and a FWHM of $\lambda_{width} = 50$ nm) A significant infrared background caused by the thermionic cathode ($T \approx 1000 - 1100°C$) was detected for wavelengths above $\lambda = 550$ nm, but could be reduced by blackening (coating with a thin carbon layer) the inside of the beam pipe at the location of the utilized viewport.

New Measurements

Due to the 180 min duration of one measurement of the signal and its corresponding background (i.e. a measurement with the electron beam turned off) digital cameras suitable for extremely low light conditions / single photon counting were considered. Scientific complementary metal-oxide-semiconductor (sCMOS) and electron-multiplying charge-coupled-device (emCCD) image sensors were tested at the electron cooler test bench. The peak quantum-efficiencies of such devices are $QE_{sCMOS} \approx 80 - 90\%$ and $QE_{emCCD} \approx 95\%$ (PMT: $QE_{PMT} \approx 35\%$). The emCCD is more fragile and its gain register can degrade over time. After taking the dark current, the readout noise, the robustness and versatility of the chip and the price into account, the sCMOS variant was chosen. The acquired camera and the used lens were then tested to optimize the position in front of the viewport with suitable aperture settings, considering its depth-of-field and to allow size comparisons for the measurements of the observed BIF, one of which can be seen in Fig. 2. It was taken over a timespan of $t_{exposure} = 30$ s with a bandpass filter ($\lambda_{CWL} = 450$ nm, $\lambda_{width} = 50$ nm). The simulated

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AD/ELENA ELECTRON COOLING EXPERIENCE DURING AND AFTER CERN LONG SHUTDOWN (LS2)

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Abstract

Electron cooling is a key ingredient of the Antimatter Factory at CERN, now composed of the AD and ELENA rings, both featuring an electron cooler. After the successful commissioning of the ELENA ring and electron cooling with antiprotons in 2018, the facility was shutdown for the CERN long shutdown (LS2). In the meantime, ELENA has been operating with H^- ions generated from a local source and electron cooling of these H^- was demonstrated. The facility has restarted with antiproton operation during summer 2021, and it is now delivering 100 keV production beams through newly installed electro-static extraction lines to all the experiments for the very first time. We will give an overview of the experience gained and difficulties encountered during the restart of the AD and ELENA electron coolers. The experience with electron cooling of H^- beam in ELENA and the comparison with antiproton cooling will also be presented.

INTRODUCTION

The Antimatter Factory at CERN is a unique facility that provides antiproton beams to several experiments [1]. The facility, originally composed only by the Antiproton Decelerator (AD) [2], was complemented with the Extremely Low ENergy Antiproton (ELENA) ring [3] which was successfully commissioned in 2018 [4]. The AD provides about 3×10^7 antiprotons in a single bunch at 5.3 MeV kinetic energy approximately every two minutes. The ELENA ring allows to further decelerate the antiprotons down to 100 keV kinetic energy and produces 4 bunches of about 5×10^6 antiprotons per bunch, which are distributed to up to 4 experiments at the same time. The cycle length of ELENA, of about 15 seconds, falls in the shadow of the next AD cycle.

Stochastic cooling (in AD) and electron cooling (both in AD and ELENA) are used on several plateaus placed at injection (in AD), during the deceleration process, and before extraction in order to counteract the adiabatic emittance increase as well as possible heating effects.

Till the end of 2018, GBAR [5] was the only experiment connected to ELENA. During CERN Long Shutdown 2 (LS2), all AD experiments were connected to ELENA with the installation of electrostatic transfer lines. Despite the unavailability of antiprotons during LS2, the ELENA ring could still be operated with beams from of a local H^-/p source [6,7]. This allowed for progressing in the optimisation of beam performance in the ELENA ring, including e-cooling, as well as to commission the transfer line beam transport well before the arrival of the first antiproton beam after LS2.

The first proton beam for pbar production after LS2 was delivered at the end of June 2021. In the following weeks the AD operation was restored, including the setup of AD stochastic cooling [8] and electron cooling. The first pbar beam was delivered to ELENA mid August 2021 and 100 keV antiproton beams were available for users starting on August 23rd, as scheduled. During this short time, only minor adjustments of the previously prepared H^- cycle were necessary to decelerate and cool pbars, demonstrating that H^- beams can be used for optics and cooling studies in ELENA without the need of pbars.

In the following sections, the achieved beam performance of the facility will be outlined followed by observations of e-cooling related aspects during the restart in 2021.

BEAM PERFORMANCE IN 2021

During the run, further optimisation of both AD and ELENA cycles allowed to improve the overall performance of the facility. By construction, the characteristics of the beam delivered to experiments are defined by the e-cooling performance and heating effects (like Intra-Beam Scattering (IBS)) on the extraction plateau of ELENA, while the final intensity is driven by the efficiency of antiproton production and collection (in AD), and deceleration. For this, stochastic and electron cooling play a key role to at least counteract the adiabatic increase of the beam transverse and longitudinal emittances. The final AD and ELENA cycle deceleration efficiency are presented in Fig. 1 and Fig. 2, respectively. In AD the beam intensity is measured by a Cryogenic Current Comparator (CCC) [9], which allows to measure the beam current also while the beam is unbunched, while in ELENA the beam intensity is estimated by the Low Level Radio Frequency (LLRF) system which only works when the beam is bunched and does not take into account for longitudinal

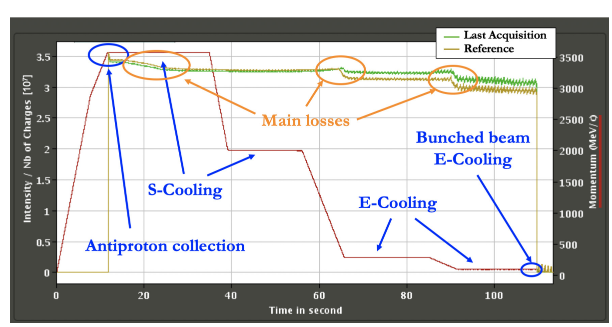

Figure 1: Beam intensity (in units of 10^7 charges) along a typical AD cycle. The main observations are highlighted.

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ELECTRON COOLING OF COLLIDING ION BEAMS IN RHIC: STATUS AND PERSPECTIVES*

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Abstract

Electron cooling of ion beams employing a high-energy approach with rf-accelerated electron bunches was recently implemented at BNL using the LEReC accelerator. Following the successful cooling commissioning in 2019, it was used to cool ion beams in both collider rings with ion beams in collision. The electron cooler LEReC successfully operated for the RHIC physics program in 2020 and 2021 and was essential in achieving the required luminosity goals. Apart from its use in RHIC operations, LEReC is used to study various aspects of electron cooling physics using short electron bunches. This report summarizes experience with electron cooling of colliding ion beams in RHIC, as well as ongoing studies.

INTRODUCTION

Electron cooling is a well-established technique for obtaining low-emittance ion beams [1]. In this method, the phase-space density of an ion beam is increased by means of dissipative forces – the dynamic friction on individual ions undergoing Coulomb collisions with electrons which have lower transverse and longitudinal temperatures.

Electron cooling of ion beams employing a high-energy approach with RF-accelerated electron bunches was recently successfully implemented at BNL [2-6]. Such a scheme of cooling with a bunched electron beam is a natural approach for the extension of electron cooling to high beam energies. As such, the successful demonstration of Low Energy RHIC electron Cooling (LEReC) serves as a prototype for future high-energy electron coolers, both in physics and technology.

The high-current high-brightness electron accelerator was commissioned in 2018 with all required electron beam parameters achieved [3]. During the 2019 RHIC run with Au ions, electron cooling was commissioned for 3.85 GeV/nucleon total energy gold beams using electrons with a kinetic energy of 1.6 MeV and then for 4.6 GeV/nucleon gold beams using 2 MeV electrons. At the same time, the first electron cooling of hadron beams in collisions was also successfully demonstrated [2]. Electron cooling of colliding gold beams became fully operational during the 2020 RHIC physics run. It successfully operated in 2020 and 2021 for the RHIC Beam Energy Scan II physics program in search of a QCD critical point on the phase diagram and was essential in achieving the required luminosity goals [7].

THE LEReC ACCELERATOR

LEReC is based on state-of-the-art accelerator physics and technology: reproducibly high quantum efficiency photocathodes with a sophisticated delivery system which can hold up to 12 cathodes simultaneously (specifically designed to support long-term operation with up to one cathode exchange per day); a high-power laser beam with laser shaping and stabilization; a high-voltage high-current DC gun; RF gymnastics using several RF cavities; instrumentation, controls and a machine protection system (see, for example, Ref. [3] and references therein).

Electron bunches are generated by illuminating a multialkali photocathode, inserted into a DC gun with an operating voltage around 400 kV. The 704 MHz fiber laser produces bunch trains with individual electron bunches of about 40 ps full length at 9 MHz bunch train frequency, which matches the repetition rate of ion bunches in RHIC. For RHIC operations, 30-36 electron bunches per bunch train were used.

Once electron bunches of the desired quality are generated from the gun, they are further accelerated to the required energy by the 704 MHz SRF booster cavity, transported to the first cooling section in the Yellow RHIC ring, used to cool the ions in that ring, turned around using a 180-degree dipole magnet, used to cool ions in the Blue RHIC ring and transported to the high-power beam dump. Figure 1 shows layout of the LEReC accelerator.

To prevent degradation of energy spread due to the longitudinal space charge forces, electron bunches are ballistically stretched after slightly off-crest acceleration in the booster cavity to produce an energy chirp (the correlation between particle position within the bunch and its energy).

A series of normal conducting RF cavities are used to reduce the energy spread within electron bunches to the required level. A warm 2.1 GHz cavity (3rd harmonic of the 704 MHz) is used to remove the non-linear energy spread introduced by the RF curvature. For operation with longer electron bunches in 2021, an additional 1.4 GHz cavity (2nd harmonic of the 704 MHz) was successfully employed. After the bunches are stretched, another 704 MHz warm RF cavity is used to remove the energy chirp. An additional 9 MHz warm RF cavity is employed to remove bunch-by-bunch energy variations within the bunch train (macrobunch) caused by beam loading in the RF cavities.

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MAGNETIZED DYNAMIC FRICTION FORCE IN THE STRONG-FIELD, SHORT-INTERACTION-TIME LIMIT*

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Abstract

Relativistic magnetized electron cooling is one of the techniques explored for achieving the ion beam luminosity requirements of the presently designed electron-ion collider (EIC) facility at Brookhaven National Lab. Because the cooling system will have to operate in previously untested parameter regimes, accurate computation of magnetized dynamic friction is required at the design stage in order to obtain reliable estimates of the cooling time. At energies of interest to the EIC cooling system design, the beam-frame interaction time in the cooler becomes short compared to the plasma period, and some assumptions applicable to the physics of cooling at lower energies become invalid in this high-energy setting. We present and discuss the results of first-principles modeling the magnetized dynamic friction force in the strong-field, short-interaction-time regime, as well as a parametric longitudinal friction force model that we developed starting with a reduced ion-electron interaction potential. The model parameters are related in a simple way to the interaction time and the ion charge. We compare our simulation results to the predictions of previously developed theoretical models.

REDUCED 1D ION-ELECTRON INTERACTION MODEL

We follow the general approach of Derbenev [1], wherein the total time-dependent E-field at the location of the ion $\vec{E}(\vec{r},\vec{v},t)$ is viewed as comprised of three contributions: (i) $\langle\vec{E}^0\rangle(\vec{r},t)$, the Coulomb field from the bulk charge of the electron distribution, (ii) $\langle\Delta\vec{E}\rangle(\vec{r},\vec{v},t)$, the dynamic friction force, the occurrence of which is due specifically to the modulation of the electron phase space distribution caused by the presence of the ion, and (iii) $\vec{E}^{fl}(\vec{r},\vec{v},t)$, statistical fluctuations due to irregularity of the electron distribution at the microscopic scale:

$$\vec{E}(\vec{r},\vec{v},t) = \langle\vec{E}^0\rangle(\vec{r},t) + \langle\Delta\vec{E}\rangle(\vec{r},\vec{v},t) + \vec{E}^{fl}(\vec{r},\vec{v},t). \quad (1)$$

The friction force is then calculated along the ion trajectory:

$$\vec{F}(\vec{r},\vec{v},t) = -Ze\ \langle\Delta\vec{E}\rangle(\vec{r},\vec{v},t)\Big|_{\vec{r}=\vec{r}(t),\dot{\vec{r}}=\vec{v}(t)}. \quad (2)$$

In practice, of interest is the dynamic friction force averaged over the time it takes the beams to traverse the cooler solenoid, which is what we compute in this paper. Furthermore, in this paper we limit discussion to the computation of the ensemble-averaged expectation value of the friction force for the ion moving longitudinally (along the magnetic field lines). We assume a constant and uniform magnetic field in the solenoid.

By short interaction time we mean interaction time T_{int} short compared to the beam-frame plasma period $T_{pl} = \sqrt{\pi/n_e r_e c^2}$, where n_e is the local, beam-frame electron number density (assumed constant over the spatial scales of interest) and $r_e = e^2/(4\pi\epsilon_0 m_e c^2)$ is the classical electron radius. In the beam frame, the interaction time is Lorentz-contracted by a factor of γ, and the plasma period is increased by a factor of $\gamma^{1/2}$ due to electron density dilation. Hence, high-energy conventional cooling systems, both magnetized and unmagnetized, that are designed to cool at $\gamma \sim 20-300$ will likely operate in the short-interaction-time regime. The model presented here assumes $T_{int} << T_{pl}$ and leaves out the Debye screening of the ion potential and the corresponding electron-electron interaction.

As a matter of convenience, we work in a reference frame where the ion remains at rest at the origin of the coordinate system during the interaction time in the cooler. In the beam frame, the dynamics are non-relativistic. The friction force is computed by adding up momentum kicks from binary ion-electron interactions, *subject to the background subtraction procedure* described below. In the limit of a strong magnetic field, to the leading order of canonical perturbation theory (with a small parameter proportional to $1/B$) the electron gyrocenters are confined to cylinders of constant radius equal to the electron's initial impact parameter D. Therefore, with the Larmor radius equal to zero in the limit of infinitely strong magnetic field, in our model the electron macroparticles move in an effective nonlinear $1D$ potential:

$$\ddot{z}(t) = -Zr_e c^2 \frac{z}{(z^2+D^2)^{3/2}}, \quad (3)$$

where Z is the ion charge number and the z axis is in the direction of the magnetic field in the solenoid.

The effective potential is a "soft" nonlinear potential, in the sense that the period of oscillations increases with amplitude and both oscillatory and unbounded orbits are possible. (The shortest possible oscillation period $T_{min} = 2\pi\sqrt{D^3/Zr_e c^2}$ for a given impact parameter D is realized in the limit of infinitely small amplitude.) Depending on the initial conditions, the electron trajectory can be classified as either unbounded, oscillatory, or technically oscillatory but with a period of oscillation that is larger (possibly, much larger) than the interaction time in the cooler. The net dynamic friction force on the ion is determined by contributions from these three orbit types and, due to the nonlinear nature of the interaction potential, it has to be evaluated numerically.

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MUON IONIZATION COOLING EXPERIMENT: RESULTS AND PROSPECTS

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Abstract

A high-energy muon collider could be the most powerful and cost-effective collider approach in the multi-TeV regime, and a neutrino source based on decay of an intense muon beam would be ideal for measurement of neutrino oscillation parameters. Muon beams may be created through the decay of pions produced in the interaction of a proton beam with a target. The muons are subsequently accelerated and injected into a storage ring where they decay producing a beam of neutrinos, or collide with counter-rotating antimuons. Cooling of the muon beam would enable more muons to be accelerated resulting in a more intense neutrino source and higher collider luminosity. Ionization cooling is the novel technique by which it is proposed to cool the beam. The Muon Ionization Cooling Experiment collaboration has constructed a section of an ionization cooling cell and used it to provide the first demonstration of ionization cooling. Here the observation of ionization cooling is described. The cooling performance is studied for a variety of beam and magnetic field configurations. The outlook for an experiment to measure muon ionization cooling in all six phase-space dimensions as part of the demonstrator facility being considered by the interna-tional Muon Collider collaboration will also be discussed.

INTRODUCTION

Muons are considered excellent beam particles for a collider applications due to their unique properties. Entire muon energy, being fundamental particle, is available for production of secondary particles. The design of such Muon collider is strongly influenced by radiative effects. The large muon mass also offers an increased coupling to Higgs boson compared to electron. Muon colliders can thus employ rings of small circumference for acceleration and collisions, reducing facility footprints and construction and operating costs. Production of high quality muon beams is challenging. Muon beam production starts by sending the high power proton beam to the target, where pions are produced subsequently decaying into muons. This way muons emerge as a tertiary beam with a very large initial emittance and energy spread, which requires a significant beam cooling in order to be able to achieve a sufficient luminosity in the collider applications. Due to the shortness of the muon lifetime the only cooling technique fast enough to be applicable to the muon beams is ionization cooling [1–3]. In muon ionization cooling, muons are passed through energy-absorbing material where the transverse and longitudinal momentum is reduced, reducing the normalised beam emittance and cooling the beam. Multiple Coulomb scattering from atomic nuclei induces an increase in transverse momentum and heats the beam. By focussing the beam tightly onto the absorber and using materials having low atomic number the heating effect may be suppressed, resulting in overall cooling. The ionization cooling of muons has been demonstrated for the first time experimentally by Muon Ionization Cooling Experiment (MICE) at RAL [4].

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EXPERIMENT

The Muon Ionization Cooling Experiment (MICE) was designed, most importantly, to demonstrate the ionization cooling principle and amplitude non-conservation. Other components of the MICE program were to demonstrate high acceptance and tight focussing solenoid lattice, then to demonstrate the integration of liquid hydrogen and lithium hydride absorbers, and also to precisely measure the absorber material properties (dE/dx and multiple scattering distributions) that determine the performance of ionization cooling. MICE was approved in 2003 at RAL. After an extended design, construction, installation, and commissioning process, MICE recorded a substantial dataset (3.5 × 10^8 events) in 2016-17 with one absorber and no RF cavities. MICE collaboration grouped over 100 scientists from 30 institutions in 10 countries.

A schematic of MICE is shown in Fig. 1. Pions arising from protons striking a target in the fringe of the ISIS synchrotron proton beam were guided to the cooling apparatus by quadrupoles, dipoles and a solenoid. Momentum of the resultant beam was selected by the dipoles. A variable thickness diffuser at the upstream end of the cooling channel served to scatter the beam enabling choice of incident emittance. The beam was passed into a solenoid focussing channel. Spectrometer Solenoid modules were placed upstream and downstream of a Focus Coil module within which the absorber was placed providing a tight focus in both transverse planes suitable for ionization cooling. Liquid hydrogen and lithium hydride absorbers were used. Particles passed through a pair of Time-of-Flight (TOF) detectors, which were used to estimate the particle velocity. Scintillating fibre trackers upstream and downstream of the experiment in fields of up to 4 T enabled characterisation of particles' position and momentum before and after passing through the cooling section. By comparing the momentum measured in the trackers and the velocity measured in the TOFs, the particle species was identified and pion and electron impurities rejected. Muons were passed through the experiment one-by-one and an ensemble of muons was accumulated. The experiment was modelled using Geant4-based simulation [5].

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PLASMA LENS IN PARAMETRIC RESONANCE IONIZATION COOLING

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Abstract

The article presents a concept of a plasma lens which will be generated in a dense hydrogen gas filled RF cavity. The plasma lens will be formed by beam-gas-plasma interactions. An exceptionally strong transverse magnetic and longitudinal RF electric focusing fields will appear in a short length. We consider that it will be integrated into a parametric-resonance muon ionization cooling channel as a strong momentum kicker to mitigate an issue of a large amplitude-dependent time of flight for a large angular distribution.

INTRODUCTION

A multi-TeV muon collider is a highly demanded machine for studying the Beyond Standard Model (BSM). Table 1 shows a step-approaching COM energy and luminosity of muon collider parameter proposed by the high energy physics theory and accelerator groups [1]. It should be noted that a 14-TeV machine is designed as a site-filler at the Fermilab campus. Besides, a 14 TeV μ+-μ- COM energy is equivalent to a 100 TeV pp collider.

Table 1: Muon Collider Parameter

Parameter (unit)	3 TeV	10 TeV	14 TeV
Lumi. L (10^{34} cm^{-2}s^{-1})	1.8	20	40
Num. of μs N_μ (10^{12})	2.2	1.8	1.8
Beam rep. rate (Hz)	5	5	5
μ beam power (MW)	5.3	14.4	20
B. field in coll. ring (T)	7	10.5	10.5
N. L. Emit. ε_L (MeV m)	7.5	7.5	7.5
E. spread (rms) ΔE/E (%)	0.1	0.1	0.1
N. T. Emit. ε_t (μm)	25	25	25
Beam size (rms) (mm)	3.0	0.9	0.63

To reach the desired luminosity, the muon beam size must be a sub-mm scale at a collision point. However, an initial size of the created muon beam is a foot-scale after the charged pions decaying. Ionization cooling is a promising technique to shrink a foot-size muon beam into a sub-mm. A timescale of the cooling should be an order of the average muon lifetime, $\gamma\tau_\mu$. A muon beam is incident into an ionization material and loses a kinetic energy due to ionizing the material. The beam lost energy is compensated by an RF accelerating field. As a result, the beam size continuously shrinks with repeating the process. However, nuclei in the material heat the muon beam via the multiple scattering. To mitigate the beam heating, a low-z element, like Hydrogen, Lithium or Beryllium are used as a cooling material and a beam window. Conventionally, a strong magnetic field is applied in a cooling channel to focus the beam at the material. The beam angular spread and therefore the beam emittance are reduced by ionization cooling. Therefore, to achieve a sub-mm-scale beam size, it requires a 50-Tesla focusing solenoid magnet in the final stage of cooling. Besides the muon beam is decelerated from 120-170 MeV to as an order of 10 MeV in the final cooling stage for applying a strong focusing force. Increasing transmission efficiency of muon beam in a high field solenoid cooling channel is challenging.

Significant progress has been made on a possible solution of the final cooling problem called Parametric-resonance Ionization Cooling [2-4]. Instead of focusing the beam by a strong focusing magnet, it uses a parametric resonant process to generate beam waist points. The beam phase space not evolutes on an elliptical trajectory (left-hand side plot in Fig. 1), but diverges on a hyperbolic function (right-hand side plot in Fig. 1). The main challenge of this solution is prevention of the beam smear at the focal points due to a large phase-space volume of even a pre-cooled muon beam. This can be done by compensating beam aberrations at the focal points or linearizing the beam dynamics between the focal points. The plasma focusing technique described in this article provides much stronger focusing magnetic fields than can be provided by conventional superconducting magnets and is also naturally compatible with and simplifies the complexity of the parametric-resonance ionization cooling approach by making the beam size smaller and therefore reducing the aberrations. The Parametric resonance Ionization Cooling scheme is described in the first half of the article. The plasma lens is presented in the second half of the article.

PARAMETRIC-RESONANCE IONIZATION COOLING CONCEPT

The limit on the minimum achievable emittances in muon ionization cooling comes from the equilibrium between the cooling process and multiple Coulomb scattering in the absorber material. The concept of Parametric-resonance Ionization Cooling (PIC) is to push this limit by an order of magnitude in each transverse dimension by focusing the muon beam very strongly in both planes at thin absorber plates. This creates a large angular spread of the beam at the absorber locations, which is then cooled to its equilibrium value resulting in greatly reduced transverse emittances. Achieving adequately strong focusing using conventional magnetic optics would require unrealistically strong magnetic fields. Instead, PIC relies on a resonant process to provide the necessary focusing. A half-integer parametric resonance is induced in a cooling channel, causing focusing of the beam with the period of the channel's free oscillations.

The resonant perturbation changes the particles' phase-space trajectories at periodic locations along the channel from their normal elliptical shapes to hyperbolic ones as shown in Fig. 1. Thus, at certain periodic focal positions, the beam becomes progressively narrower in x and wider in x' as it passes down the channel. Without damping, the

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WIGGLER ENHANCED PLASMA AMPLIFIER FOR COHERENT ELECTRON COOLING*

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Abstract

Coherent electron cooling [1] using a plasma-cascade amplifier (PCA) [2] can provide much faster cooling rates of hadrons than the conventional microwave stochastic cooling due to an extremely wide bandwidth of a pickup modulator, a kicker, and the amplifier. A PCA creates unstable plasma oscillations using modulation of the plasma frequency by varying the transverse beam size along the beam line with strong field solenoids. In this work we propose an alternative approach to the problem: the plasma frequency is modulated in a sequence of wiggler magnets separated by drifts or chicanes. This approach has the promise of obtaining a compact amplifier due to a more efficient modulation of the plasma frequency, although it requires separation of the hadron and electron orbits in the amplifier region to synchronize their time of flight through the cooling system.

INTRODUCTION

Coherent electron cooling [1] (CEC) can provide much faster cooling rates of hadrons than the conventional microwave stochastic cooling due to a wide bandwidth of the pickup modulator, the kicker, and the amplifier. While the original idea of coherent cooling relied on a free electron laser as an amplifier, which has a relatively narrow bandwidth [3], a later development of the idea involved a broadband amplifier based on the microbunching instability [4–6]. This approach is known under the acronym of MBEC (microbunched electron cooling). More recently, in Ref. [2], the idea of a plasma cascade amplifier (PCA) was proposed that conceptually has an even broader bandwidth than MBEC. The PCA creates unstable plasma oscillations using modulation of the plasma frequency by varying the transverse beam size along the beam line with strong-field solenoids. Unfortunately, the PCA length with several amplification sections can become prohibitively long because the plasma wavelength increases with the Lorentz gamma factor as $\gamma^{3/2}$. In this work we propose an alternative approach to the problem: the plasma frequency is modulated in a sequence of wiggler magnets separated by drifts or small chicanes. We refer to this scheme as the *wiggler enhanced plasma amplifier*, or WEPA. This approach has the promise of obtaining a compact amplifier due to a more efficient modulation of the plasma frequency.

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PLASMA OSCILLATIONS IN A RELATIVISTIC BEAM

We begin with a derivation of the frequency of plasma oscillations when a relativistic beam propagates inside a wiggler or in a drift. In our derivation, we neglect the particle energy spread assuming a cold beam. Our interest here is in short-wavelength plasma perturbations (with wavelength in the micron range, or even shorter) so we can treat the beam in local approximation assuming that its linear density n_0 is constant and neglecting its dependence on the longitudinal coordinate z. We consider the linear density perturbation $\Delta n(s,z)$ and the relative energy perturbation $\Delta\eta(s,z) = \Delta E(s,z)/E_0$, where z is the longitudinal coordinate in the beam relative to a reference particle, and s is the path length along the beam line. These quantities are Fourier transformed over the coordinate z: $\Delta\hat{n}_k(s) = \int_{-\infty}^{\infty} \Delta n(s,z) e^{-ikz} dz$ and $\Delta\hat{\eta}_k(s) = \int_{-\infty}^{\infty} \Delta\eta(s,z) e^{-ikz} dz$.

In a drift, we have the linearized continuity equation for cold plasma,

$$\frac{\partial \Delta n(s,z)}{\partial s} + \frac{1}{\gamma^2}\frac{\partial}{\partial z} n_0 \Delta\eta(s,z) = 0. \tag{1}$$

Applying the Fourier transform to this equation yields

$$\frac{d\delta\hat{n}_k}{ds} = -\frac{ikl}{\gamma^2} n_0 \Delta\hat{\eta}_k. \tag{2}$$

In a wiggler, particles move along the s coordinate with a smaller longitudinal velocity corresponding to the *longitudinal* gamma factor

$$\gamma_z = \frac{1}{\sqrt{1 - v_z^2/c^2}} = \frac{\gamma}{\sqrt{1 + K^2/2}}, \tag{3}$$

where $K = eB\lambda_w/2\pi mc^2$ is the wiggler parameter with B the amplitude magnetic field in the wiggler and λ_w the wiggler period. Here we assume a plane wiggler. Correspondingly, in a wiggler, we replace γ^2 by γ_z^2 in the continuity equation Eq. (2),

$$\frac{d\Delta\hat{n}_k}{ds} = -ik\frac{1}{\gamma_z^2} n_0 \Delta\hat{\eta}_k. \tag{4}$$

The equation for $\Delta\hat{\eta}_k$ describes the energy exchange between the particles due to the Coulomb interaction. Here we will accept the model of Ref. [5] in which the interaction between the particles of the beam is replaced by the Coulomb interaction of charged disks (or slices of the beam) with a Gaussian surface charge distribution. Then the equation for

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SIMULATION OF HIGH ENERGY PROTON BEAM COOLING IN EICC*

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Abstract

The hadron beam cooling plays an important role in the future e-i collider machines to achieve various physical goals. In EicC, two-stage beam cooling scheme is proposed to maintain the luminosity during the long time collision. First, a traditional electron cooler will be used to pre-cool the low energy proton beam in the BRing. Then, an ERL-based electron cooler will be applied at the pRing to cool the proton beam at high energy. The main purpose of cooling is to counteract the emittance growth due to the IBS. In this paper, we focus on the high energy beam cooling and present some simulation studies on how the cooling rate will be affected by the electron bunch size, magnetic field, and ring parameters in the cooling section, which would be helpful for the cooler design.

INTRODUCTION

EicC is proposed to study of hadron structure and the strong interaction and to carry out the frontier research on both nuclear and particle physics [1]. It will be constructed based on the High Intensity heavy ion Accelerator Facility (HIAF) with an additional newly constructed electron ring and a proton ring. The proposed collider will provide highly polarized electrons (with the polarization ~80%) and protons (with the polarization ~70%) with the variable center of mass energies from 15 to 20 GeV and the luminosity of $(2-4)\times 10^{33}\ cm^{-2}s^{-1}$. The ion accelerator complex of the EicC accelerator facility mainly consists of a polarized ion source, the iLinac, the booster ring BRing, and the collider ring pRing with proton beam energy up to 19.08 GeV, and the electron accelerator complex is composed of an electron injector and an electron collider ring eRing. There are two identical interaction regions in the EicC accelerator design, as shown in Fig. 1.

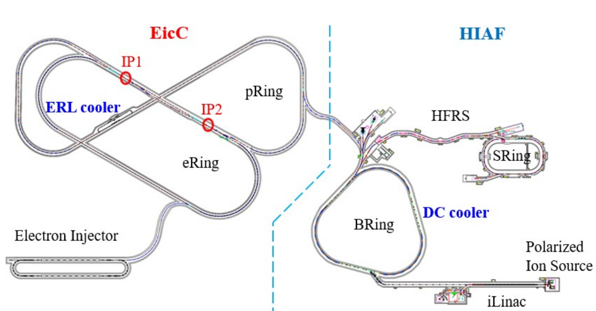

Figure 1: General layout of the EicC accelerator complex.

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To achieve the high luminosity and long collision lifetime, beam cooling is required to counteract the emittance growth caused by IBS. In the past decades, electron cooling has become one of the most effective and well-developed methods. Based on ref. [2], the cooling rate will be significantly weakened at high energy, as described by Eq. (1).

$$\frac{1}{\tau_{cool}} \propto \frac{Z^2}{A}\frac{n_e L_c}{\beta^4\gamma^5\theta^3_{rel}} \tag{1}$$

Considering this effect, the EicC will adopt a two-stage electron cooling scheme to improve the cooling efficiency. In the first cooling stage, an electron cooler, based on conventional electrostatic high voltage acceleration, will be installed in the BRing to reduce the transverse emittance and the momentum spread of the medium-energy ion beams. In the second cooling stage, a high energy electron cooler, based on ERL, will be installed in the pRing to compensate the IBS effect and maintain the emittance of the ion beam during the collisions, which can ensure high luminosity and long collision life required by the scientific goals. Due to reduced emittance after the low-energy cooling in the first stage, the cooling time for the high-energy beam can also be largely reduced, leading to a shortened total cooling time and enhanced cooling efficiency.

STUDIES ON BUNCHED BEAM COOLING IN PRING

In order to calculate the bunched beam cooling parameters efficiently and accurately, a flexible multiparticle tracking code is developed based on BETACOOL physics guide [3] and JSPEC code [4]. The magnetized friction force is calculated through the semi-empirical formula by V. Parkhomchuk [5] and the Martini model [6] is chosen for IBS calculation in this code. It has been benchmarked with BETACOOL program and they agree very well. In the following, we will give some simulation results and select the optimal parameters to achieve a high cooling rate. All the simulation input parameters are shown in Table 1.

IBS Effect During the Collision

Because of the long collision time, the emittance growth during the collision must be considered which have a great effect on the luminosity. Here we only considered the IBS effect, as shown in Fig. 2, beam emittance in three dimensions are all increased, which significantly affect the luminosity. Especially for the horizontal emittance growth rate, it will grow from 0.3 um to 0.7 um in three hours and the growth rate is about $2.3\times 10^{-4}\ s^{-1}$. The luminosity will decrease to $1.4\times 10^{33}\ cm^{-2}s^{-1}$ within three hours. To obtain a great

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SIMULATION OF TRANSVERSE ELECTRON COOLING AND IBS OF 20 GeV PROTON BEAM AT EICC*

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Abstract

The transverse electron cooling and intra-beam scattering processes of 20GeV proton beam were simulated with the help of the code at Electron Ion collider in China. The transverse cooling time were obtained in the different parameter configurations of storage ring, proton beam, electron cooling device and electron beam. The scattering time of proton beam were presented in the cases of different initial emittance and particle number. The final equilibrium transverse emittance were estimated in the cases of different initial emittance and particle number. From the simulated results, the transverse cooling time of 20GeV proton beam is over 100 seconds. The transverse cooling time can be shorten with the help of proper configuration of the parameters.

INTRODUCTION

Based on the HIAF (the Heavy Ion High Intensity Accelerator Facility, approved in 2015 in China), a high luminosity polarized Electron Ion Collider facility in China (EicC) was proposed to study of hadron structure and the strong interaction and to carry out the frontier research on both nuclear and particle physics.

EicC will be constructed in two phases, EicC-I and EicC-II. In the first phase, the proton beam with energy between 15~20GeV will collide with electron beam with energy between 2.8~5GeV in the collider. Both electron and proton beam are polarized. The luminosity will expect to achieve $2\sim4\times10^{33}cm^{-2}\cdot s^{-1}$.

In the second phase, the energy of proton will upgrade to 60~100GeV, and the energy of electron beam will increase to 5~10GeV, the luminosity will expect to achieve 1×10^{35}. The primary design and some initial parameters of EicC will be found in the reference [1].

In order to obtain the expected luminosity in collider, the polarized proton beam should be cooled by various cooling methods among the whole energy range. In the case of high intensity high energy proton beam especially, the intra-beam scattering effect should be taken into account in the collider design. Some primary simulation on the transverse electron cooling and intra-beam scattering were presented in this contribution.

SIMULATION OF ELECTRON COOLING

The transverse electron cooling time not only depends on the lattice parameters of the storage ring, the Betatron function, dispersion of the cooling section, such as energy, initial emittance and momentum spread of proton beam , but also on the construction parameters of electron cooling device, the strength of magnetic field, the parallelism of magnetic field in the cooling section, the effective cooling length, and the parameters of electron beam, such as radius, density and transverse temperature of electron beam. These parameters are determined by the storage ring and the technology limitation, on the other hand, they are influenced and restricted each other.

With the help of the electron cooling simulation code SIMCOOL [2, 3], the transverse electron cooling time of proton beam were extensive simulated in various parameters in the EicC, such as proton beam energy, initial transverse emittance, and momentum spread. The influence of the machine lattice parameters-Betatron function, and dispersion function on the cooling time was investigated. The parameters of electron beam and cooling devices were taken into account, such as effective cooling length, magnetic field strength and its parallelism in cooling section, and electron beam current.

Proton Beam Parameters

Left diagram of Fig. 1 shows the transverse electron cooling time as a function of the initial emittance. Right diagram of Fig. 1 gives the dependence of transverse cooling time of the transverse direction on the particle number in the proton beam. In the case of other parameters were fixed, the transverse electron cooling time increases with the initial emittance and slightly decreases with the particle number in the proton beam.

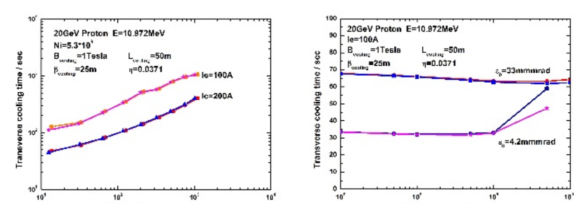

Figure 1: The transverse electron cooling time as a function of the initial emittance (left) and the particle number in the proton beam (right).

Electron Beam Parameters

In order to decrease the transverse cooling time, the current of electron beam and length of cooling section was set as a bigger value. Left diagram of Fig. 2 presents the transverse cooling time as a function of the electron beam current. Right diagram of Fig. 2 indicates the transverse cooling time depends on the transverse temperature of electron beam. In the case of other parameters were fixed, the transverse cooling time decreases with the increasing electron beam current and decreasing transverse temperature of electron beam.

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COMPARISON OF AVAILABLE MODELS OF ELECTRON COOLING AND THEIR IMPLEMENTATIONS

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Abstract

Modelling of the electron cooling process is complex and challenging. The simulation needs to include elements like ions, plasma of electrons, the thermal effects of electrons and the influence of the magnetic field. In this work, the performance of three available tools, namely RF-Track [1], Betacool [2], and JSPEC [3], are discussed taking into account only the cooling and neglecting any heating effect. The friction force and cooling times are studied in a wide range of different parameters presenting the main behaviour of the available models together with the limitations of particular simulation codes. Furthermore, a qualitative comparison with experimental data is performed.

INTRODUCTION

The study is focused on the dependence of the friction force and of the cooling time on crucial parameters. A short introduction of the analysis is presented in this paper, while details can be found in [4].

Several simulation codes and models of electron cooling implementation have been used for this analysis. The key aspect of each simulation software and model are presented in the following.

RF-Track

RF-Track [1] is a tracking code developed at CERN. Here, electron cooling is modelled on the basis of the description given in Ref. [5], in which the force is expressed as the sum of unmagnetized and magnetised components:

$$\vec{F} = -\frac{4\pi n_e K^2}{\mu}\left\{F_{\text{unmagnetized}} + F_{\text{magnetized}}\right\}. \quad (1)$$

The unmagnetized part is implemented as:

$$F_{\text{unmagnetized}} = L_F \iiint \left[\frac{\vec{U}}{U^3}\right] f(\vec{v}_e)d\vec{v}_e \quad (2)$$

whereas three different versions of $F_{\text{magnetized}}$ have been implemented due to ambiguities in the description provided in [5]:

RF-Track A

$$L_M \iiint \left[\frac{U_{B\perp}^2}{U_B^5}\left(\vec{U}_{B\parallel}^5 + \frac{\vec{U}_{B\perp}}{2}\left(1-\frac{U_{B\parallel}^2}{U_{B\perp}^2}\right) f(v_e)dv_e\right)\right] \quad (3)$$

RF-Track B

$$L_M \int \left[\frac{U_{B\perp}^2}{U_B^5}\left(\vec{U}_{B\parallel}^5 + \frac{\vec{U}_{B\perp}}{2}\left(1-\frac{U_{B\parallel}^2}{U_{B\perp}^2}\right)\right)\right] f(v_{e\parallel})dv_{e\parallel} \quad (4)$$

RF-Track C

$$\int \left[L_A\frac{\vec{U}_B}{U_B^3} + L_{M2}\frac{U_{B\perp}^2}{U_B^5}\left(\vec{U}_{B\parallel}^5 + \frac{\vec{U}_{B\perp}}{2}\left(1-\frac{U_{B\parallel}^2}{U_{B\perp}^2}\right)\right)\right] f(v_{e\parallel})dv_{e\parallel} \quad (5)$$

with L being the so called Coulomb logarithms:

$$L_F = \frac{1}{2}\log\left(1+\frac{r_F^2}{r_{\min}^2}\right),\ L_M = \log\frac{r_{\max}}{r_L},$$

$$L_{M2} = \log\frac{r_{\max}}{r_F},\ L_A = \frac{1}{2}\log\left(1+\frac{r_L^2}{r_F^2}\right)$$

based on the following impact parameters:

$$r_L = \frac{\sqrt{V_{e\perp}^2+\Delta_{e\perp}^2}}{\omega_e},\quad r_F = \frac{\sqrt{U_{B\parallel}^2+\Delta_{e\parallel}^2}}{\omega_e},$$

$$r_{\min} = \frac{K}{\mu(U^2+\Delta_e^2/3)},\quad r_{\max} = \min\left(r_a, \lambda_D\sqrt{1+\frac{U^2}{\Delta_e^2/3}}, U\Delta t\right)$$

where $\vec{U}$ is the velocity difference between ions and mean electron velocity, and Δ_e is the electron temperature. Detailed meaning of all symbols is provided in [4].

BETACOOL

Betacool [2] is a widely used code for simulating beam dynamics developed at JINR. It includes a broad-range of effects that can be used and few models of electron cooling:

Parkhomchuk It is the simplest and commonly used model described by the following semi-empirical formula:

$$F = -4\frac{Z^2e^4n_e}{m}\log\left(\frac{b_{\max}+b_{\min}+\rho_c}{b_{\min}+\rho_c}\right)\frac{\vec{U}}{(U^2+v_{\text{eff}}^2)^{3/2}} \quad (6)$$

with impact parameters:

$$b_{\max} = \frac{v_i}{1/\tau_{\text{flight}}+\omega_p},\quad b_{\min} = \frac{Ze^2}{m}\frac{1}{U^2+v_{\text{eff}}},\quad \rho_c = \frac{cmv_\perp}{eB}$$

A key parameter of this model is v_{eff}, the effective velocity, which is a tuning parameter that can be used to take into account magnetic field line perturbations and other imperfections and it can help to fit the simulation to actual results.

Debrenev-Skrinsky-Meskov It assumes three types of collisions – fast, adiabatic and magnetized, depending on the value of impact parameter with respect to the Larmor radius (r_L). The role of those interactions depends on the relative velocities of electrons and ions, which defines three regions of velocities and impact parameters. This model allows choosing between asymptotic and numerical approaches [2]. After first short tests the asymptotic version was discarded because of nonphysical discontinuities, and therefore not mentioned in this work.

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DESIGN OF THE SRING ELECTRON TARGET

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Abstract

An electron target is proposed for high precision experimental measurement at the SRing (Spectrometry Ring) of HIAF (High Intensity heavy ion Accelerator Facility). It provides low temperature electron beam with a few meV for DR (Dielectronic Recombination) experiments at the energy of 1-80 keV. For such a low temperature, the conventional method is adopted by magnetic adiabatic expansion with a factor of 30 after acceleration within 1.2T longitudinal magnetic field at gun section. In this paper, the design optimization of the electron target is introduced.

INTRODUCTION

The Spectrometry ring (SRing) is an in-building dedicated experimental storage ring of the accelerator complex High Intensity heavy-ion Accelerator Facility (HIAF) [1]. It is designed to operate in four modes of the isochronous for time-of-flight nuclei mass measurement, of the internal target for gas-jet experiment, of the normal for Schottky nuclei mass measurement and atomic spectrometry study, and of the stacking. Collision of storage electron-cooled (E-cooled) ions with the cold electron beam is proposed at the SRing for Dielectronic Recombination (DR) spectroscopy measurement of Li-like, H-like, and He-like highly charged heavy ions when fruitful results have been obtained at HIIRFL-CSR electron cooler [2, 3]. Figure 1 shows layout of the SRing.

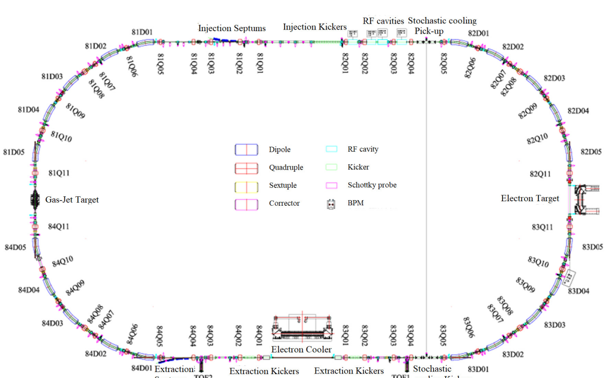

Figure 1: Layout of the Spectrometry Ring.

An electron-target (E-target) is dedicated to the DR experiments. It merges the cold electron beam of transverse temperature $kT_{e\perp}$ 5 meV and longitudinal one $kT_{e\parallel}$ 0.1 meV with the circulating e-cooled ion beam within 2.24 m length the target section. Electrons start from a 10 mm thermionic cathode, and accelerated to the energy range of 10-80 keV

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Table 1: Main parameters of SRing and E-target

SRing Nor-2 optics	
Circumference	277.3 m
Typical ions	$^{197}Au^{(76-78)+}$, $^{238}U^{(89-92)+}$
Beam Intensity	$10^4 - 10^8$
Rigidity	3.5-15 Tm
Energy	85-835 MeV/u ($^{238}U^{92+}$)
Accepted ϵ_h/ϵ_v, $\delta p/p$	120/30 $\pi mmmrad$, $\pm 1.1\%$
E-cooled ϵ_h/ϵ_v, $\delta p/p$	0.2/0.2 $\pi mmmrad$, $\pm 1 \cdot 10^{-4}$
E-Target parameters	
Electron energy	10-80 keV
$kT_{e\perp}$ in experiment	5 meV
$kT_{e\parallel}$ in experiment	0.1 meV
n_e in experiment	$2 \cdot 10^6$ cm^{-3}
Cathode diameter	10 mm
Expansion factor	30
B_s at target	0.04 T
B_s at gun/collector	1.2/0.2 T
Cooled beam σ_x/σ_y	4.7/3.7mm
Vacuum pressure	$1 \cdot 10^{-9}$Pa
Aperture through target	275 mm
$\beta_x/\beta_y, D_x$ at target	18 m/17 m, 4.7 m
Target solenoid length	2.24 m
E-target total length	5.5 m
E-target orientation	horizontal

within the 1.2 T guiding magnetic field. Then the electron beam get the transverse temperature reduced by a transverse expansion with a factor of 30 along the guiding field. After transition through magnetic bending coils in the toroid, electrons are merged with the circulating highly charged ions in the target solenoid. Collisions between cold electrons and e-cooled storage ions make DR spectrometry investigation possible. After interaction with ions in the target section, the electrons are bent away from the circulating ion beam through electron plates in the Toroid, and finally dumped into the collector after deceleration.

For DR experiments, the SRing will operate in the Nor-2 optics mode within the magnetic rigidity 3.5-15 Tm. As a feature of the e-target, ion beam will been cooled down with $\sigma_x/\sigma_y = 4.7/3.7mm$ at target section, that makes it possible for the colder electrons in a small radius to collision with the e-cooled ions.

Besides, three isochronous modes are designed at SRing and secondary beam in target section has the largest horizontal envelope 261 mm when the transition energy $\gamma_{tr} = 1.43$. This limit the minimal aperture at the target section. In

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ELECTRON COOLING USING A PULSED AND DITHERING BEAM FROM AN ELECTROSTATIC ELECTRON COOLER

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Abstract

In this paper we report results of an experimental study of a pulsed-beam electron cooler. We have found the effects of the electron bunch length and longitudinal ion focusing strength on the temporal evolution of the longitudinal and transverse ion beam profile and demonstrate the detrimental effect of timing jitter as predicted by the space-charge theory and simulations.

Our experiment has suggested the need of further investigations into specific aspects of bunched cooling such as synchro-betatron coupling and phase dithering effects of using a relative shorter electron bunch to cool a longer ion bunch.

INTRODUCTION

Electron cooling continues to be an invaluable technique to reduce and maintain the emittance in hadron storage rings, for example the US Electron-Ion Collider (EIC) and the Electron-Ion Collider in China (EICC) where stochastic cooling is inefficient in cooling the proton beam and radiative cooling is negligible. Extending the energy range of electron coolers beyond what is feasible with a conventional, electrostatic approach necessitates the use of RF fields for acceleration and, thus, a bunched electron beam. To experimentally investigate how the relative time structure of the two beams affects the cooling properties, we have set up a pulsed-beam cooling device by adding a synchronized pulsing circuit to the conventional electron source of the main Cooler Storage Ring (CSRm) cooler at Institute of Modern Physics (IMP) in China. The experiment conducted in December 2019, using both synchronized [1] and modulated synchronization of electron pulses to the ion beam bunches. This "Dithering" technique modulates the electron bunch arrival time relative the ion revolution frequency by using a shorter electron bunch to cool a longer ion bunch. It is sometimes called "longitudinal painting" in some references.

EXPERIMENT SETUP

Table 1 lists the experimental parameters for both pulsed beam and dithering beam cases. An electron cooler and an RF cavity are placed in the dispersion-free sections in the CSRm ring at Institute of Morden Physics (IMP). The active length of the electron cooler is 3.4 m. The RF voltage ramped from 0.6 to 2 kV in the frequency range of 0.25 to 1.7 MHz. Figure 1 illustrates arrival time *Δt* verses real time *t* with a triangle wave variation. The modulation hardware delays or advances the phase of the signal with respect to the reference signal V_{ref} by an amount of $asin(V_{mod}/V_{ref})$ with V_{mod} being the instantaneous value of the modulating voltage. The magnitude of phase change is determined by the reference voltage and was kept constant in the experiment at a value of about 600 ns peak-to-peak. This corresponds to approximately +/- 40° of phase with respect to the reference signal which occurs at 2 × 191.5 kHz. The modulation frequency was changing from 100 Hz to 1000 Hz during the experiment.

Table 1: Beam and Instrumentation Parameters

ion beam	
particle type	$^{86}Kr^{25+}$
beam current	< 100 μA
rest mass	930.5 MeV/nucleon
kinetic energy	5.0 MeV/nucleon
β	0.103
γ	1.005
revolution frequency f_{rev}	191.5 kHz
harmonic number h	2
RF voltage V_{RF}	0.6–2 kV
electron cooler	
acceleration voltage	2.7 kV
positive grid voltage	50 V
negative grid voltage	–551 V
peak current	30 mA
pulse length	> 100 ns

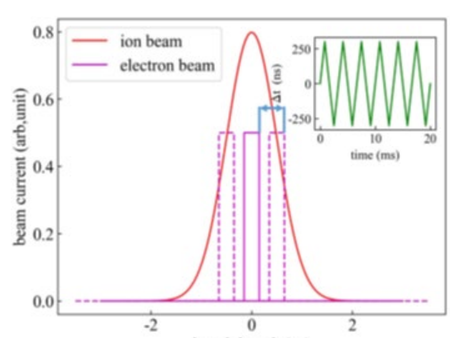

Figure 1: Experimental setup for the longitudinal phase modulation using a triangle waveform. The example here uses a 300 ns square electron pulse to cool an ion beam with a 0.5 μs rms bunch length. The modulation amplitude is 300 ns with frequency of 300 Hz.

After a fixed-frequency experiment with *Δt*=0 during which there was almost no beam loss for Krypton bunch

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OPTIMIZATION OF THE ELECTRON EMISSION FROM CARBON NANOTUBES FOR ELECTRON COOLING IN ELENA

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Abstract

Electron cooling guarantees beam quality in low energy antimatter facilities. The ELENA e-cooler permits to reduce the emittance blow-up of the $\bar{p}$ beam, thus delivering highly focused and bright beams at the unprecedented low energy of 100 keV to the experiments. To have a "cold" beam at such low energy, the electron gun must emit a mono-energetic and relatively intense electron beam. Efficient cooling can be achieved with a 5 mA electron beam having transverse energy spread < 100 meV and longitudinal energy spread ~ 1 meV. The thermionic gun used in operation limits the cooling performances due to a relatively high transverse energy of the emitted beam (>> 100 meV). An optimization of the e-gun is being studied, aiming to develop a cold cathode gun based on carbon nanotubes (CNTs). The use of CNTs implies the need of an extracting grid to allow for a stable and uniform emission, although the grid's features are critical to control the electron beam properties.

INTRODUCTION

In field emission the electron extraction is achieved applying a strong electric field between a cathode and an anode. The high intensity of the electric field necessary to enable significant emission has always hindered the use of field emitting cathodes. The arise of tip-like nano-structures has paved the way to field enhancement, so that it is now possible to extract large currents, in the order of many mA, with an electric field in the order of a few V/μm. CNTs are considered among the best field emitters because of their chemical stability, the possibility of mass production with scalable techniques and the large currents that they can emit and withstand [1, 2]. The major issues that have limited their use in operation are related to emission stability and lifetime. In ELENA, CNTs would be required to stably emit for hundreds or even thousands of hours without significant signs of degradation. In our previous work we investigated the best conditioning process necessary to ensure optimal emission stability and a lifetime that is compatible with operational use. If CNTs are operated in optimal conditions and trained appropriately, they can emit for hundreds of hours without significant degradation while emitting current densities of about 2 mA/cm^2; a value that would suffice for the requirements of ELENA's e-gun, e.g. 5 mA [3, 4]. An emission for more than 1500 hours has been proved for a CNT array, testing it in both DC and switching mode [5, 6]. In order to extract electrons from a large area cathode while obtaining an homogeneous emission an extracting grid becomes necessary. For this reason, a thorough study of the grid effect is essential for tuning the electron beam features according to the requirements. Although in this work we are aiming at using CNTs, this study still holds in the case of any field emitting cathode and in general to any case where an extracting grid is deemed necessary.

EXPERIMENTS

Several grid parameters can affect the beam properties. The grid distance from the cathode defines the voltage to be applied on the grid in order to get the desired electric field. The hole size severely affects the beam properties because of the distortion of the field lines within the hole. The relation between hole size and the pitch determines the transmittance of the grid. Additionally, the hole shape and holes arrangement must be devised cleverly in order to maximize the grid's transmittance. Finally, the feasibility of physically manufacture the desired grid according to the current technology must be taken into account. We have started analysing six different grid types: Grid 250 – 50. Hole size: 250 μm, Pitch size: 50 μm. Grid 200 – 40. hole size: 200 μm, pitch size: 40 μm. Grid 150 – 30: hole size: 150 μm, pitch size: 30 μm. Grid 100 – 20: hole size: 100 μm, pitch size: 20 μm. Grid 50 – 10: hole size: 50 μm, pitch size: 10 μm. Grid 25 – 5: hole size: 25 μm, pitch size: 5μm. The latter represents what is most likely the smallest grid which is possible to realise at the time of writing. All grids are devised to have squared holes in order to maximize the holes packing and consequently the transmittance. The pitch is hereby defined as the solid spacing between each hole.

All simulations are conducted with the software CST Studio and the simulation design allows for straight field lines in the whole emission region. The only source of field lines distortion is represent by the grid. The main simulation types are two and both have the layout illustrated in Fig. 1.

Simulation 1. Parametric simulation of the electron beam varying the grid distance from 0.4 to 5 mm with a step width of 0.2 mm. The electric field is kept constant. The initial beam energy is set to 0.1 eV in order to run a critical test for all grids. We were then able to derive the maximum deviation % of the voltage along the grid and the beam offset, "r" (calculated via the CST built-in "Envelope" option), which represents the difference between the radii of the emitted

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SUSPENDED GROUND MICROSTRIP COUPLED SLOTLINE ELECTRODE FOR STOCHASTIC COOLING

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Abstract

An alternative design of a slotline electrode has been developed and simulated. In contrast to the planar slotline pick-up designed for FAIR CR and the slot-ring electrode built by FZJ for FAIR HESR, the presented design uses suspended microstrip lines for the coupling to a planar slotline. This has some advantages and disadvantages for kicker and pick-up applications in respect of losses, power handling, and mechanical aspects.

INTRODUCTION

At the moment there are two different electrode designs foreseen for the FAIR Collector Ring (CR), one planar slotline electrode as plunging pickup [1] (also called PU17) and the well-known Forschungszentrum Jülich (FZJ) slot-ring electrode design [2] as kicker (see Fig. 1).

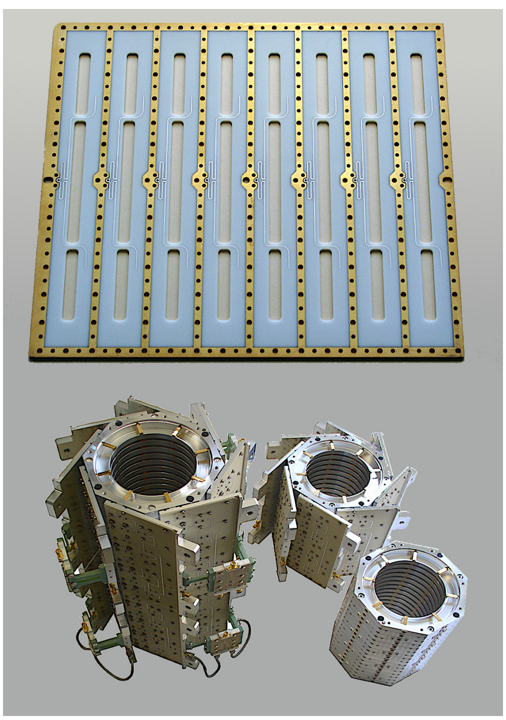

Figure 1: Top: Planar slotline electrode PU17 combiner (non beam) side. Bottom: FZJ slot-ring kickers (for FAIR HESR [2]).

All electrodes are optimized for antiprotons (pbars) at a velocity factor of $\beta = 0.97$ (3 GeV), but should also be functional for rare isotope beams (RIBs) at $\beta = 0.83$ (740 MeV/u) within the CR stochastic cooling band $f = 1$ to 2 GHz and $f = 2$ to 4 GHz for the HESR, respectively.

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Design Comparison

Both designs exhibit high impedances, flat frequency response and large beam apertures. Whereas the FZJ design is especially suited as a kicker due to its robust design and large structures, PU17 is less suited as kicker because of the fine microstrip structures on the non beam side (see Fig. 1), which can only handle a limited amount of power. An additional disadvantage of PU17 is the thick 1.905 mm Al_2O_3 ceramic, which is expensive and difficult to manufacture.

The FZJ slot-ring kicker is—due to its mechanical design—not able to be used as plunging pick-up. Whereas PU17 is especially designed for plunging operation, with beneficial factors like planar structures and low mass.

Since every slot of PU17 is housed in its own compartment, and thereby isolated from its neighboring slots, it is possible to inject a test signal into each slot—via an additional coupling loop—for testing without beam. This feature is not foreseen for the FZJ kicker.

Conclusion

While PU17 has some advantages, there is also the inherent disadvantage of not being able to be used as kicker and the fact that it uses thick Al_2O_3 ceramic, which not only increases cost but also lowers manufacturing quality. Thereby increasing risk of failure and lowering performance characteristics, i. e. non constant characteristic impedance and high resistive losses along its microstrip structures.

Therefore, it was decided to start a new development of a slotline electrode with suspended ground technology.

NEW DEVELOPMENT

The original slotline electrode design PU17 was used as a starting point to create a new suspended ground design PU18. Suspended ground microstrip lines experience a significantly lower effective dielectric constant ε_{eff}, thus the mechanical dimensions of the structures have to become larger to exhibit the same characteristic impedance Z_0. This results not only in reduced ohmic losses but also in reduced thermal resistance along the microstrip lines. Furthermore, suspended ground structures tend to have lower dielectric losses and less dispersion effects.

Design

A 6 mm wide slot line milled thru aluminum sheet, perpendicular to the beam, is used as a coupling element between beam (compartment) and an internal suspended coupling bridge. The coupling bridge itself is placed in a distance of ~ $\lambda/4$ to the end of the slotline, it is designed as a spring element which holds two suspended ground printed circuit boards (PCBs) with 635 µm Al_2O_3 substrate in their

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CONTROL FEATURES OF THE PLUNGING PICK-UP ELECTRODES WITH REAL TIME DIGTAL DATA PROCESSING

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Abstract

The Pick-Up electrodes of the CR Stochastic cooling system can be positioned very precisely and fast. In the normal operating state, a function without jerk provides the set values for an underlying position control loop. Moving the electrodes however with the drives within a narrow tank can be very challenging. For installation and service, we need a manual control facility, which allows to steer the mobile drive rods slowly to the electrodes. Hence eight hand wheels, one at each drive, will make manual positioning of each. A bus-shaped network from several wheel-controllers to a central computer was implemented. A smooth and data saving transmission can be achieved by applying approved techniques from real time data processing. The equipment of analogue drive systems with digital regulation and controls allows to change the proportion between drive distance and angle of rotation of a hand wheel only by means of software.

OPERATIONAL CONCEPT FOR THE CR PLUNGING PICK-UP ELECTRODES

The CR plunging Pick-Up electrodes are moved at cryogenic temperatures within a vacuum tank. They are propelled by linear motors outside this tank, vacuum sealed by bellows. Pre-compressed springs slightly overcompensate the vacuum force, thus avoid dropping the electrodes into the beam axis in case of a power failure. But using this drive construct for fast and precise movements requires damping the inherent resonance of a heavy mass with a strong spring. The solution is a control loop consisting of the motor, the moving payload, the motor controller, a position sensor and a regulator, whose set values can be forced due to almost any desired function [1]. A movement profile can be defined as a periodic function. This can be considered as the future "**automatic mode**". The digital design of the motor controller and the position sensor allowed to implement a digital regulator completely in software. This offers the opportunity to feed the regulator's set values for a desired position by any actuator with a convenient digital interface to the controlling computer. Thus the control software had been supplemented by two additional branches. The first can be considered as "**adjustment mode**" in order to set up the positon control loop. The second can be called "**manual mode**" and provides the input of a man-machine interface for a real time control of the drives. A stepping motor with a special interface hardware was equipped with a hand wheel, linked to the control computer and used as high resolution incremental encoder.

While the hand wheel gets twisted, the pulses are counted and transferred to a controlling computer, which accumulates them to an absolute position set value for the underlying control loop. A change of the ratio between the turned wheel angle and the advance of the carriage is carried out classically by a gear transmission. The fully digital implementation allows the change of it without any additional mechanics – just by multiplying the motor pulses with another factor. Thus, each counted pulse has to be assigned to an actual distance, let's assume 100 µm. A continuous turn of the wheel results in a stairway-shaped function, whose steps have a minimum height and whose length lasts always one millisecond. The basic sampling frequency of 1 kHz is given by the motor controller and resides in the audible range. Decreasing the step size down to a few microns can avoid visible jumps, but due to the logarithmic sense of the human ear, the discrete steps remain audible. Thus, this raw kind of counting procedure ends up in a very unpleasant sound, approximately like a rusted machine without any grease. In order to overcome this, an equidistant choice of sampling points was connected by consecutive cubic spline interpolations. Then the ugly sound turned into gentle clicks.

This initial three-mode concept was enhanced from one to eight control channels by digital addressing and transmission techniques, shown on top of Fig. 1. It is proven with up to two manually controlled drives working virtually in parallel. The manual control feature was designed to facilitate all kinds of assembling, service and maintenance tasks. It is not intended for operation with beam.

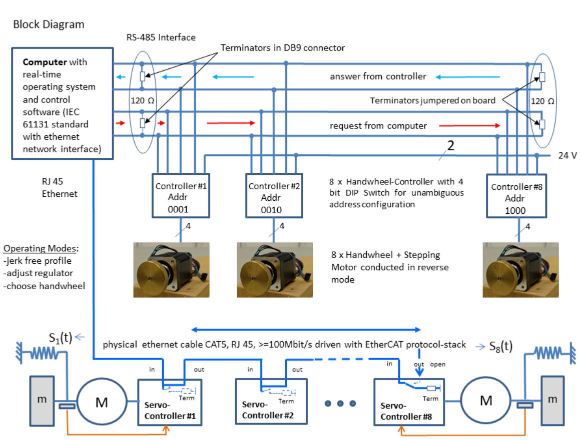

Figure 1: Linear drive control scheme for CR stochastic cooling pickup tanks, supplemented by eight addressable rotary encoders, attached to a four-wire RS-485 bus.

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A NEW ELECTRON COOLER FOR THE CERN ANTIPROTON DECELERATOR (AD)

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Abstract

The current electron cooler at the Antiproton Decelerator (AD) at CERN was built in the second half of the 1970s and is thus well over 40 years old. It was built for the Initial Cooling Experiment (ICE) where stochastic and electron cooling were tested to ascertain the feasibility of using these techniques to generate high intensity antiproton beams for the SPpS. The ICE electron cooler was subsequently upgraded and installed in LEAR (Low Energy Antiproton Ring) to help generate intense beams of antiprotons at low energies. After the stop of the anti-proton physics at LEAR in 1996 and two years of studies of electron cooling of Pb ions, the electron cooler was moved to the AD where it has been in use ever since.

With the new ELENA ring becoming operational, a major consolidation project has been launched to extend the lifetime of the AD and as a part of this a new electron cooler for the AD is being built. In this paper, we describe some of the design considerations and challenges of this project as well as the expected gains in terms of cooling performance.

INTRODUCTION

Since the completion of the LEAR physics program a simplified scheme using a modified AC (antiproton collector) as a decelerator (AD) was implemented at CERN to deliver antiprotons to experiments at an energy of 5.3 MeV. The scheme relies on stochastic and electron cooling to efficiently decelerate and extract high brightness beams to the experimental zones. With the recent addition of the ELENA ring to the CERN antimatter complex and an electron cooler with more than 40 years of operation [1], it was decided that a new cooler should be built to ensure reliable operations for the next 20 years.

Table 1: Main Parameters of the new Electron Cooler

	Value	Comment
E_e	68 keV	Cooling at 500 MeV/c
B_{gun}	2400 G	Expansion factor 2
Ie@68keV	3.5 A	
Ie@3keV	0.45 A	Factor 4 more current

The new device (Fig. 1) has been designed to cool antiprotons at a considerably higher energy than what is presently possible. Cooling at a higher energy will limit the adiabatic blow-up of the emittance of the circulating beam by a factor of three making the cooling of this “hot” beam more efficient. The cooler will also have an electron beam expansion system to obtain an electron beam with a reduced transverse energy for efficient and faster cooling of the circulating beam. It will be installed horizontally allowing easier access to the device for maintenance and repairs. Some of the main parameters and the potential gains of the new cooler are given in Table 1.

ELECTRON GUN

A high perveance electron gun capable of operating up to 80 kV is presently under design (Fig. 2). It is based on a study of various gun optics (Fig. 3) performed some years ago [2] and incorporates some ideas inspired by the decelerating tube of the Gbar experiment at CERN [3]. With a four times higher perveance, the gun will be able to deliver up to 450 mA of electron current for cooling at the lowest energy plateau of 5.3 MeV. At the top energy for electron cooling, the current will be limited to 3.5A.

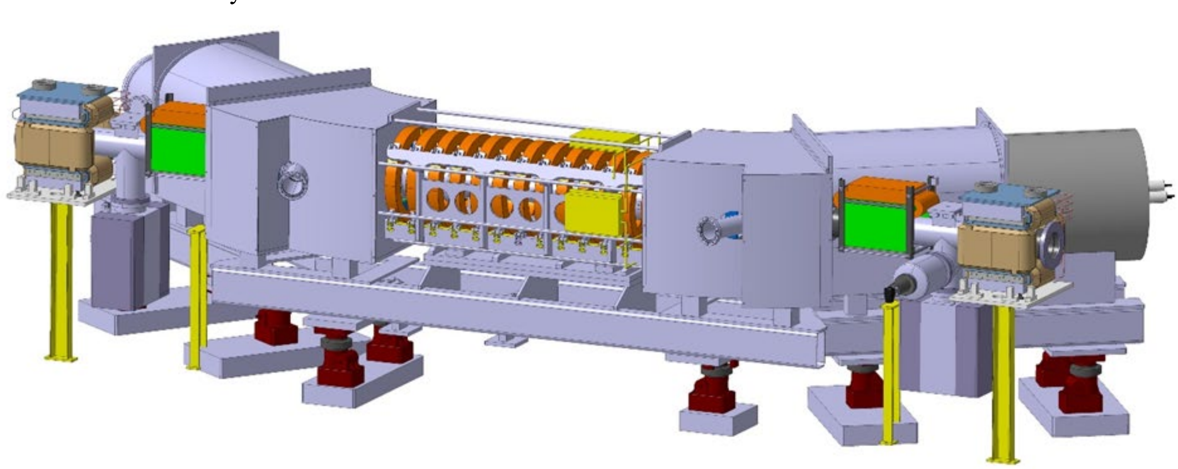

Figure 1: Mechanical design of the new AD electron cooler.

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TESTS OF THE GUN PROTOTYPE FOR THE ELECTRON COOLING SYSTEM OF THE NICA COLLIDER

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Abstract

The efficiency of the electron cooling depends on the electron beam quality produced be the electron gun. The characteristics of the electron gun were tested on the test bench with the linear transport channel. For the beam diagnostics, we used beam position monitors alongside with the W-Re wire sensor for 1-D quantitative profile measurements. We also used a high-definition CCD camera with high sensitivity for qualitative 2-D measurements of the electron density distribution via the wire thermal radiation.

INTRODUCTION

This work is related to the new electron cooling system, developed for the NICA collider facility, located in Dubna.

Unlike the previous electron cooling systems manufactured in the Budker Institute [1], the NICA collider requires the electron beam with higher current density for the effective cooling. Meanwhile, the size of the electron beam is not required to be as large as in the previous systems. Therefore, we decided to develop a new electron gun.

ELECTRON GUN

The electron gun we developed and tested is based on the Pierce optics with the shield electrode placed near a flat BaO cathode and with an additional four-sector control electrode [2] (Fig. 1).

The anode controls the overall emission, whereas the control electrode controls the emission from the edges of the cathode. This allows us to change the electron current density distribution of the beam. Also an auxiliary electrode is introduced, which controls the output energy of the electron beam on the desired distance from the anode.

To prevent the beam from expanding due to the space charge the gun is emerged into the longitudinal magnetic field.

The geometry, position and voltages of the electron gun electrodes were calculated in an iterative manner using the SAM software developed at BINP [3] in order to minimize the amplitude of Larmour oscillations. The parameters of the electron gun are in Table 1.

Table 1: Parameters of the Electron Gun

Parameter	Value
Anode voltage, kV	0-20
Control electrode voltage, kV	-3..+3
Electrons output energy, keV	1-30
Cathode / Electron beam diameter, cm	1
Electron current density, A/cm^2	0..1.5
Magnetic field, G	900-1000

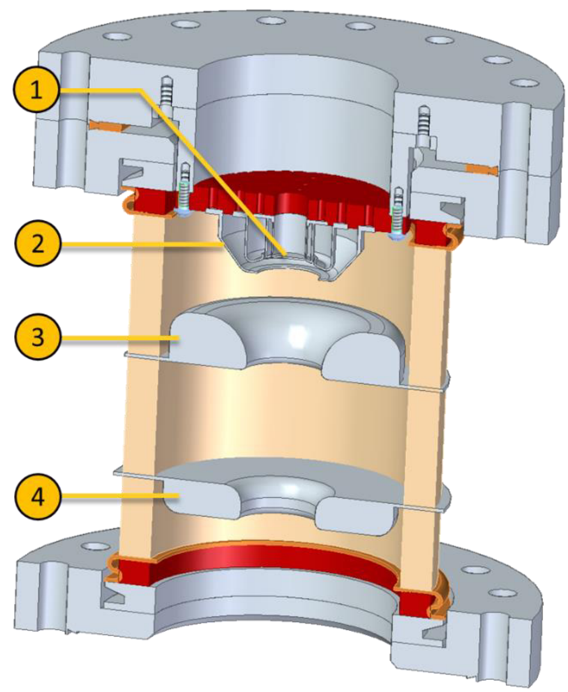

Figure 1: A design of the electron gun based on the Pierce optics. The gun includes a cathode (1), a control electrode (2), an anode (3) and an auxiliary electrode (4) for setting the electrons output energy.

TEST STAND

For testing the electron gun and developing the beam diagnostics techniques the test stand with a linear structure was assembled (Fig. 2 and Fig 3). It bases on the test stand used for testing the electron gun for the EC-300 electron cooling system. It includes the magnetic coils for providing a longitudinal magnetic field about 900-1000 Gauss along the beam transport channel.

The modified version of the test stand has a longer transport channel for the electron beam. Additional coils create the longitudinal magnetic field for the gun and collector. Magnetic coil correctors allow shifting the electron beam in the transverse direction. Additional magnetic coils placed in the centre of the transport channel change the longitudinal magnetic field locally in order to control the Larmour oscillation phase.

We also added a beam diagnostics chamber for measuring the beam position and beam current density profile. The electrons energy is up to 30 keV.

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CASCADE TRANSFORMER FOR HIGH VOLTAGE COOLER

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Abstract

Experience of using the different systems for powering the high voltage coolers are discussed. The acceleration and deceleration tube need the electric power for operating. At BINP several different power transferring systems were used. The multistage cascade transformers, and the system based on the turbo generators powered by the compressed gas flow.

HIGH VOLTAGE COOLER

The electrons in the electron cooling section should have the low temperature in the rest frame of the electron beam. For this we use strong focusing by the magnetic fields not only in the cooling section but in the entire transport channel of the electron beam, in the acceleration tube and near the electron gun. The last two parts of the electron cooling systems require to supply enough electric power in order to create the necessary magnetic field and also to power the gun and collector electronics.

Figure 1 shows the design of the cascade transformer which will be used for the high-voltage electron cooling system for the NICA collider [1].

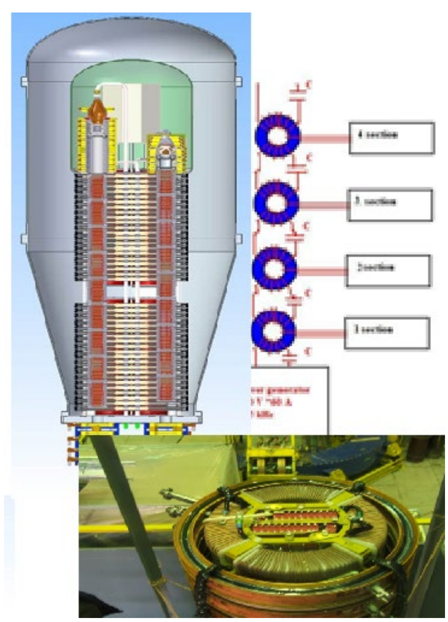

Figure 1: The design of cooler and power supply.

The cascade transformer design is similar to the design of the acceleration tube. The transformer consists of alternating ceramic and metal rings. Inside the metal ring there is a magnetic circuit with two high-voltage sectioned windings and one winding under the potential of the magnetic core to power the electronics of the high-voltage section. One high-voltage winding serves to transfer power to the next stage up, the other winding for communication with the lower section of the transformer [2].

The parameters of the cascade transformer section are presented in the Table 1.

Table 1: Parameters of a Single Section of the Cascade Transformer

Parameter	Value
Diameter of the magnetic core (outer/inner), mm	280/200
Thickness, mm	20
Mass, kg	4.8
Operational magnetic field, T	0.25
Power losses in the yank, W/kg	12
Coils current (r.m.s.), A	≤ 50
Voltage (r.m.s.), V	≤ 700
Transferred power, kW	≤ 35
Power losses, kW	7
Number of turns	28
Mass of the wires, g	230
Wires cross section, mm^2	5.8
Wires resistance, Ohm	0.015

A NEW DESIGN OF THE CASCADE TRANSFORMER

A prototype of a new cascade transformer consists of three magnetic core rings connected by eight parallel turns for communication was obtained from the manufactory and tested (Fig. 1). When making measurements (according to point 2), the input winding W1=32 turns, the first lower magnetic circuit is powered by a voltage generator (U gen)with a frequency of 25 kHz. The output winding W2=32 turns, a load with a resistance R=62 ohms is connected to the third upper magnetic circuit, and with an overall dissipation power of up to 3000W.

To calculate the coupling coefficient of two pairs of connected cascades, the input inductance of the transformer was measured in two modes-with the secondary winding of the transformer open and shorted: Inductance Lopen=15.5 mH Inductance Lshort=56 uH. The calculated coupling coefficient for one pair of cascades is equal to: Kc=0.9991.

Measurement of the voltage transfer coefficient to the load: A measuring current transformer with a current transfer coefficient of 75/1 is included in the loads circuit.

The voltages on the input W1(Ugener)and output W2 (ULoad) windings of the cascade transformer are measured using an oscilloscope in the rms cycle voltage measurement mode for a period.

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IMPROVEMENTS TO SIMULATIONS OF MICROBUNCHED ELECTRON COOLING FOR THE EIC*

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Abstract

Microbunched electron cooling (MBEC) is a promising new technique for cooling dense hadron beams. It operates by copropagating the hadron beam with a beam of electrons, during which time the hadrons induce an energy modulation on the electrons. This is amplified, turned into a density modulation, and acts back on the hadrons in order to give them energy kicks which tend to reduce their initial energy spread and emittance. We plan to use this technique to cool the proton beams at the Electron-Ion Collider (EIC). In order to better understand the process, we have expanded on our simulation codes of cooling times and saturation effects, allowing us to explore such issues as variable Courant-Snyder parameters within the lattice elements.

MICROBUNCHED ELECTRON COOLING THEORY

In order to cool the dense proton beams in the future Electron-Ion Collider (EIC), we plan to make use of microbunched electron cooling (MBEC) [1]. The theory of MBEC was first developed in [2] and expanded upon in [3–6], and full details can be found therein. The main idea is that the hadrons which one wishes to cool are copropagated with an electron bunch in a straight "modulator" section, where the hadrons induce an energy perturbation in the electron beam. The electrons and hadrons are then separated. The electron beam passes through an amplification section, where its energy perturbation is amplified and transformed into a density perturbation. The hadrons pass through a chicane with non-zero R_{51}, R_{52}, and R_{56} values, so that its delay depends on its initial energy and transverse offsets. In the "kicker" section, the hadrons and electrons again copropagate, and the density perturbations in the electron beam provide energy kicks to the hadrons, with the kick magnitude as a function of hadron delay defined by a wake function. By adjusting the hadron optics appropriately, we can arrange for these kicks to on average cool the hadrons longitudinally and transversely. A diagram of the setup is shown in Fig. 1. Parameters used for this paper are shown in Tab. 1, with the quoted Courant-Snyder parameters evaluated at the center of the appropriate element.

WAKE SENSITIVITY TO VARYING OPTICS

We had noticed that the density perturbations in the electron beam can become comparable to the total electron density, and so saturation effects cause deviations from the linear cooling theory. To account for this effect, we have developed a one-dimensional simulation code to track hadron and electron macroparticles through the elements of the cooling section using a cloud-in-cell formalism [7] and empirically determine the effective hadron wake function. Details of this simulation code may be found in [8].

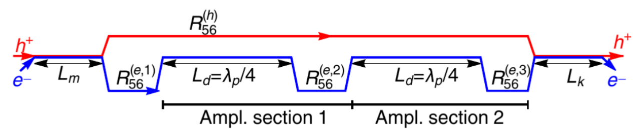

Figure 1: Layout of the MBEC cooler. Figure from [4].

Of particular note here is that the previous version of the code made the simplifying assumption that the beam sizes of the electrons and hadrons did not change within the accelerator elements, so that the inter-particle forces only had to be computed once for each element. This is of course not the case in reality, where beta functions of the electrons and hadrons will evolve within the modulator, amplifier straights, and kicker. We assume that the electrons are focused by a simple FODO scheme in each element and that the hadrons experience a drift in the modulator and kicker straights, as illustrated in Fig. 2 and Fig. 3.

We run the simulation code in two separate configurations. First, we run a detailed simulation in which we take 1m steps in the modulator and 10cm steps in the amplifiers and kicker,[1] re-evaluating the beam sizes and electron/electron and electron/hadron interaction functions at each step. We also run a simulation similar to what we had done previously, where we average the beta functions and dispersions across each element for each particle species and use these to create constant beam sizes and interaction functions in each element. We then track the macroparticles in 1m steps. Using 100 random noise seeds, we obtain the effective wake functions from these two methods, as shown in Fig. 4. We see that the use of average Courant-Snyder parameters in an element gives essentially the same result as doing the full detailed tracking.

INSENSITIVITY OF LOCATION OF ENERGY KICK

We have also developed a turn-by-turn code to simulate the multi-turn cooling dynamics in detail. This tracks hadron macroparticles in the bunch through a simplified lattice consisting of the modulator, kicker, and RF section, so that synchrotron motion may be included. Details of the code may be found in [9]. Each turn, each hadron macropar-

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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[1] A smaller step size was chosen in those elements due to the faster variation in the electron beta functions.

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A PERTURBATIVE TECHNIQUE FOR 3D MODELING OF THE MICROBUNCHED ELECTRON COOLING CONCEPT*

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Abstract

Because the efficacy of conventional electron cooling falls off rapidly with energy, reaching the required cooling time at collision energies targeted by the Electron-Ion Collider (EIC) design [1] can be challenging. A possible solution is offered by cooling schemes that are based on fundamentally different approaches such as microbunched electron cooling (MBEC) [2]. Regular particle-in-cell (PIC) simulations in the parameter regime of the EIC cooling system would require a prohibitively large number of particles to resolve the evolution of the ion-imprinted phase space density modulation. We explored a solution to this problem by developing and implementing in the code Warp a computational approach based on two perturbative techniques, the beam-frame δf method and a variant of the distribution difference (DD) technique. To model the dynamics of the ion-seeded modulation in the MBEC chicanes, we developed an approach that combines the DD and quiet start techniques with analysis of correlations between the divergence of pairs of DD trajectories and their location within the e-beam. We have also prototyped in Warp the computation of the time-dependent 3D wakefield in the MBEC kicker.

δf SIMULATION OF THE MODULATOR SECTION

We have prototyped the δf algorithm [3–5] for modeling the ion-induced modulation dynamics in the modulator section of the EIC cooler, assuming a single-chicane MBEC layout [2, 6] for this initial investigation. In the δf-PIC approach, the phase space density f of the electron beam is decomposed into the sum of (i) the background distribution f_0, assumed to be an analytically known function of the phase space variables and time, and (ii) the perturbation δf which is represented by variable-weight macroparticles whose weights w and phase space coordinated evolve in response to the perturbing influence (e.g., the ion) and the background. Two key aspects of the dynamics in the modulator are the interaction of the δf particles with the ion and the space charge forces associated with the e-beam density modulation. It is therefore advantageous to work in the beam frame where the relevant dynamics are non-relativistic and an electrostatic field solver can be used. We have developed a hybrid formulation of the δf algorithm, where the phase space coordinates and weights of the δf particles evolve in the beam frame, while the background distribution f_0, whose gradients enter the evolution equations, is given in terms of the *beam-frame* phase space coordinates and the Twiss parameters of the e-beam specified in the lab frame. Such formulation allows us to include in simulations the effects of focusing quadrupoles on the electron beam dynamics. This is important for modeling the actual cooler lattice that includes multiple quadrupole focusing sections, because the transverse-to-longitudinal coupling in the quads can perturb the electrons' longitudinal momentum modulation imprinted by the ion.

We take $f_0(s)$ to mean the background e-beam distribution evolving in response to the external focusing magnet fields as well as (for non-emittance-dominated beams) the bulk space charge self-force. The growth of the perturbation $\delta f(s)$ is then due to the beam-frame Coulomb field of the ion and the Coulomb field of the ion-induced electron density perturbation, the latter expected to be a small fraction of the field of the ion in the parameter regime of the EIC cooler modulator section. We employ an approximation that f_0 is separable in x, y, and the longitudinal phase space coordinates:

$$f_0(s;x,x',y,y',z,v_z) = f_0^{(x)}(s,x,x')f_0^{(y)}(s,y,y')f_0^{(z)}(s,z,v_z) \tag{1}$$

with $f_0^{(x)}$ and $f_0^{(y)}$ bi-Gaussian in their respective trace spaces, and $f_0^{(z)}$ constant in z and Maxwellian in v_z, *i.e.*,

$$f_0^{(x)}(s,x,x') = C\exp\left(-\frac{\hat\gamma_x(s)x^2 + 2\hat\alpha_x(s)xx' + \hat\beta_x(s)x'^2}{2\epsilon_x}\right) \tag{2}$$

and similarly for the y trace space.

With the above assumptions, we obtain the δf particle weight evolution equation:

$$\begin{aligned}\frac{dw}{dt} = -\frac{1}{f_0}(1-w)\frac{df_0}{dt} = -(1-w)\Bigg(&\frac{\partial}{\partial t} + \vec v\frac{\partial}{\partial \vec x}\\ &+\frac{q}{m}(\vec E_{total} + \vec v\times\vec B_{total})\frac{\partial}{\partial\vec v}\Bigg)\ln(f_0).\end{aligned} \tag{3}$$

Because we work in the beam frame, the gradients of the f_0 have to be expressed in terms of the beam frame variables (labeled by "b"), and the beam-frame time $t_b = s/\gamma_0\beta_0 c$ is used to parametrize the dynamics. The partial derivatives of f_0 that enter Eq. (3) are given by

$$\begin{aligned}\frac{\partial}{\partial t_b}\ln f_0^{(x)} = -\frac{\gamma_0\beta_0 c}{\epsilon_x}\Bigg[&\frac{\hat\alpha_x(s)}{\hat\beta_x(s)}\left(\frac{\partial\hat\alpha_x(s)}{\partial s} + \hat\gamma_x(s)\right)x^2\\ &+\frac{1}{\gamma_0\beta_0 c}\frac{\partial\hat\alpha_x(s)}{\partial s}xv_{bx} - \frac{\hat\alpha_x(s)}{(\gamma_0\beta_0 c)^2}v_{bx}^2\Bigg],\end{aligned} \tag{4}$$

$$\frac{\partial}{\partial x}\ln f_0^{(x)} = -\frac{1}{\epsilon_x}\left[\hat\gamma_x(s)x + \frac{\hat\alpha_x(s)}{\gamma_0\beta_0 c}v_{bx}\right], \tag{5}$$

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FEATURES OF THE PICKUP DIAGNOSTIC AT LOW ENERGY IN THE COOLER OF NICA BOOSTER

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Abstract

This work deals with an experimental study of changes in the amplitude of the sum signal induced at pickup stations, which can be associated with the formation of space charge waves arising along the electron beam. In the case of low electron energies, the space charge of the beam can have a significant effect on the interpretation of the obtained experimental data.

INTRODUCTION

The electron cooling system of the NICA booster is designed to accumulate an ion beam during injection and to cool it after acceleration to a certain intermediate energy. This system was developed and tested at the BINP SB RAS [1]. The maximum electron beam energy in it is 50 keV, which corresponds to an ion energy of 100 MeV / nucleon. The minimum energy of 1.74 keV corresponds to the injection energy. The schematic design of the electron cooler is shown in Fig. 1 and the main specification at the Table 1.

The electron beam is generated by an electron gun immersed into the longitudinal magnetic field. After that the electron beam is accelerated, moves in the toroid magnet to the cooling section where it will interact with ions of Booster storage ring. After interaction the electron beam is decelerated and absorbed in the collector. The centrifugal force in toroid magnets is compensated by the electrostatic plates.

Table 1: Main Specifications of the Cooler.

ions type	from p+ up to $^{197}Au^{31+}$
electron energy, E	1,5 ÷ 50 keV
electron beam current, I	0.2 ÷ 1.0 Amp.
energy stability, $\Delta E/E$	$\leq 1\cdot 10^{-5}$
electron current stability, $\Delta I/I$	$\leq 1\cdot 10^{-4}$
electron current losses, $\delta I/I$	less than $3\cdot 10^{-5}$
longitudinal magnetic field	0.1 ÷ 0.2 T
inhomogeneity of the field in the cooling section, $\Delta B/B$	$\leq 3\cdot 10^{-5}$
transverse electron temperature	≤ 0.3 eV
ion orbit correction:	
residual gas pressure	10^{-11} mbar.

For the effective realization of the electron cooling method, it is necessary to accurate combine both beams inside cooling section. For this purpose, electrostatic sensors or pickup electrodes are used. For position measurements the ion beam must be bunched using the RF system of booster. In order to measure the position of the electron beam, it is modulated with sinusoidal voltage at 3 MHz with amplitude 10 V applied to the control electrode. The magnitude of the electron current modulation is usually much less than the total current of the electron beam. In order to get additional information about the dynamics of the electron beam a system of 4 pickups located along its trajectory is used.

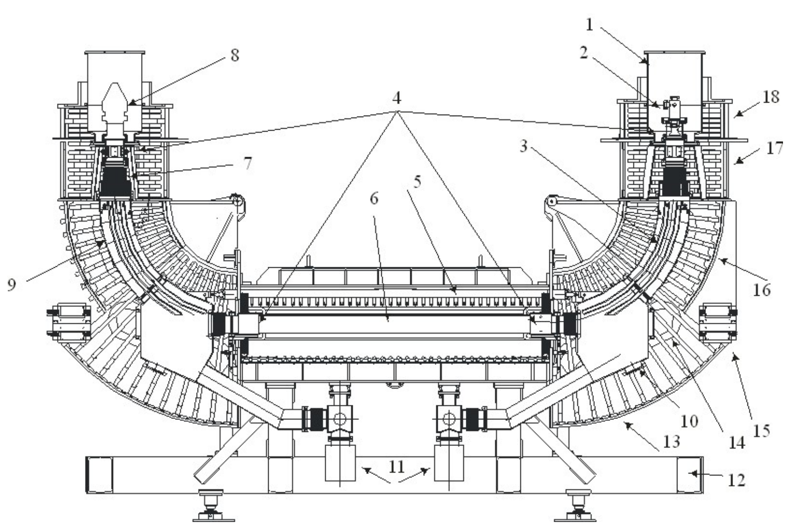

Figure 1: Design of electron cooler for NICA booster. The SF_6 vessel is 1, the electron gun is 2, the electrostatic plate is 3, pickups are 4, cooling section is 5, the vacuum chamber of cooling section is 6, NEG pump is 7, collector is 8, the vacuum chamber of toroid is 9, titanium pump is 10, the ion pumps are 11, the support is 12, the toroid is 13, the correction coil is 14, the corrector of ion beam is 15, the toroid solenoid is 16, the matching solenoid is 17, the gun solenoid is 18.