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COSY EXPERIENCE OF ELECTRON COOLING

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Abstract

The 2 MeV electron cooling system for COSY-Jülich has highest energy for the electron cooler with strong longitudinal magnetic field. During operation the cooling process was detailed investigated at 908 keV energy of electron beam. The proton beam was cooled at different regimes: RF, barrier bucket RF, cluster target and stochastic cooling. This article deals with the experience of electron cooling at high energy.

INTRODUCTION

In the present time a large experience of using magnetized cooling was collected [1-3]. The first experiments in BINP and further experiments in the other scientific centres show the usefulness of the idea of magnetized cooling. There are many electron cooler devices that operate now at low and middle energy (CSRm, CSRe, LEIR, ESR, e.t.c). The 2 MeV electron cooling system for COSY-Jülich has the highest energy of all coolers based on the idea of magnetized cooling and transport of the electron beam [4-5].

The schematic design of the electron cooler is shown in Fig. 1. The electron beam is generated by an electron gun and accelerated by an electrostatic generator that consists of 33 individual sections connected in series. It is then guided to the cooling sections through the transport line by means of a longitudinal magnetic field. There it will interact with protons. After interaction the electron beam returns to the electrostatic generator where it is decelerated and absorbed in the collector.

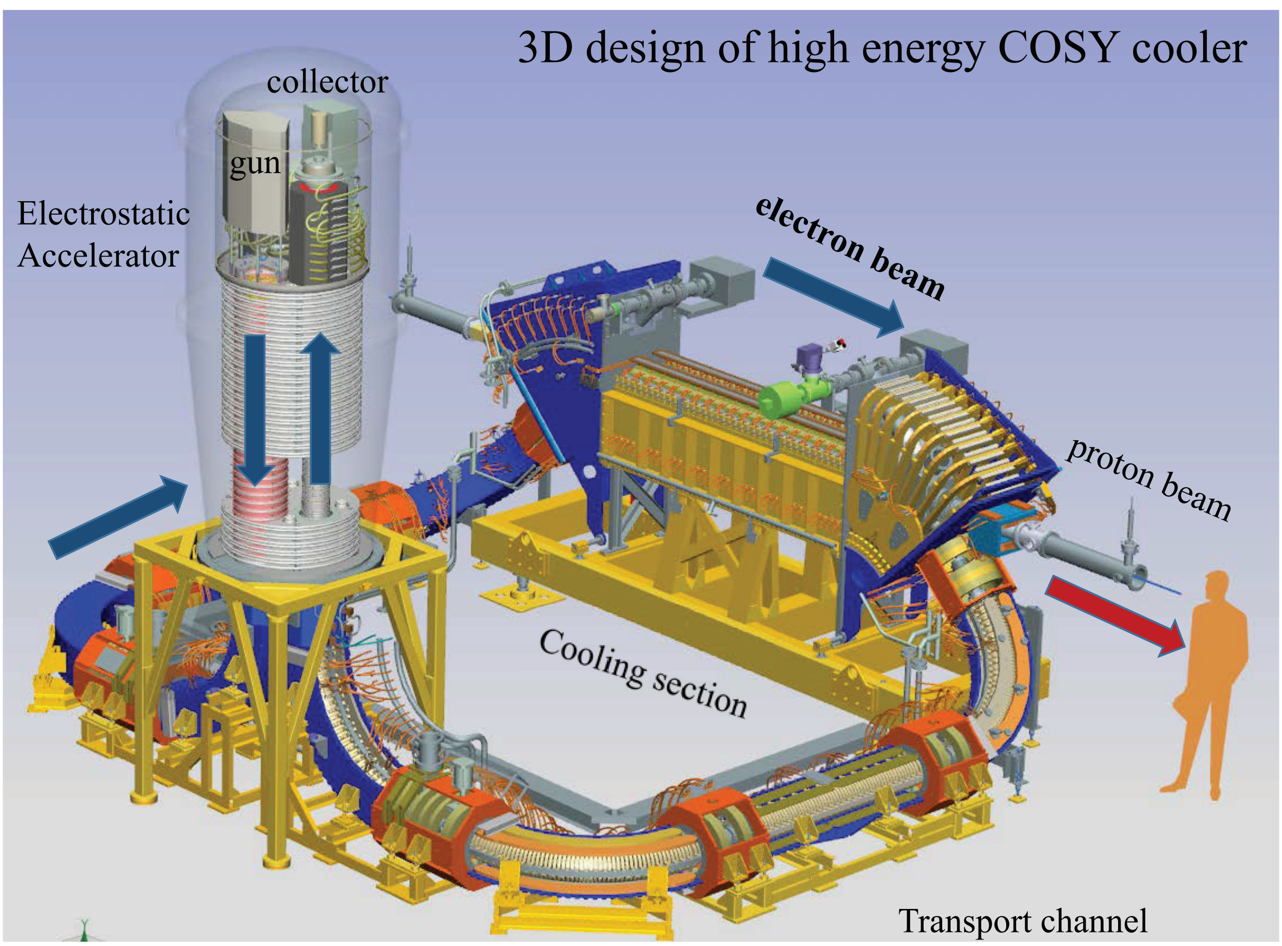

Figure 1: 3D design of 2 MeV COSY cooler.

The optics of the 2 MeV cooler for COSY is designed close to the classical low-energy coolers. The motion of the electron beam is magnetized (or close to magnetized conditions) along the whole trajectory from gun to collector.

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FIRST OPERATION FOR STOCHASTIC COOLING OF P-BARS IN THE CERN AD USING OPTICAL DELAY NOTCH FILTER AND PLANS FOR 2021 OPERATION

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Abstract

As part of the consolidation of the stochastic cooling system of the CERN Antiproton Decelerator a notch filter with optical delay lines has been developed. During the 2018 run this new notch filter for the longitudinal cooling at 3.57 GeV/c was successfully tested with beam for the first time. We summarize the hardware implemented including a comparison of hardware transfer functions of the new system and the original system using a coaxial cable plant for the same purpose. Automatic monitoring of the hardware transfer function, being prepared for 2021, will be provided in order to periodically check drifts of the system and send corrections to the control of the system. Integration of this monitoring and feed forward system into the CERN controls environment will be shown.

INTRODUCTION

The CERN antiproton decelerator (AD) has been conceived reusing parts of the former antiproton accelerator complex at CERN which has served to provide antiprotons to the Sp$\bar{\text{p}}$ collider from the 1980's onwards [1, 2]. The AD which started operation some 20 years ago in 1998 is designed to provide low energy antiprotons in the range down to 100 MeV/c momentum to a set of experiments located in the AD experimental hall [3].

Antiprotons generated at a target by a primary proton beam from the PS are injected at a momentum of 3.57 GeV/c into the AD ring. Stochastic cooling is applied in all three planes, horizontal, vertical and longitudinal, first at the injection plateau of 3.57 GeV/c and then after deceleration to 2 GeV/c [4].

AD CYCLE AND STOCHASTIC COOLING SYSTEM OVERVIEW

Initially projected for a cycle time of 60 s the AD is today run with a ~100 s long cycle with sufficiently long cooling plateaus in order to provide the nominal emittances with some margin. Ramp rates and idling time at flat-top are limited by magnet cooling and magnet power converters.

Figure 1 shows an overview of the stochastic cooling system. Two pick-ups are used, one horizontal and one vertical. The signal for longitudinal cooling is taken from a combination of the common mode signal from the two transverse pick-ups. The three paths of the signal processing are linked with coaxial 1 5/8" RF lines ($v \simeq c$) to the location of the 48 power amplifiers across the AD hall. These 100 W power amplifiers are installed on top of the shielding of the AD machine gallery. The overall bandwidth of the system ranges from 0.9 GHz to 1.65 GHz with smooth tapering of the gain at the edges of the pass band to minimise changes of delay with frequency that would be detrimental to cooling. The longitudinal signal is combined with the transverse signals at the amplifier platform before signals are split to feed the 24 kicker elements on plunging support structures in each tank through individual feedthroughs. The kicker tank features water cooled loads inside the vacuum tank and the pick-up tank combiner loads are cooled with liquid helium to provide a low noise signal source temperature.

The longitudinal branches of the cooling employ a comb type notch filter with a periodicity equal to the beam revolution frequency at the respective energy. The filter is obtained by combining a directly transmitted longitudinal signal with a signal delayed by one turn. In the original system the delayed branch is realised with coaxial cables with lumped circuits and amplification to match the frequency dependent attenuation, group delay, and the dispersion of the direct path. Part of the direct transmission is realised by a mechanically delicate, ~10 m long thin (< 0.5 mm) coaxial cable to achieve matching of the transmission characteristics. The overall length of the short path is critical at 3.57 GeV/c with a velocity factor of > 98% implemented for the combined length of ~ 40 m of 1 5/8" coaxial line.

In the new system, which was used for the first time with beam in 2018, the transmission for the 1-turn delay has been replaced by an optical fiber cable with low attenuation. Consequently the compensating circuits and the thin coaxial cable of the direct path could be suppressed gaining around 16 ns of delay. Commissioning of this new system is described in more detail further below.

Tables 1,2 shows the performance in cooling as achieved in regular operation and with the classical electric delay line notch filter.

Table 1: Parameters for Cooling at 3.57 GeV/c [4, 5]

Parameter	Design	Achieved
Intensity at 3.57 GeV/c	5×10^7	$\simeq 4 \times 10^7$
Cooling time	20 s	20 s
Hor. emittance (95%)	5π mm mrad	3π mm mrad
Ver. emittance (95%)	5π mm mrad	4π mm mrad
Momentum width	$\pm0.5 \times 10^{-3}$	$\pm0.35 \times 10^{-3}$

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STATUS OF THE TURBINE-DRIVEN HV-GENERATOR FOR A RELATIVISTIC ELECTRON COOLER

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Abstract

Power generation by gas turbines at high potentials can become an alternative to insulating transformers or rotating shafts in electron coolers operating in the range of several MeV. Our main objective is to explore this technique for an application in a high energy cooling device at HESR. The status of the project, its potential advantages and the perspectives are discussed.

INTRODUCTION

Since electron cooling requires fulfilling the condition of equal ion and electron velocity it is mandatory to provide powerful electron beams in the MeV range for the upcoming HESR storage ring at the FAIR facility. The 2 MeV cooler from COSY [1] could be used but will only cover the lower energy range whereas antiproton cooling at the highest HESR-energies would require almost V=8 MV acceleration potential. One should keep in mind that cooling times can be significantly reduced if the beam is magnetized which will be necessary to counteract the heating effect of the internal target at the PANDA-experiment in HESR.

The longitudinal magnetization field is provided by a chain of solenoids which also has to cover the acceleration stage. The solenoids then sit at different potentials and need floating power supplies. Another supply is needed for the electron source/collector system at the HV-terminal. Therefore, several acceleration modules with an individual power supply are needed. If the number of modules is N, the potential difference between the stages is V/N. In a recent design study by Budker Institute for Nuclear Physics (BINP) it was suggested to choose V/N=0.6 MV, which allows using established HV-generators to maintain the voltage between the modules while keeping a pair of solenoids (for accelerated and decelerated beam respectively) at the potential of the module-deck. This arrangement of solenoids would still provide a reasonable field quality.

A number of N = 14 modules is needed to have some margin for an 8 MV device. The power consumption of a stage will be less than 3.5 kW. Including the terminal, a power ~ 50 kW on different HV potentials may be needed. The main purpose of the ongoing work is to demonstrate the reliability of the power generation approach and the scalability of the stages. Therefore, "HESR-prototype" HV-modules of 1:1 scale are being tested. An important question is the method of potential- free ("floating") power generation for which we use a special set-up at Helmholtz Institut Mainz (HIM). We address power generation in the next section and describe the status of HV-module experiments afterwards. Finally, the long-range plans will be explained in the "outlook"-section.

TURBINE APPROACH

There are several potential advantages of turbines as floating power generators compared to existing technologies like insulating transformers or generators driven by insulating rotating shafts which have powered devices at the ~5 MV level already [2,3].

We have demonstrated [4] that commercially available turbine-generators can provide the required power level for extended periods of time (>1000 h) without the need for maintenance. The turbo-generators are sold under the trade name "Green Energy Turbine" (GET) by the company DEPRAG [5] and deliver 5 kW per unit, so a single turbine can drive a HV-module. Investment costs are ~10 €/Watt (including the cost of the compressor) on the terminal and energy efficiency from wall plug to terminal is about 15% for our application. This can be considered as affordable as far as HESR operation is concerned.

The relatively low efficiency is to some extent caused by the pre-cooling of the compressed gas in our commercial compressor system (Fig. 1). The heat of the compressed gas is taken away by cooling water and is therefore lost. This happens *outside* the HV-device. Then the gas is sent to the HV-tank inlet at approximately room temperature. The expanding gas from the turbine *inside the HV-tank* is cooled since energy in form of electrical power is extracted from it. The electrical power is finally transformed again into heat by the loads. It is evident that the exhaust gas can be used to absorb this heat again. In our present set-up this is done by an air/liquid heat exchanger on the HV-deck. Stable thermal conditions at moderate temperature levels of the individual devices can be realized. A thermal management becomes thus possible, keeping temperatures inside the HV-tank at appropriate values. This feature is an advantage for the turbine, since other methods of power generation need additional cooling circuits with connection to heat exchangers at ground potential.

SET-UP AT HIM

Figure 1 shows the compressor with buffer tanks for the compressed gas. Copper tubes lead to the HV-module-inlet from where the gas is guided by a plastic tube towards the turbine. The compressor can drive three such turbines. In September 2018 BINP delivered the first HV-module to HIM, which carries a turbine on the HV-deck. The functionality was successfully tested albeit only at a voltage level of 60 kV due to the absence of a pressure vessel.

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THE ELECTRON COOLING SYSTEM FOR HIAF PROJECT IN CHINA*

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Abstract

A classical 450 keV magnetized DC electron cooling system is proposed to boost the luminosity of high-density internal targets experiment in the spectrometer ring (SRing) at HIAF. Electron cooling will provide highest phase space density of the stored highly charged heavy ion beams and compensate beam heating during internal target experiments. In addition, it will be used to suppress the beam loss in the deceleration mode. In this paper, the technical design of the electron cooling system is reported. The manufacturing of the key components such as the electron gun and collector is described.

INTRODUCTION

High Intensity heavy-ion Accelerator Facility (HIAF) is a new accelerator complex being constructed at the IMP site in China [1]. 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 after deceleration. A powerful electron cooling system is needed for the stable ion beams in the energy range of 800 to 30 MeV/u. It also allows few intermediate energies cooling in the deceleration operation mode, to obtain a high efficiency and low losses during the deceleration of ion beams. The electron beam should be turned off during the ramping of the high voltage deceleration. In addition, the electron cooling involves isotopes beam cooling together with the stochastic cooling system. Figure 1 shows the layout of the HIAF accelerator complex. The electron cooler will be installed in the 16 meter-straight section of SRing. The length of the cooler in ion beam direction is 11.2 m. the height is limited by the tunnel up to 6 m. Therefore, the high voltage tank is equipped on the side of the cooler.

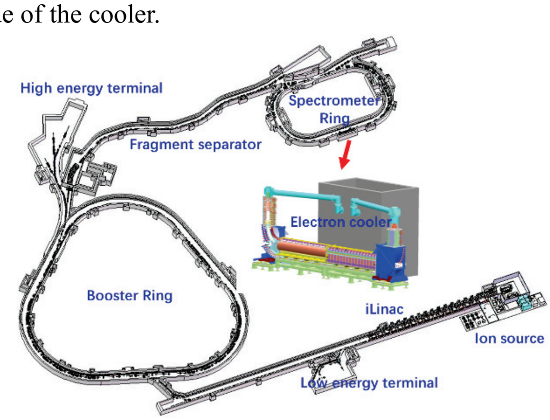

Figure 1: Layout of the HIAF accelerator and its cooler.

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CHOICE OF PARAMETERS

The ion beam $^{238}U^{92+}$ is taken as a reference in the simulation and design work of SRing. The ion energy ranges from 800 MeV/u to 30 MeV/u (deceleration) that corresponds to the electron energy range of 15 keV and 450 keV. The initial beam parameters are defined by the fast extraction system of the booster ring (BRing), as listed in Table 1. The calculations in this paper were performed a multi-particle tracking code, in which the cooling rate was derived from Parkhomchuk cooling force formula:

$$G = \frac{1}{\gamma^2}\frac{4cr_e r_i n_e \eta_c}{\left(\beta^2\gamma^2\frac{\varepsilon_\perp}{\beta_\perp}+\beta^2\left(\frac{\Delta p}{p}\right)^2+\left(\frac{v_{eff}}{c}\right)^2\right)^{\frac{3}{2}}}\frac{Z^2}{A}\ln\left(1+\frac{\rho_{max}}{\rho_{min}+\rho_l}\right). \quad (1)$$

the definition of the parameters can be found in [2]. All parameters should be written in the laboratory reference system.

Table 1: Initial Beam Parameters of SRing

Parameters	Value
Ion	$^{238}U^{92+}$
Energy	800 MeV/u
Emittance (hort./vert.)	4.0/2.0 π.mm.mrad
Momentum spread	8.0×10^{-4}
Stored particle number	10^9

The circumference of SRing is 277.3 m and the longest straight section is 16.0 m. The cooling rate grows linearly with the cooler length. Thus, a long cooler has a high cooling rate. Especially it is essential at the injection (top energy) stage when the emittance and the momentum spread are large. Based on the CSR cooler design, a U-shape electron cooler was proposed with the bending radius of 1.0 m. Further, a space for the compensation solenoids and correctors was considered at upstream and downstream of the cooler. Finally, an 8 m cooling solenoid was chosen for the SRing cooler. The designed β function at the centre of the cooler is 10.0 m, we estimated the maximum β function is not larger than 13.0 m according to the formula $\beta + s^2/\beta$.

The electron intensity also determines the cooling rate. Generally, the cooling rate is proportional to the electron beam current. But on the other hand, the effective velocity induced by a space charge electron drift in the longitudinal magnetic field could reduce the cooling rate. Thus, a very high electron current becomes useless. Figure 2 shows the cooling rate versus the electron current at different values of the magnetic field. The other parameters used in the calculation are listed in Table 2. Based on the operation experience of CSRe 300 kV cooler, and in consideration of the power consumption on the high voltage terminal, the maximum electron currents up to 2.0 A was designed for the

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DESIGN OF A COMPACT ELECTRON GUN FOR THE HIGH-VOLTAGE ELECTRON COOLING SYSTEM OF THE NICA COLLIDER

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Abstract

The low temperature of the electron beam is the key for the high efficiency of the electron cooling, and the strong guiding magnetic field is the means for it. However, high-voltage electron cooling systems come with the challenge of providing the low-temperature beams, as the guiding magnetic field is limited. The electron gun design for the NICA collider cooling systems combines the utilizing the magnetic field and the electrical field constructing, by using the electrodes of special shapes.

INTRODUCTION

The NICA collider is designed to operate ion beams with energies up to 4.5 GeV/u [1]. In order to increase the ions accumulation efficiency and ions lifetime in the collider the electron cooling system must provide 2.5 MeV electron beams [2]. During the electron cooling process, the ions lose excess energy due to electrical interactions with electrons. The more electrons, the more energy it can take from ions. Therefore, the efficiency of the cooling depends on the electron beam current density and the momentum spread in the electron beam [3].

Budker Institute of Nuclear physics has a lot of experience in creating electron cooling systems for different beam energies, starting from the first electron cooling system where the very principle of the electron cooling were demonstrated [4], ending with the high-voltage cooler for COSY [5] and low-energy cooling system for NICA [6] Booster. All those systems exploit the similar design of an electron gun, sometimes with small modifications. The main part of the used gun designs is a control electrode, which allows controlling the emission from different parts of a cathode. Later, for electron coolers for COSY and NICA Booster the design of the control electrode was improved by splitting it into four sectors with independent high-voltage power supplies.

The previous design of electron guns used in electron cooling systems produced in BINP exploit a 3 cm diameter cathode. The radius of ion beams in NICA collider is just 0.3 cm (rms). The high-voltage electron cooling system for the NICA collider will use a new electron gun able to produce a 1 cm diameter continuous electron beam with current up to 1 A.

REQUIREMENTS FOR THE ELECTRON GUN

Electron Beam Current Density

The electron beam current density and momentum spread are two major factors that affect the cooling efficiency. According to Parkhomchuk's empirical formula (1), the cooling time is inversely proportional to the electrons density, and for the NICA collider we want it to be at least one order of magnitude lower than the IBS growth time.

$$\frac{d\vec{p_i'}}{dt'} = \frac{4Z^2e^4n_e'\Lambda}{m_e}\cdot\frac{-\vec{v_i'}}{\left[{v_i'}^2 + v_{eff}^2\right]^{3/2}} \tag{1}$$

Here n_e', v_i', p_i' are the electron density, ions velocity and momentum in the beams frame of reference. v_{eff} is the parameter describing the magnitude of electrons motion, and Λ is a Coulomb logarithm.

Taking into account the NICA collider design parameters, shown in Table 1, and using the cooling time estimation (2) resulting from Parkhomchuk's formula, the necessary electron current density amounts to 0.8 A/cm^2. The final design electron current is 1 A, corresponding to 1.5 A/cm^2.

Table 1: NICA Collider Parameters for Cooling Time Estimations

Parameter	Value		
Z/A	79 / 197		
Ion energy, GeV/u	1.0	3.0	4.5
Hor/ver rms emittance, π·mm·mrad	1.1 / 0.95	1.1 / 0.85	1.1 / 0.75
IBS growth time, s,	160	460	1800
Beta function at the cooling section, m	10		
Collider circumference (L_P), m	503		
Cooling section length (L_C), m	6		
Cooling time (t_{Cool}), s	16	46	180
j_e, A/cm^2	0.05	0.6	0.8

$$\tau_{Cool} \sim \frac{x'^3}{j_e}\cdot\frac{A}{Z^2}\cdot\frac{\gamma^5 m_e m_p v_0^4}{4e^3\Lambda}\cdot\frac{L_P}{L_C} \tag{2}$$

Here v_0 is the mean ion beam velocity, x' is the r.m.s. angle in the ion beam in the cooling section, L_P/L_C is used to take into account that the cooling takes place only in a small part of the ion collider. Λ is approximately equal to 5.

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STATUS OF THE ELECTRON COOLER FOR NICA BOOSTER AND RESULTS OF ITS COMMISSIONING

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Abstract

The electron cooling system of the NICA booster is intended for accumulation of the ion beam at the injection energy and for cooling at some intermediate energy value before acceleration to the extraction energy. The system was produced in BINP (Novosibirsk, Russia) and commissioned in the JINR (Dubna, Russia) in 2019. The current status of the electron cooler and the results of its tests are presented in the article.

INTRODUCTION

In order to achieve needed parameters of the ion beam in the NICA booster the ring will be equipped with low energy electron cooling system, which provides accumulation of ions on injection energy (3.2 MeV/u) and on some intermediate energy (60-100 MeV/u) to prepare the beam for acceleration to the extraction energy.

The electron cooling system was developed and commissioned in the BINP in 2016. In 2017 it was assembled and commissioned in the JINR. Its main parameters are shown in the Table 1.

Table 1: Main Parameters of the Cooler

Parameter	Value
Ion type	$^{197}Au^{31+}$
Electron energy, E	1.5÷60 keV
Electron beam current, I	0.2÷1.0 A
Energy stability, ΔE/E	$<10^{-5}$
Electron current stability, ΔI/I	$<10^{-4}$
Longitudinal magnetic field, B	0.1÷0.2 T
Electron current loses, I_{leak}/I	$<3\cdot10^{-5}$
Vacuum pressure, Pa	$\approx10^{-11}$ mbar

Important feature of the system is possibility of work on different energies in one cycle of booster ring (ramp regime). Since length of booster cycle is several seconds, regime of the cooler have to be changed from injection to intermediate energy in period of about 0.5-1 sec.

CONSTRUCTION

The cooler is produced with the classical scheme (Fig. 1). The DC electron beam is formed in the gun and then it is accelerated to work energy. After acceleration it moves through the toroid magnet to the cooling section, where it interacts with ion beam. After that the electrons move though another toroid to the electron collector where them are decelerated and absorbed on collector surface. Deceleration before collector is made to recuperate electron energy.

On whole way from gun to collector the beam moves in longitudinal magnetic field. There are two reasons for it: the field provides transverse focusing of the beam; in the cooling section the field allows to make, so called, fast electron cooling [1]. In order to reach high homogeneity of longitudinal magnetic field in the cooling section, the solenoid is made of separate coils with possibility to rotate each coil around two transverse axes [2].

To compensate centrifugal force in toroid magnets special electrostatic plates, which produce transverse electric field, are used. Use of electric filed instead of magnetic to compensate centrifugal force allows to increase recuperation efficiency without improving of collector efficiency [3,4].

The gun and the collector are based on constructions used in previous coolers produced in BINP. The collector consists of two parts: main massive, oil cooled, electrode and ceramic insertion before it, which contains suppressor and pre-collector electrodes. The suppressor allows to produce potential barrier on the collector entrance in order to lock secondary electron in the collector, to increase its efficiency. The pre-collector electrode has the same voltage as the collector and provides symmetry of the potential in suppressor region. The electrostatic barrier in the collector is supplemented by magnetic plug, which is produced by special shape of the magnetic filed.

The main gun feature is four sector control electrode that provides measure not only beam position (with the help of beam position monitors, by modulation of voltage on all four sectors simultaneously) but also beam size (by modulation of voltage on every sector separately) [5].

Solenoids of the magnetic system are powered with 4 independent high current power supplies (PS, IST type). Nominal value of the longitudinal field in the system is 1-2 kG.

Besides high current supplies the system contains set of low current power supplies (5 and 20 A), which power magnetic correctors of the cooler.

In order to work in ramp regime, correctors and HV system must have capability to change output parameters for a period of 0.5-1 sec. It was decided, that high current PS (IST) will not change output current during ramp, because

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RF ACCELERATOR FOR ELECTRON COOLING OF ULTRARELATIVISTIC HADRONS

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Abstract

New projects of high-energy hadron colliders could be improved by far by using the electron cooling technique. However, a source of high-current relativistic electron beam appears to be a technical challenge. Indeed, the intrinsic energy limitations of high-voltage DC accelerators lead to necessity to perform acceleration using not static but vortex electrical fields. Induction and radiofrequency (RF) accelerators employ such fields. Moreover, to keep the damping times small enough at high energies, it is necessary to increase the electron peak current to tens of amperes. The feasibility of RF energy recovery linac (ERL) application to electron cooling is discussed. The ERL of the Novosibirsk free electron laser facility is used as a reliable prototype.

INTRODUCTION

New projects of high-energy hadron colliders could be improved by far by using the electron cooling technique [1-7]. However, a source of high-current relativistic electron beam appears to be a technical challenge. Indeed, the intrinsic energy limitations of high-voltage DC accelerators lead to necessity to perform acceleration using not static but vortex electrical fields. Induction and radiofrequency (RF) accelerators employ such fields. Moreover, to keep the damping times small enough at high energies, it is necessary to increase the electron peak current to tens of amperes. As the duty factor of the cooler shall also be high, the desirable average beam current of the cooling electron beam is about 1 A or more.

Skipping at this point the betatron option, we will discuss the feasibility of RF energy recovery linac (ERL) application to electron cooling.

The necessity of high current and relatively low (less than 100 MeV) electron energy leads to the choice of an ERL with a low-frequency non-superconducting accelerating RF system. Indeed, the characteristic parameters for longitudinal stability of the average electron beam current I_{beam} and charge per bunch q are the ratio of the beam power to the power consumption in the RF cavities

$$\frac{P_{beam}}{P_{RF}} \approx \frac{I_{beam}U}{U^2/(2R)} = \frac{2I_{beam}R}{U} = \frac{QI_{beam}2(R/Q)}{U} \sim \frac{QI_{beam}}{10\,\text{kA}} \tag{1}$$

and the energy deposition per bunch to the stored energy of RF cavity

$$\frac{qU}{CU^2/2} = \frac{q\omega 2(R/Q)}{U} \sim \frac{q\omega}{10\,kA}, \tag{2}$$

where R/Q, ω, $C = (\omega R/Q)^{-1}$, and U are the characteristic impedance, fundamental eigenfrequency, effective capacity, and voltage amplitude of single cavity, respectively. For the typical values U = 1 MV and $2R/Q$ = 100 Ohm, $U/(2R/Q)$ = 10 kA. Then Eqs. (1) and (2) give the following limitations for the average current and the bunch charge:

$$I_{beam} < \frac{10\text{kA}}{Q} \tag{3}$$

and

$$q < \frac{10\text{kA}}{\omega}. \tag{4}$$

For the non-superconducting cavities of the Novosibirsk free electron laser (FEL) facility [8, 9], ERL Q = 20000 and $\omega = 2\pi\cdot 180$ MHz, and Eqs. (3) and (4) give reasonable limiting values of 0.5 A and 10 μC, but for the superconducting cavities they are several orders of magnitude lower. For low-frequency non-superconducting RF systems, the transverse stability conditions are also much easier.

INJECTOR

To provide high charge per bunch, one can use a low-frequency RF gun. A 90 MHz CW RF gun with an average current of more than 0.1 A was built and tested at Budker INP [10]. In fact, in more than twenty years, Budker INP has manufactured tens of RF guns with electron energy of up to 1 MeV as industrial accelerators, referred to as ILU-8 [11]. The ILU-8 accelerators operate in a high duty cycle pulse mode and provide a peak current of up to 5 A.

For further gain in the bunch charge, it is necessary to increase the cathode diameter and decrease the RF and bunch repetition frequencies. A frequency of 30 MHz seems to be as a reasonable compromise between increasing the RF cavity size and obtaining more than 10 nC in each bunch. With a peak cathode current of 4 A and an initial bunch duration of about 4 ns, one can obtain a bunch charge of 16 nC. To have a significant accelerating gradient in an RF structure, it is necessary to use a higher RF frequency. Then, for further RF acceleration it is necessary to compress the bunch. In the consideration below, we will

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PROGRESS IN MUON IONIZATION COOLING DEMONSTRATION WITH MICE*

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on behalf of the MICE collaboration

Abstract

The Muon Ionization Cooling Experiment (MICE) at RAL has collected extensive data to study the ionization cooling of muons. Several million individual particle tracks have been recorded passing through a series of focusing magnets in a number of different configurations and a liquid-hydrogen, lithium-hydride, or polyethylene-wedge absorber. Via measurement of the tracks upstream and downstream of the absorber, we have observed ionization cooling. Our measurement is in good agreement with our simulation of the effect. Further studies are now providing more and deeper insight.

INTRODUCTION

High-energy lepton colliders have been proposed as potential future facilities to follow up on discoveries made and to be made at the LHC. The design of such machines is strongly influenced by radiative effects (synchrotron radiation and beamstrahlung). Since these scale with the fourth power of lepton mass, the use of the muon rather than the electron would substantially suppress them. Muon colliders can thus employ rings of small circumference for acceleration and collisions, reducing facility footprints and construction and operating costs. Muons likewise give more-monochromatic collisions and allow much higher energies (10 TeV or more) [1,2] than do electrons. Moreover, the coupling of the Higgs field to leptons being proportional to the square of lepton mass, the muon collider has the unique ability to produce the Higgs boson exclusively, in the *s* channel. This, along with the highly precise muon beam energy spread and calibration ($\Delta E/E \lesssim 10^{-5}$), enables a direct measurement of the Higgs mass and width [3]. While it complicates beam handling, muon decay (mean lifetime = 2.2 μs) enables stored-muon-beam neutrino factories—the most capable technique yet devised for precision measurements of neutrino oscillation and searches for new physics in the neutrino sector [4-10].

Figure 1 compares muon collider and neutrino factory schematic layouts. Two muon-production approaches are under consideration: via pion production and decay, or via $e^+e^- \to \mu^+\mu^-$ just above threshold (in a positron storage ring with internal target)—the Low EMittance Muon Accelerator, or LEMMA [11]. While potentially bypassing the need for muon cooling, the LEMMA approach itself has significant technical challenges to overcome if the desired high $\mu^+\mu^-$ luminosity ($\geq 10^{34}$ cm^{-2} s^{-1}) is to be achieved; it also produces insufficient muons for use as a neutrino factory.

If the pion-production approach is chosen, the facility performance and cost depend on the degree to which a muon beam can be cooled. The desired emittance reduction factor for a neutrino factory is $\mathcal{O}(10\text{–}100)$, with 4D transverse cooling sufficing, while that for a muon collider is $\mathcal{O}(10^6)$, and 6D cooling is required [12,13].

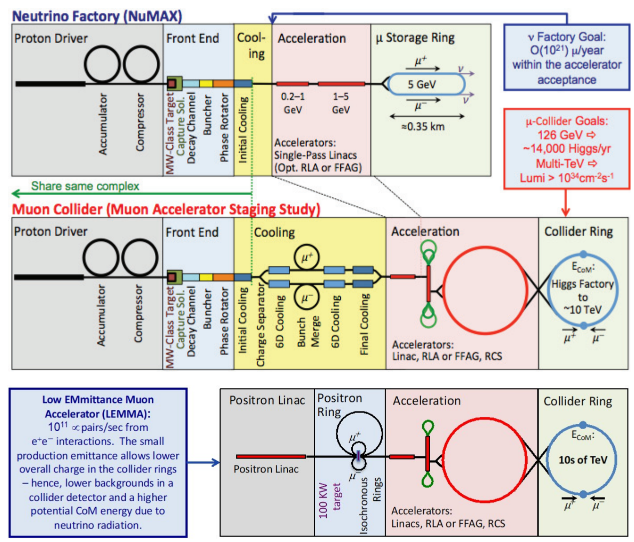

Figure 1: Schematic layouts of possible muon accelerator facilities: (top) neutrino factory; (center) muon collider, employing pion production and decay; and (bottom) employing $\mu^+\mu^-$ pair production in fixed-target e^+e^- collisions (LEMMA).

IONIZATION COOLING

Established methods of particle-beam cooling (electron, laser, stochastic, and synchrotron-radiation cooling) are ineffective for the muon due to its short lifetime, large mass, and lack of internal substructure, thus non-traditional approaches are required. Only one cooling mechanism —ionization cooling[1] [14-19] — works on muons in microseconds, allowing small enough emittances to be reached with $\mathcal{O}(10^{-2\pm1})$ muon survival. Moreover, like electron cooling, ionization cooling was first proposed at the Budker Institute of Nuclear Physics (BINP). Thus it is fitting that we report here at BINP at the COOL'19 Workshop on the progress of its experimental demonstration.

* Work supported by STFC
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[1] Essentially a form of electron cooling, but with an electron density many orders of magnitude larger than is possible in an electron beam.

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COHERENT ELECTRON COOLING EXPERIMENT AT RHIC: STATUS AND PLANS *

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Abstract

We present currents status of the CeC experiment at RHIC and plans for future. Special focus will be given to unexpected experimental results obtained during RHIC Run 18 and discovery of a previously unknown type of microwave instability. We called this new phenomenon micro-bunching Plasma Cascade Instability (PCI). During this year we demonstration control of this instability in our SRF CW accelerator. We present plan for future experiments using this instability as a broad-band amplifier in the CeC system – so called PCA-based CeC.

INTRODUCTION

An effective cooling of ion and hadron beams at energy of collision is of critical importance for the productivity of present and future colliders. Coherent electron cooling (CeC) [1] promises to be a revolutionary cooling technique which would outperform competing techniques by orders of magnitude. It is possibly the only technique, which is capable of cooling intense proton beams at energy of 100 GeV and above.

The CeC concept is built upon already explored technology (such as high-gain FELs) and well-understood processes in plasma physics. Since 2007 we have developed a significant arsenal of analytical and numerical tools to predict performance of a CeC. Nevertheless, being a novel concept, the CeC should be first demonstrated experimentally before it can be relied upon in the up-grades of present and in the designs of future colliders.

A dedicated experimental set-up with FEL amplifier, shown in Fig. 1, has been under design, manufacturing, installation and finally commissioning during last few years [2-4]. The CeC system is comprised of the SRF accelerator and the CeC section followed by a beam-dump system. It is designed to cool a single bunch circulating in RHIC's yellow ring (indicated by yellow arrow in Fig. 1). A 1.25 MeV electron beam for the CeC accelerator is generated in an 113 MHz SRF quarter-wave photo-electron gun and first focused by a gun solenoid. Its energy is chirped by two 500 MHz room-temperature RF cavities and ballistically compressed in 9-meter long low energy beamline compromising five focusing solenoids. A 5-cell 704 MHz SRF linac accelerates the compressed beam to 14.5 MeV. Accelerated beam is transported through an achromatic dogleg to merge with ion bunch circulating in RHIC's yellow ring. In CeC interaction between ions and electron beam occurs in the common section, e.g. a proper coherent electron cooler. The CeC works as follows: In the modulator, each hadron induces density modulation in electron beam that is amplified in the CeC amplifier; in the kicker, the hadrons interact with the self-induced electric field of the electron beam and receive energy kicks toward their central energy. The process reduces the hadron's energy spread, i.e. cools the hadron beam.

Finally, the used electron beam is bent towards an aluminum high-power beam dump equipped with two quadrupoles to over-focus the beam.

STATUS

The CeC accelerator SRF system uses liquid helium from RHIC refrigerator system, which operates only during RHIC runs. The commissioning of the CeC accelerator was accomplished during RHIC 15-18 runs. Electron beam parameters at the design level or above, except the beam energy, had been successfully demonstrated – see Table 1 [5-16]. Accordingly, we had adjusted the ion beam energy to 26.5 GeV/u to match relativistic factors with that of electron beam.

Our attempt to demonstrate cooling during RHIC run 18 was not successful. While the attempt was hindered by a number of technical problems beyond control of the CeC group, the main reason for our inability to demonstrate cooling was excessive noise in the electron beam at frequencies ~ 10 THz (wavelength ~ 30 μm).

As soon as we achieved all necessary electron beam parameters, we demonstrated high gain operation of our FEL by observing very strong amplification of the IR radiation from the FEL with increase of the beam peak current. The power of generated radiation was measured by broad-band IR diagnostics [17] (including a spectrometer), which was upgraded to be sensitive in far-IR range before the 2018 run. After that we verifiably aligned electron and an ion bunches both transversely and temporarily well within the

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RECENT RESULTS FROM MICE ON MULTIPLE COULOMB SCATTERING AND ENERGY LOSS

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Abstract

Multiple coulomb scattering and energy loss are well known phenomena experienced by charged particles as they traverse a material. However, from recent measurements by the MuScat collaboration, it is known that the available simulation codes (Geant4, for example) overestimate the scattering of muons in low Z materials. This is of particular interest to the Muon Ionization Cooling Experiment (MICE) collaboration which has the goal of measuring the reduction of the emittance of a muon beam induced by energy loss in low Z absorbers. MICE took data without magnetic field suitable for multiple scattering measurements in the spring of 2016 using a lithium hydride absorber. The scattering data are compared with the predictions of various models, including the default Geant4 model.

INTRODUCTION

Results from atmospheric neutrinos at Super-Kamiokande [1] and from solar neutrinos at the Sudbury Neutrino Observatory [2] conclusively demonstrated that neutrinos have a non-zero mass and oscillate between different flavours. A facility promising precision measurement of neutrino oscillations parameters is the Neutrino Factory [3], where neutrinos would be produced via muon decay rings. Before the muons are injected into the storage ring the phase-space volume of the beam must be reduced. The only cooling technique which can act within the lifetime of the muon is ionization cooling and has shown in simulation to reduce the phase-space volume of the beam by a factor of 100,000. MICE Step IV is current taking data to provide the first measurement of ionization cooling. This demonstration is an essential part of the worldwide research effort towards building a Neutrino Factory. A Neutrino Factory is the only proposed facility with the capability to measure the CP violation phase, δ_{CP}, with 5° accuracy.

MICE BEAM LINE AND EXPERIMENT

The MICE experiment is located at the Rutherford Appleton Laboratory (RAL) in the UK and operates parasitically on the ISIS proton accelerator [4], producing beam for the newly built MICE Muon Beam (MMB) by the insertion of an internal pion-production target. MICE is a novel single particle experiment designed to perform high precision measurements of normalized emittance both upstream and downstream of the ionization cooling equipment. The MMB

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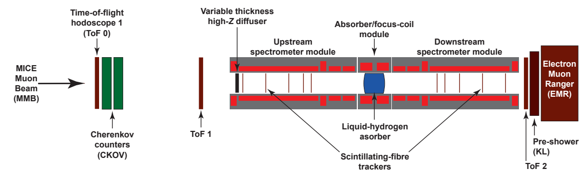

Figure 1: Schematic of Step IV of the MICE experiment, with the Absorber Focus Coil module between the two Spectrometer Solenoids.

is composed of three quadrupole triplets, two dipole magnets, which select the momentum, and a decay solenoid (DS), which increases the number of muons in the beam. The MICE Step IV setup is shown in Fig. 1. It consists of an Absorber Focus Coil (AFC) module located between two measurement stations. These stations are composed of particle identification suites including a total of three time-of-flight detectors (TOFs) [5], two Cherenkov detectors (Ckova and Ckovb) [6], the KLOE-light sampling calorimeter (KL) [7] and the Electron Muon Ranger (EMR) [8]. Each station has a Tracker [9] with five planes of scintillating fibres inside a 4 T Spectrometer Solenoid (SS) to measure track and momentum information (x, y, p_x and p_y), so as to reconstruct the emittance before and after cooling. The AFC module, which houses the liquid hydrogen or lithium hydride absorber within a pair of focusing coils, is located between the two measurement stations.

OVERVIEW OF MULTIPLE COULOMB SCATTERING

The PDG recommends an approximate multiple scattering formula [10], [11], which is found to be accurate to approximately 11%:

$$\theta_0 \approx \frac{13.6\,\mathrm{MeV}}{p_\mu \beta_\perp} \sqrt{\frac{\Delta z}{X_0}} \left[1 + 0.0038 \ln \left(\frac{\Delta z}{X_0} \right) \right], \quad (1)$$

where θ_0 is the rms width of the projected scattering angle distribution, X_0 is the radiation length of the material and Δz is the thickness of the absorber, p_μ is the momentum of the muon and the muon velocity is $\beta_\perp\ p_\mu c/E_\mu$, with E_μ its energy. From this an approximate cooling formula can be derived (ignoring the logarithmic term of equation 1),

$$\frac{d\varepsilon_n}{dz} \approx -\frac{\varepsilon_n}{E_\mu \beta_{\mathrm{rel}}^2} \left\langle \frac{dE_\mu}{dz} \right\rangle + \frac{\beta}{2 m_\mu \beta_{\mathrm{rel}}^3} \frac{(13.6\,\mathrm{MeV})^2}{E_\mu X_0}, \quad (2)$$

where ε_n is the normalised transverse (two-dimensional) emittance of the beam, β is the betatron function, and m_μ

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PLASMA-CASCADE INSTABILITY

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Abstract

In this paper we describe a new micro-bunching instability occurring in charged particle beams propagating along a straight trajectory. Based on the dynamics of this parametric instability we named it a Plasma-Cascade Instability. Such instability can strongly intensify longitudinal micro-bunching originating from the beam's shot noise, and even saturate it. On the other hand, such instability can drive novel high-power sources of broadband radiation. We discovered this phenomenon in a search of a broadband amplifier for Coherent electron Cooling [1,2], which does not require separating electron and hadron beams.

INTRODUCTION

High brightness intense charged particle beams play critical role in the exploration of modern science frontiers Such beams are central for high luminosity hadron colliders as well as for X-ray free-electron-lasers (FEL) with ultra-fast time structures reaching the femtosecond level. Dynamics of intense charged particle beams is driven by both external factors – such as focusing and accelerating fields - and self-induced (collective) effects.

While external factors are typically designed to preserve beam quality, the collective effects can result in an instability. Such instabilities can severely degrade beam quality by spoiling its emittance(s) – increasing beam's momentum spread or creating density modulation or even filamentation in the beam. On the other hand, such instabilities can be deliberately built-in to attain specific results [1-6]. The Plasma-Cascade micro-bunching Instability (PCI) occurs in a beam propagating along a straight line. By its nature, the PCI is a parametric instability driven by variation of the electron beam density and corresponding change of the plasma oscillation frequency [5]. Conventional micro-bunching instability in beams travelling along a curved trajectory (for example, in a magnetic chicane or in an arc of an accelerator) is a well-known. But none of them includes PCI –a micro-bunching longitudinal instability driven by modulations of the transverse beam size.

PLASMA-CASCADE INSTABILITY

We start from a qualitative description of the PCI, which will be followed by rigorous theory, 3D simulations and experimental observation of this phenomena. Figure 1 depicts periodic focusing structure where the charged particle beam undergoes periodic variations of its transverse size. It is known small electron density perturbations $\tilde{n}(\vec{r}), |\tilde{n}| << n_o$ in a cold, infinite and homogeneous plasma will result in oscillations with plasma frequency, ω_p [7]:

$$\frac{d^2\tilde{n}}{dt^2} + \omega_p^2 \tilde{n} = 0; \; \omega_p = c\sqrt{4\pi n_o r_c}, \qquad (1)$$

where n_o is the particles density (in our case, in the beam's co-moving frame), c is the speed of the light and $r_c = e^2 / mc^2$ is classical radius of the particles.

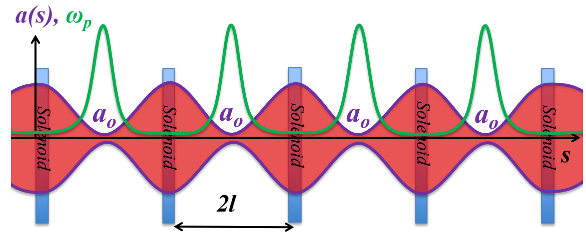

Figure 1: A sketch of four focusing solenoids cells with periodic modulations of beam envelope, *a(s),* and the plasma frequency, ω_p. Beam envelope has waists, a_o, in the middle of each cell where plasma frequency peaks. Both vertical and horizontal scale are optimized for illustration of the process.

For the beam propagating with velocity v_o in the periodic lattice with period *2l*, shown in Fig. 1, it would lead to a periodic modulation of the density $n_o \sim 1/a^2$ and the plasma frequency $\omega_p \sim 1/a$ with a period of $T = 2l/\gamma_o v_o$, where we took into account the relativistic time dilation in the co-moving frame by the beam's relativistic factor $\gamma_o = \left(1-\beta_o^2\right)^{-1/2}, \beta_o = v_o / c$. It is well known in classical oscillator theory [8] that rigidity modulation close to a half of oscillation period would result in exponential growth of oscillation amplitude: the phenomena known as parametric resonance. The extreme case of δ-function-like modulation is also well known: periodic focusing lenses with focal length is shorter than a quarter of the separating distances a ray instability in system. Hence the modulation of the transverse size could, in principle, results in unstable, e.g. growing longitudinal oscillation density. Such instability can also be a result of aperiodic frequency modulation: it is well known in accelerator physics that a solution of *s*-dependent Hill's equation, $x'' + K(s)x = 0$,can lead to unstable oscillations in focusing system with $K(s)>0$.

Analytical Studies

To switch from qualitative to qualitative description of PCI we need to identify a problem which is analytically tractable. In mathematical terms, we need to separate transverse and longitudinal degrees of freedom. As shown in [5,6] desirable separation is possible for long bunch, σ_s

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ELENA COMMISSIONING

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Abstract

The Extra Low Energy Antiproton storage ring (ELENA) is an upgrade project at the CERN Antiproton Decelerator (AD). ELENA will further decelerate the 5.3 MeV antiprotons coming from the AD down to 100 keV and allow the experiments typically operating traps to increase the capture efficiency. ELENA features electron cooling for emittance control during the deceleration and therefore preserve the beam intensity and to generate bright bunches extracted towards the experiments. The ring has been completed with the installation of the electron cooler at the beginning of 2018. The electron cooler is meant to operate at an electron energy of 355 eV and 54 eV, corresponding to a pbar momentum of 35 MeV/c and 13.7 MeV/c. First observations of cooling have been observed at both energies, and decelerated ion beams with characteristics close to the design values have been obtained before the start of CERN Long Shutdown 2 (LS2). The latest results of ELENA commissioning will be presented, together with an overview of the project and status and plans.

INTRODUCTION

The antimatter experiments at CERN presently take 5.3 MeV kinetic energy antiprotons beams from the AD decelerator. The recent installation of ELENA and its ability to further decelerate the antiprotons down to 100 keV will be a major breakthrough for the antimatter physics research, as it will allow to trap and study at least one order of magnitude more antiprotons per shot than what has typically been achieved before. A more detailed report on the ELENA Commissioning have been recently presented and described in [1]. In the following, only a short summary of [1] is reported.

ELENA OVERVIEW

The ELENA ring has a hexagonal shape and its circumference is about 30 m. Figure 1 shows a picture of the ring after its complete installation in 2018, with its main components highlighted.

For machine commissioning purposes, a standalone ion source able to provide 100 keV H^- or proton beams is installed next to the ELENA ring, between the ELENA injection and extraction beamlines shown in Fig. 2. An electrostatic ion switch installed at the intersection between injection and extraction lines allows for injecting H^- and proton beams in either directions in the ring. Unfortunately, the insulation transformer of the ion source High Voltage (HV) cabinet had several problems, and it eventually failed completely during the 2018 run, preventing further use of ion beams. Moreover, observed shot-to-shot H^- intensity variation limited the amount of studies that could be done while the source was operational. Despite several attempt to solve those problems, most of the ELENA commissioning had to be performed with limited pbar beam-time dedicated by AD to ELENA.

The typical pbar decelerating cycle is depicted in Fig. 3. The beam is injected as a single bunch from the AD at 100 MeV/c in a waiting RF bucket in ELENA. A first deceleration step brings the beam down to 35 MeV/c where the beam is debunched and the electron cooler is used to reduce the beam emittances to compensate for the adiabatic emittance blow-up (about a factor 3) induced by the deceleration. After being re-bunched, the beam is further decelerate down to 13.7 MeV/c where it is again debunched and cooled.

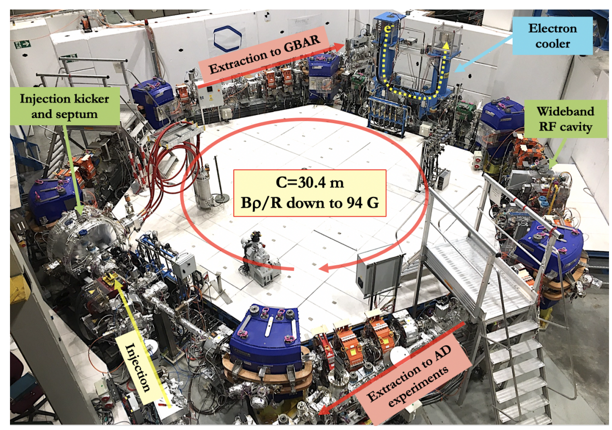

Figure 1: Picture of the ELENA Ring after installation. The main components, including the electron cooler, are highlighted.

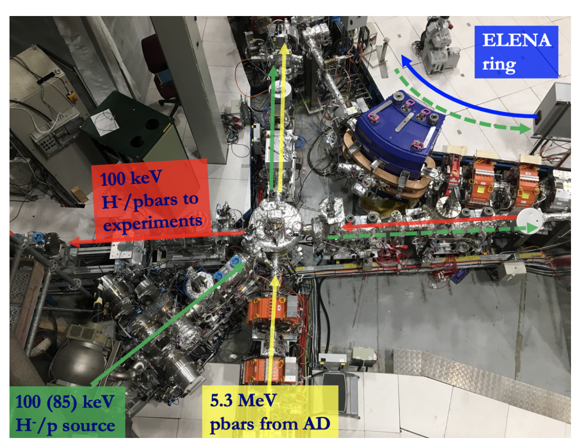

Figure 2: Injection and extraction lines toward main experiments. The ion source is partially visible in the bottom left corner. The possible beam paths are highlighted.

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THE STATUS OF THE ELECTRON COOLING SYSTEM FOR THE NICA COLLIDER *

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Abstract

The new electron cooling system is being designed to cool two heavy ion beams propagating in opposite directions at a distance of about 30 cm from each other. Engineering solutions for its basic elements are presented. The measurements of the magnetic system of the electron cooler and the influence of the adjacent solenoids in the cooling section on the resulting magnetic field are described. The potential opportunities to improve parameters of experiments with ion beams using the electron cooling system are discussed

INTRODUCTION

The history of the development of electron cooling began at the Institute of Nuclear Physics (Novosibirsk) just after the first successful experiments conducted there with electron-electron and electron-positron colliding beams. Radiation cooling plays a decisive role in achieving high luminosity in electron and electron-positron colliders. Cooling based on ionization losses in the matter was suggested earlier, but the interaction with the target nuclei hampered application of this method because it makes the beam lifetime too short.

The idea of using electron cooling, proposed by G.I. Budker in 1965 [1], consisted in switching from cooling with a stationary target to using a pure beam of electrons (without nuclei). The electron cooling progress began in 1967 with theoretical studies [2] and the development of an electron beam facility [3] (Fig. 1). That project was to verify the electron cooling concept. The electrons travel with the same average velocity as the proton beam does. Of course, the electron beam density is much smaller than the electron density in condensed matter, but in this case electrons are traveling together with the proton beam and the interaction efficiency between the two beams depends only on the spread of relative velocities of the protons and the electrons. The drift motion of the electron beam because of space charge repulsion is suppressed using a high magnetic field B along the electron trajectory. A strong longitudinal magnet field in the cooling section is used for suppression of ion-electron recombination. The main feature of cooling by magnetized electron beams is the possibility of suppression of the ion electron recombination due to high transverse temperature of electrons without losses in the cooling efficiency [4].

Since 1991 BINP have produced a lot of coolers for different laboratories: GSI SIS-18, IMP CSRm, CSRe, and CERN LEIR. The cooler with a highest voltage of 2 MV was designed for Forschungszentrum Julich (KFA) GmbH. The experience of designing the COSY cooler was used as a base for the 2.5 MV cooler for the NICA ion*ion collider at JINR (DUBNA). Figure 2 shows the origination of the NICA cooler.

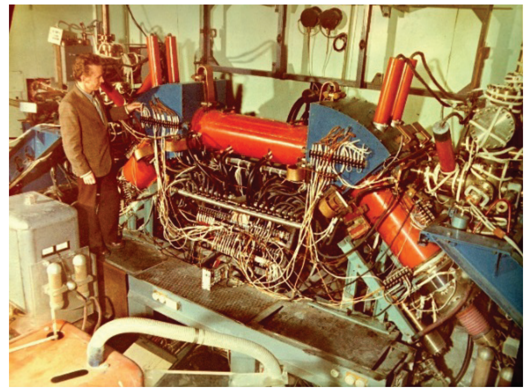

Figure 1: First electron cooling installation in NAP-M storage ring (1974).

The cooler will be placed in a special building near the beam straight section of the NICA ring. The vertical distance between the ion beams is only 32 cm, and the design of two solenoids with such a small gap is a very complicated task. For testing the design, a prototype 1 m long of the cooling section was created (Fig. 3).

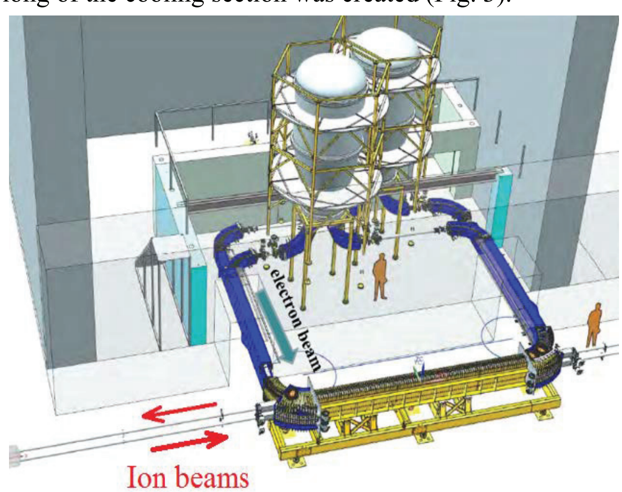

Figure 2: 3D design view of 2.5 MV NICA cooler.

The maximum magnetic field in the cooling section is 0.2 T. The solenoids consist of adjustable coils for straightening the lines of magnet field by rotating coils. This procedure will involve a specially designed compass with a laser beam reflecting from the compass mirror for precise angle measurement.

The penetration of the transverse magnetic field from the upper solenoid to the lower solenoid does not exceed 0.01, and thus the procedure of magnetic field measure-

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ELECTRON COOLING IN THE NICA PROJECT: STATUS AND PROBLEMS

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Abstract

The Nuclotron-based Ion Collider fAcility (NICA) project at the Joint Institute for Nuclear Research (JINR, Dubna, Russia), reached the phase of mounting and commissioning of the accelerator complex elements. The first stage of the project is "The Baryonic Matter at Nuclotron" (BM@N), fixed target experiment. It requires operation of the heavy ion synchrotron Booster, where electron cooler is used for formation of ion beam of a high intensity. One of limitation of intensity of partially ionized heavy ion beams is recombination with cooling electrons. This process is planned to be studied on the Booster, which is under mounting presently. The experiments at NICA collider with the heavy ion beams is the second stage of the project. High energy electron cooler that is under fabrication at BINP is a key tool for NICA collider allowing to reach the project luminosity in all ion energy range of $\sqrt{s_{NN}} = 4 \div 11$ GeV/u. Recombination of bare nuclei of heavy ions in the electron cooler leads to significant beam losses that shorten ion life time and may generate considerable background in NICA detector (MultiPurpose Detector — MPD). The third stage is spin physics studies in collisions of polarized protons ($\sqrt{s_{NN}} = 27$ GeV) and deuterons. This stage expect the use of the Spin Physics Detector — SPD. The report presents status of the NICA project development and discusses the problems described above.

INTRODUCTION: THE NICA PROJECT AT JINR

The NICA project aims to design, construction and commissioning at JINR a modern accelerator complex based on existing synchrotron Nuclotron equipped with two detectors: MPD and SPD. Experimental studies planned at NICA will be dedicated to search of the mixed phase of baryonic matter and the nature of nucleon/particle spin. Briefly speaking, we intend to study the Universe as it was 13.799 ± 0.021 billion years ago [1] and of the order of $10 \div 100$ µs after Big Bang, the first goal. The second goal is to understand the nature of particle spin, so called "spin puzzle".

The project development has three stages as described in the Abstract and in the [2]. The scheme below (Fig. 1) demonstrates all main elements of the NICA.

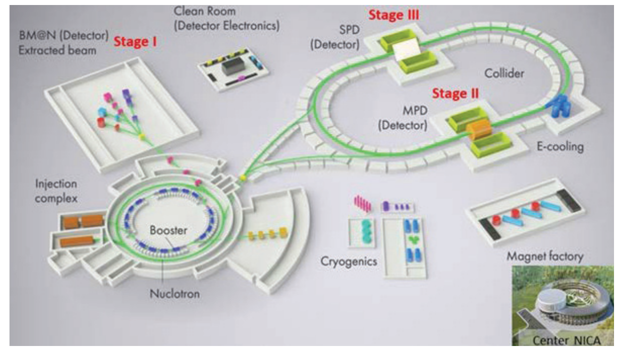

Figure 1: Scheme of the NICA facility.

NICA STAGE I: EXPERIMENT "THE BARYONIC MATTER AT NUCLOTRON"

For the full configuration of the Stage I we need [2] the following elements and accelerators.

1. Injector: Cryogenic ion source KRION + Heavy ion Linear Accelerator (HILAC) + Beam transfer line (BTL) from HILAC to the Booster;
2. KRION is in the stage of "working prototype" that will be used for generation of heavy ion beam. The main goal is generation of $^{197}Au^{31+}$. The HILAC was commissioned in 2016. Construction of the BTL is close to completion and will be tested with the ion beam this year;
3. Booster — superconducting (SC) synchrotron is under mounting (Fig. 2, 3). Its electron cooler was constructed by BINP and is under commissioning in the working position on the Booster. First test of the SC focusing system of the Booster is planned at the end of this year, ion beam injection into Booster is expected in May 2020;
4. BTL Booster-Nuclotron (under manufacturing at BINP, to be finally delivered to JINR in July 2020, commissioning — October 2020);
5. Upgrade of BTL Nuclotron-BM@N for transportation of ions accelerated in Nuclotron and extracted by slow extraction system. The upgrade includes improvement of vacuum condition in the channel and development of power supplies for the channel magnets.

The first run of BM@N experiment with heavy ions at maximum energy of Nuclotron is scheduled for November 2020.

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LONGITUDINAL PARTICLE DYNAMICS AND COOLING IN NICA COLLIDER

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Abstract

A feature of the NICA acceleration complex is high luminosity of colliding beams. Three types of RF stations will be used in the NICA Collider to reach the necessary beam parameters. The first type is for accumulation of particles in the longitudinal phase space with the moving barrier buckets under action of stochastic and/or electron cooling systems. The second and the third RF stations are for formation of the final bunch size in the colliding regime. This report presents brief description of three types of RF stations constructed in BINP and numerical simulations of longitudinal beam dynamics which take into consideration account the longitudinal space charge effect, cooling and IBS during the accumulation and bunching procedures.

INTRODUCTION

The goal of the NICA facility [1] in the heavy ion collision mode is to reach the luminosity level of 10^{27} $cm^{-2}s^{-1}$ in the energy range from 1 GeV/n to 4.5 GeV/n.

The RF systems of the Collider [1] have to provide accumulation of required numbers of ions in the energy range 1-3.9 GeV/n, accumulation at some optimum energy and acceleration to the energy of the experiment in the range of 1-4.5 GeV/n, formation of 22 ion bunches, and achievement of the required bunch parameters.

This can be done with the help of three RF systems [1], one of the broad-band type and two narrow-bands ones. The first one accumulates particles in longitudinal phase space with application of RF barrier bucket technique. The maximal voltage of the barrier is 5 kV, it has rectangular shape with phase length $\pi/12$. By applying additional voltage of 300 V, one can also use the meander between the barriers for inductive acceleration. The second RF system works on the 22nd harmonic of the revolution frequency and is used for formation of the proper number of bunches. The maximal RF2 voltage is 100 kV. The RF2 can also be used for beam acceleration or deceleration. The third RF system works on the 66th harmonic and is used for the final bunch formation and maintenance of the bunch parameters during the collision mode. The maximal RF3 voltage is 1 MV. The RF3 system is also used for ion beam acceleration or deceleration. All stages of the bunch formation as well as the collision mode are accompanied by a cooling process, either stochastic or electron.

Previous calculations modelling longitudinal beam dynamics were fulfilled in approach neglecting change of transverse emittance and cooling time during accumulation or bunching [2]. Now we take into account dependence of IBS and electron cooling force on transverse emittance which also changes in accordance with these effects in RMS model.

ACCUMULATION OF IONS

Moving Barrier Buckets

Accumulation is fulfilled with separated regions of injection and storage. Two pairs of voltage impulses form 2 separatrices, the 1st one for injection, the 2nd - for storage of ions (stack). After injection the impulses of injection separatrix move close to the stack, then impulses separating injected bunch from stack decrease, and separatrices join (Fig.1). If the length of combined separatrix exceeds half of the ring perimeter, it will be compressed.

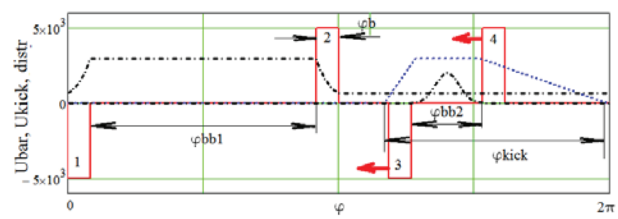

Figure 1: Barrier voltage (red line), density of stored and newly injected beam (black dash-dot line), impulse of kicker(blue dashes). φ_b, $\varphi_{bb1,2}$, φ_{kick} - phase lengths of voltage impulse, 2 separatrices and kicker impulse.

Calculation Model

At the calculation all the effects are separated (movement of barrier buckets, cooling, IBS, loss of ions at injection). All movements are slow, with conserved longitudinal emittance.

Electron cooling force is taken into account in a form of V.Parkhomchuk [3], with parameters of the electron beam (current, radius, transverse and longitudinal temperatures) $I_e = 1A$, $r_e = 1\,cm$, $T_{et} = 5\,V$, $T_{el} = 5\,mV$. We use in calculacion the longitudinal component of cooling force averaged over transverse velocities and averaged over all 3 velocities distributions values of longitudinal and transverse decrements.

IBS is taken into account in a form of a diffusion coefficients calculated with a model of S.Nagaitsev [4], for NICA magnetic structure of 2018.

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SIMULATION OF ELECTRON-OPTICAL SYSTEMS OF ELECTRON COOLERS

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Abstract

To provide successful operation of electron coolers one need thorough simulation and development of electron-optical system. In this paper simulations of electron gun, accelerating structure and collector are discoursed. Particular attention is paid to obtaining high perveance electron beam with a small transversal temperature and controlled profile, and collector with low flux of secondary electrons. Bends of electron beam are also considered.

Main program for simulations is SAM code. This code is based on boundary integral method, its main advantage is precision and speed of calculations.

INTRUDUCTION

At the development of such large facilities as electron coolers, it is necessary to perform an initial numerical simulation of all the important parts. In this paper, we focus on numerical calculations and optimization of the electron-optical system of electron coolers and the dynamics of electron beams in them. Since the coolers created in BINP use magnetized beams, the following tasks can be distinguished: first, it is necessary to build and optimize the magnetic system in the region of the electron gun and the collector. The second task is the numerical development of the electron gun itself as well as the collector. The third task is the development of a magnetic system for bends and matching system and optimization the beam motion in these regions.

To solve these problems, SAM [1, 2] and MAG3D [3] packages are mainly used in BINP. These programs were developed at the Institute; their main peculiarity is the use of integral methods for calculations, which ensures good accuracy and speed of calculations. The SAM program is intended for simulation of axially symmetric electron optical systems with space charge consideration. These systems can include electrodes, dielectrics, coils, permanent magnets, linear ferromagnetics. Tasks with space charge can also be simulated with help of the SAM program, that allows calculation of electron guns and collectors. MAG3D program is used to solve problems of nonlinear 3D magnetostatics.

SIMULATION OF ELECTRON GUNS

The specificity of electron cooling makes the following requirements for electron guns used in coolers:

- required perveance;
- independent current and energy control;
- low (< 1 eV) transverse temperature of the beam;
- independent adjustment of the current density distribution across the beam.

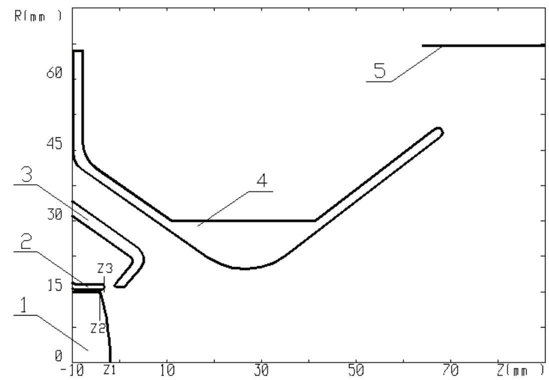

Figure 1: Geometry of electrodes of the electron gun with variable beam profile.

To meet these requirements, an electron gun was developed in the Institute, the drawing of which is shown in Fig. 1. The convex cathode 1 immersed into longitudinal magnetic field is used. To form the electron beam control electrode 3 is used together with anode 4. The control electrode is placed near the cathode edge and influences the emission from this area. By applying different potential on this electrode the beam with radial current density distribution from parabolic to hollow can be obtained.

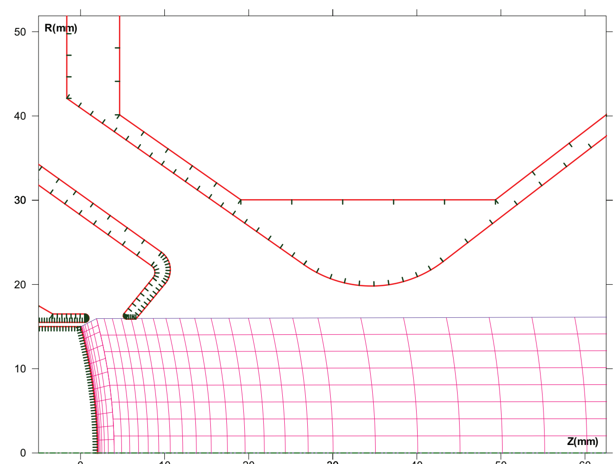

Figure 2: The mesh used for calculation of the electron gun.

The calculation and optimization of this gun was performed using the SAM package, the mesh used for the calculations and the collocation points are shown in Fig. 2. The total number of collocation points is less than 200, total number of cells in mesh – less than 500. With such a number of nodes calculation takes little time – less than 1 minute, even on a relatively low-power personal computer. However, the ability of the SAM complex to

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RECENT DEVELOPMENTS AND EXPERIMENTAL RESULTS FROM ELECTRON COOLING OF A 2.4 GeV/c PROTON BEAM AT COSY

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Abstract

The COSY control system as well as other subsystems are being upgraded. The 2 MeV electron cooler was recently extended with the EPICS control system and thereby integrated into the control and data acquisition system of the Cooler Synchrotron COSY. Taking advantages of the new software capabilities, studies of transverse and longitudinal magnetized electron cooling of a proton beam at 2.4 GeV/c were carried out. Electron and stochastic cooling were combined to reduce the cooling time while achieving lowest possible emittance and momentum spread. Results from experiments are discussed including cooling dynamics during operation of an internal cluster-jet target designed for the PANDA experiment at HESR. We present the results of probing the electron velocity distribution by means of the strongly cooled beam itself. The shape of the measured distibution may be caused by the galloping/scalloping effects within the electron beam. This effect plays a significant role in the strong dependence of the longitudinal and transverse electron cooling process on the proton beam size. Also discussed are the technical developments, achievements and further plans regarding the control system upgrade.

INTRODUCTION

The Cooler Synchrotron (COSY) is a storage ring operated at the Nuclear Physics Institute (IKP) at Forschungszentrum Jülich. Polarized as well as unpolarized proton and deuteron beams in the energy range 45 MeV to 2700 MeV can be delivered.It is equipped with a stochastic cooling system and two electron coolers. Currently a stochastic cooling system for the HESR is tested. While the 100 keV electron cooler operates mostly at injection energy, the 2 MeV electron cooler is designed for proton beam momenta beyond the COSY operating range of up to 4.5 GeV/c. The high energy electron cooler was developed at the Budker Institute of Nuclear Physics [1] and is being operated at COSY since 2013 [2].

TECHNICAL DEVELOPMENTS

EPICS Integration

The control system of the 2 MeV electron cooler was originally designed as a standalone-system. Six servers exist for control and diagnostics of the hardware components: the primary and secondary magnetic guiding system controlling the electron beam orbit, the beam position monitors (BPM) measuring the orbit, the electron gun and collector, the high-voltage accelerating sections as well as an interlock system for safety aspects. These systems are located in a separated environment with a custom control system.

In the course of upgrading the COSY control system to the Experimental Physics and Industrial Control System (EPICS) [3] it was decided to incorporate the 2 MeV electron cooler into the new control system. Having a common standard allows not only to further automate the beam cooling systems but also eases the handling of experimental data across various systems.

In order to integrate the 2 MeV electron cooler's control system into EPICS, an Input-Output-Controller (IOC) was developed. The IOC communicates with the cooler's systems using the EPICS modules *Stream* and *AsynDriver* while leaving the existing systems untouched. It provides the various parameters as process variables (PVs) to the EPICS control system, taking care of binary conversion and physical quantities. In addition, the EPICS alarm system is used to notify operators of critical values outside the normal operation ranges. [4]

Table 1 gives a statistical overview of the PVs made available. Currently the parameters of all systems are provided for readout and additional PVs exist to control the magnetic guiding system and electron gun. It is planned to further expand the control capabilities.

By having incorporated the 2 MeV electron cooler into the COSY control system EPICS, several advantages were achieved. The cooler's data is now centrally archived in a time correlated manner. This provides easier data-analysis after the experiments because all data is now saved continuously and stored in one single place. It is much easier to correlate the electron cooling data with other accelerator systems like beam diagnostics or timing. Furthermore a wide range of established tools designed for EPICS is used, e.g. to analyse data on-the-fly, producing physically meaningful displays which are vital for machine operation. Due to the

Table 1: Implemented Parameters

	Readout	**Control**
Analogue	610	63
DAC	*71*	*63*
ADC	*539*	
Binary status	381	60
Other	38	
Total	1029	123

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SIMULATION OF ELECTRON COOLING AND IBS AT EICC*

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Abstract

Electron Cooling will be considered in the future project EICC. In this high energy region, electron cooling is very different from the traditional low energy situation. For getting high luminosity, the high intensity and long lifetime of ion beam was required with the help of electron cooling. Electron cooling and IBS were simulated in the cases of high energy and high intensity for typical ion, proton and Uranium. Some initial parameters were obtained from the simulation. It will be helpful for the understanding of high energy electron cooling.

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 12~30 GeV will collide with electron beam with energy between 3~5 GeV in the collider. Both electron and ion beam are polarized. The luminosity will expect to achieve 4×10^{33}.

In the second phase, the energy of proton will upgrade to 60~100 GeV, and the energy of electron beam will increase to 5~10 GeV, 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 ion beam especially, the intra-beam scattering effect should be taken into account in the collider design. Some primary simulation on the electron cooling and intra-beam scattering were presented in this contribution.

SIMULATION OF COOLING

The cooling rate not only depends on the storage ring lattice parameters, the Betatron function, dispersion of the cooling section, initial emittance and momentum spread of ion, energy and charge state of ion beam, but also on the construction 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 electron cooling code SIMCOOL [2, 3], the cooling time of ion beam were extensive simulated in various parameters of the ion beam in the EicC, such as ion 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, electron beam current.

Ion Beam Parameters

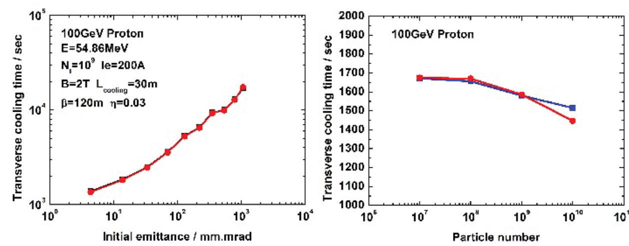

Figure 1: The transverse cooling time as a function of the initial emittance (left) and the particle number in the ion beam (right).

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

Electron Beam Parameters

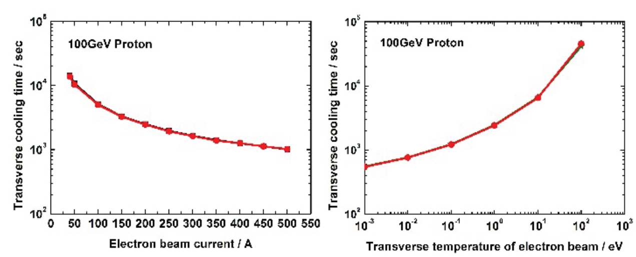

Figure 2: The transverse cooling time as a function of the electron beam current (left) and the transverse temperature of electron beam (right).

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 cooling time depends on the transverse temperature of electron beam. In

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VACUUM SYSTEMS FOR THE COOLERS OF THE NICA PROJECT

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Abstract

The NICA accelerator complex contains two electron coolers, one sits at booster and another at NICA collider. They have requirements for the vacuum of 10^{-11} mbar. Despite the coolers have different design the problems of getting vacuum are similar, lack of space along vacuum chambers, presence of the electron beam and oxide cathode usage. The solutions for achieving such a strict requirements are discussed in the article.

INTRODUCTION

The main part of the NICA accelerator complex is the collider for heavy ions up to $^{197}Au^{31+}$, which contains the 2.5MeV cooler. The injection chain of the NICA complex have the gold ions booster. Low energy cooler is one of the elements of the booster that provides sufficient improvement of the ion beam quality. The requirement for vacuum condition is usual for heavy ion accelerators of about 1×10^{-11} mbar [1,2].

VACUUM SYSTEMS

Vacuum system of the high energy cooler consist of two similar parts as shown on Fig. 1. They have identical structure and a little bit different size. Every system may be separated on to three parts by means of gate valves. Main part contains cooling section, which is installed at straight line of the collider so the chamber belongs to the cooler and collider, simultaneously. Other two parts are similar and include part of the transport channel and accelerating (or decelerating) column as shown on Fig. 2.

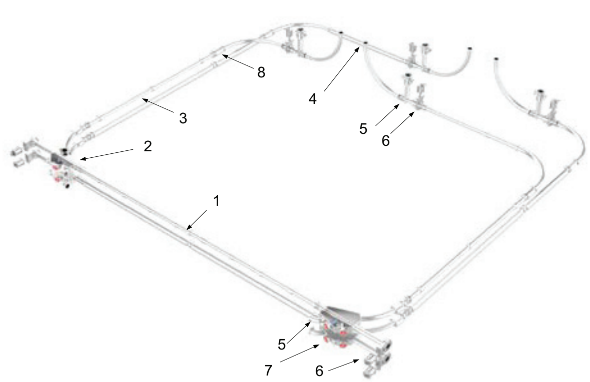

Figure 1: 1 - Cooling section vacuum chamber with BPMs (every one meter), 2 – toroid bend chamber equipped with two 2000 l/s NEG cartridges each, 3 – straight transport channel chamber with BPM, 4 – transition to the electrostatic accelerator, 5 – pumping ports, 6 – gate valves, 7 - NEG cartridges, 8 – special insertion with 1400 l/s NEG cartridge.

VACUUM GENERATION

The vacuum system of the cooler of the NICA booster has similar structure as the main part of vacuum system for the collider despite of the fact that they have completely different size and the shape. As the low energy cooler was successfully commissioned [3] and vacuum condition of 2×10^{-11} mbar was achieved, we rely on all solutions applied for this. Vacuum equipment is similar for both coolers (see Table 1).

Table 1: Vacuum Equipment for One Vacuum System of the High Energy Cooler

Cooling section	Agilent VacIon Plus 300 Noble Diode with TSP Cartridge	2
	CAPACITORR CF 100 MK5 NEG cartridge	4
	Pfeiffer IMR 430, Extractor-system, DN 40 CF-F	1
	VAT All-metal angle valve DN160CF	2
	Turbomolecular pump 700 l/s	1
Transport channels	UHV1400 WAFER MODULE NEG cartridge	1
	VAT All-metal angle valve DN100CF	1
Accelerating column with bending chamber	Agilent VacIon Plus 300 Noble Diode with TSP Cartridge	1
	CAPACITORR D 100 NEG cartridge	4
	Pfeiffer IMR 430, Extractor-system, DN 40 CF-F	1
	Turbomolecular pump 300 l/s	1

Both coolers have oxide cathode as an electron emitter for the electron gun. The oxide cathode, as required, has to be activated during the vacuum system bake-out with back pumping. The activation process is very sensitive to the vacuum condition when the cathode surface is overheated to provide necessary temperature.

Use of the NEG pumps for the distributed pumping was chosen for all vacuum systems belonged to high or low energy coolers. All of those pumps have to be activated at first time of use and reactivated in a definite period according to manual. In a process of reactivation the sufficient amount of hydrogen is released from the pumps surface that have to be pumped with the turbomolecular

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PRELIMINARY STUDIES OF BEAM-INDUCED FLUORESCENCE AND STATUS OF THE BEAM-CURRENT UPGRADE OF THE ELECTRON-COOLER TEST-BENCH AT HIM*

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Abstract

First wavelength-resolved studies of the beam-induced fluorescence (BIF) have been made at the cooler teststand. Its upgrade to 30 kV has been completed, which will allow operation at 1 Ampere beam current. Operation with the upgraded parameters is imminent and options for further experiments will be discussed.

ELECTRON COOLER TEST BENCH AT HIM

A electron cooler test bench including components from TSL (Uppsala) and BINP (Novosibirsk) has been put into operation at Helmholtz-Institut Mainz (HIM) and is currently working at $U_{\text{Source}} = 17\,\text{kV}$, $U_{\text{Collector}} = 3\,\text{kV}$ and $I = 0.55\,\text{A}$ (figure 1). From the source to the collector, the beam is immersed in a longitudinal magnetic field. So far, the main investigations were related to the relative number of backstreaming electrons from the collector. The results indicate that the flow of electrons towards ground potential in a fully magnetized high energy cooler is very low. This is mainly due to the implementation of the Wien filter, which was already installed in the COSY cooler developed by BINP [1]. A detailed description of our apparatus and the results achieved can be found in [2]. The present study aims at optical detection as a method of obtaining information about the electron beam intensity distribution.

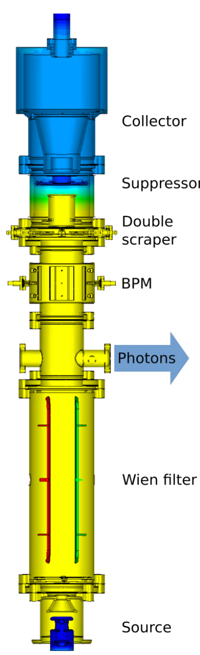

Figure 1: Schematic sketch of the electron cooler at HIM.

OPTICAL BEAM DIAGNOSTICS

We have observed that even under UHV conditions (pressure when electron beam is on: $< 2\cdot10^{-10}$mbar) photons are emitted from the apparatus. In order to find out if they are related to the beam or to other background sources (e.g. light emitted from the collector), we have performed several test experiments.

At the windowed flange just above the Wien filter (position marked “Photons” in figure 1), photons emitted from the beam pipe can be observed. These were measured by an optical setup consisting of a remotely controllable lens and slit in front of a cooled photomultiplier tube (PMT, $T_{\text{PMT}} = -20\,°\text{C}$). The distance of the lens from the beam orbit is varied with the intention to find a distance where a sharp image is obtained. The definition of the image was investigated in one dimension by moving the slit laterally in front of the PMT (figure 2).

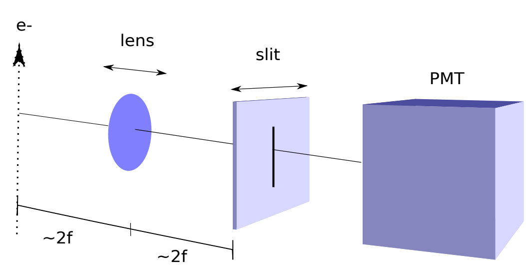

Figure 2: Schematic of the optical setup.

A series of bandpass filters with different center wavelengths (400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 650 nm, 700 nm) and a FWHM bandwidth of $\lambda_{\text{FWHM}} = 50\,\text{nm}$ were added behind slit in order to obtain wavelength-resolved measurements. Transmission of the sapphire viewport (79-84%) and the quantum efficiency of the PMT (15-30%) were taken into consideration. This

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THE HIGH VOLTAGE POWER SUPPLY SYSTEM FOR THE ELECTRON COOLER FOR CSRe

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Abstract

The high-voltage power supply system for upgrade of the electron cooling system of CSRe ring in the IMP, was developed at the BINP in 2014 - 2019. The main features are - maximum voltage is 300 kV, stability - 10ppm, with the ability of quick changing of voltage in range ±10% of nominal voltage for a time not more than 500 μs. The key points of this design are presented in this article.

INTRODUCTION

In 2014 – 2019 upgrade of the electron cooling system of CSRe ring in the IMP (Lanzhou, China) was carried out. The high-voltage power supply system for upgrading was developed at the BINP. The power supply system consists of 10 controlled modules, distributed by the high voltage potential. Each module has a precision controlled voltage source. All the systems are controlled through the wireless network interface. System was installed and tested at CSRe ring in IMP at May – June of 2019.

High voltage system of such a modular structure already was created in BINP earlier for an high voltage electron cooler for heavy ions, which was installed on the COSY accelerator (Jülich, Germany) [1, 2]. New system has essential differences from old one. It does not have current sources for solenoids, but it has additional circuits for detuning mode. This mode allows change the energy of electron beam within 10% range from mean level. The main parameters of the cooler are as follows: the electron energy is from 5 keV to 300 keV and the current is up to 2 A. The energy instability of the new supply system will not exceed 10 ppm. Main limitations for installation is the need to fit into an existing vessel installed on an already-existing electron cooling system.

The main parameters of the accelerator column of the cooler are presented in Table 1.

Table 1: Main Parameters of the Power Supply System

Parameter	Units	Value
Supply voltage	kV	5 - 300
Voltage instability, less than	ppm	10
External power supply	V	400 - 500
Carrier frequency	kHz	20
Power consumption	kW	3-5
Total height of the column	m	1

Designed power supply system along with precision output parameters should have high reliability and resistance to high voltage discharges.

STRUCTURE OF THE POWER SUPPLY SYSTEM

The structure of the power supply system is shown in Fig. 1.

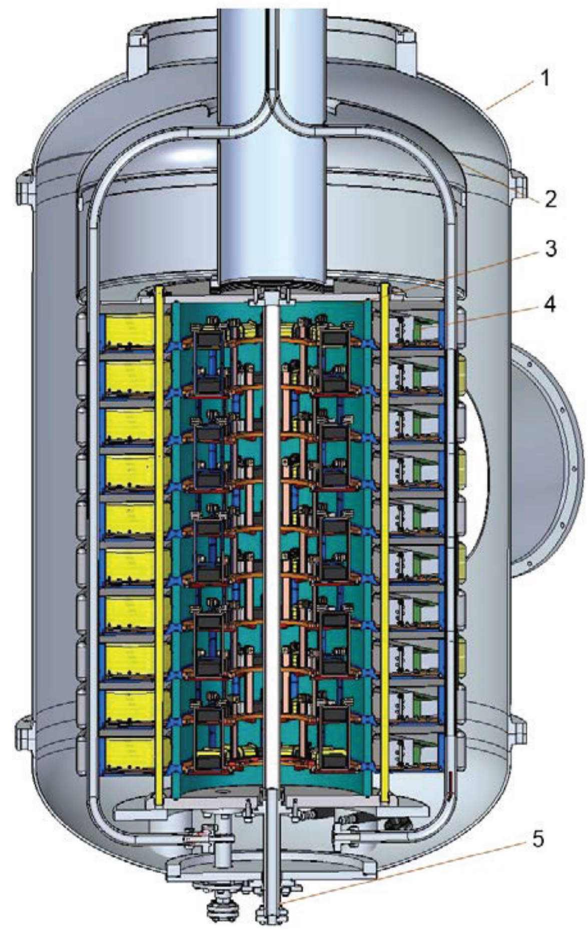

Figure 1: The structure of the high voltage column. 1 – SF_6 tank; 2 – shielding cover; 3 – high voltage cascade transformer; 4 – high voltage section; 5 – isolating and cooling oil tubes.

The high voltage column is placed in the tank, filled with SF_6, and contains high-voltage sections, cascade transformer, oil tubes for high voltage terminal, and communication circuits.

The SF_6 tank already exists in the cooling system, so dimensions of sections are determined by the tank dimensions and high voltage clearances. The cascade transformer provides required power for the high voltage sections and high-voltage terminal. The high voltage

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ELECTRON COOLING SIMULATION BENCHMARKING

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Abstract

Electron coolers are commonly used in storage rings to reduce the phase space volume of heavy particles such as protons, antiprotons and ions. Their effect depends on the Coulomb interactions between the circulating beam and the cold electrons at small relative velocities. The cooling process can be modelled through different approaches and the behaviour of the cooling force, can be described by various formulas, which include different parameters. The aim of the present study is to compare the accuracy of the cooling simulations performed by two distinct beam-tracking codes: Betacool and RF-Track. Being based on different models and formulas, the two simulation tools require different parameters in order to realistically describe electron cooling. In this contribution, the impact of these parameters is discussed, and simulation predictions are compared with experimental data from LEIR (Low Energy Ion Ring) at CERN and ESR (Experimentier-Speicher-Ring) at GSI. Furthermore, the friction force is calculated for the new antimatter storage ring ELENA (Extra Low Energy Antiproton) at CERN.

INTRODUCTION

Electron cooling is an effective technique to reduce the phase space volume of a circulating beam of heavy particles [1] such as protons, antiprotons and ions in a storage ring [2-4]. The working principle is basically the following: a charged particle beam and an electron beam are overlaid in a small section of the machine and whilst moving at small relative velocities interact by means of electromagnetic forces. However, the simplicity of the concept is side by side with the complexity of the related physics. The phenomena involved fall into the realms of charged particle beam dynamics and plasma physics.

The resulting cooling force can be derived through two different approaches: dielectric theory and the binary collision model [5]. Unfortunately, neither of them can provide a closed form solution in case of a finite-strength magnetic solenoidal field. In order to be able to predict the parameter of the circulating beam after interacting with the electron cooler, it is then necessary to make approximations or to perform numerical evaluations.

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To take into account the finite value of the solenoidal magnetic field, a semi-empirical expression of the cooling force was proposed by Parkhomchuk [6].

An alternative approach is to use the analytical formula directly and carry out a numerical evaluation as opted by Nersisyan in his study of the stopping force [7]. In this contribution, simulation results using these two different approaches are compared in the context of the following facilities: LEIR and ELENA at CERN, and ESR at GSI.

SIMULATION CODES

Simulations of the cooling force in an experiment are important to determine the physical conditions in which the cooling process takes place and hence to optimise the parameters of the cooling system. Several tracking codes have been developed to simulate beam dynamics under different conditions. Betacool [8] and RF-Track [9] are two of them, both designed to simulate cooling processes. In this contribution, both codes are compared and contrasted against one another and measured data of the cooling force from existing electron coolers.

Betacool

The code has been developed since 1994 at JINR (Joint Institute of Nuclear Research, Dubna, Russia) electron cooling group and benchmarked against many experiments [10, 11]. The program represents the ion beam as an array of model particles which undergo a transformation of coordinates when interacting with the cooler. The cooling processes involved in the simulation lead to changes in the particle momentum components, which are calculated using a linear matrix for random phase advance. The cooling force can be chosen from a library of formulas or user written. For the purpose of this study the formula applied by Betacool simulations is the semi-empirical Parkhomchuk formula:

$$\vec{F} = -\vec{V}\frac{4Z^2e^4N_eL_p}{m_e}\frac{1}{\left(V^2+\Delta_{eff}^2\right)^{3/2}}, \qquad (1)$$

where V is the relative ion-electron velocity, L_P is the Coulomb logarithm, N_e is the electron density per squared meter, m_e is the electron mass and Δ_{eff} is the longitudinal effective velocity spread of the electrons. Betacool uses an effective temperature $T_{eff} = m_e\Delta_{eff}^2$ as an input parameter that can be chosen to fit experimental data. Moreover, the electron beam can be described by different

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WINSAM AND WINMAG – NEW PROGRAM PACKAGES FOR SIMULATION OF ELECTRON-OPTICAL SYSTEMS

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Abstract

In BINP new program packages WinSAM and WinMAG have been developed. The main goal of WinSAM program is the simulation of axially symmetric electron optical systems with space charge consideration. This program is the further development of SAM code with greatly improved interface and enhanced scope of considered tasks. WinMAG is developed to solve 3D non-linear magnetostatic tasks, direct integral method is used in this code. Several types of coils including user-defined coils can be entered, magnetic volumes can be described by several basic volumes.

INTRUDUCTION

Over the years, software packages for modeling electron-optical systems are developed in BINP SB RAS. These software packages, along with well-known commercial programs such as COMSOL Multiphysics or OPERA, are widely used in the Institute for the development of various elements of accelerators and other physical installations. Especially intensively these programs are applied at development of electron coolers. The peculiarity of some of these software packages, considered below, is the use of integral methods of calculation, allowing to maintain accuracy with relatively small number of mesh cells, which leads to a significant reduction in the calculation time.

The first of the programs considered in the article is the SAM complex, which is designed for simulation of axially symmetric electron optical systems with space charge consideration [1, 2]. These systems can include electrodes, dielectrics, coils, permanent magnets, linear ferromagnetics. Tasks with space charge can also be simulated with help of SAM program, that allows calculation of electron guns and collectors. Another program under consideration is the MAG3D complex for solving problems of nonlinear 3D magnetostatics [3].

Despite the wide application of these programs, there was a need for their further serious modernization. The most serious problem is their outdated interface. This makes it difficult for existing users to work with these programs, and prevents the attraction of new users. In addition, a confusing interface can lead to errors when specifying the geometry of the problem and the choice of calculation parameters. It is especially necessary to have a simple and intuitive interface in the program MAG3D, performing three-dimensional calculations. Updating the interface is also required for the efficient operation of the postprocessor, facilitating the output of the results of calculations. In addition, the accumulated experience with these programs allowed us to identify those areas of the computational part that need further development to improve the accuracy of calculations.

WINSAM

Basic Calculation Methods

The SAM software package is based on the method of boundary integral equations. This method uses a general solution of the Poisson equation to solve electrostatics problems:

$$\phi(\vec{r}_0) = \int\limits_{S_e+S_d} \frac{\sigma(\vec{r})\, dS}{|\vec{r}_0 - \vec{r}|} + \int\limits_{V_b} \frac{\rho(\vec{r})\, dV}{|\vec{r}_0 - \vec{r}|},$$

where S_e and S_d – surfaces of electrodes and dielectrics, V_b – volume occupied by beam space charge. Substituting this solution into boundary conditions on the surface of electrodes and dielectrics results in a system of integral equations for an unknown surface charge distribution:

$$\int\limits_{S_e+S_d} \sigma(\vec{r}) \frac{1}{|\vec{r}_e - \vec{r}|} dS = \varphi_e - \int\limits_{V_b} \frac{\rho(\vec{r})\, dV}{|\vec{r}_e - \vec{r}|},$$

$$2\pi \frac{\varepsilon_2 + \varepsilon_1}{\varepsilon_2 - \varepsilon_1} \sigma(\vec{r}_d) - \int\limits_{S_e+S_d} \sigma(\vec{r}) \frac{\partial}{\partial n_d}\left(\frac{1}{|\vec{r}_d - \vec{r}|}\right) dS = = \int\limits_{V_b} \rho(\vec{r}) \frac{\partial}{\partial n_d}\left(\frac{1}{|\vec{r}_d - \vec{r}|}\right) dV,$$

where $\vec{r}_e$ and $\vec{r}_d$ – points on the surfaces of electrodes and demarcation boundaries of dielectrics respectively. If an axially symmetric problem is considered, these equations must be integrated with respect to the angle, and the integral over the surface becomes the integral over the contours of the electrodes and dielectrics. Consideration of the problem of linear magnetostatics leads to an integral equation, similar to the second of the above, with respect to the surface density of effective magnetic charges, which describe the field induced by magnetized magnetic materials.

To solve these integral equations a collocation method with spline interpolation of the solution is used in the SAM package. A set of points is placed on the surface of the elements under consideration, the surface charge density is described by linear spline interpolation from the density values at these points. The requirement is put forward – the integral equations must be exactly fulfilled at these points. Due to these conditions, the integral equations are transformed into a system of linear algebraic equations that can be easily solved.

When calculating electron guns and collectors, the right parts of the integral equations describing the effect of the space charge are unknown in advance. In this case, a complete solution of the self-consistent problem is required, which is performed by an iterative method. At

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BEAM POSITION MONITOR SYSTEM FOR HIGH VOLTAGE ELECTRON COOLER FOR NICA COLLIDER

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Abstract

The high voltage (2.5 MV) electron cooler for NICA collider is now designing in BINP. Beam position monitor (BPM) system for orbit measurements has been developed at BINP. The system contains 16 BPMs inside the cooling sections, 4 BPMs inside the high voltage vessels and 22 BPMs in transport channels. Continuous electron beam is modulated with 10 MHz sinusoidal signal for capability to get signals from pickup electrodes. The beam current modulation can be varied in the range of 0.3-5 mA. The modulation signal may be supplied to each sector of the control electrode. So, the position of one quadrant sector of the electron beam can be measured by BPM system. Comparing the positions of each sectors from BPM to BPM it is possible to analyse the shape of the electron beam in the transport channel and cooling section. The BPMs inside the cooling section can measure both electron and ion beams. It is achieved by means of switching the reference signals inside the BPM electronics. The prototypes of new BPM electronics have been fabricated and tested. The BPM electronics provides highly precise beam position measurements. Position measurement error doesn't exceed a few micron. Design features of the BPM system, its parameters and testing results are presented in this paper.

INTRODUCTION

The high voltage (2.5 MV) electron cooler for NICA collider is now designing in BINP [1]. Beam position monitor (BPM) system consists of 42 BPMs and electronics. 16 BPMs are located inside the cooling sections, 4 BPMs are installed inside the high voltage vessels and 22 BPMs are installed in transport channels. Continuous electron beam current is modulated with a ~10 MHz signal for capability to get signals from BPM electrodes. Some parameters of cooler and main BPM system requirements are presented in Table 1.

Table 1: Main Requirements to BPM System

Electron current	0.1-1 A
Modulation amplitude of electron current	0.3-1.5 mA
NICA collider revolution frequency F_0	523-586 kHz
Number of ion bunches N_b	22
Position measurement error	< 100 μm
Measurement rate	0.1-1 sec

To achieve the best cooling effectiveness electron and proton beams must be aligned inside the cooling section with accuracy better than 100 μm. This condition requires simultaneous measurements of electron and proton beams position by 16 BPMs located inside the cooling sections. 22 BPMs in the transport channels and 4 BPMs inside the high voltage vessels measure only electron beam position. A feature of the gun four-sector control electrode using before in the COSY cooler allows measuring not only electron beam position but the beam shape and rotation [2].

SYSTEM STUCTURE

The structure chart of the BPM system is presented in Fig. 1.

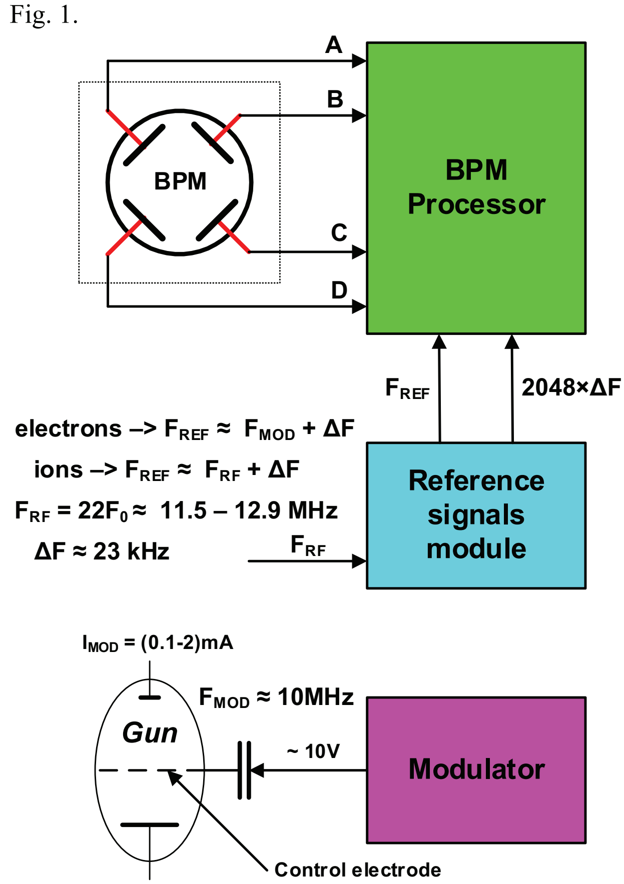

Figure 1: The structure of the BPM system.

The system consists of 42 BPMs, Signal Processing Electronics, including 21 BPM Processors and 38

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ELECTRON COOLER INTRODUCED PERTURBATIONS ON ION BEAM

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Abstract

The influence of electron cooler on stored ion beams in heavy ion synchrotron has been studied for many years. Usually, only the influence on lattice from the magnetic field of solenoid and toroids were considered, in addition to the cooling effect from Coulomb Scattering. However, electron cooling experiments show that there exist limits on intensity of electron beam and the stored ion beams. Meanwhile, experiments of cooling with pulsed e-beam show structure instability that should be explained. The influence of electron beam induced electromagnetic field on ion beams was studied in this paper by means of Lie Algebraic method. The combined transport matrix of solenoid and e-beam field focusing is given. Application of the matrix may help to understand the above phenomena.

INTRODUCTION

As is well known, the general requirements for an e-cooler includes:

1. Parallel and similar velocity of e-beam and ion-beam;
2. Lower electron beam temperature;
3. Adequate cooling force (electron density n_e and length L_e);
4. Compensable or Neglectable influence on ion beam.

In order to satisfy these requirements, solenoid with high uniformity field is introduced to constrain the electron beam and keep its temperature, toroids and/or electrostatic inflectors are introduced to guide the e-beam orbit. The magnetic field of solenoid and toroids will affect the ions passing through it, and usually these effects will be compensated for. The coupling effects of solenoid field can be compensated by a pair of additional solenoids or skew quadrupoles, but the focusing effects are usually neglected. The bending effects of toroid field can be compensated by dipole correctors.

Another source may come from the space charge and current focusing of electron beam, which was usually neglected in practice.

In this paper, we will focus on the study of the e-cooler introduced focusing effects of solenoid and the e-beam field. The combined transport matrix of solenoid and e-beam field will be deduced by means of Lie Algebraic method [1].

Application of the matrix may help to understand why high current e-beam not be used to cool low energy ion beam, why in pulsed e-beam cooling the electron bunches should have the same pulse frequency of ion bunch pulse and cover the ion bunches, and how to get higher deceleration efficiency.

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EFFECTS OF ELECTRON BEAM

In addition to the cooling effect from Coulomb Scattering, the electron beam also affects the ion beam by its self-field.

For a round uniformly distributed electron beam, its space charge electric field is given by the following formula:

$$\bar{E}(r) = -\frac{n_e e}{2\varepsilon_0} r \quad (1)$$

where n_e is the electron density, e is the electron charge. From Eq.(1), the focusing strength can be given as:

$$K_E = \frac{n_e e}{2\varepsilon_0 \, \beta c \, B\rho} \quad (2)$$

where βc is the velocity of ion/electron, $B\rho$ is the magnetic rigidity of the ion beam.

For a round uniformly distributed electron beam, its current induced magnetic field is given by the following formula:

$$\bar{B}(r) = \frac{\mu_0}{2\pi r^2} I \times r = \frac{\mu_0 n_e \, e \, c}{2\, r} \beta \times r \quad (3)$$

From Eq.(3), the focusing strength can be given as:

$$K_B = -\frac{\mu_0 n_e \, e \, \beta c}{2\, B\rho} = -\beta^2 K_E \quad (4)$$

The total focusing strength of electromagnetic field of electron beam can be given as:

$$k = K_E + K_B = (1-\beta^2)\frac{n_e \, e}{2\varepsilon_0 \, \beta c \, B\rho} \quad (5)$$

For the stand-alone electron beam, its transport matrix can be written as:

$$R_{ef} = \begin{bmatrix} \cos(\sqrt{k}L) & \frac{1}{\sqrt{k}}\sin(\sqrt{k}L) & 0 & 0 \\ -\sqrt{k}\sin(\sqrt{k}L) & \cos(\sqrt{k}L) & 0 & 0 \\ 0 & 0 & \cos(\sqrt{k}L) & \frac{1}{\sqrt{k}}\sin(\sqrt{k}L) \\ 0 & 0 & -\sqrt{k}\cdot\sin(\sqrt{k}L) & \cos(\sqrt{k}L) \end{bmatrix} \quad (6)$$

From Eq.(5) we noticed that the focusing strength of electron beam induced field will decrease along with the beam energy.

DEDUCING OF COMBINED TRANSPORT MATRIX

To deduce the combined transport matrix of solenoid and electron beam, Lie Algebraic method is adopted [1]. The simplified combined Hamiltonian for transversal movement is:

$$H = \frac{1}{2}\left(\left(x' + \frac{1}{2}k_s y\right)^2 + \left(y' - \frac{1}{2}k_s x\right)^2\right) + \frac{k}{2}\cdot(x^2+y^2) \quad (7)$$

where $k_s = \frac{B_s}{2B\rho}$ is the strength of solenoid field, B_s is the magnetic field of solenoid, and k is the strength of e-beam field.

As well known, the Lie transformation associated with $f(x,x',y,y') = -L\cdot H$ will give out the polynomial representation of the elements of transport matrix. It's not convenient and not precise to use the truncated polynomial in

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POWER SUPPLIES FOR CORRECTORS OF THE 2.5 MeV ELECTRON COOLING SYSTEM FOR THE COLLIDER NICA

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Abstract

To achieve the design luminosity of 10^{27} cm^{-2}s^{-1} in the collider NICA [1] on colliding high-intensity ion beams with energy of up to 4.5 GeV/nucleon in the center-of-mass system, it is necessary to form short bunches with small transverse emittance. That will be done using electron cooling of ion beams at the energy of the experiment, which corresponds to an electron energy of 0.2 to 2.5 MeV. For simultaneous cooling of both ion beams, an electron cooling system consisting of two independent coolers has been designed [2].

INTRODUCTION

Each cooler of the electron cooling system includes the gun, where the electron beam appears, the accelerating/decelerating electrostatic tube, the transport beam line, and the cooling section. For correction of electron beams, both coolers use 144 correcting electromagnets (correctors), which need separate power supplies. All the power supplies of the correctors have been developed and produced at BINP.

The correction system includes six types of correctors:

- Correctors of beam position in the transport beam line and cooling section.
- Correctors for alignment of the force line straightness in the cooling section.
- Correctors for alignment of beam shape in the bends.
- Correctors for reducing the Larmor beam gyration (dipole mode and galloping mode).
- Correctors of the section for coordination of the transition from the electrostatic accelerator to the transport beam line.
- Correctors of the section for coordination of the transition from the transport beam line to the cooling section.

According to the power supply type, all the correctors can be divided into two groups:

- Correctors controlled by current of up to 6 A: 112 pcs.
- Correctors controlled by current of up to 20 A: 32 pcs.

However, correctors relating to the group with power sources of up to 6 A differ greatly in the total winding resistance (from 0.7 to 16 Ω, excluding the resistance of the leads). Therefore, the power supplies within the group have different output voltages.

Table 1 shows the numbers of different power supplies used for correction of the electron beam of the electron cooling system. The magnetic system of the electron cooling includes sections where longitudinal field correction is required, but the design makes it impossible to place free-standing correctors. The longitudinal magnetic field is formed by several series-connected sections, energized from a common power supply. For correction of the magnetic field, each section is connected in parallel with an additional, galvanically isolated, power supply, which produces an additional current of up to 20 A, which corresponds to 15% of the main power source current. In total, there are 16 additional current sources. They use the same power supply as the correctors.

Table 1: Power Supplies of Correctors

Type of power supply	Quantity, pcs.	Output current range, A	Maximum output voltage, V
MPS-6-24	32	-6 ÷ 6	24
MPS-6-60	32	-6 ÷ 6	60
MPS-6-140	48	-6 ÷ 6	140
MPS-20-50	48	-20 ÷ 20	50

STRUCTURE OF POWER SUPPLIES

Correctors with current of up to 6 A are powered by multichannel modular power supplies. Figure 1 shows a block diagram of eight-channel module of power supply MPS-6.

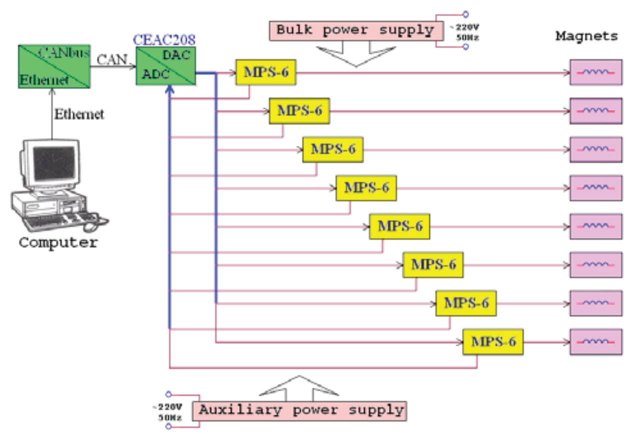

Figure 1: Structure of power module MPS-6.

The module includes 1 to 8 converters of the bulk power supply voltage to DC current. Each of these blocks supplies constant current to the respective load. The MPS-6 converters are monitored and controlled by means of analog signals. All MPS-6 converters within a module have common buffer and auxiliary power supplies, as well as common controller comprising digital-to-analog and analog-to-digital converters. Such a structure has the following advantages:

- The maximum output voltage of all MPS-6 converters within a module is determined by the voltage of the buffer power supply, and thus all the MPS-6 converters can be produced identical, which reduces the number of different blocks.

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THE CASCADE TRANSFORMER FOR THE HIGH-VOLTAGE ELECTRON COOLING SYSTEM FOR THE NICA COLLIDER

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Abstract

The 2.5 MeV electron cooling system for the NICA collider (JINR, Dubna) will use cascade transformers for distributing the power among the sections of the high-voltage column and for transferring power to the high-voltage terminal. The design of the cascade transformer and the measurements of its prototype are described.

INTRODUCTION

The NICA collider is designed to operate ion beams with energies up to 4.5 GeV/u [1]. In order to increase the ions accumulation efficiency and ions lifetime in the collider the electron cooling system must provide 2.5 MeV electron beams [2]. The designed electron cooling system uses the guiding magnetic field along the entire transport channel of the electron beam, including the high-voltage column. Magnetic coils and the power supply for electron collector constitute the major power consumption of the high-voltage column.

There are several common ways to transfer the electrical power to high-voltage regions, described in [3]. Methods involving the transmission of mechanical energy are not suitable for the new electron cooler, as some of them require larger space, entail the power consumption overhead or tend to be unstable. Instead, the electron cooling system will use a cascade transformed with high coupling coefficient between cascades, which transfers power from section to section through electrically isolated windings (Fig. 1).

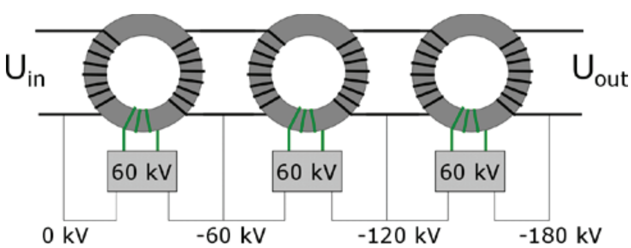

Figure 1: The schematic diagram of a power transferring cascade transformer.

A single high-voltage column includes two cascade transformers with 42 sections each: for transferring power to the high-voltage terminal and for distributing the power among the column sections.

POWER CONSUMPTION OF THE HIGH-VOLTAGE COLUMN

Each section of the high-voltage column (Fig. 2) has two coils for creating 500 G longitudinal magnetic field for focusing the electrons. The power consumption of a single coil is about 100 W. The electronics in a section together with high-voltage power supplies takes additional 220 W. Another consumer is the high-voltage terminal. It includes a 10 kW power supply for the collector rectifier and a 5 kW solenoid for focusing a low energy electron beam. The design parameters of the high-voltage column related to power consumption are presented in Table 1.

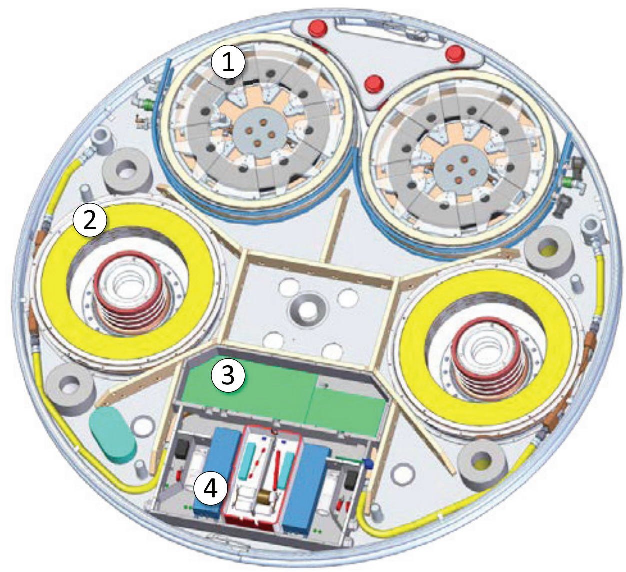

Figure 2: Section of the high-voltage column: (1) a single ring of the cascade transformer, (2) a magnetic coil for creating a guiding magnetic field in the accelerating tube, (3) control electronics, (4) high-voltage power supplies.

Table 1: Power Consumption of the High-Voltage Column

Consumer	Power
Magnetic coils of a section	200 W
HV power supply per a section	120 W
Control electronics per a section	100 W
Collector rectifier	10 kW
Control electronics of the HV terminal	700 W
Magnetic coils in the HV terminal	5 kW
Sections of the HV column	17.6 kW
HV terminal	15.7 kW

DESIGN OF THE CASCADE TRANSFORMER

The cascade transformer consist of 42 sections stacked one onto another with 6.4 cm period. To prevent overheating of the transformer during its operation, it is placed inside an oil-cooled tank (Fig. 3). As voltage between adjacent sections of the transformer reaches 60

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ELECTRON COOLING APPLICATION FOR HADRON THERAPY

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Abstract

The project of synchrotron for hadron therapy with electron cooling is developing in the Budker Institute of Nuclear Physics. The main goal of the project is design of the effective and low cost hadron therapy facility. The electron cooling is applied for an ion beam accumulation, cooling and preparation for slow extraction. The high quality cooled ion beam with an extreme small emittance and energy spread allows significantly decrease the synchrotron and beam transfer lines apertures. Moreover, the electron cooling can be applied for accumulation of short-lived radioactive isotopes that can be used for online visualization of treatment.

INTRODUCTION

Cancer is now the origin of death in one out of every four lives. Overcoming this scourge is a common goal for all of humanity. The common treatment for cancer includes surgery, chemotherapy and radiation therapy. The radiation therapy is one of the effective methods for cancer treatment and is prescribed to more than 50% of all patients. It is based on delivering high doses of ionizing radiation to localized tumours in the body. The goal is to destroy all the tumour cells with acceptable damage effects to the surrounding normal tissue, which is unavoidably irradiated.

Photons are used for most patients treated with a conventional radiotherapy. They deposit most of energy upstream of the tumour in healthy tissue. Special irradiation system from many directions and intensity modulation are used to increase the ratio of tumour to healthy tissue dose. The conventional therapy by photons is relatively inexpensive and wide world use.

Beams of protons and ions offer important advantages over conventional radiotherapy. The protons and ions power does not decrease exponentially with penetration in the body. Instead, they deposit more energy as they slow down, culminating in a Bragg peak. The depth at which the peak occurs can be operated by the value of particles energy are given by the accelerator. The proton and ion beams have little lateral scattering and can be precisely controlled. Therefore, the beam energy can be delivered accurately to the treatment volume without seriously damage of surrounding tissues or adjacent critical organs.

The hadron beam therapy has been shown to be effective in such cases as relatively large tumours of the esophagus and lung, liver, prostate and rectum, tumours of the head and neck, and eye.

For physical as well as for biological reasons, the light ions yield better clinical results than protons. Light ions, such as carbon, have a higher RBE than protons and provided treatment that is more effective for certain, deep-seated tumours that are often radio-resistant.

The clinical success of carbon therapy at the NIRS, Chiba, Japan and GSI, Darmstadt, Germany has led to the establishment of 10 more carbon ion therapy centres in Japan, Germany, Italy, Austria and China [1-3]. Several other centres are planned or are under construction in Europe and Asia. However, the high capital and operating costs limit the wide application of ion therapy. The development of robust, effective, and low costs ion therapy system is a paramount task to increase the availability of treatment to the patients.

ELECTRON COOLING APPLICATION

The idea of electron cooling was proposed and developed at BINP [4]. The electron and ion beams are converged inside the cooling section and during the particles co-moving the heat energy transfers from ions to electrons. Thus, the electron cooling reduces the spread in the longitudinal and transverse ion velocities, which means a decrease in the momentum spread and transverse emittance of the ion beam. Now, the low energy electron cooling is a routine and effective technique wide used in the high energy and nuclear physics. In particular, electron coolers are installed at the leading centres were methods of ion therapy was developed and continues to develop [5, 6]. However, at developing of standard design for ion therapy facility the electron cooling technology was not in demand. Usually, this is argued that the electron cooling is expensive and very complex equipment, redundant for therapy facility. The main goal of present article is the demonstration that electron cooling application helps design robust and not expensive medical accelerator.

The accumulated at BINP experience allows transferring the electron cooling technology to the application field. The ion therapy is the most favourable application. The ion beam energy range required for the cancer therapy is fully overlapped by the standard design of the BINP electron cooler (Fig. 1). This base design demonstrates the effective and robust long time operation at GSI (Darmstadt), IMP (Lanzhou) and LEIR (CERN) with success [7,8].

The cooled high intensity ion beam with extreme small energy spread and transverse emittance is a superior therapeutic instrument allowing irradiate tumour with high accuracy. Certainly, the size of beam spot on the tumour is determined primary by multiple scattering and fluctuations of ionization losses during the path in depth of tissues. Nevertheless, the electron cooling eliminates the beam spot broadening due to the inherent beam emittance and energy spread.

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THE MAGNETIC SYSTEM OF ELECTRON COOLERS OF COLLIDER NICA

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Abstract

The complex of electron cooling is created in the BINP SB RAS. Complex is duplex of electron coolers. According to technical specifications total power consumption of the complex should not exceed 500 kW, electron energy from 0.2 to 2.5 MeV, magnetic field in solenoids of cooling up to 2kG, and distance between the centers of solenoids should be 320mm. In general, the layout of this complex is similar to the layout of the cooler created in BINP for COSY [1], but its production due to the above specifications is much more complicated.

LAYOUT OF MAGNETIC SYSTEM. POWER SUPPLIES.

Magnetic system of coolers complex is shown on Fig. 1. The units of upper cooler of this system marked counterclockwise from gun to collector: **1**–gun, **2**–accelerating tube, **3**–match-1, **4**–bend-1, **5**–line08-1, **6**–bend-2, **7**–insert-1, **8**–transport channel-1, **9**–insert-2, **10**–tor90-1, **11**–ion dipole-1, **12**–ins&match-1, **13**–solenoid, **14**–ins&match-2, **15**–ion dipole-2, **16**–tor90-2, **17**–insert-3, **18**–transport channel-2, **19**–insert-4, **20**–bend-3, **21**–insert-5, **22**–transport channel-3, **23**–line08-2, **24**–bend-4, **25**–match-2, **26**–decelerating tube, **27**–collector.

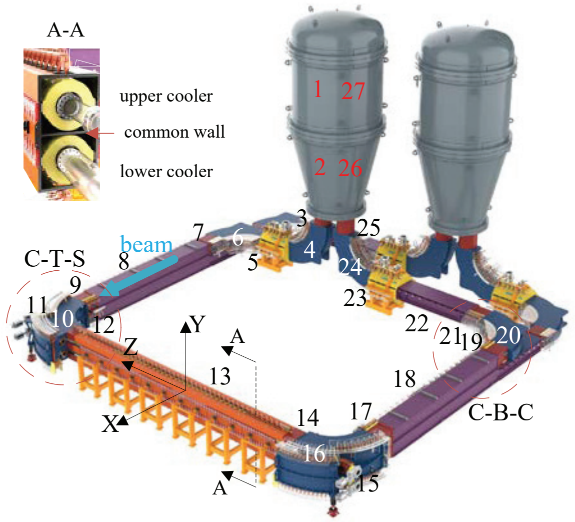

Figure 1: Layout of magnetic system. C-B-C – reference segment, C-T-S – multifunctional segment.

The same units of the lower cooler are placed clockwise from gun to collector (on direction of electron beam). Total length of transport channels here is 1.4 times greater.

The power consumption is determined by the specified value of longitudinal field B_s in units of system and permissible winding height in their coils. The radial or vertical dimensions of the vacuum elements determine inner radius r_{in} of the round coils or inner size on Y of the toroidal coils: ≥87 mm. The common wall of the magnetic shields of electron coolers with a thickness of 15mm and the distance between the beams (320 mm) limit the outer radius of round coils: r_{out}=150mm. To minimize the power loss, it was necessary to implement the maximum possible winding height in round coils: $r_{out} - r_{in}$ = 63mm. In this case, the losses per 1 m in the solenoid (at 2 kG) are equal to 10 kW/m. Coils of bending field (B_b) are locates above and below coils of longitudinal field (B_s) in toroids and bends. Minimal thickness of the bending coil is 17mm. As a result, winding height of these coils is reduced by 17 mm. Such restrictions on the winding height determine the value of the B_s field in these and other units of the magnetic system: no more than 1kG. For this reason, short units of field matching (ins&match **12**, **14**) are inserted into each gap between the solenoid (**13**, 2 kG) and the toroids (**10**, **16**, 1 kG).

Each cooler will use twelve high-current power sources (PS). PS of upper cooler are show in Table 1. IST-9up and IST-5up are PS of bending field B_b. IST-10up and IST-11up are PS of ion dipoles. Others IST-s are PS of longitudinal field B_s of the rest units.

Table 1: PS of Upper Cooler

PS	Magnetic system units	I(A)	P(kW)
IST-1up	solenoid (**13**)	221	61
IST-2up	tor90-1 (**10**)	710	19.8
IST-12up	tor90-2 (**16**)	710	19.8
IST-9up	∑Btor90 (**10**,**16**)	295	3.72
IST-3up	∑bend (**4**,**6**,**20**,**24**)	195	31.5
IST-5up	∑Bbend (**4**,**6**,**20**,**24**)	295	7.45
IST-4up	∑line08 (**5**,**23**)	250	19.3
IST-7up	∑channel(**8**,**18**,**22**)	135	30.1
IST-6up	∑ins(**7**,**9**,**12**,**14**,**17**,**19**,**21**)	320	21.9
IST-8up	∑ins&match (**12**,**14**)	440	7.56
IST-10up	ion dipole-1 (**11**)	440	4.93
IST-11up	ion dipole-2 (**15**)	440	4.93

Full power of upper cooler is 232kW. Power of lower cooler is 244kW (more due to the length of channels).

REFERENCE SEGMENT: CHANNEL– BEND – CHANNEL

Properties of turn of electrons by 90° in the case, when centrifugal force compensates by Lorentz force only on average, studied when creating a COSY cooler [1]. Let's consider the a similar variant adapted to NICA cooling complex. Calculations performed using proven MAG3D code [1]. Sizes of coils and ferromagnets as close to real as possible. Radius of turn is R=1m. The longitudinal field B_s=1kG. The electron passage of the bend is resonant in

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PARAMETER OPTIMISATION OF RING SLOT COUPLER PICKUP AND KICKER FOR NICA STOCHASTIC COOLING SYSTEM

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Abstract

Pickup and kicker structures for the NICA stochastic cooling system are supposed to be based on ring slot couplers proposed in [1]. However, it differs from the original design by the insertion of a ceramic vacuum chamber that shifts frequency of the structure down to 1-1.5 GHz. Possible design solution of the rings was proposed to shift frequency of the structure to the desired 2 – 4 GHz.

INTRODUCTION

Ring slot coupler structures proposed for HESR stochastic cooling system (SCS) [1] were successfully used for the beam cooling at Nuclotron and COSY [2, 3]. The demonstrated performance within 2-4 GHz frequency band satisfies to requirements of the NICA collider SCS. In the ring structure with octagonal arrangement of shorted electrodes (Fig. 1) the total image current passes the surrounding uninterrupted gap formed by two adjacent rings.

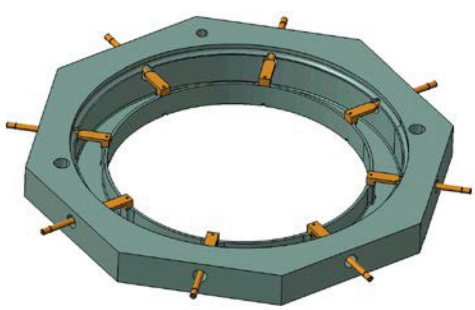

Figure 1: Schematics of single ring of the ring slot coupler structure.

However, the external sealing used in the systems mentioned above makes it problematic to achieve ultra-high vacuum of 10^{-11} Torr which is essential for NICA. Therefore, strict vacuum requirements force us to produce pickups and kickers with internal sealing. In this case, pickup and kicker is assembled over the cylindrical ceramic tube made of Al_2O_3 material (Fig. 2). The ceramic tube shifts frequency of the structure down to 1-1.5 GHz. The goal of this work is to demonstrate possibility to modify design of the pickup and kicker for effective work in the same 2 – 4 GHz band – so in this case we can use the other elements of the system without changes.

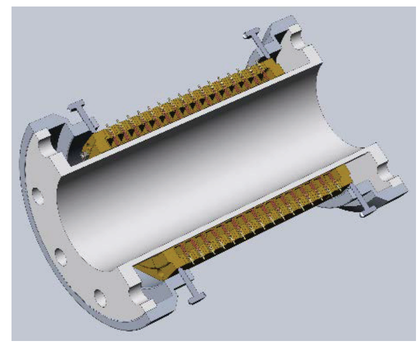

Figure 2: Schematics of pickup (kicker) with internal sealing using ceramic vacuum chamber.

MODELING

Parameters of the Model

The study and design optimisation was done in CST Microwave Studio. The goal was to qualitatively evaluate the field of optimal structure parameters. So maximal simplification of model and calculation settings were done – to make faster calculations even to the detriment of accuracy. Lumped elements and ports were used; the form of feeding loop was not taken into account, lose free materials so as maximal mesh step were used.

Model Benchmarking

To estimate the accuracy of modelling method the original structure was modelled (Fig. 3) and the results were compared with the same obtained earlier [4].

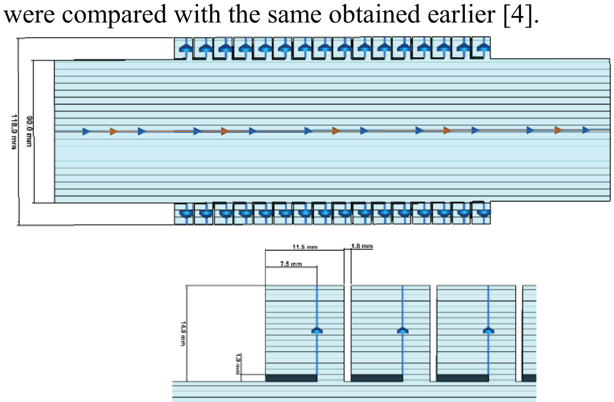

Figure 3: Dimensions of the model.

Electrical field of structure on different frequencies for infinite number of cells and for 17 cells was calculated. The results are given in Fig. 4.

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PHASE STEP METHOD FOR FRICTION FORCE MEASUREMENT IN FILTER STOCHASTIC COOLING

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Abstract

Voltage step method for friction force measurement in electron cooling is well known. The similar method for friction force measurement in longitudinal stochastic cooling with comb filter is provided. First test of the method during the run at COSY has been implemented.

INTRODUCTION

Stochastic cooling systems (SCS) for High Energy Storage Ring (HESR) and Nuclotron-based Ion Collider fAcility (NICA) are under development in GSI Helmholtz Centre for Heavy Ion Research [1] and in Joint Institute for Nuclear Research [2] respectively. The preparatory experimental work on stochastic cooling for HESR and NICA is carried out at COoler SYnchrotron (COSY) at Forschungszentrum Jülich [1]. During this work hardware solutions and automation techniques for system adjustment had been worked out and tested. The automation technique is based on the cooling process simulation which is described by Fokker-Planck equation (FPE) [3]. One of the notions defining the evolution of the cooling process is drift term of the FPE which is also known as friction force. The measurement of friction force may be fruitful for fine tuning of cooling systems. The approach for friction force measurement in filter stochastic cooling is discussed below.

DESCRIPTION OF THE METHOD

Procedure

Originally the method of longitudinal friction force measurement was widely used in electron cooling [4 – 7]. Cold electrons interchange their temperature with hot ions during the electron cooling process. Cathode voltage of the electron cooler defines energy of electrons. If the mean energy of electrons is slightly different than the one of ions the ion energy distribution evolves to the new equilibrium.

The experimental procedure is the following: at first the mean electron energy is equal to the ion one, then after a rapid voltage step on the cooler cathode the friction force shifts along the energy as shown in Fig. 1 and ion energy distribution starts to evolve as shown in Fig. 3. By the evolution of maximum and/or mean values of ion energy distribution one can evaluate the actual friction force. The evaluation is described in details in the next section.

Similar procedure where the shift of the friction force is provided for momentum stochastic cooling can be done with a comb filter. Such technique is simpler for filter stochastic cooling due to comb filter has more parameters to adjust (see Fig. 2) in comparison with other methods for momentum stochastic cooling. Simulation based on FPE approach [2] shows that proper shift of the friction force along the energy is performed by adding extra delay Δt_{filter} in the long leg of the comb filter and proportional system delay

$$\Delta t_{sys} = \frac{T_{P\to K}}{T_0} \Delta t_{Filter},$$

where $T_{P\to K}$ is time of flight between pickup and kicker for the reference particle and T_0 is the revolution period. So the only difference in procedures for friction force measurement between electron and filter stochastic cooling is that instead of changing one parameter of cathode voltage for electron cooling there are two proportional parameters Δt_{filter} and Δt_{sys} which should be stepped simultaneously.

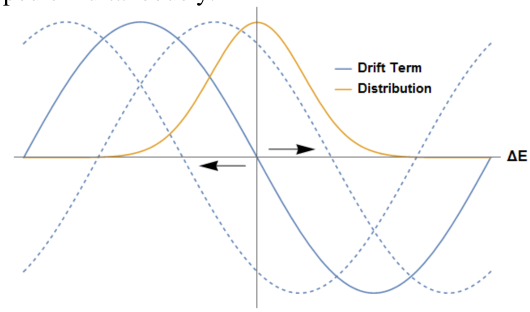

Figure 1: FPE drift term a.k.a. friction force (blue): initial (solid) and shifted to the left or to the right (dashed) in comparison with distribution function (orange).

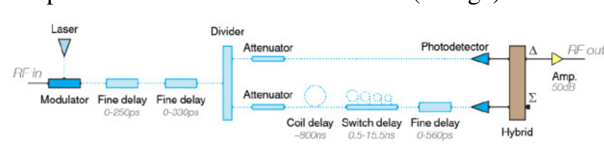

Figure 2: Scheme of optical comb filter

The friction force of the momentum stochastic cooling is alternating and during the adjustment several possible delay combinations lead to cooling. The optimal combination of delay parameters is when system delay is equal to the reference particle’s transit time between pickup and kicker and filter delay is equal to the revolution period. If SCS has optimal adjustment the friction force is close to an odd function. In our case we intentionally chosen not optimal adjustment of the system by adding extra system delay in order to have asymmetric friction force. The transfer function of the SCS which is proportional to the friction force is shown in Fig. 4.

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STOCHASTIC COOLING SIMULATION OF RARE ISOTOPE BEAMS ON THE SPECTROMETER RING OF THE HIGH ENERGY AND HIGH INTENSITY ACCELERATOR FACILITY*

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Abstract

Among various cooling methods, stochastic cooling is an effective way of cooling low intensity beams with larger size[1]. For the HIAF (High energy and high Intensity Accelerator Facility) project, stochastic cooling will be built on the SRing (Spectrometer Ring). This paper mainly concerns on cooling effects based on different stochastic cooling methods, aiming at finding the optimal cooling method and cooling parameters for different physical experiment purposes. Besides, TOF cooling combined with filter cooling was also studied. Simulation analysis will provide theoretical reference and support for the engineering construction.

INTRODUCTION TO HIAF STOCHASTIC COOLING SYSTEM

The High Intensity heavy ion Accelerator Facility (HIAF) is high intensity facility in nuclear physics and related research fields, and stochastic cooling system will be built on the Spectrometer Ring (SRing) of the HIAF project. For the SRing stochastic cooling, 2 pickup tanks and 2 kicker tanks will be performed for both transverse and longitudinal cooling. The cooling electrodes will be installed in the straight section without dispersion, and it is advantageous to prevent the coupling between phase subspaces. For transverse cooling, the designed betatron phase advances between pickup and kicker are almost 90 deg.

The momentum spread of the radioactive beam injected into SRing is almost ±1.5e-2. Stochastic cooling is not suitable for cooling this kind of hot beam, because the cooling frequency would be designed relatively smaller, which will greatly reduce the performance. Fortunately, it is planned to decrease the momentum spread to ±4.0e-3 firstly by using bunch rotation, and then stochastic cooling combined with electron cooling will further decrease the momentum spread to the desired value.

For the SRing stochastic cooling system, the beam energy is 740 MeV/u, bandwidths are different based on the different initial momentum spreads. With bunch rotation, the initial momentum spread for stochastic cooling is ±4.0e-3, but without bunch rotation, the initial momentum spread is ±1.5e-2. Therefore, bandwidth is designed differently in order to involve initial momentum spread with the cooling acceptance.

For longitudinal cooling on SRing, TOF cooling [2,3] will be used for cooling of hot beam firstly, and filter cooling [4] will be used for continuous cooling to further reduce the momentum spread subsequently.

LONGITUDINAL STOCHASTIC COOLING SIMULATION ON SRING

Cooling with Bunch Rotation

Table 1: Longitudinal Stochastic Cooling Parameters

Physical parameters	values
Ion	$^{132}Sn^{50+}$
Kinetic energy	740 MeV/u
Total number of RI	1.0e5
Initial Δp/p	±4.0e-3/±1.5e-2 (TOF Cooling) ±7.0e-4/±2.0e-3 (Filter Cooling)
γt	3.37
Local γt	2.752
Bandwidth	0.6-1.2 GHz/0.2-0.6 GHz
Number of slot rings for Pickup/Kicker	64/64
Temperature	300 K
Lpk	92.01 m

The SRing stochastic cooling parameters are listed in Table 1. Slot ring coupler is adopted for the pickup and kicker structure, for the shunt impedance per meter of the slot ring structure is higher compared to other structures such as Faltin structure. The shunt impedance response per cell is shown in Fig. 1.

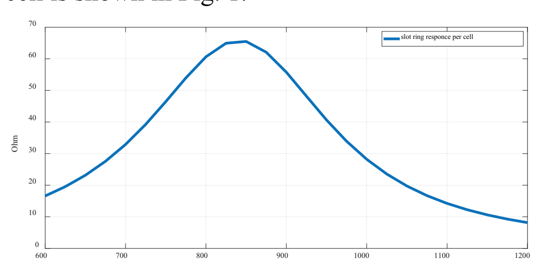

Figure 1: Shunt impedance response of slot ring structure per cell.

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ADJUSTING UNIT OF LONGITUDINAL FIELD COILS FOR NICA HV ELECTRON COOLER'S SOLENOID

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Abstract
Adjusting unit of longitudinal field coils is necessary element used to obtaining a rectilinear longitudinal field in cooling solenoids of electron cooling machines. Due to limited distance between cooling channels of HV electron cooler (320 mm) previously used adjusting unit for longitudinal coil couldn't been applied. Possible orientation of adjusting unit is 90 degrees rotated and gravity force could not load longitudinal field coil mounting to make adjusting unit working. New design of preloaded coil mounting unit, made by BINP, solves this problem and provides necessary adjusting range and adjusting precision of longitudinal field coils for NICA HV electron cooler's solenoid.

DESCRIPTION

Electron cooling systems with magnetized electrons have high requirements for magnetic field quality, i.e. $\Delta B_{\perp}/B=\theta<10^{-5}$ [1]. Other words, for good cooling it is necessary to have strait magnetic field lines in longitudinal axis area of cooling solenoid.

The design of cooling solenoid of the NICA collider is based on a set of discreet coils used to obtain longitudinal magnetic field. Procedures for measuring and adjusting of such solenoids are described in the article [2]. Briefly, the field can be tuned by tilting and rotation of separate coils in solenoid. Usually used in BINP adjusting unit shown on schematic diagram (Fig. 1) consists of longitudinal field coil (1), coil mounting with ball bearing (2) and adjusting screws (3). Unfortunately, this mechanics works only when gravity force loads coil mounting by the coil weight and could not been used in other positions.

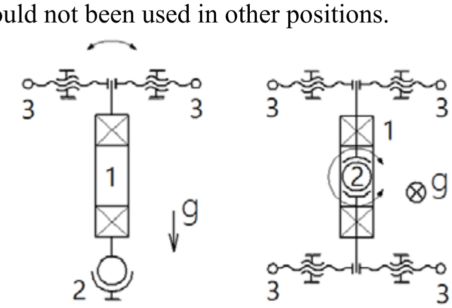

Figure 1: Schematic diagram of coil tilting (left) and rotation (right).

Cooling solenoid of NICA collider is a duplex of lower and upper cooling cannels with distance at 320 mm between cannels axes shown on Fig. 2 and consists of six separated sections. Each section have a length of about 1 meter. Totally, each solenoid have 90 longitudinal field coils placed with a pitch of 66.5 mm [3]. Coil cross-section area is $61.2\text{x}56^{+2}$ mm, and outer radius of the coil are $146^{+1.5}$ mm. Under this dimensions of the coil and distance between cooling cannels the gap between the coil and body wall (magnetic shield wall) at a bottom of upper cannel is about only of 5 mm. And this does not allow to use normal spherical bearing mounting for this coils in upper solenoid. Founded solution is to rotate coil mounting at 90 degrees, and use the Belleville spring to preload spherical bearing unit. Mounting unit shown on the right side of solenoid body on Fig. 2.

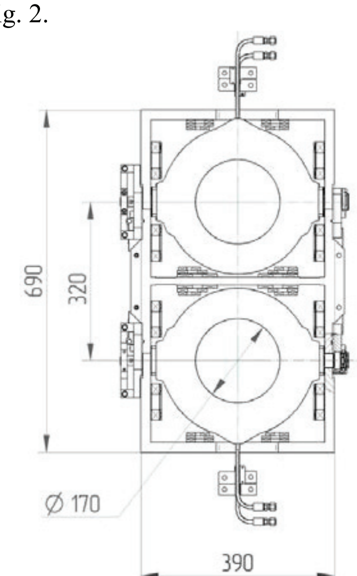

Figure 2: Cooling solenoid cross-section.

This solution shown on Fig. 3 have several parts: ball bearing (2) mounted in case (5) and coil semiaxle (1) is loaded with Belleville spring assembly (3) throw small ball (4) to keep coil tilting and suppress clearances, all this parts are installed in mounting body (6) which is fixed to solenoid section body (7), mark placed in tilting center. In addition, case (5) with bearing can be moved along semiaxle direction to compensate displacement of the coil center.

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