

# THE MUON IONIZATION COOLING EXPERIMENT\*

M. A. Uchida<sup>†</sup>, Imperial College London, UK  
*for the MICE collaboration*

## Abstract

The Muon Ionization Cooling Experiment (MICE) is designed to demonstrate a measurable reduction in muon beam emittance due to ionization cooling. This demonstration will be an important step in establishing the feasibility of muon accelerators for particle physics. The emittance of a variety of muon beams is measured before and after a "cooling cell", allowing the change in the phase-space distribution due to the presence of an absorber to be measured.

Two solenoid spectrometers are instrumented with high-precision scintillating-fibre tracking detectors (Trackers) before and after the cooling cell which measure the normalized emittance reduction.

Data has been taken since the end of 2015 to study several beams of varying momentum and input emittance as well as three absorber materials in the cooling cell, over a range of optics. The experiment and an overview of the analyses are described here.

## INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) is a collaboration of over 100 scientists from 10 countries and 30 institutes around the world. Based at the Rutherford Appleton Laboratory in the UK it is designed to demonstrate a measurable reduction in emittance in a muon beam due to ionization cooling.

Ionization cooling [1] is the process of reducing the beam emittance (phase space) through energy loss in ionization as particles cross an absorber material, this combined with restoration of the longitudinal momentum of the beam through re-acceleration (using RF cavities) makes sustainable cooling.

Muon colliders and neutrino factories are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies and precision measurements of parameters of the Higgs boson and the neutrino mixing matrix. Ionization cooling is the only practical solution to preparing high intensity muon beams for use in these facilities. Muon ionization cooling is necessary for a Muon Collider or neutrino factory [2,3], as the short lifetime of the muon ( $\tau_\mu \sim 2.2 \mu\text{s}$ ) and the large emittance of muon beams (as muons are tertiary particles) means that traditional beam cooling techniques which reduce emittance cannot be used and ionization cooling is the only viable technique to reduce the emittance of the beam within their lifetime.

MICE is currently the only experiment studying ionization cooling of muons.

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<sup>†</sup> m.a.uchida@imperial.ac.uk

## MUON IONIZATION COOLING

Muon cooling can be characterized by the rate of change of the normalized emittance (phase space occupied by the beam). Where the muons lose both longitudinal and transverse momentum through ionization energy loss as they pass through the absorber, a proportion of the lost longitudinal momentum can then be restored using accelerating RF cavities that follow the absorber. Along with this cooling, however, there is a heating effect produced as a result of multiple scattering through the system, therefore, the net cooling is a balance between these two effects. This is described in Eq. (1), where the first term on the right hand side represents the cooling effect and the second term the heating effect:

$$\frac{d\epsilon_n}{ds} \sim -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014 \text{ GeV})^2}{2E_\mu m_\mu L_R} \quad (1)$$

$\frac{d\epsilon_n}{ds}$  is the rate of change of normalized-emittance within the absorber;  $\beta$ ,  $E_\mu$  and  $m_\mu$  the ratio of the muon velocity to the speed of light, muon energy, and mass respectively;  $\beta_\perp$  is the lattice betatron function at the absorber; and  $L_R$  is the radiation length of the absorber material.

The effect of the heating and cooling terms defines an equilibrium emittance:

$$\epsilon_{n,eq} \propto \frac{\beta_\perp}{\beta X_0} \left\langle \frac{dE_\mu}{ds} \right\rangle \quad (2)$$

below which the beam cannot be cooled. However, as input emittance increases, beam scraping results in increased beam loss and so the two must be balanced.

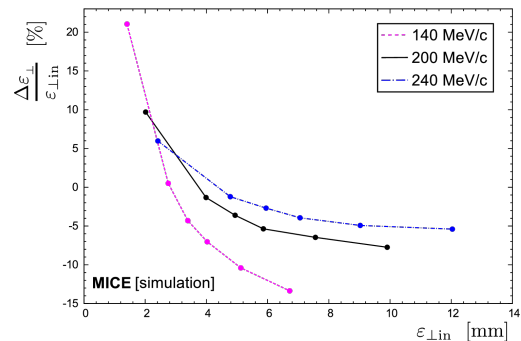


Figure 1: Change in emittance in percent vs. input emittance for a range of MICE beam momenta.

MICE will study this in order to obtain a complete experimental characterization of the cooling process, see Figs. 1 and 2. The cooling equation will be studied in detail for a variety of input beams, magnetic lattices and absorbers to demonstrate the feasibility of this technique. Since a typical

# MEASUREMENT OF PHASE SPACE DENSITY EVOLUTION IN MICE

F. Drielsma\*, Université de Genève, Geneva, Switzerland  
 D. Maletic†, Institute of Physics Belgrade, Belgrade, Serbia

## Abstract

The Muon Ionization Cooling Experiment (MICE) collaboration will demonstrate the feasibility of ionization cooling, the technique by which it is proposed to cool the muon beam at a future neutrino factory or muon collider. The position and momentum reconstruction of individual muons in the MICE trackers allows for the development of alternative figures of merit in addition to beam emittance. Contraction of the phase space volume occupied by a fraction of the sample, or equivalently the increase in phase space density at its core, is an unequivocal cooling signature. Single-particle amplitude and nonparametric statistics provide reliable methods to estimate the phase space density function. These techniques are robust to transmission losses and non-linearities, making them optimally suited to perform a quantitative cooling measurement in MICE.

## INTRODUCTION

Future facilities such as the Muon Collider and the Neutrino Factory will require high intensity and low emittance stored muon beams [1, 2]. Muons are produced as tertiary particles ( $p + N \rightarrow \pi + X$ ,  $\pi \rightarrow \mu + \nu$ ) inheriting a large emittance from the isotropic decay of the pions. For efficient acceleration, the phase space volume of these beams must be reduced significantly, i.e. “cooled”, to fit within the acceptance of a storage ring or accelerator beam pipe. Due to the short muon lifetime, ionization cooling is the only practical and efficient technique to cool muon beams [3, 4]. Each muon in the beam loses momentum in all dimensions through ionization energy loss in an absorbing material, reducing the RMS emittance and increasing its phase space density. Subsequent acceleration through radio frequency cavities restores longitudinal energy, resulting in a beam with reduced transverse emittance. A factor of close to  $10^6$  in reduced 6D emittance has been achieved in simulation with a 970 m long channel [5]. The rate of change in normalized transverse RMS emittance,  $\epsilon_N$ , is given by the ionization cooling equation [3]:

$$\frac{d\epsilon_N}{ds} \simeq -\frac{\epsilon_N}{\beta^2 E_\mu} \left| \frac{dE_\mu}{ds} \right| + \frac{\beta_\perp (13.6 \text{ MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}, \quad (1)$$

where  $\beta c$  is the muon velocity,  $|dE/ds|$  is the average rate of energy loss,  $E_\mu$  and  $m_\mu$  are the muon energy and mass,  $\beta_\perp$  is the transverse betatron function and  $X_0$  is the radiation length of the absorber material. The first term on the right can be referred to as the “cooling” term driven by energy loss, while the second term is the “heating term” that uses the PDG approximation for the multiple Coulomb scattering.

\* francois.drielsma@unige.ch

† Speaker

MICE [6] is currently taking data in the Step IV configuration in order to make detailed measurements of the scattering, energy loss [7] and phase space evolution at different momenta and channel configurations, with lithium hydride and liquid hydrogen absorbers. A schematic drawing of MICE Step IV is shown in Figure 1. MICE consists of two scintillating fiber trackers upstream and downstream of the absorber in strong solenoid fields to accurately reconstruct the position and the momentum of individual muons selected in a series of particle identification detectors, including 3 time-of-flight hodoscopes (ToF0/1/2), 2 threshold Cherenkov counters, a pre-shower calorimeter (KL) and a fully active tracker-calorimeter (EMR) [8–11].

## COOLING CHANNEL

The two spectrometer solenoid modules each generate a region of uniform 3 T field in which diagnostic trackers are situated and a matching region that transports the beam from the solenoid to the focus coil module. The focus coil module, positioned between the solenoids, provides additional focusing to increase the angular divergence of the beam at the absorber, improving the amount of emittance reduction that can be achieved. The magnetic field model is shown in Figure 2. The absorber was a single 65 mm thickness lithium hydride disk. Lithium hydride was chosen as an absorber material as it provides less multiple Coulomb scattering for a given energy loss.

In this paper the evolution of phase space density is reported for a single configuration of the cooling apparatus. Results from one transfer line configuration are reported, with the accumulated muon sample having a nominal emittance of 6 mm at momenta around 140 MeV/c in the upstream spectrometer solenoid, denoted as ‘6–140’.

As MICE measures each particle event individually, it is possible to select a particle ensemble from the collection of measured tracks. This enables the study of momentum spread and transverse beam parameters on the cooling. In this analysis, muons have been selected with:

- longitudinal momentum in the range 135 to 145 MeV/c;
- time-of-flight between TOF0 and TOF1 consistent with muons in this momentum range; and
- a single, good quality track formed in the upstream diagnostics.

In order to study the evolution of the phase space density through the whole cooling channel and across the absorber, a realistic simulation of the setting of interest was produced. The betatron function of the selected muon ensemble is shown for the Monte Carlo (MC) simulation, the

# EMITTANCE EVOLUTION IN MICE\*

M. A. Uchida<sup>†</sup>, Imperial College London, UK  
*for the MICE collaboration*

## Abstract

The Muon Ionization Cooling Experiment (MICE) was designed to demonstrate a measurable reduction in beam emittance due to ionization cooling. The emittance of a variety of muon beams was reconstructed before and after a “cooling cell”, allowing the change in the phase-space distribution due to the presence of an absorber to be measured.

The core of the MICE experiment is a cooling cell that can contain a range of solid and cryogenic absorbers inside a focussing solenoid magnet. For the data described here, a single lithium hydride (LiH) absorber was installed and two different emittance beam have been analysed. Distributions that demonstrate emittance increase and equilibrium have been reconstructed, in agreement with theoretical predictions.

Data taken during 2016 and 2017 is currently being analysed to evaluate the change in emittance with a range of absorber materials, different initial emittance beams and various magnetic lattice settings. The current status and the most recent results of these analyses is presented.

## INTRODUCTION

The International Muon Ionization Cooling Experiment (MICE) was designed and constructed to demonstrate the process of ionization cooling [1], applied to muon beams. It was constructed at the Rutherford Appleton Laboratory, and has been successfully taking data since 2015. Figure 1 shows the total number of integrated event triggers, as a function of time for the current configuration of the experiment.

MICE is a single particle experiment where each event contains a single muon passing through the beamline. Individual muon tracks are then reconstructed in each of the detectors. This data is aggregated at analysis in order to study the evolution of both individual track parameters and ensemble effects, when various absorber materials are placed within the cooling channel.

The primary goal is to measure the phase-space volume of the muon beam before and after a cooling cell by reconstructing the normalised, transverse RMS emittance (referred to simply as “emittance”). This corresponds the volume occupied by the central 68% of a gaussian-distributed ensemble of particles. This is easily calculated by constructing the covariance matrix for an ensemble,  $\Sigma$ , in the position-momentum phase-space, using the variables:  $x, p_x, y, p_y$ . The emittance can then be calculated as:

$$\epsilon_{\perp} = \frac{|\Sigma|^{\frac{1}{4}}}{m}, \quad (1)$$

\* Work supported by the (UK) Science and Technology Facilities Council and the (US) Dept. of Energy and National Science Foundation

<sup>†</sup> m.a.uchida@imperial.ac.uk

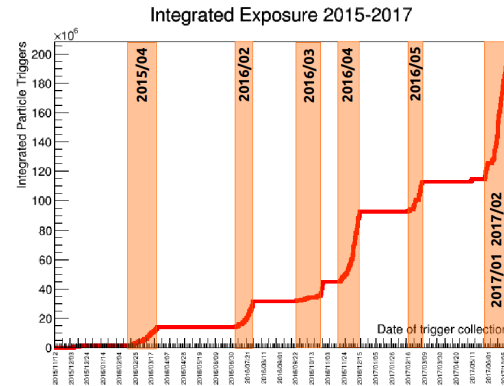


Figure 1: The integrated number of event triggers as a function of time. The ISIS user periods in which MICE is operational are highlighted.

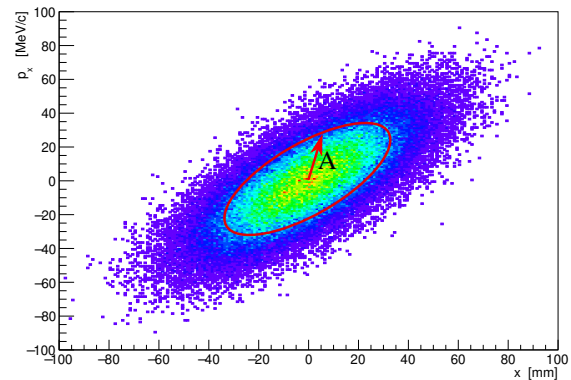


Figure 2: Example phase-space distribution with a contour of equal amplitude marked in red.

where  $\epsilon_{\perp}$  is the emittance, and  $m$  is the muon mass.

In order to analyse the effect of a single muon on the evolution of emittance, an additional quantity is defined: the single particle amplitude,  $A_{\perp}$ . This corresponds to the scalar distance a given particle is found from the centre of the beam (Figure 2). The definition is weighted by the covariance matrix such that amplitude is invariant under conservative transformations, e.g. focussing. It is defined by,

$$A_{\perp} = \epsilon_{\perp} \mathbf{v}^{\top} \Sigma^{-1} \mathbf{v} \quad (2)$$

where  $\mathbf{v} = (x, p_x, y, p_y)$  is the particle’s coordinate vector.

The behaviour of the beam emittance in the presence of an absorber material can be approximated by the cooling

# RECENT RESULTS FROM MICE ON MULTIPLE COULOMB SCATTERING AND ENERGY LOSS

J. C. Nugent\*, P. Soler, University of Glasgow, Glasgow, United Kingdom  
 R. Bayes, Laurentian University, Sudbury, Canada

## 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 [4–6]. 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,  $\delta_{CP}$ , 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 [7], 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 is composed of three quadrupole triplets, two dipole magnets, which select the momentum, and a decay solenoid

\* john.nugent@glasgow.ac.uk

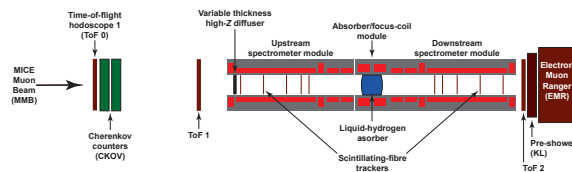


Figure 1: Schematic of Step IV of the MICE experiment, with the Absorber Focus Coil between the two Spectrometer Solenoids.

(DS), which increases the number of muons in the beam. The MICE Step IV setup is shown in Figure 1. It consists of an Absorber Focus Coil (AFC) located between two measurement stations. These stations are composed of particle identification suites including a total of three time-of-flight detectors (TOFs) [8], two Cherenkov detectors (Ckova and Ckvb) [9], the KLOE-type sampling calorimeter (KL) [10] and the Electron Muon Ranger (EMR) [11]. Each station has a Tracker 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. In MICE Step IV the AFC module, which houses the liquid hydrogen or lithium hydride absorber within a focusing coil, is located between the two measurement stations.

## OVERVIEW OF MULTIPLE COULOMB SCATTERING

The PDG recommends an approximate multiple scattering formula [12, 13], which is found to be accurate to approximately 11%:

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

where  $\theta_0$  is the rms width of the projected scattering angle distribution,  $X_0$  is the radiation length of the material and  $\Delta z$  is the thickness of the absorber,  $p_\mu$  is the momentum of the muon and  $\beta_{\text{rel}} = p_\mu c / E_\mu$ , with  $E_\mu$  its energy. From this an approximate cooling formula can be derived (ignoring the logarithmic term of Equation (1)),

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

where  $\varepsilon_n$  is the normalised transverse (two-dimensional) emittance of the beam,  $\beta$  is the betatron function, and  $m_\mu$  the energy and mass of the muons [14]. Given that the goal of

# LOW ENERGY ELECTRON COOLER FOR THE NICA BOOSTER

Alexander Bublely, Maxim Bryzgunov, Vladimir Chekavinskiy, Anatoly Goncharov,  
 Konstantin Gorchakov, Igor Gusev, Vitalij Panasyuk, Vasily Parkhomchuk,  
 Vladimir Reva, Dmitriy Senkov, BINP SB RAS, Novosibirsk, Russia  
 Alexander V. Smirnov, JINR, Dubna, Moscow Region, Russia

## Abstract

The low energy electron cooler for the NICA booster has recently been installed at the booster ring of the NICA facility. The article describes results of various measurements obtained during its commissioning. In addition, some details of design and construction of the cooler are discussed.

## INTRODUCTION

NICA collider contains a big number of complicated systems and subsystems. One of them is gold ion booster which is located at the existing hall of former synchro-phasotron, and new superconductive magnets sit inside old giant iron yokes [1]. Low energy cooler is one of the elements of the booster those provides sufficient improvement of the ion beam quality.

Main specifications of the cooler are listed below:

ions type	p+ up to $^{197}\text{Au}^{31+}$
electron energy, $E$	$1,5 \div 50$ keV
electron beam current, $I$	$0,2 \div 1,0$ Amp.
energy stability, $\Delta E/E$	$\leq 1 \cdot 10^{-5}$
electron current stability, $\Delta I/I$	$\leq 1 \cdot 10^{-4}$
electron current losses, $\delta I/I$	less than $3 \cdot 10^{-5}$
longitudinal magnetic field	$0,1 \div 0,2$ T
inhomogeneity of the field, $\Delta B/B$	$\leq 3 \cdot 10^{-5}$
transverse electron temperature	$\leq 0,3$ eV
ion orbit correction:	
displacement	$\leq 1,0$ mm
angular deviation	$\leq 1,0$ mrad
residual gas reassurement	$\leq 1 \cdot 10^{-11}$ mbar.

## MAGNETIC MEASUREMENT RESULTS

Magnetic system of the cooler consists of central solenoid, bending toroids, gun-collector solenoids and correctors [2]. Requirement for the magnetic field straightness is  $\Delta B/B \leq 3 \cdot 10^{-5}$  for the central (cooling) solenoid.

Measurements were performed with compass based measurement system [3].

The results of those measurements are shown on Fig. 1. Vertical and horizontal components of the magnetic field were measured several times during solenoid adjustment. Starting data (just after shipping of the cooler) are drawn as black curves. Red curves present final results of solenoid adjustment thus the requirement was fulfilled.

The solenoid was tuned at 1 kG of the longitudinal field as long as it is a middle of required field range. If we apply other values of magnetic field the vertical component

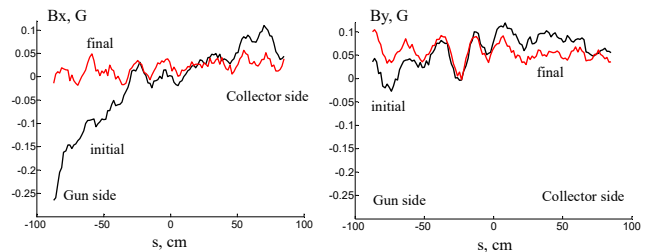


Figure 1: Horizontal (left) and vertical (right) magnetic field components before (black) and after (red) coils adjustment.

will change (Figs. 2 and 3). To improve the situation the cooler is equipped with linear correction coils attached along the solenoid so as each value of longitudinal field corresponds to amplitude of current applied to the linear corrector.

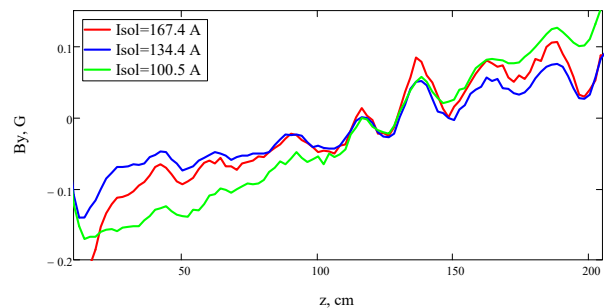


Figure 2: Vertical field component measured at different value of the longitudinal field. Red – 1 kG, blue – 800 G, green – 700 G.

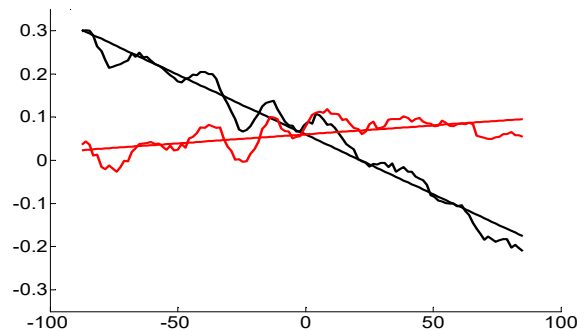


Figure 3: Linear (vertical) corrector calibration.

For the solenoid tuning its coils are slightly rotated or inclined depending on direction of the transverse field to be corrected. The movement of the coils on 0.1 mm corresponds to  $3 \cdot 10^{-4}$  in angle of the field that by order of magnitude higher than required accuracy.

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## HIGH VOLTAGE COOLER NICA STATUS AND IDEAS

V.B. Reva<sup>1</sup>, M.I. Bryzgunov, A.V. Bublely, A.D. Goncharov, N.S. Kremnev, V.M. Panasyuk,  
 V.V. Parkhomchuk<sup>1</sup>, V.A. Polukhin, A.A. Putmakov BINP, Novosibirsk, Russia  
<sup>1</sup>also at Novosibirsk State University, Novosibirsk, Russia

### Abstract

The new accelerator complex NICA [1-2] is designed at the Joint Institute for Nuclear Research (JINR, Dubna, Russia) to do experiment with ion-ion and ion-proton collision in the range energy 1-4.5 GeV/u. The main regime of the complex operation is ion collision of heavy ion up to Au for study properties of dense baryonic matter at extreme values of temperature and density. The planned luminosity in these experiments is  $10^{27} \text{ cm}^{-2} \cdot \text{s}^{-1}$ . This value can be obtained with help of very short bunches with small transverse size. This beam quality can be realized with electron and stochastic cooling at energy of the physics experiment. The subject of the report is the problem of the technical feasibility of fast electron cooling for collider in the energy range between 0.2 and 2.5 MeV.

### SETUP DESCRIPTION

The NICA collider for study nuclear physics at range of relativistic physics 1-4.5 GeV/u requires powerful electron cooling system to obtain high luminosity. The basic idea of this cooler is to use high magnetic field along all orbit of the electron beam from the electron gun to the electron collector. At this case we have chance to have high enough the electron beam density at cooling section with low effective temperature. The schematic design of the setup is shown in Figure 1. The electron beam is accelerated by an electrostatic generator that consists of 42 individual sections connected in series. Each section has high-voltage power supplies with maximum voltage 60 kV and current 1 mA. The electron beam is generated in electron gun immersed into the longitudinal magnetic field. After that the electron beam is accelerated, moves in the transport line to the cooling section where it will interact with ions of NICA storage ring. After interaction the electron beam returns to electrostatic generator where it is decelerated and absorbed in the collector. Because the NICA is collider there are two electron lines for both ion beams located up and down. Both electron coolers are independent from each other.

The optics of 2 MeV cooler for NICA is designed close to the COSY high-energy coolers [3]. The motion of the electron beam is magnetized (or close to magnetized conditions) along whole trajectory from a gun to a collector. This decision is stimulated by requirement to operate in the wide energy range from 200 keV to 2.5 MeV. So, the longitudinal field is higher than transverse component of the magnetic fields. The essential challenge of this design is low value of the energy consumption of magnetic field 500-700 kW for both coolers. So, the volume of copper in

the coils is maximum as possible taken into account the small distance between beam lines. This distance is 32 cm. The length of the linear magnets is defined by the necessity to locate the electrostatic generator outside the shield area of the storage ring.

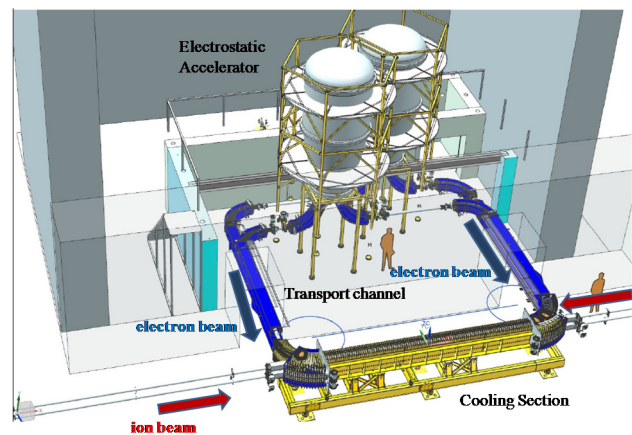


Figure 1: 3D design of 2 MeV COSY cooler.

The vacuum chamber will be pumped down by ion, getter and titanium sublimation pumps. The typical diameter of the vacuum chamber is 100 mm and the aperture in the transport channel and cooling section is close to this value. The diameter of the accelerating tube is 60 mm. The main parameters of NICA cooler can be found in Table 1.

Table 1: Specifications of NICA Cooler

Parameter	Value
Energy range	0.2÷2.5 MeV
Number of the cooling section	2
Stability of energy ( $\Delta U/U$ )	$\leq 10^{-4}$
Electron current	0.1÷1 A
Diameter of electron beam in the cooling section	5÷20 mm
Length of cooling section	6 m
Bending radius in the transport channel	1 m
Magnetic field in the cooling section	0.5÷2 kG
Vacuum pressure in the cooling section	$10^{-11}$ mbar
Height of the beam lines	1500/1820 mm
Total power consumption	500-700 kW

# MODEL DEVELOPMENT FOR THE AUTOMATED SETUP OF THE 2 MeV ELECTRON COOLER TRANSPORT CHANNEL

A. J. Halama and V. Kamerdzhiev  
Forschungszentrum Jülich (FZJ), Jülich, Germany

## Abstract

The 2 MeV electron cooler allows for cooling the proton and deuteron beams in the entire energy range of COSY and thereby study magnetized high energy electron cooling for the HESR [1] and NICA [2]. Manual electron beam adjustment in the high energy, high current regime proves a cumbersome and time consuming task. Special difficulties are presented by the particular geometry of the e-beam transport channel, limited beam diagnostics and general technical limitations. A model has been developed to track electrons through the transport channel of the cooler. This allows the offline study of response schemes around any particular setting of the cooler. It is envisaged to control linear, dipole and quadrupole behavior of the e-beam. Application of the model will result in optimized e-beam transport settings for a lossless and cool beam transport. This will improve cooling and recuperation efficiency and allow quick adjustment of the e-beam to the various operational modes of the machine. A good relative agreement of the model and the cooler could be shown. Main focus lies now in overhauling the software and finding suitable initial conditions to improve the agreement to an absolute degree.

## MOTIVATION

In need of support for setting up the electron cooler, the model based approach offers a vast amount of advantages to the current manual way of operation. The model will at one point be able to predict the electron trajectory for any given machine setting. Additionally It will be able to calculate beam responses much faster than obtainable by measurements. The speed of obtaining responses scales progressively with the order of motion of the parameter of interest. Thus setting up the cooler will be faster, more reliable and will offer more information on the beam behavior throughout the transport channel, compared to the manual operation. The main objective of the model based adjustment is to achieve a brilliant electron beam quality for high cooling rates and optimal recuperation conditions. With respect to the safety during operation, this will result in improved vacuum conditions and causes less x-ray radiation. The model is embedded in a software suit that reads inputs from the cooler and is able to apply changes to the transport channel settings. With proper procedures and algorithms one will be able to compensate coupled effects between the different orders of beam motion types and to predict beam behavior also for yet unexplored beam regimes.

## OVERVIEW

### *Machine Characteristics and Limitations*

There are certain in and outputs available to handle the electron beam. The beam responds to the set currents i.e. the main currents and corrector currents. Main currents are internally called, “Cooling section”, “Longitudinal field”, “Bending field”, “Toroid 45° field”, and “Straight field”. Where it should be pointed out that the shown elements share the same current, as shown in Fig. 1. About 50 corrector currents are used to supply mostly dipoles, distributed along the transport channel and some more particular ones [3]. Feedback on the beams behavior is obtained by the Beam Position Monitor (BPM) system, and by the readouts from the vacuum system, leakage current and radiation monitors. Information on the beam shape can be obtained as the electron gun is capable of modulating the beam quadrant-wise [4], as only the modulated portion of the e beam is visible to the BPM system.

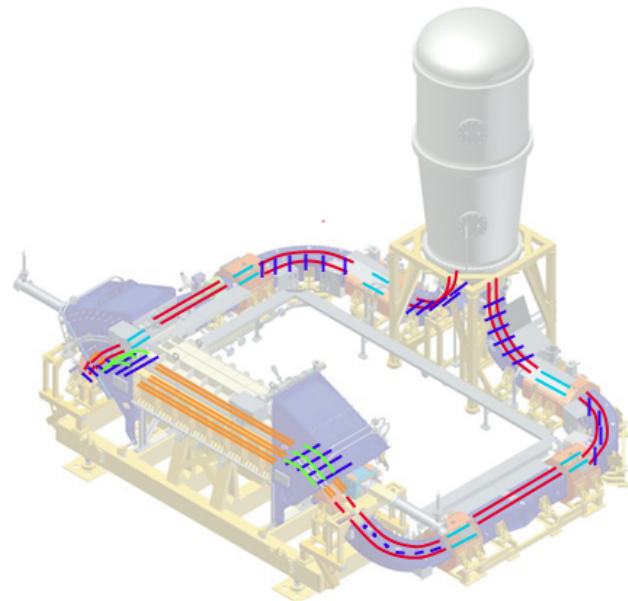


Figure 1: Image of the 2 MeV electron cooler. Equally colored symbolic field lines represent coils that share the same power supply. Orange: “Cooling section”, red: “Longitudinal field”, blue: “Bending field”, green: “Toroid 45° field”, and cyan: “Straight field”.

### *E Beam Parameters*

The e beam parameters of interest for the transport channel setup are the parameterized orders of motion, i.e. linear, dipole and quadrupole. There is only the possibility for an

# MUON INTENSITY INCREASE BY WEDGE ABSORBERS FOR LOW-E MUON EXPERIMENTS\*

D. V. Neuffer<sup>#</sup>, D. Stratakis, J. Bradley<sup>&</sup>, Fermilab, Batavia IL 60510, USA

## Abstract

Low energy muon experiments such as mu2e and g-2 have a limited energy spread acceptance. Following techniques developed in muon cooling studies and the MICE experiment, the number of muons within the desired energy spread can be increased by the matched use of wedge absorbers. More generally, the phase space of muon beams can be manipulated by absorbers in beam transport lines. Applications with simulation results are presented.

## INTRODUCTION

Low energy muon experiments, such as the Fermilab-based mu2e [1, 2] and g-2 experiments, [3] have a limited phase space acceptance for useful muons. The mu2e experiment can only accept a small momentum slice of the incident muon momentum spectrum ( $P\mu < \sim 50$  MeV/c, see below). The g-2 experiment only accepts a momentum spread of  $\delta P = \pm 0.1\%$  around the design momentum of  $\sim 3.1$  GeV/c. Methods that can increase the number of muons within the momentum acceptance are desirable.

Similar or complementary constraints occurred in the exploration of ionization cooling for muons [4]. Wedge absorbers are needed to transform the intrinsic transverse cooling effect to include longitudinal cooling, and introduce exchanges between longitudinal and transverse phase space densities. In cooling channels incremental exchanges were developed so that large increases in phase space density could be obtained over a multistage system. In final cooling toward the extreme parameters needed for a high luminosity collider, it was noted that very large exchanges in single wedges were needed [5, 6]. In that limit it was noted that a wedge could be treated as an optical element in a transport system and large exchanges can occur with single wedges [7], which can be used to match the final beam to desired distributions (smaller transverse emittance with larger  $\delta p$  or vice versa). As an example the use of a wedge, and its effects in large exchanges, can be measured in the MICE experiment [8, 9].

The method can also be adapted for phase space matching into low energy muon experiments, and matched placement of wedges in the beam transport could obtain more muons within experiment acceptances. We note that use of a wedge to reduce  $\delta P$  increases the transverse emittance, and changes the matched optics. Some iterations in beam matching may be needed to increase the number muons accepted.

In this paper we first describe the wedge process and its approximation as a transport element

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<sup>#</sup>neuffer@fnal.gov

<sup>&</sup> current address: University of Edinburgh, Edinburgh, Scotland.

The parameters of mu2e and g-2 are discussed and potential uses of wedge absorbers and their adaptation to increase acceptance into the experiments are described. Simulations that test these possibilities are presented and the results are discussed.

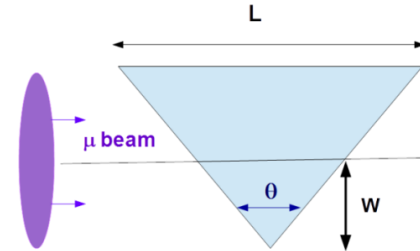


Figure 1: Schematic view of a muon beam passing through a wedge.

## WEDGE EFFECTS ON BEAM - FIRST ORDER ESTIMATES

Figure 1 shows a stylized view of the passage of a beam with dispersion  $\eta_0$  through a wedge absorber. The wedge is approximated as an object that changes particle momentum offset  $\delta = \Delta p/P_0$  as a function of  $x$ , and the wedge is shaped such that that change is linear in  $x$ . (The change in average momentum  $P_0$  is ignored in this approximation. Energy straggling and multiple scattering are also ignored.) The rms beam properties entering the wedge are given by the transverse emittance  $\epsilon_0$ , betatron amplitude  $\beta_0$ , dispersion  $\eta_0$  and relative momentum width  $\delta_0$ . (To simplify discussion the beam is focussed to a betatron and dispersion waist at the wedge:  $\beta_0', \eta_0' = 0$ . This avoids the complication of changes in  $\beta', \eta'$  in the wedge.) The wedge is represented by its relative effect on the momentum offsets  $\delta$  of particles within the bunch at position  $x$ :

$$\frac{\Delta p}{p} = \delta \rightarrow \delta - \frac{2(dp/ds) \tan(\theta/2)}{P_0} x = \delta - \delta'x$$

$dp/ds$  is the momentum loss rate in the material ( $dp/ds = \beta^1 dE/ds$ ).  $2x \tan(\theta/2)$  is the wedge thickness at transverse position  $x$  (relative to the central orbit at  $x=0$ ), and  $\delta' = 2dp/ds \tan(\theta/2) / P_0$  indicates the change of  $\delta$  with  $x$ .

Under these approximations, the initial dispersion and the wedge can be represented as linear transformations in the  $x-\delta$  phase space projections and the transformations are phase-space preserving. The dispersion can be represented by the matrix:  $\mathbf{M}_\eta = \begin{bmatrix} 1 & \eta_0 \\ 0 & 1 \end{bmatrix}$ , since  $x \Rightarrow x + \eta_0\delta$ .

The wedge can be represented by the matrix:  $\mathbf{M}_\delta = \begin{bmatrix} 1 & 0 \\ -\delta' & 1 \end{bmatrix}$ , obtaining  $\mathbf{M}_{\eta\delta} = \begin{bmatrix} 1 & \eta_0 \\ -\delta' & 1 - \delta'\eta_0 \end{bmatrix}$ . Writing the  $x-\delta$  beam distribution as a phase-space ellipse:



# STOCHASTIC COOLING AS WIENER PROCESS

N. Shurkhno<sup>†</sup>, Forschungszentrum Jülich, Jülich, Germany

## Abstract

Traditional theoretical description of stochastic cooling process involves either ordinary differential equations for desired rms quantities or corresponding Fokker-Planck equations. Both approaches use different methods of derivation and seem independent, making transition from one to another quite an issue, incidentally entangling somewhat the basic physics underneath. On the other hand, treatment of the stochastic cooling as Wiener process and starting from the single-particle dynamics written in the form of Langevin equation seems to bring more clarity and integrity. Present work is an attempt to apply Wiener process formalism to the stochastic cooling in order to have a simple and consistent way of deriving its well-known equations.

## INTRODUCTION

There are two traditional approaches for theoretical description of the stochastic cooling process – studying parameter evolution of either a single particle or a particle distribution function [1].

The single particle approach involves ordinary differential equations for the rms-particle (i.e. having rms value of a given parameter). The equations are derived by calculation of the first two moments of the kick for a random particle. The cooling process is then described with a coherent effect, which is a particle's own signal, and incoherent effect, which includes all noises for the particle.

The other approach involves Fokker-Planck equations for the particle distribution functions. The derivation is either straightforward and based on the continuity equation analogues to the usual drift-diffusion equation derivation [2] or thorough and based on basic kinetic equations involving all other particle interactions with following simplifications [3]. In this case the cooling is described with quite similar coherent and incoherent terms, which are introduced as drift and diffusion coefficients of the Fokker-Planck equation.

The approach, involving treatment of particle distribution functions over given parameters, is more appropriate for the stochastic cooling simulation, unless we are interested in the initial cooling time or fast draft calculations. Nevertheless, single particle approach is the main tool for the betatron cooling simulation, since the diffusion term is defined by longitudinal dynamics and in this case could be considered constant (or defined by a function).

The connection of coherent and incoherent effects between different approaches was mentioned casually in [4], but it was never explicitly used. Eventually each approach requires its own derivation of coherent and incoherent terms. But both single particle and particle distribution function descriptions use the same underlying model of the cooling process, which involves particle beam, accelerator and stochastic cooling system. This process appears to be

a continuous Wiener process (or Brownian process), and corresponding formalism could be immediately applied to the stochastic cooling, giving a straightforward and clear way of deriving the equations and its' coefficients.

## LANGEVIN EQUATION

Consider an ensemble of non-interacting particles orbiting in an accelerator and undergoing a stochastic cooling. We are interested in the evolution of some parameter  $x$  (momentum spread, emittance, rms betatron amplitudes, etc.) of an arbitrary particle under influence of stochastic cooling system. On each revolution every particle receives a correction kick, or parameter change, from the cooling system, that is the sum of the self-signal of that particle (coherent signal  $x_c$ ) and some random noise signal due to signals from other particles and noises in the electronics (incoherent signal  $\tilde{x}_{ic}$ ):

$$\Delta x_{kick} = x_c + \tilde{x}_{ic}.$$

Since particle parameter depends solely on its present state and kick's interval (revolution period) in most cases could be considered much smaller than cooling time ( $T_0 \ll \tau_{cool}$ ), the process of stochastic cooling is a continuous Wiener process and all related formalism could be directly applied.

The starting point is then a derivation of a corresponding Langevin equation. The drift  $F$  and diffusion  $D$  coefficients could be defined in a usual way as:

$$F(x, t) = f_0 \Delta x_c(x, t),$$

$$D(x, t) = 1/2 f_0 \Delta x_{ic}^2(x, t),$$

where  $\Delta x_{ic}^2 = \langle \Delta x_{kick}^2 \rangle$ ,  $f_0$  – revolution frequency.

Then for the given model of stochastic cooling process with non-constant diffusion the corresponding Langevin equation will have the following form [5]:

$$\frac{dx}{dt} = F + \frac{1}{2} \frac{\partial D}{\partial x} + \sqrt{D} \xi(t), \quad (1)$$

where  $\xi(t)$  represents Gaussian white noise with the following statistics:

$$\langle \xi \rangle = 0,$$

$$\langle \xi(t) \xi(t') \rangle = 2\delta(t - t').$$

The summand with diffusion derivative in the Equation (1) is needed to compensate the effect of non-constant diffusion, a so-called *noise-induced drift*, which will be introduced later. The logic behind is the same as in explanation of Fick's law of diffusion, some additional details could be found in [5]. The Equation (1) could be used for tracking simulations in a software like Betacool in order to include

# PRELIMINARY DESIGN OF ELECTRON TARGET FOR SRING AT HIAF\*

J. Li<sup>†</sup>, L. J. Mao, X.D. Yang, J. C. Yang, M.T. Tang, L. X. Zhao, H. Zhao, Z. K. Huang, S. X. Wang  
 Institute of Modern Physics, CAS, Lanzhou, China

## Abstract

A 13 Tm multifunction storage ring dedicated to nucleon and atomic experiment research - the SRing (Spectrometry Ring) is a significant part of the new heavy-ion research complex - HIAF (High Intensity heavy ion Accelerator Facility). In addition to an electron cooler and a gas internal target planned at the SRing, a beam of low temperature electron is also required to collide with the storage beam and to cool the decelerated ion beam at low energy. A magnetic adiabatic expansion is proposed to attain a low temperature by applying a 1.2 T longitudinal magnetic field upon the thermionic cathode at the electron gun. In this paper, preliminary design of the electron target is introduced.

## INTRODUCTION

The High Intensity heavy-ion Accelerator Facility (HIAF) is a new heavy ion accelerator complex under detailed design by institute of modern physics [1]. Two typical particles of  $^{238}\text{U}^{35+}$  and proton is considered in the design. The particles derive from a Superconducting Electron Cyclotron Resonance (SECR) ion source or an intense proton source, and are accelerated mainly by an ion linear accelerator (iLinac) and an booster ring (BRing). The iLinac delivers  $H_2^+$  at 48 MeV and  $^{238}\text{U}^{35+}$  at 17 MeV/u for the BRing that has a maximal rigidity of 34 Tm. The  $H_2^+$  is stripped into proton at the entrance of the BRing, after accumulation combined with two-plane painting and then is accelerated to the top plateau of 9.3 GeV. The  $^{238}\text{U}^{35+}$  is injected into the BRing by multi-turn two-plane painting scheme, after accumulation with the help of electron cooling, then accelerated to 0.2-0.83 GeV/u for extraction. At beam line of the HIAF FFragment Separator (HFRS), the ejected  $^{238}\text{U}^{35+}$  is stripped into  $^{238}\text{U}^{92+}$  and injected to the Spectrometer Ring (SRing) for high precision physics experiments. In addition, five external target stations of T1 - T5 are planned for nuclear and atomic experimental researches with an energy range of 5.8-830 MeV/u for the typical  $^{238}\text{U}^{35+}$  beam. Global layout of the HIAF complex is illustrated in Fig. 1.

### Overview of the SRing

The SRing is a 15 Tm spectrometer ring designed to collect secondary particles or stripped highly charged heavy ions like  $^{238}\text{U}^{92+}$  that derive from bombing the internal targets at HFRS. The typical particle of  $^{238}\text{U}^{92+}$  and proton can be stored at the upper limit of energy at 0.83 GeV/u and 9.3 GeV respectively. In addition, the deceleration to a low energy of  $^{238}\text{U}^{92+}$  to 30 MeV/u is also planned for

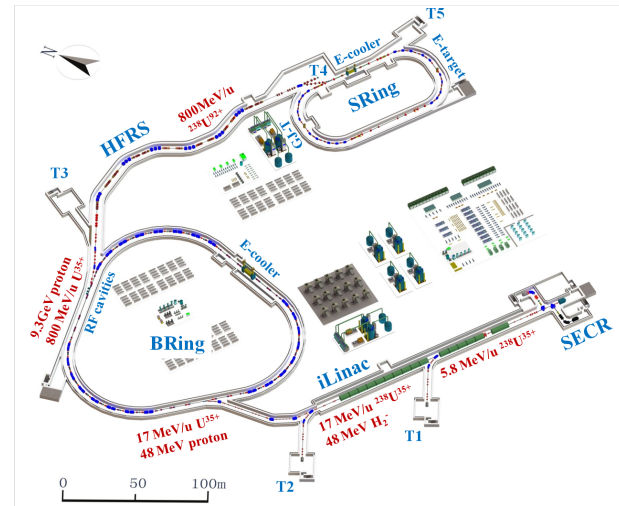


Figure 1: General layout of the HIAF complex.

atomic physics experiments. The ring has three operational modes of normal for cooling helped experiments with long life-time secondary particles, of internal for atomic physics experiments with electron-target (e-target), gas internal-target (GJ-Target), or laser cooling, and of isochronous for mass measurement of unstable nucleon with lifetime at tens of microsecond. Both electron cooler (e-cooler) and stochastic cooling system will be installed at the SRing. The e-cooler occupies one of the two longer straight section with a length of 11.2 m. The two shorter straight section are assigned to the e-target and gas-jet target. Main parameters of  $^{238}\text{U}^{92+}$  at the SRing are listed in Table 1.

Table 1: Main Parameters of  $^{238}\text{U}^{92+}$  at the SRing

Circumference	270.5 m
Magnetic rigidity	2-15 Tm
$\gamma_{tr}$	1.43-1.84
Energy	30-830 MeV/u
Acceptance ( $H/V, \delta p/p$ )	40/40 $\pi$ mmrad, $\pm 15\%$

### Electron Cooling System for SRing

The e-cooler at SRing has a maximal energy of 460 keV that can cool the storage beam to an relative energy spread of  $3 \cdot 10^{-5}$  and transverse emittances of  $0.1\pi$ mmrad at 0.83 GeV/u. The high precision measurement in dielectronic recombination (DR) experiment requires a continuous cooling at low energy. RF cavities in DR experiments is mainly performed by the 460 keV e-cooler. In addition to act as a target, the e-target system also provides another approach of cooling that can cool the storage ion beam with energy up to 109 MeV/u.

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<sup>†</sup> lijie@impcas.ac.cn

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# PROJECT OF HIGH-VOLTAGE SYSTEM WITH FAST CHANGING POTENTIAL FOR DR EXPERIMENT

V.B.Reva<sup>1</sup>, D.N.Skorobogatov, A.Denisov<sup>1</sup>, V.V.Parkhomchuk<sup>1</sup>, A.Putmakov,  
 BINP, Novosibirsk, Russia  
 X.Ma, J.Li, L.Mao, IMP, Lanzhou, China  
<sup>1</sup>also Novosibirsk State University, Novosibirsk, Russia

## Abstract

A storage ring equipped with an electron cooler is an ideal platform for dielectronic recombination (DR) experiments [1]. In order to fulfil the requirement of DR measurements the system of the precision control of the relative energy between the ion beam and the electron beam should be installed in the electron cooler device. This report describes the project of such system that is designed with section approach like COSY electron cooler. Each section consist of the section of cascade transformer and two power supplies for low and fast detuning of potential of high-voltage terminal. This project can be used in CSRe [2] and future HIAF storage rings [3].

## MODULATION SYSTEM

The idea of the fast modulation of the electron beam energy is based on idea of two power supplies connected in series as it is shown in Figure 1. The power supply 300 kV produces the constant voltage (CPS) for the accelerating of the electron beam to the fixed energy. The pulse power supply (PPS)  $\pm 30$  kV produces the fast switching between two values of the electron energy and realize the pulsing energy of the electron beam near the fixed value (see Fig. 2). Because of the high value of the pulse  $\pm 30$  kV it is difficult to realize it as single unit power supply (PS). Such solution was used at design of the detuning system in EC-35 cooler (CSRm storage ring). Because of this, the PPS should be divided on the several sections with typical pulse voltage  $\pm 3$  kV and CPS with typical continuous voltage  $+30$  kV also. So, the detuning system looks as a few section connected in series. Each section provides the DC voltage  $+1 - +30$  kV and pulse voltage  $\pm 3$  kV. Each section should have independent energy source isolated from ground and other sections. This energy source may be realized as section of the cascade transformer. Thus the construction of new detuning system for CSRe looks as the acceleration section of COSY electron cooler device [4].

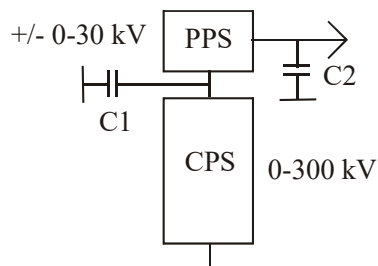


Figure 1: Idea of two power supply connected in series.

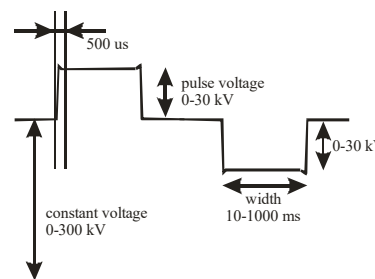


Figure 2: Shape of the detuning system.

The sketch of detuning system for CSRe is shown in Figure 3. It consists of 10 section connected in series. Each section contains CPS, PPS and section of cascade transformer. The high voltage terminal (HVT) contains all power supplies for the electron beam operation. The main problem of such system is inevitable presence of the slow feedback system of CPS (see Fig. 1). The fast change of potential is connected with the capacitance divider with parasitic capacitance C1, C2 of the HVT and 300 kV PS to ground. So after pulse not only the potential in the point B is change, but also the potential in the point A is change too. After that the CPS modules with slow feedback system of 300 kV set the potential of the HVT to the previous value. The parasitic capacitance C2 cannot be decreased from technician point of view. So, we have system with simultaneously operation of two feedback system - fast and slow and both systems see the action of each other.

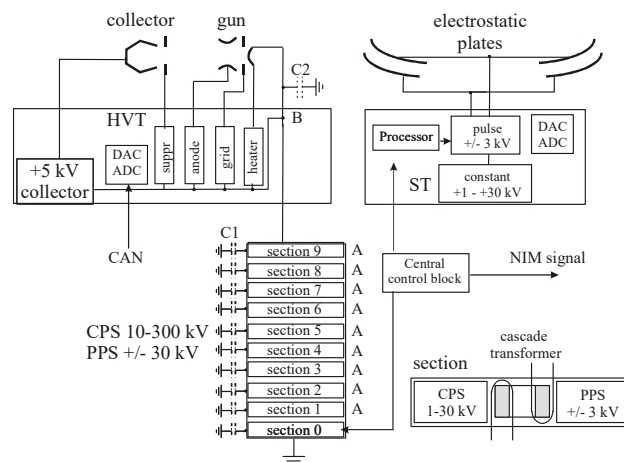


Figure 3: Pulsing system for fast changing of the electron beam energy.

High voltage pulse power supply with feedback can be produced with linear wideband transistor. In spite of the progress in semiconductor technique the transistors aren't

# THE INTERACTION BETWEEN ELECTRONS AND IONS IN COMOVING AND STATIC ELECTRON COLUMNS

V. A. Britten\*, M. Droba, O. Meusel, H. Podlech, A. Schempp, K. Schulte  
 Institute of Applied Physics (IAP), Goethe-University, Frankfurt am Main, Germany

## Abstract

The interaction between electrons and positive ion beams and its application in accelerator physics are investigated. A space charge lens called Gabor lens was developed which confines electrons in a static column by external fields. The confined electrons are used for focusing and support space charge compensation of ion beams. In this configuration the relative velocity between the ions and the electrons is maximal and corresponds to the beam velocity. In comparison an electron lens as at the Tevatron [1] is operated with a lower relative velocity in order to compensate the beam, to clean the beam abort gap or to excite the beam for beam dynamics measurements [2]. Another application is electron cooling, which needs the same velocity of the ion and the electron beam. The following study contains the superposition of electric and magnetic self-fields and their impact on the density distribution of the ion beam and of the electron beam. Recombination and ionisation processes are neglected. This is the beginning of an interface between these topics to find differences and similarities of the interaction between ions and electrons with different relative velocities. This will open up opportunities e.g. for the diagnostics of particle beams.

## INTRODUCTION

The investigated Gabor lens for a static electron column is used as a focusing element in a linear accelerator [3]. Future application is planned as space charge compensation device in ring accelerators. An electron lens also fulfils this purpose with a comoving electron beam. The advantage of a static electron column is that it does not require an electron gun and the undesired effects of the fringe fields are low. Early efforts to utilise a static electron column in a ring accelerator are done at IOTA [4]. To investigate the radius influence on the interaction between a proton beam with the initial radius  $r_p$  and a static electron column with radius  $r_e$ , the cases  $r_e < r_p$  and  $r_e > r_p$  were simulated.

## STATIC ELECTRON COLUMN

A static electron column can be confined by a superposition of electric and magnetic fields. An electrode system and e.g. a solenoid is used in a device called Gabor lens (Fig. 1).

The maximum electron density is limited in radial direction because of the Brillouin limit [5]

$$n_r = \frac{\epsilon_0 B_z^2}{2m_e} \quad (1)$$

\* virginia.a.britten@stud.uni-frankfurt.de

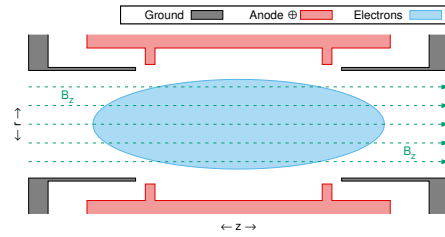


Figure 1: Schematic view of a Gabor lens to confine electrons with a superposition of magnetic and electric fields.

where  $\epsilon_0$  is the vacuum permittivity,  $B_z$  the maximum magnetic field in  $z$ -direction and  $m_e$  the electron mass.

In longitudinal direction the maximum density is limited by the anode potential  $\Phi_A$  and is given by

$$n_l = \frac{4\epsilon_0\Phi_A}{er_e^2 \left(1 + 2 \ln \frac{r_A}{r_e}\right)} \quad (2)$$

where  $e$  is the elementary charge,  $r_e$  the maximum radius of the electron column and  $r_A$  the inner radius of the anode.

An optimal confinement is achieved if both conditions (Eq. (1) and (2)) are fulfilled at once. This results in the working function for a Gabor lens [3]

$$\Phi_A = \frac{er_e^2 \left(1 + 2 \ln \frac{r_A}{r_e}\right) B_z^2}{8m_e} \quad (3)$$

With this system, it is possible to adjust the desired density in the static electron column by external parameters.

## INTERACTION WITH AN IDEAL STATIC ELECTRON COLUMN

Fringe field effects are neglected by assuming an infinite electron column along the longitudinal axis which is called ideal static electron column. In the following, the influence of the proton beam radius  $r_p$  in comparison to the radius of this ideal static electron column  $r_e$  is discussed.

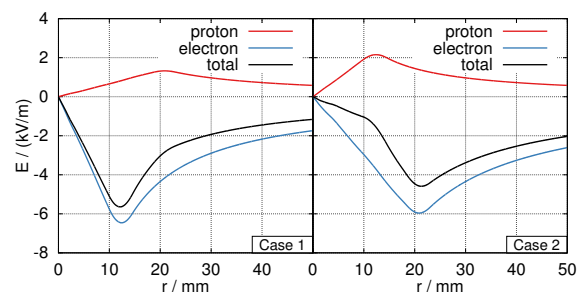


Figure 2: Radial electric fields of the initial homogeneous distributions for case 1 ( $r_e < r_p$ ) and case 2 ( $r_e > r_p$ ) split into the proton and electron part and the resulting field.

# SIMULATION OF LOW ENERGY ION BEAM COOLING WITH PULSED ELECTRON BEAM ON CSRm

H. Zhao<sup>1</sup>, L. J. Mao<sup>†</sup>, X. D. Yang, J. Li, M. T. Tang, J. C. Yang,  
 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China  
<sup>1</sup>also at University of Chinese Academy of Sciences, Beijing, China

## Abstract

The pulsed electron beam can be applied to high energy beam cooling and the researches of ion-electron interaction in the future. In this paper, we studied the pulsed e-beam cooling effects on coasting and bunched ion beam by simulation code which is based on the theory of electron cooling, IBS and space charge effect etc. In the simulation, a rectangular distribution of electron beam was applied to 7 MeV/u <sup>12</sup>C<sup>6+</sup> ion beam on CSRm. It is found that the coasting ion beam was bunched by the pulsed e-beam and the rising and falling region of electron beam current play an important role for the bunching effect, and similar phenomenon was found for the bunched ion beam. In addition, the analyses of these phenomena in simulation were discussed.

## INTRODUCTION

There are several high energy facilities that need electron cooler to acquire high quality, high intensity or short bunch length ion beam are under discussion or construction [1,2]. Classical DC cooler cannot satisfy these requirements because of the large power and the high voltage. The bunched electron beam from cooler or a Linac should be applied in that case. Before the application of high energy cooling, the investigation on low energy beam cooling with bunched electron beam is studied by simulation. It is observed that the grouping effect was happen for coasting or bunched ion beam and the rising and falling edge of e-beam has a strong effect on cooling rate and beam distribution. The simulation code is based on the theory of electron cooling, IBS and space charge effect. The simulation results and some analysis are given in the paper.

## COASTING ION BEAM COOLING

In the simulation, a pulsed electron beam was used to cool the coasting ion beam. The initial beam emittance and momentum spread are 0.3/0.2 pi mm.mrad and 2E-4. The parameters are listed in Table 1. It is observed that the coasting beam is bunched by pulsed electron beam and almost all of the particles are bunched into the region where have electrons as shown in Figure 1.

The revolution period of ion beam is about 4.44 us and the width of pulse electron beam is 2 us with peak current 30 mA. Considering the e-beam current increases linearly to peak with rising and falling time 10 ns, which will generate the electric field due to the space charge effect, and the longitudinal electric field in Laboratory Reference Frame (LRF) is given by

$$E_z(z) = -\frac{g}{4\pi\epsilon_0\beta c\gamma^2} \frac{dI_e(z)}{dz} \quad (1)$$

where  $g$  is the geometric factor. It is obviously the electric field only exist in the rising and falling region. The electric field in longitudinal is calculated ( $E_z=67.7$  V/m) as shown in Figure 1. When particles passing through cooling section, some of them meet the electric field will be kicked by the electric field and the effective voltage seen by the particle in this region is  $V_{\text{kick}}=E_z L_{\text{cooler}}=230.5$  V. It is found that the kick voltage plays a crucial role in the bunching process that all particles are bunched to the e-beam region, as shown in Figure 2. When using the pulse electron beam without the kick voltage, the bunch effect is so weak that only part of particles will be bunched. It can be explained by the barrier bucket theory that the particles are restricted in the region between the two barriers [3]. Because of cooling effect, all particles even that with large momentum spread will be cooled to that region and can't pass through the barrier during the motion in longitudinal phase space.

Table 1: Initial Parameters Used in Simulation

Name	Initial Value
Ion energy	7.0 MeV/u
Particle number per bunch	1E7
Emittance (RMS)	0.3/.2 pi mm mrad
Momentum spread (RMS)	2E-4
Betatron function @cooler	10/10 m
Cooler length	3.4 m
Transition gamma	5.42
E-beam current	30 mA
E-beam radius	3.0 cm
E-beam Temp.	0.2/1E-4 eV
Magnetic field @cooler	1000 Gs
Pulse width	2 us
Rising/falling time	10 ns

In the cooling section, the electrons at different radius inside the beam have different longitudinal velocities because of the space charge effect. Accordingly, the longitudinal velocity component of an ion at a certain radius should be corrected with respect to that of an electron at the same radius [4]. For coasting beam, most ions will be cooled down to positive momentum respect to the reference particle in the equilibrium status. Considering the electric field of electron beam, the motion of particles in phase space is a circle when it is cooled down to the poten-

<sup>†</sup> maolijun@impcas.ac.cn

# CALCULATIONS OF THE GUN AND COLLECTOR FOR ELECTRON COOLING SYSTEMS OF HIAF\*

Mei-Tang Tang, Li-Jun Mao<sup>†</sup>, He Zhao, Jie Li, Xiao-Ming Ma, Xiao-Dong Yang, Hai-Jiao Lu, Li-Xia Zhao, Institute of Modern Physics, Lanzhou, China  
 A. V. Ivanov, Budker Institute of Nuclear Physics, Novosibirsk, Russia

## Abstract

Two electron coolers are designed for the new project HIAF, one cooler with the highest energy 50keV is for the booster ring (BRing) to decreasing the transverse emittance of injected beams and another one with the highest energy 450keV is for the high precision Spectrometer Ring (SRing). In this paper the results of the gun and collector simulation for these two electron coolers are presented. After optimization, the gun can produce 2A profile variable electron beam. The one time collecting efficiency is higher than 99.99%. The results of electron motions in toroid calculated by a numerical method are also summarized in this paper.

## INTRODUCTION

The new accelerate facility HIAF is under design at the Institute of Modern Physics (IMP) [1], Chinese Academy of Sciences, which aimed to provide high intensity heavy ion beams for a wide range of research fields, such as high energy density physics, nuclear physics, atomic physics and so on. It consists of three ion sources (two Superconducting Electron Cyclotron-Resonance and (SECR) and a high intensity  $H^{2+}$  ion source(LIPS)), a superconducting Ion Linac as a injector (iLinac), a Booster Ring (BRing), a high precision Spectrometer Ring (SRing) and some terminals for experiments. The schematic layout of the HIAF facility is shown in Fig. 1

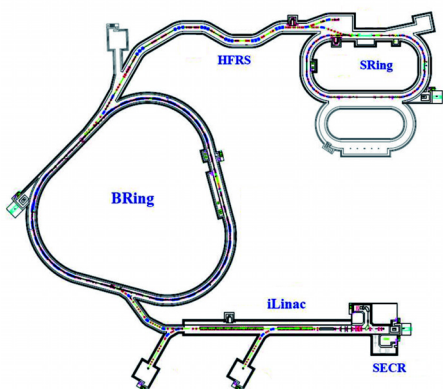


Figure 1: Layout of the HIAF accelerator facility.

Two magnetized electron cooling systems are planned to be used in the BRing and SRing to obtain intense ion

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<sup>†</sup> maolijun@impcas.ac.cn

beams and to improve beam quality [2]. The main parameters of these two cooler are summarised in Table 1.

Table 1: Main Parameters of Electron Coolers of HIAF

Parameters	BRing	SRing
Maximum energy [keV]	50	450
Electron beam current [A]	2	2
Cathode radius [cm]	1.3	1.3
Maximum $B_{\text{gun}}$ [kGs]	2.5	4.0
Maximum $B_{\text{cool}}$ [kGs]	1.5	1.5
Maximum $B_{\text{coll}}$ [kGs]	1.7	2.0
Effective cooling length [m]	7.4	7.4
Angle of toroid [deg.]	90	90
Radius of toroid [m]	1	1

## ELECTRON GUN

Electron guns designed for electron coolers of BRing and SRing have same geometry. The structure of the gun is shown in Fig. 2a. A convex cathode with the curvature radius equal to 48mm is used. A grid and an anode are used to control the electron beam current and the transverse distribution through changing the potential distribution nearby the cathode.

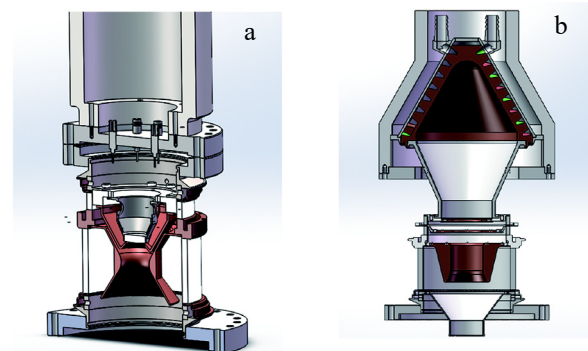


Figure 2: Structures of the electron gun and collector for cooler of HIAF.

Electron gun are calculated by code ULTRASAM [3]. Figure 3 shows the electron beam density distribution with different voltage on grid and anode relative to the cathode. The lines with different colours red, green, yellow and black respectively correspond the situation that voltage on grid equal to 2.5kV, 1.9kV, 1.7kV, 1kV and voltage on anode equal to 3.7kV, 7.7kV, 9.2kV, 13.7kV. When voltage is large enough, 2A parabolic beam and hollow beam can be produced by the gun.

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# INVESTIGATION ON THE SUPPRESSION OF INTRABEAM SCATTERING IN THE HIGH INTENSITY HEAVY ION BEAM WITH THE HELP OF LONGITUDINAL MULTI-BUNCH CHAIN OF ELECTRON\*

X. D. Yang<sup>†</sup>, L. J. Mao, J. Li, X. M. Ma, T. L. Yan, M. T. Tang, H. Zhao  
Institute of Modern Physics, CAS, Lanzhou, China

## Abstract

Intrabeam scattering is the main reason of degradation of the beam brightness and shortening of brightness lifetime in the collider, light source and storage ring. The intrabeam scattering presents dissimilar influence in the different facilities. Electron cooling was chosen to suppress the effect of intrabeam scattering and another unexpected effect happened during the cooling. The distribution of ion beam quickly deviates from the initial Gaussian type, then form a denser core and long tail. The ions standing in the tail of beam will loss soon owing to large amplitude. This solution will focus on the investigation on the suppression of intrabeam scattering in the high intensity heavy ion beam in the storage ring with the help of longitudinally modulated electron beam. The stronger cooling was expected in the tail of ion beam and the weaker cooling was performed in the tail of ion beam. The particle outside will experience stronger cooling and will be driven back into the centre of ion beam during which the ion loss will decrease and the lifetime will increase. The intensity of ion beam in the storage ring will be kept and maintain for a long time.

## INTRODUCTION

This solution will focus on the investigation on the suppression of intrabeam scattering in the high intensity heavy ion beam in the storage ring with the help of longitudinally modulated electron beam. The traditional DC electron beam in the electron cooler was modulated into electron bunch with different longitudinal distribution. The stronger cooling was expected in the tail of ion beam and the weaker cooling was performed in the tail of ion beam. The particle outside will experience stronger cooling and will be driven back into the centre of ion beam. The ion loss will lessen and the lifetime will be increased. The intensity of ion beam in the storage ring will be kept and maintain for a long time. Two functions will be combined into one electron cooler. The more short pulse, the more high intensity and more low emittance heavy ion beam was expected in the cooler storage ring. In the future, these results of this project will be constructive to the upgrade and improvement for existing machine and also be helpful to the design and operation for future storage and high energy electron cooler.

## SOME CONSIDERATIONS

The final equilibrium transverse emittance and longitu-

dinal momentum spread were determined by the cooling effect and intra-beam scattering heating effect together in the case of fixed ion energy and particle number. If we want to get more particle number, in other words, more intensive ion beam, a new parameters configuration will be necessary in the new equilibrium state. In the absence of electron cooling, the transverse ion beam will be blown-up due to not suppression intra-beam scattering effect. The transverse dimension and longitudinal length of ion beam will increase with time, as a result, some ion will loss and the lifetime of ion beam will become short.

## LIFETIME AND INTENSITY OF ION BEAM

The ion beam of  $^{238}\text{U}^{92+}$  with population  $1 \cdot 10^{11}$  particle was required in the high energy high intensity accelerator facility [1]. In this situation, the final emittance and momentum spread were the key parameters which the physics experiments concerned, more important parameters of ion beam were lifetime and the ion number in the detectors.

## MOTIVATION

Two essential questions should be certainly answered and clearly described in advance.

The first question concerned by physics experiment is that whether enough particle [2] be provided to the experiments terminals.

The second one concerned the lifetime [3] of the ion beam with so high intensity whether enough to satisfy the requirements of physics experiments, because it determines the efficiency of experiments.

## NEW SOLUTION PROPOSED

There are three points in this solution. The first point, the intensity of electron bunch presents certain distribution according to the ion bunch distribution in the longitudinal direction. The second point, the electron bunch distribution will change actively according to the ion beam distribution in the cooling process. As a result, the electron beam will provide different strength cooling in the different periods. The third point, the transverse intensity distribution can change also, the electron beam can present different transverse distribution according to the transverse distribution of ion beam in the cooling process. The purpose of this solution will aim to suppress the effect of IBS, increase the lifetime of ion beam and reduce

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<sup>†</sup> yangxd@impcas.ac.cn

# EXPERIMENTAL DEMONSTRATION OF ELECTRON COOLING WITH BUNCHED ELECTRON BEAM\*

L. J. Mao<sup>†</sup>, H. Zhao, M. T. Tang, J. Li, X. M. Ma, X. D. Yang, J. C. Yang, H. W. Zhao  
Institute of Modern Physics, Lanzhou, China

A. Hutton, K. Jordan, T. Powers, R. A. Rimmer, M. Spata, H. Wang, S. Wang, H. Zhang, Y. Zhang  
Jefferson Lab, Newport News, Virginia, U.S.A.

## Abstract

Electron cooling at high energy is presently considered for several ion colliders, in order to achieve high luminosities by enabling a significant reduction of emittance of hadron beams. Electron beam at cooling channel in a few to tens MeV can be accelerated by a RF/SRF linac, and thus using bunched electrons to cool bunched ions. To study such cooling process, the DC electron gun of EC35 cooler was modified by pulsing the grid voltage, by which a 0.07-3.5  $\mu$ s of electron bunch length with a repetition frequency of less than 250 kHz was obtained. The first experiment demonstrated cooling coasting and bunched ion beam by a bunched electron beam was carried out at the storage ring CSRm at IMP. A preliminary data analysis has indicated the bunch length shrinkage and the momentum spread reduction of bunched 12C+6 ion beam. A longitudinal grouping effect of coasting ion beam by the electron bunch has also observed. In this paper, we will present the experiment result and its preliminary comparison to the simulation modelling.

## INTRODUCTION

Electron cooling, a well-established method proposed by Budker to improve the phase space densities of stored ion beams, was applied successfully in many proton, antiproton and ion storage rings [1]. The first electron cooling experiment was carried out at NAP-M (Novosibirsk) with protons at the energy of 68 MeV in 1974. After that, several electron cooling devices were built for low-energy proton and ion storage rings in twentieth century. The first relativistic electron cooling of 8.9 GeV/c antiprotons was demonstrated in 2005 at Fermi lab [2]. Later, a 2 MeV magnetized electron cooling device was installed in COSY at Juelich and a cooling of proton beam at the energy of 1.67 GeV/c was achieved [3]. Furthermore, various possibilities such as coherent electron cooling and micro-bunched electron cooling have been proposed for using the electron beam's instabilities to enhance cooling rate. A prototype based on ERL has been developing at BNL to demonstrate longitudinal cooling in coherent electron cooling mode [4]. All electron cooling systems which were in operation so far employed electron beam generated with an electrostatic electron gun in DC operating mode. Such conventional DC

electrostatic accelerator is quite possible to provide electrons of kinetic energies of up to about 5-8 MeV. For even higher energies the most promising approach would appear to be the RF accelerator of electron beam in an energy-recovering linac system and thus using bunched electron beam for cooling [5]. Some efforts were devoted to explore various aspects of such bunched electron beam cooling but experimental studies of such cooling are still lacking.

The first experiment to demonstrate electron cooling by a bunched electron beam was carried out in the storage ring CSRm at IMP. The 35keV conventional magnetized DC electron cooler provides pulsed electron beam by a modification of its high voltage platform. The electron beam is generated by a thermionic cathode. The grid electrode situated near the cathode edge can produce the negative electric field at the cathode thereby suppressing the emission of electrons. The grid electrode was originally designed for providing hollow electron beam to avoid instabilities of over-cooling beams. By varying the potential of this electrode it is possible to obtain electron beam with variable transverse profile. In our case, a pulsed voltage is applied on it to switch on and off the electron beam fast. Modifications are also made on the connection between grid and anode in order to have good characteristics for time pulse shape. Figure 1 provides a pulsed electron beam measurement by the modified 35 keV electron cooler.

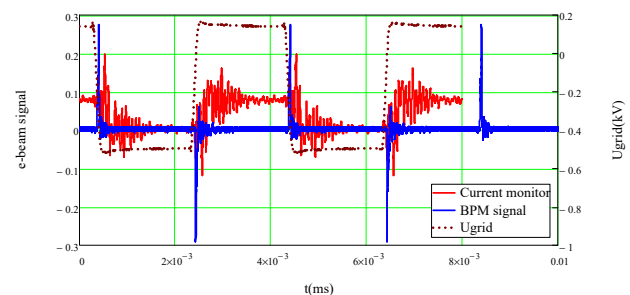


Figure 1: Modulated voltage on the grid electrode of the gun (dash line), pulsed electron beam current (red) and BPM signal generated by pulsed electron beam in the cooler.

In this experiment, a 7.0 MeV/u  $C^{6+}$  ions provided by the cyclotron SFC were injected and accumulated in CSRm. The electron cooling system and the RF station can be switched on respectively to study the pulsed electron cooling of coasting or bunched ion beam. The main parameters of experiment are listed in Table.1.

\* Work supported by National Natural Science Foundation of China No. 11575264, No. 11375245, No. 11475235 and the Hundred Talents Project of the Chinese Academy of Sciences

<sup>†</sup> email address: maolijun@impcas.ac.cn



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# LATEST NEWS FROM STOCHASTIC COOLING DEVELOPMENTS FOR THE COLLECTOR RING AT FAIR

R. Hettrich, A. Bardonnier, R. Böhm, C. Dimopoulou, C. Peschke, A. Stuhl, S. Wunderlich  
 GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

F. Caspers, CERN, Geneva, Switzerland and European Scientific Institute (ESI), Archamps, France

## Abstract

The CR stochastic cooling system aims at fast 3D cooling of antiprotons, rare isotopes and stable ions. Because of the large apertures and the high electronic gain, damping within the 1-2 GHz band of the unwanted microwave modes propagating through the vacuum chambers is essential. It will be realised within the ultrahigh vacuum using resistively coated ceramic tubes and ferrites. The greatest challenge is increasing the signal to noise ratio for antiproton cooling by means of cryogenic movable (plunging) pickup electrodes, which follow the shrinking beam during cooling and then withdraw fast before the new injection. Linear motor drive units plunge synchronously the pickup electrodes on both sides of the ion beam (horizontal/vertical). Their technical concept is summarized. Their performance has been demonstrated in successive measurements inside testing chambers at GSI. Recent simulations of the critical antiproton cooling with the designed system are shown.

## CONCEPT OF PICKUP DRIVES

The concept of linear motor drives for plunging the pickups has been verified. Latest measurements and adjustments have shown that a safe drive concept, with inherent freeing of the aperture in case of an emergency power shutdown, can be built with a single mechanical construction for the all drive orientations.

The springs are the only parts which have to be adjusted for horizontal, vertical top or vertical bottom orientation. Due to the weight of the sliding mass in combination with the vacuum force, springs with three different strengths are needed. In a special test chamber the given forces have been measured and adjusted in order to optimize the dynamic performance. The basic idea is that the drives for the plunging electrodes are outside the vacuum chamber and the movement is decoupled with fatigue enduring bellows. This imposes the full static vacuum force of about 440 N on the drives. To avoid dropping the electrodes onto the beam axis in case of power failure, these vacuum forces are over-compensated with pre-compressed springs. This concept induces an outgoing force on the drives, which increases proportionally to the distance from the outer edge position. The slope of this increase should be as low as possible. The limit is given by the part of the drive length, which can be used for spring pre-compression. In order to get zero total static force at the outer edge position the springs were chosen with maximum length left for pre-compression and spring constants as low as possible. Further, the static forces of the drives including the electrodes and a dummy weight

to account planed enhancements have been measured. Then, adequate spacers for precise adjustment of the springs pre-compression have been inserted into the spring enclosure. Thus, for all three orientations a minimum static force configuration has been achieved. The plots for the orientations with the highest and lowest slope of the force versus the ‘distance-from-beam-axis’ are shown in Fig. 1.

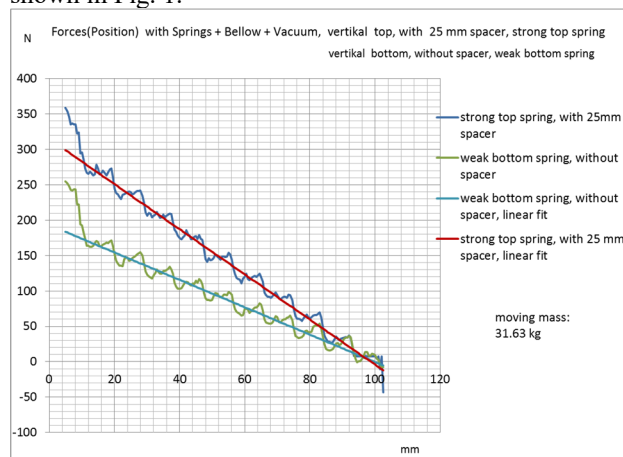


Figure 1: Static forces push out with a ripple from the permanent magnetic field of the motor (current off).

## PLUNGING TRAJECTORIES

For the most critical case with the highest slope, the static force could be kept about 100 N below the maximum static force of the motor. This is enough to achieve a 70 mm full scale movement within 120 milliseconds without additional mechanical shock from the inner to the outer edge of the tank in vertical top orientation. This is shown in Fig. 2.

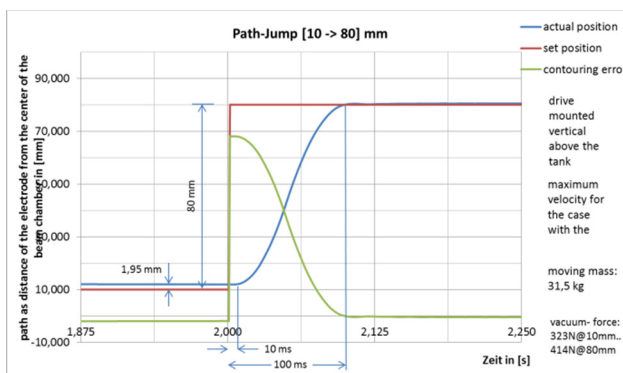


Figure 2: Minimum settling time response (blue) to a full drive distance path jump (red).

# DESIGN OF STOCHASTIC PICK-UPS AND KICKERS FOR LOW BETA PARTICLE BEAMS

B. Breitschneid†, R. Stassen, H. Stockhorst  
 Forschungszentrum Jülich, 52425 Jülich, Germany

## Abstract

The COSY facility hosts experiments for the JEDI (Jülich Electric Dipole moment Investigations) collaboration. Polarized deuteron beams with a momentum of 970 MeV/c are stored in the ring. To achieve polarization times in the order of several minutes, small emittances and momentum spread are crucial. Therefore, the beam is pre-cooled with the 100-kV electron cooler. To further improve the spin coherence time, cooling during the experiments would be desirable. That way, the beam blow-up due to intra beam scattering could be compensated. But since the focusing solenoids in the e-cooler may not be perfectly compensated, it cannot be used to cool during the experiments. The existing stochastic cooling (SC) system is not sensitive at low beam velocities. Thus, it is proposed to build a dedicated SC system for low beta beams. This work presents the proposed system. It emphasizes the design process of pick-up and kicker hardware. Starting from the slot-ring structures that have been developed for HESR, an optimization towards a high sensitivity at a beta of 0.46 is undertaken.

## INTRODUCTION

The discovery of an electric dipole moment (EDM) of hadrons would constitute a breakthrough in the search for CP violations. Since the proposed values of less than  $10^{-24}$  e·cm are hard to resolve, great effort is done to design high precision experiments.

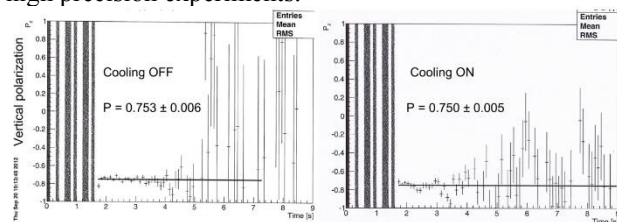


Figure 1: Vertical polarization measurement results after 30 minutes beam storage time, once without and once with vertical stochastic cooling.

The JEDI collaboration faces this task by investigating polarized beams in storage rings [1]. The precursor experiments currently done at COSY use vertically polarized deuterons at momenta of 970 MeV/c [2]. The goal is to increase the polarization lifetime up to the order of 1000 seconds. The beam is pre-cooled with the 100-kV electron cooler to reduce the beam emittances and momentum spread, and consequently increase the spin coherence time [3]. Unfortunately, the focusing in the e-cooler is done by a solenoid, which applies an unwanted longitudinal po-

larizing force to the beam. Thus, the solenoid is compensated by two additional solenoids before and after the beam intersection range. But this compensation is not perfect, and may not fulfil the desired accuracies.

To avoid such depolarization problems, the use of stochastic cooling (SC) instead of electron cooling is investigated. SC systems do not need focusing magnets at all. Thus, the cooling may be applied even during the experiment, counteracting the beam blow-up caused by intra-beam-scattering (IBS).

The influence of the SC system itself on the beam polarization was investigated in [4], concluding that no depolarizing influence is to be expected. To verify this result, vertical cooling was applied to a vertically polarized proton beam (1,965 MeV/c,  $N = 3 \times 10^8$ ). Vertical cooling causes horizontal magnetic RF-fields, thus a horizontal polarization may build up. But after 30 minutes of cooled flat-top, no vertical polarization loss was investigated in comparison to an uncooled setup, as shown in figure 1. It is expected that this will be also true for low energy deuterons in EDM experiments.

## PAST AND PRESENT STATE OF COSY COOLING SYSTEMS

The COLer SYnchrotron (COSY) of the Forschungszentrum Jülich started its operation in 1993 [5]. Protons and deuterons are accelerated in the 184-m long ring and stored at momenta from 0.3 to 3.7 GeV/c. Remarkable features are polarized sources for both deuterons and protons, and the eponymous beam cooling systems.

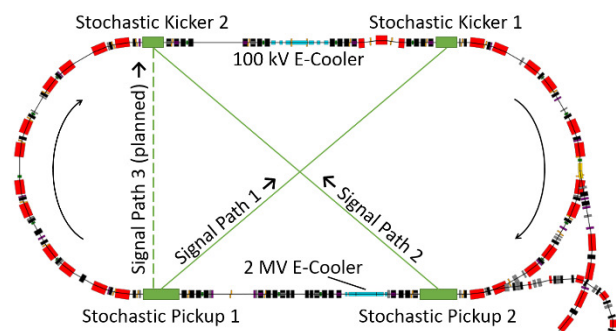


Figure 2: Cooling systems at COSY: Two electron coolers, the high energy SC system at signal path 1, the deprecated vertical and longitudinal system at path 2, and the planned low energy system at path 3.

In figure 2, an overview of the installed cooling systems is given. The initial configuration of COSY consisted of a 100-kV e-cooler for low energies, and a 3D SC system for the upper energy range.

† b.breitschneid@fz-juelich.de

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# DEVELOPMENT OF A BUNCHED BEAM ELECTRON COOLER BASED ON ERL AND CIRCULATOR RING TECHNOLOGY FOR THE JEFFERSON LAB ELECTRON-ION COLLIDER\*

Stephen Benson<sup>†</sup>, Yaroslav Derbenev, David Douglas, Fay Hannon, Andrew Hutton, Rui Li, Robert Rimmer, Yves Roblin, Chris Tennant, Haipeng Wang, He Zhang, Yuhong Zhang,  
 Jefferson Lab, Newport News VA, USA

## Abstract

Jefferson Lab is in the process of designing an electron ion collider with unprecedented luminosity at a 45 GeV center-of-mass energy. This luminosity relies on ion cooling in both the booster and the storage ring of the accelerator complex. The cooling in the booster will use a conventional DC cooler similar to the one at COSY. The high-energy storage ring, operating at a momentum of up to 100 GeV/nucleon, requires novel use of bunched-beam cooling. There are two designs for such a cooler. The first uses a conventional Energy Recovery Linac (ERL) with a magnetized beam while the second uses a circulating ring to enhance both peak and average currents experienced by the ion beam. This presentation will describe the design of both the Circulator Cooling Ring (CCR) design and that of the backup option using the stand-alone ERL operated at lower charge but higher repetition rate than the ERL injector required by the CCR-based design.

## INTRODUCTION

The JLEIC electron-ion collider is designed to produce extremely high luminosity at 45 GeV center-of-mass (CM) energy in electron ion collisions [1]. To accomplish this, the proton or ion beams must be cooled during the operation of the collider. The ion and proton energy is as high as 100 GeV so an electron cooling beam must have an energy of 55 MeV to match the velocity of the protons. To produce a beam of such an energy requires an RF accelerator so the electron beam used to cool the protons/ions must be bunched rather than CW.

We have attempted to design an electron cooling system for JLEIC that strongly cools the ion or proton beams. The specifications for the cooler are shown in Table 1 for the electron and Table 2 for the proton beams for two different CM energies. The electron beam parameters are difficult to achieve due to both the very high charge and high average current. Space charge forces, coherent synchrotron radiation, and wakes tend to create large energy shifts in the electrons. The layout of the cooling complex is shown in Fig. 1. The ion ring is cooled by a Circulating Cooler Ring (CCR) that circulates high-charge bunches 11 times through the ion or proton beam.

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<sup>†</sup>felman@jlab.org

The bunches are injected from an Energy Recovery Linac (ERL) via a harmonic kicker [2]. After 11 round trips, the electron bunches are extracted and decelerated in the ERL and diverted to the dump. The gun frequency is then one eleventh of the cooling ring frequency.

At full CM energy (63.5 GeV), the colliding beams are reduced to one third of their usual frequency while the proton bunch charge is tripled. This is the worst case for cooling so we will consider that case first.

Table 1: Electron Specifications for Strong Cooling

Parameter	Value
Energy	20–55 MeV
Charge	3.2 nC
CCR pulse frequency	476.3 MHz
Gun frequency	43.3 MHz
Bunch length (tophat)	2 cm (23°)
Thermal emittance	<19 mm-mrad
Cathode spot radius	2.2 mm
Cathode field	0.1 T
Gun voltage	400 kV
Norm. hor. drift emittance	36 mm-mrad
<i>rms</i> Eng. spread (uncorr.)*	$3 \times 10^{-4}$
Energy spread (p-p corr.)*	$<6 \times 10^{-4}$
Solenoid field	1 T
Electron beta in cooler	36 cm
Solenoid length	4x15 m

Table 2: Proton Specifications for Strong Cooling

Parameter	63.5 GeV CM	45 GeV CM
Energy	100 GeV	100 GeV
Particles/bunch	$2.0 \times 10^{10}$	$6.6 \times 10^9$
Repetition rate	158.77 MHz	476.3 MHz
Bunch length (rms)	2.5 cm	1.0 cm
Normalized emittance (x/y)	1.2/0.6 mm-mrad	1.0/0.5 mm-mrad
Betatron function	100 m	100 m

Note that we have chosen to use a magnetized beam in the cooler [3]. In a magnetized source, the cathode is immersed in a solenoid. The gun generates an almost parallel (laminar) electron beam. This beam state is then transplanted to the solenoid in the cooling section. The

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## STATUS OF PROOF-OF-PRINCIPLE EXPERIMENT OF COHERENT ELECTRON COOLING AT BNL

V.N.Litvinenko<sup>1,2,#</sup>, I.Pinayev<sup>1</sup>, J.Tuozzollo<sup>1</sup>, J.C.Brutus<sup>1</sup>, Z.Altinbas<sup>1</sup>, R.Anderson<sup>1</sup>, S. Belomestnykh<sup>1</sup>, K.A.Brown<sup>1</sup>, C.Boulware<sup>3</sup>, A.Curcio<sup>1</sup>, A.Di Lieto<sup>1</sup>, C.Folz<sup>1</sup>, D.Gassner<sup>1</sup>, T.Grimm<sup>3</sup>, T.Hayes<sup>1</sup>, R.Hulsart<sup>1</sup>, P.Inacker<sup>1</sup>, J.Jamilkowski<sup>1</sup>, Y.Jing<sup>1,2</sup>, D.Kayran<sup>1,2</sup>, R.Kellermann<sup>1</sup>, R.Lambiase<sup>1</sup>, G.Mahler<sup>1</sup>, M.Mapes<sup>1</sup>, A.Marusic<sup>1</sup>, W.Meng<sup>1</sup>, K.Mernick<sup>1</sup>, R.Michnoff<sup>1</sup>, K.Mihara<sup>1,2</sup>, T.A.Miller<sup>1</sup>, M.Minty<sup>1</sup>, G.Narayan<sup>1</sup>, P.Orfin<sup>1</sup>, I.Petrushina<sup>1,2</sup>, D.Phillips<sup>1</sup>, T.Rao<sup>1,2</sup>, D.Ravikumar<sup>1,2</sup>, J.Reich<sup>1</sup>, G.Robert-Demolaize<sup>1</sup>, T.Roser<sup>1</sup>, B.Sheehy<sup>1</sup>, S.Seberg<sup>1</sup>, F.Severino<sup>1</sup>, K.Shih<sup>1,2</sup>, J.Skaritka<sup>1</sup>, L.A.Smart<sup>1</sup>, K.Smith<sup>1</sup>, L.Snydstrup<sup>1</sup>, V.Soria<sup>1</sup>, Y.Than<sup>1</sup>, C.Theisen<sup>1</sup>, J.Walsh<sup>1</sup>, E.Wang<sup>1</sup>, G.Wang<sup>1,2</sup>, D.Weiss<sup>1</sup>, B.Xiao<sup>1</sup>, T.Xin<sup>1</sup>, W.Xu<sup>1</sup>, A.Zaltsman<sup>1</sup>, Z.Zhao<sup>1</sup>

<sup>1</sup>Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA

<sup>2</sup>Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

<sup>3</sup>Niowave Inc., 1012 N. Walnut St., Lansing, MI, USA

### Abstract

An FEL-based Coherent electron Cooling (CeC) has a potential to significantly boosting luminosity of high-energy, high-intensity hadron-hadron and electron-hadron colliders. In a CeC system, a hadron beam interacts with a cooling electron beam. A perturbation of the electron density caused by ions is amplified and fed back to the ions to reduce the energy spread and the emittance of the ion beam. To demonstrate the feasibility of CEC we pursue a proof-of-principle experiment at Relativistic Heavy Ion Collider (RHIC) using an SRF accelerator and SRF photo-injector. In this paper, we present status of the CeC systems and our plans for next year.

### 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 upgrades of present and in the designs of future colliders.

A dedicated experimental set-up, 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 1.5 MeV electron beam for the CeC accelerator is generated in an 113 MHz SRF quarter-wave photo-electron gun and first focussed 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 comprising five focusing solenoids. A 5-cell 704 MHz SRF linac accelerates the compressed beam to 15 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 high-gain FEL; 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. Fourteen quadrupoles are used to optimize the e-beam interaction with the ion beam and FEL performance.

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

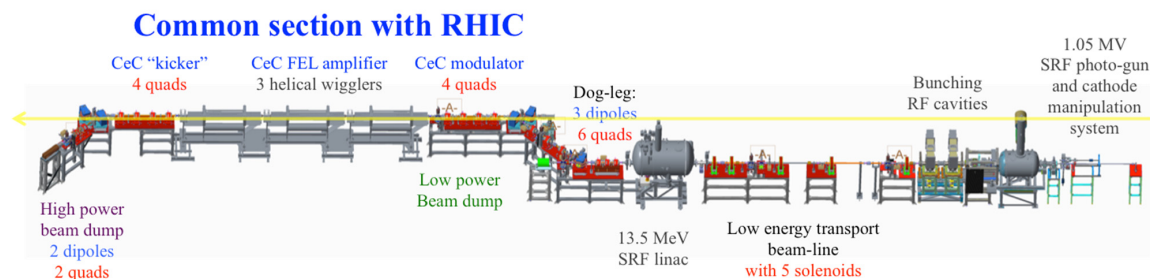


Figure 1: Layout of the CeC proof-of-principle system at IP2 of RHIC.

#vl@bnl.gov

# COMMISSIONING OF THE LOW ENERGY STORAGE RING FACILITY CRYRING@ESR

F. Herfurth, M. Lestinsky, Z. Andelkovic, M. Bai, A. Bräuning-Demian, V. Chetvertkova,  
O. Geithner, W. Geithner, O. Gorda, S. Litvinov, Th. Stöhlker, G. Vorobjev, U. Weinrich  
GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

A. Källberg

Fysikum, Stockholm University, SE-106 91 Stockholm, Sweden

## Abstract

CRYRING@ESR is the early installation of the low-energy storage ring LSR, a Swedish in-kind contribution to FAIR, which was proposed as the central decelerator ring for antiprotons at the FLAIR facility. An early installation opens the opportunity to explore part of the low energy atomic physics with heavy, highly charged ions as proposed by the SPARC collaboration but also experiments of nuclear physics background much sooner than foreseen in the FAIR general schedule. Furthermore, the ring follows in large parts FAIR standards, and is used to test the FAIR control system.

CRYRING@ESR has been installed behind the existing experimental storage ring ESR starting in 2013. It has a local injector that is used for commissioning. In November 2016 the commissioning of the storage ring started and a first turn was achieved. After a complete bake out cycle and substantial developments of control system, diagnosis and others, commissioning was continued in late summer 2017. Stored as well as accelerated beam has been achieved by now. The remaining step is to take the electron cooler into operation, which is planned for November this year.

## INTRODUCTION

In Darmstadt, the facility for antiproton and ion research is being built. Based on the GSI accelerators for injection it will open up new areas of research with heavy ions and, new in Darmstadt, with antiprotons. When it comes to experiments with slow and stored heavy, highly charged ions and antiprotons, two collaborations, the Stored Particles Atomic Physics Research Collaboration - SPARC and the Facility for Low-Energy Antiproton and Ion Research - FLAIR, have been formed to move into one building complex, the FLAIR building.

The low energy storage ring LSR shall provide the highly charged ions and antiprotons at low energy at the FAIR facility for those two collaborations, SPARC and FLAIR. The LSR evolves from the heavy-ion storage ring CRYRING, which has been operated at the Manne Siegbahn Laboratory in Stockholm until 2010 [1]. The main-focus is on precision experiments, which requires low energy and well-controlled beam properties that is typically achieved by beam cooling. The LSR will be installed as intermediate step between the new experimental storage run NESR and the low energy facilities HITRAP and the ultra low energy storage ring USR. The LSR is a Swedish in-kind contribution to the FAIR facility in

Darmstadt, i.e. part of the investment done by the Swedish physics community into the FAIR project.

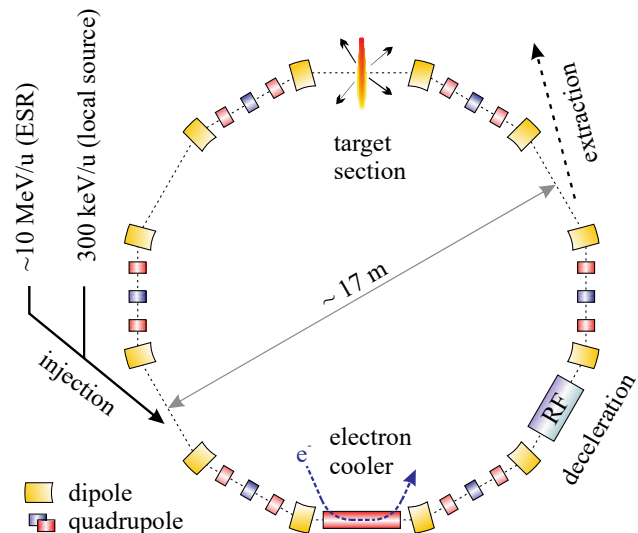


Figure 1: Schematic layout of CRYRING@ESR. The main components; injection, extraction, electron cooler, RF section, and the target section are indicated.

After careful cost evaluation a staged approach was put into place that does not include the NESR in its start version. However, contrary to the original plans the present storage ring at GSI, the ESR, will not be disassembled for component reuse but continue running. Consequently, instead of warehousing the ring components until installation at the Facility for Antiproton and Ion Research, FAIR, the immediate installation behind the existing Experimental Storage Ring, ESR [2, 3], has been proposed and worked out in detail by a Swedish-German working group. The estimated efforts for installation and operation of CRYRING at the ESR have been summarized in a report [4] published by that working group in 2012.

A schematic overview of the storage ring and its facilities is shown in Fig. 1. CRYRING as it is now installed behind the ESR can decelerate, cool and store heavy, highly charged ions from about 10 MeV/nucleon and antiprotons from about 30 MeV/nucleon down to a few 100 keV/nucleon. It provides a high performance electron cooler in combination with a gas jet target. It is equipped with its own injector and ion source, to allow for standalone commissioning. For more detailed ring parameters see also Table 1.

# NICA PROJECT: THREE STAGES AND THREE COOLERS

I. N. Meshkov<sup>†1,2</sup>, G.V. Trubnikov<sup>1,2</sup>

<sup>1</sup>Joint Institute for Nuclear Research, Dubna, Russia

<sup>2</sup>Sankt-Petersburg State University, Sankt-Petersburg, Russia

## Abstract

The Nuclotron-based Ion Collider fAcility (NICA) project is being developed at JINR in three stages. The 1st stage, is a fixed target experiment with ions accelerated in the linac and tandem of two superconducting (SC) synchrotrons providing for ions  $^{197}\text{Au}^{79+}$  maximum kinetic energy of 4.5 GeV/u ( $\sqrt{s}\text{NN} = 3.45$  GeV/u). The 2nd stage extends  $\sqrt{s}\text{NN}$  to 11 GeV/u in colliding beams' mode. Both stages have a goal of experimental study of both hot and dense baryonic matter to search for so-called Mixed Phase formation in collisions of heavy relativistic ions and search for “new physics”. The third stage is spin physics studies in collisions of polarized protons ( $\sqrt{s}\text{NN} = 27$  GeV) and deuterons. The report focuses on beam dynamics in the NICA and the cooling methods application.

## INTRODUCTION: THE NICA PROJECT AT JINR

The NICA project aims to design, construction and commissioning at the Joint Institute for Nuclear Research (Dubna, Russia) a modern accelerator complex Nuclotron-based Ion Collider fAcility (NICA) equipped with two detectors: the MultiPurpose Detector (MPD) and the Spin Physics Detector (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. The project development has three stages:

**Stage I:** the fixed target experiment on heavy ions generated in the ion source and accelerated in the chain Heavy-Ion Linac (HILAc) – Booster synchrotron – Nuclotron.

**Stage II:** development of the same accelerator chain and transfer of the accelerated ions to the Collider rings and performance of the experiments on the ion beams in collider mode.

**Stage III:** generation and acceleration of polarized protons and deuterons and performance of the experiments on the colliding beams of the polarized particles.

A study of hot and dense baryonic matter should shed light on in-medium properties of hadrons and the nuclear matter equation of state; onset of deconfinement and/or chiral symmetry restoration; phase transition, mixed phase and the critical end-point; and possible local parity violation in strong interactions [1]. It has been indicated in series of theoretical works, in particular, in [2], that heavy-ion collisions at the nucleon-nucleon center-of-mass energy  $\sqrt{s}\text{NN} \sim 10$  GeV allow one to reach the highest possible net baryon density.

The NICA project is under development as a flagship JINR project [3] in high-energy physics. Its main goal is

construction of a collider facility providing ion collisions in collider mode at the energy range of  $\sqrt{s}\text{NN} = 4 - 11$  GeV for  $\text{Au}^{79+}$  with luminosities up to  $L = 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ . NICA will also provide the polarized proton and deuteron beams up to  $\sqrt{s}\text{NN} = 27$  GeV for pp collisions with luminosity up to  $L = 10^{32} \text{ cm}^{-2} \cdot \text{s}^{-1}$ . The high intensity and high polarization ( $> 50\%$ ) of the colliding beams will present a unique possibility for spin physics research, which is of crucial importance for the solution of the nucleon spin problem (“spin puzzle”) - one of the main tasks of the modern hadron physics.

## NICA – STAGE I

The program “The Baryonic Matter at Nuclotron” (BM@N) is complementary to that one of the Stage II. It is presently under active development and uses presently for testing experiment the existing Nuclotron facility. The last one currently consists of the “Old injector”, new Heavy Ion Linac (HILAc) and the Nuclotron. The “Old injector” contains a set of light ion sources including a source of polarized protons and deuterons and an Alvarez-type linac LU-20 (Fig. 1, pos. 1). In this year the old fore-injector of LU-20 – electrostatic generator of 625 kV voltage has been replaced by new RFQ fore-injector that provides output energy of 156 keV for all ions. The LU-20 is capable to accelerate protons at the second harmonics only. Therefore the output proton energy, as well as other ions at  $A/Z = 2$ , is of 5 MeV.

The “New injector” (pos. 2) contains the ESIS-type ion source, which provides  $^{197}\text{Au}^{32+}$  ions of intensity of  $2 \cdot 10^9$  ions per pulse of about  $7 \mu\text{s}$  duration at a repetition rate of 10 Hz, and the heavy ion linear accelerator (HILAc), consisting of RFQ and RFQ Drift Tube Linac sections. The HILAc accelerates the ions at  $A/Z \leq 8$  up to the energy of 3 MeV/u, at efficiency no less than 80% ( $A, Z$  are ion mass and charge numbers). It was fabricated by the BEVATECH Company (Germany) in 2014 - 2015 and has been commissioned at JINR in 2016.

The Stage I will be commissioned for experiments after construction of the Booster-synchrotron (pos. 4), transfer channels from HILAC to the Booster and from Booster to existing Nuclotron, and the BM@N detector.

### The NICA Booster

The ring of the SC Booster-synchrotron of the circumference of 215 m is housed inside the Synchrotron yoke (pos. 3). Its SC magnetic system provides a maximum magnetic rigidity of 25 Tm that allows us to accelerate ions  $^{197}\text{Au}^{31+}$  to the energy of 578 MeV/u. It is sufficient for stripping these ions up to state of bare nuclei. Then, after transfer to Nuclotron (see below) the nuclei can be accelerated up to maximum project energy of 4.5 GeV/u. This

<sup>†</sup> meshkov@jinr.ru

# THE HESR STOCHASTIC COOLING SYSTEM, DESIGN, CONSTRUCTION AND TEST EXPERIMENTS IN COSY

R. Stassen\*, B. Breitzkreutz, N. Shurkhno, H. Stockhorst  
Forschungszentrum Jülich, 52425 Jülich, Germany  
L. Thorndahl, CERN, 1211 Geneva 23, Switzerland

## Abstract

The construction phase of the stochastic cooling tanks for the HESR has started. Meanwhile two pickups (PU) and one kicker (KI) are fabricated. One PU and one KI are installed into the COSY ring for testing the new stochastic cooling system with real beam at various momenta. Small test-structures were already successfully operated at the Nuclotron in Dubna for longitudinal filter cooling, but not for transverse cooling and as small PU in COSY. During the last COSY beam-time in 2017 additional transverse and ToF cooling were achieved. The first two series high power amplifiers were used for cooling and to test the temperature behaviour of the combinerboards at the KI. The system layout includes all components as planned for the HESR like low noise amplifier, switchable delay-lines and optical notch-filter. The HESR needs fast transmission-lines between PU and KI. Beside air-filled coax-lines, optical hollow fiber-lines are very attractive. First results with such a fiber used for the transverse signal path will be presented.

## STOCHASTIC COOLING SYSTEM OF HESR

Stochastic cooling at HESR is not only used to reduce beam size and momentum spread during the experiment, but also to accumulate antiprotons due to the postponed Recuperated Experimental Storage Ring (RESR) [1, 2] of the modularized start version of the FAIR project.

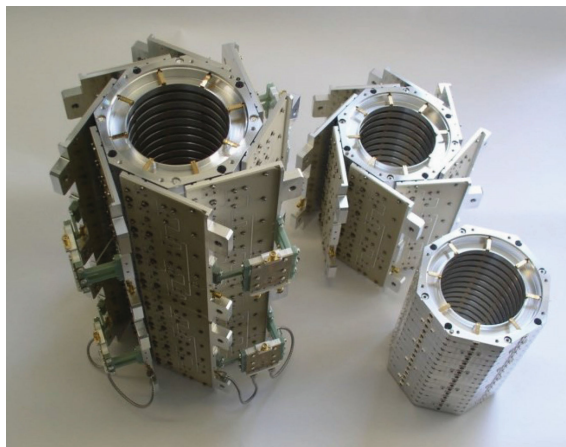


Figure 1: Stacks of slot ring couplers with and without 16:1 combiner-boards and two stacks mounted together including 2:1 combiner with heat-trap.

\* r.stassen@fz-juelich.de

The system is based on dedicated structures. Each beam-surrounding slot of these so called slot-ring couplers covers the whole image current without a reduction of the HESR aperture [3]. Each resonant ring structure is heavily loaded with eight  $50\ \Omega$  electrodes for a broadband operation. The rings are screwed together to a selfsupporting structure in stacks of 16 rings. Four of these stacks will build the spindle for one tank. Figure 1 shows these stacks; one without combiner one with combinerboard and a combination of two stacks including additional 2:1 combiner especially designed to minimize the heat flow to the 16:1 combiners. Meanwhile a new structure has been designed for a special cooling system operating in the frequency range 350 – 700 MHz [4].

Beside the main 2 – 4 GHz system a 4 – 6 GHz system was planned for additional longitudinal cooling. This system will be substituted by an additional 2 – 4 GHz system with modified combiner-boards to cool heavy ions at lower energies [5].

The first HESR series pickup was installed into COSY during the winter-shutdown 2015/2016 and is used to measure routinely Schottky spectra for several experiments. Two cryo-pumps are installed to cool down the pickup and increase the signal to noise ratio. The inner structure of the pickup was cooled down to less than 20 K within 10 h and although the tank is not bakeable, the vacuum reached already  $5 \cdot 10^{-10}$  mbar. During the summer shutdown 2016 the first HESR kicker tank was installed in COSY at the position of the old vertical kicker.

First commissioning started in February 2017 after installing the new notch-filter, measurement system and prototype of the GaN power amplifiers.

The automated frequency adjustment of the notch-filter was successfully tested and takes less than a minute for frequency and gain - whereas with the old system the typical setup time was in the order of one hour. The program determines also the frequency error for each notch with respect to the fundamental frequency. The fluctuations of the Notch-frequency were within  $\pm 10$  Hz taking into account the harmonic number. This is pretty small and does not influence the cooling time and power, but can still increase the equilibrium momentum spread due to the small  $\eta$ -value in the HESR. These fluctuations are dominated by the transimpedance amplifiers in the optical receivers and can be further reduced by pairing the receivers.

The algorithms for automatic open-loop measurements and system delay adjustment were also successfully tested and refined. The open-loop measurements now can be carried out for the full bandwidth within single sweep or by