# BEAM COOLING, PAST, PRESENT AND FUTURE*

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## *Abstract*

This review paper has the purpose to describe the history of creation of the cooling methods, the highlights of their application to experimental physics, present status of development and application of the methods, future projects with cooling methods use, trends in their development and some novel ideas appeared during recent years.

## INTRODUCTION

The truism saying "the history does not teach anything" has no relation to physics. The longstanding history of cooling methods development is a fascinating "novel" of fighting with famous theorem formulated by Joseph Liouville in 1838: the theorem of phase space density conservation [1]. And very first significant step has been done by A. Kolomensky and A. Lebedev [2] more than one century later. They have described process of particle momentum spread decrease ("damping") in electron beam subjected to synchrotron radiation (SR) and have derived the formula for characteristic time of the process. The development of the SR damping theory was continued by K.W. Robinson who deduced the theorem on sum of decrements, the rule of decrements redistribution, etc. [3]. However, the synchrotron radiation is "a gift of nature" that does not work for heavy particles (SR intensity is inversely proportional to cube of particle mass for given particle energy value). Therefore we consider here "the cooling methods" which allow to reduce phase space volume of heavy particles beams, i. e. enhance the beam phase space density. Beginning with description of the first proposals and methods development in the past we consider present status of this activity and the methods applications and discuss novel ideas and projects under design intended for future.

## PAST

### *First Proposals*

The very first step in creation of a cooling method for heavy particles has been done by A. Kolomensky in 1965. He proposed [4] to use particle ionization losses in a medium. However, the nature turned out to be merciless to strongly interacting particles – the particle loss rate is higher of cooling rate by two orders of magnitude in relativistic energy range ($\varepsilon > m_p c^2$) where *ionization cooling* works. Nevertheless, it was a good start idea that has been reformulated later (see below, 1970). First really effective cooling method – *the electron cooling* – was developed at the same time by G. Budker [5]. Soon, together with A. Skrinsky, they proposed to apply this method to storage of antiprotons in an accelerator ring. In 1968 S. van der Meer has published the idea of *stochastic cooling* [6]. It is worth to quote his Nobel lecture [7]: "Such a system resembles Maxwell's demon, which is supposed to reduce the entropy of a gas by going through a very similar routine, violating the second law of thermodynamics in the process. It has been shown by Szilard that the measurement performed by the demon implies an entropy increase that compensates any reduction of entropy in the gas. Moreover, in practical stochastic cooling systems, the kicker action is far from reversible; such systems are therefore even less devilish than the demon itself." And two years later G. Budker and A. Skrinsky proposed to use ionization cooling method for cooling of muons which are devoid of strong interaction [8, 9]. This version of the method is known nowadays as "*muon cooling*".

### *First Experimental Proof*

It has taken 8 years until first experiment on *electron cooling of protons* at NAP-M storage ring has been performed in INP, Novosibirsk. Simultaneously first approximation of the method theory has been developed (see details in [10]). One year later the first *stochastic cooling* has been demonstrated at ISR (CERN) [11].

### *Cooling Boom*

After first advance of the middle of the 70th in experimental corroboration of two cooling methods a cooling "boom" seized many accelerator laboratories around the World. Twelve laboratories constructed cooler rings and performed experiments on study of cooling physics during the 80th and beginning of the 90th (Table 1).

In 1984 by initiative of H. Poth the first Workshop dedicated to electron cooling had been organized and performed in Karlsruhe Kernforschungszentrum. It is followed with biennial periodicity since then and until now.

### *1990-2012: The Productive Years*

As result of following advance in cooling methods development many remarkable results have been achieved. First the creation of *laser cooling* should be pointed out. These studies were performed at TSR (1990) [12] and ASTRID (1991) [13] cooler storage rings. Extremely low ion longitudinal temperature, of the order of a few meV, has been obtained.

During these years both electron and stochastic cooling systems became routine tools at cooler storage rings. The BETACOOL code for cooling processes simulation was developed (JINR) [14] and experimentally tested at COSY, ESR, CELSIUS, S-LSR, LEAR,

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# RHIC LUMINOSITY INCREASE WITH BUNCHED BEAM STOCHASTIC COOLING*

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*Abstract*

The RHIC luminosity increase with bunched beam stochastic cooling is reviewed. Most notably, during 2012 with uranium beams, we observed a tripling of instantaneous luminosity and a 5 fold increase in integrated luminosity.

## INTRODUCTION

A stochastic cooling system is a wide band feedback loop [1, 2]. A pickup detects fluctuations in the beam current or transverse position. This signal is filtered, amplified and sent to a kicker. When the system is correctly adjusted the perturbations created by the kicker reduce the detected signal. Over time this acts as a viscous force causing the beam to condense or cool. The fundamentals are illustrated in Figure 1. The Schottky current from the beam $I_S$ is detected by the pickup $P$. There is also a signal associated with the coherent response of the beam due to the kicker, $I_1$. The sum of these currents is filtered and amplified through an effective transfer impedance, $Z_T$. A voltage, $V_K = -Z_T(I_S + I_1)$ is generated by the kicker. For appropriate phases and gains the beam is cooled, resulting in a small change to the Schottky signal. In addition to the desired change to the Schottky signal there is a much larger coherent response due to the beam transfer function, $I_1 = BV_K$. The beam transfer function depends on the beam properties in the fluid limit and evolves slowly over a cooling time. Over time scales short compared to the cooling time one may neglect the slow evolution of $B$ and directly relate the kicker voltage to the Schottky current,

$$V_K = \frac{-Z_T I_S}{1 + BZ_T}. \qquad (1)$$

Some additional calculation yields

$$I_{total} = I_1 + I_S = \frac{I_S}{1 + BZ_T}. \qquad (2)$$

The second result demonstrates signal suppression or shielding [3]. The total current, $I_{total}$ is directly measurable. The transfer impedance is adjusted to give $I_{total} \approx I_S/2$ and $I_S$ measured with feedback off. With system bandwidth $W$ one obtains a time resolution $\tau \sim 1/2W$. For a beam of particles with charge $q$ and current $I$, the longitudinal cooling system measures the average energy of samples containing $N_s = I\tau/q$ particles each turn. This signal is filtered, amplified and applied to the beam so as to reduce the energy spread. If the beam requires $M$ turns to mix the samples into statistical independence, the optimal cooling time scales as $\sigma_E/\dot{\sigma}_E \approx 2N_s T_0 M$ where the revolution period is $T_0 = 12.8\mu$s for RHIC.

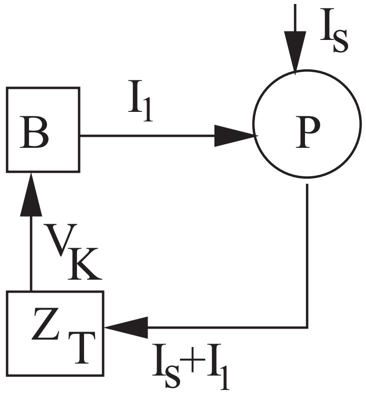

Figure 1: Schematic of the cooling feedback loop.

The RHIC system has greatly benefitted from previous work. Bunched beam stochastic cooling was first observed in 1978 in ICE [4]. In the initial publication it was noted that correlated synchrotron sidebands imply that the optimal cooling gain need not be flat in frequency, as in the coasting beam case, but could have maxima spaced at the inverse of the bunch length. The RHIC system exploits this property.

A theory of bunched beam cooling was developed in the early eighties [5, 6, 7, 8] and stochastic cooling systems for the SPS [7, 9] and the Tevatron [7, 10] were explored. Stochastic cooling in RHIC was first studied by Van de Meer [11] and extended by Wei and Ruggerio [12, 13]. Experimental studies for the SPS and the Tevatron were started and early on [10, 14, 15, 16, 17] it was found that "RF activity" extending up to very high frequencies dwarfed the true Schottky signal. Nonetheless, stochastic cooling work in the Tevatron continued. Promising results were obtained but not pursued [18].

Experimental studies in RHIC began in 2002 with measurements of gold Schottky spectra and preliminary calculations [19]. In 2003 longitudinal beam transfer functions were presented and quantitative agreement of kicker voltage with beam response was obtained [20]. In 2004 the longitudinal kicker voltage was estimated at several kilovolts [21], similar to earlier estimates[11]. Around the same time the notion of using narrow band cavities and a Fourier series implementation was introduced [22]. The

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# MUON COOLING, MUON COLLIDERS, AND THE MICE EXPERIMENT*

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## *Abstract*

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. The performance and cost of these depend on how well a beam of muons can be cooled. Recent progress in muon cooling design studies and prototype tests nourishes the hope that such facilities can be built during the coming decade. The status of the key technologies and their various demonstration experiments is summarized.

## MUON COLLIDERS AND NEUTRINO FACTORIES

Discussed since the 1960s [1, 2], muon colliders (Fig. 1) are now reaching the threshold at which their construction can be realistically contemplated. Their interest stems from the important advantages over electrons that muons confer for high-energy lepton colliders: suppression of radiative processes by the 200-times greater mass of the muon, enabling the use of storage rings and recirculating accelerators, and of "beamstrahlung" interactions, which limit $e^+e^-$-collider luminosity as energy increases [3]. The smaller size of a muon collider (Fig. 2) eases the siting issues and suggests that the cost will be less as well. Furthermore, the muon/electron cross-section ratio for $s$-channel annihilation to Higgs bosons, $(m_\mu/m_e)^2 = 4.3 \times 10^4$, gives the muon collider unique access to precision Higgs measurements [4, 5, 6, 7]. For example, at the $\approx 126\,\mathrm{GeV}/c^2$ mass measured by ATLAS and CMS [8], only a muon collider can directly the observe the (4 MeV) width and lineshape of a Standard Model Higgs boson [4] (see Fig. 3). Furthermore, should the Higgs have closely spaced supersymmetric partner states at higher mass, only a muon collider has the mass resolution required to distinguish them. (The same argument applies as well to closely spaced scalar states in any other new-physics scenario.)

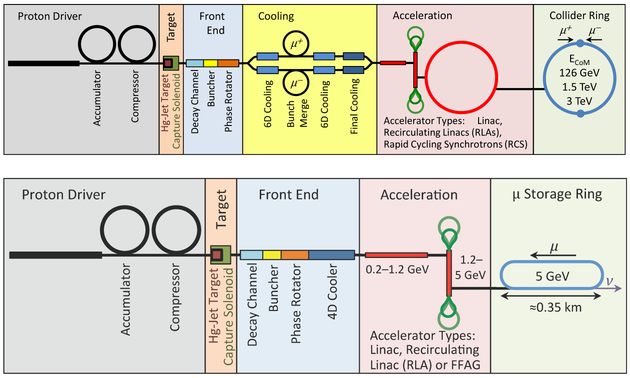

Figure 1: (top) Muon collider and (bottom) neutrino factory schematic diagrams.

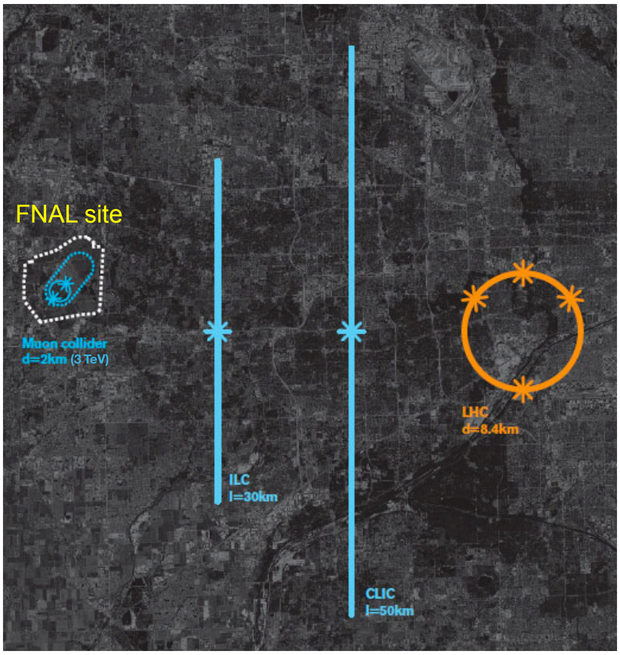

Figure 2: Collider sizes compared with FNAL site. A muon collider with $\sqrt{s} > 3\,\mathrm{TeV}$ fits on existing sites.

The neutrino factory (Fig. 1) is a newer idea [9]. A muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \to e^-\nu_\mu\overline{\nu}_e$ and $\mu^+ \to e^+\overline{\nu}_\mu\nu_e$, it can provide collimated, high-energy neutrino beams with well-understood composition and properties. The clean identification of final-state muons in far detectors enables low-background appearance measurements using $\nu_e$ and $\overline{\nu}_e$ beams. Distinguishing oscillated from non-oscillated events requires a magnetized detector: if $\mu^-$ are stored in the ring, the oscillated events contain $\mu^+$, and vice versa if $\mu^+$ are stored. Now that a non-zero $\theta_{13}$ neutrino mixing angle has been measured [10], observing or ruling out neutrino CP violation becomes the *sine qua non* of neutrino physics, from which the needed neutrino factory performance follows. For this physics, the neutrino factory has been shown to be superior to all other facilities [11]. A staged plan proceeding through a series of neutrino factories and muon colliders is under development [12, 13], beginning with a short-baseline neutrino ex-

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# AN OVERVIEW OF THE US MUON ACCELERATOR PROGRAM*

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## *Abstract*

The Muon Accelerator Program (MAP) is the U.S. organization tasked with carrying out the R&D necessary to evaluate the feasibility of future facilities based on muon accelerators. This includes research that could lead to the construction of a neutrino factory, Higgs factory and/or multi-TeV muon collider. Activities include design work for all stages of a muon accelerator complex, from the proton driver and target through the collider and/or muon decay rings, development of the critical technologies needed for such a facility, and support for experiments demonstrating key principles such as muon cooling (eg, the Muon Ionization Cooling Experiment). MAP coordinates a collaboration that includes participants from 18 U.S. institutions, which span the national laboratory system, universities and industry. The major research thrusts and goals as well as the structure of the research program are summarized.

## INTRODUCTION

In 2008, the U.S. Particle Physics Project Prioritization Panel (P5) defined 3 frontiers that encompassed the major thrusts of the U.S. high-energy physics program [1,2]: the Energy, Intensity and Cosmic Frontiers. Together, research across these three frontiers explores the nature of the origin of the universe and the fundamental forces with which it operates. A principal motivation for a research program to develop a Muon Accelerator capability is the fact that such machines can support a cutting edge research program that spans both the Intensity and Energy Frontiers. On the Intensity Frontier, a Neutrino Factory (NF) would provide the most precise and intense source of electron and muon neutrinos that has ever been conceived. Such a facility could provide a beam containing $5\times10^{20}$ $\nu_e$ and $\nu_\mu$, each, to a far detector. Such capability would enable measurements of CP violation in the neutrino sector with comparable precision to measurements that have been made with the B-factories in the quark sector. At the boundary between the Intensity and Energy Frontiers, Muon Accelerators also offer a route to a Muon Collider designed for very small energy spread at a center-of-mass energy corresponding to the Higgs mass. By utilizing s-channel production of the Higgs, current machine designs are projected to provide roughly 40,000 Higgs decays per year [3,4]. The very small energy spread of such a machine, $\delta E/E$~3-4$\times10^{-5,}$ would enable a direct measurement of the Higgs width. Finally, such a facility would provide a route to an Energy Frontier Muon Collider (MC) in the 1-10 TeV center-of-mass energy range, which would be able to exploit any TeV-scale discoveries by the Large Hadron Collider (LHC).

## THE U.S. MUON ACCELERATOR PROGRAM

The U.S. Muon Accelerator Program (MAP) was approved in early 2011 to assess the feasibility of the technologies required for the construction of a high intensity Neutrino Factory (NF) and a Muon Collider (MC). The MAP effort grew out of the merger of two previous efforts: the Neutrino Factory Muon Collider Collaboration (NFMCC) and Fermilab's Muon Collider Task Force (MCTF). The program is taking an approach where the feasibility assessment is sub-divided into 3-year phases, with clear deliverables and intermediate assessments specified for each phase. In anticipation of a successful conclusion of the feasibility assessment, the goal of MAP is to prepare a proposal, by the end of this decade, for a follow-on effort to develop the detailed technical design for a Muon Accelerator Facility, which can support both NF and MC capabilities.

Figure 1 shows the major accelerator sub-systems required to support a NF and MC. Many of the major systems could be shared for the two applications. The major components of these facilities include:

- [NF+MC] A high intensity, multi-MW class ***Proton Driver*** that is able to provide a suitable bunch structure to a high power target. At Fermilab, the proton driver would be based on Project X [5]. An initial implementation, with 1 MW of incident proton power based on Stage II of Project X, could support operation of the first long baseline NF.
- [NF+MC] A ***Target*** and high-field (~20 T) ***Capture Solenoid***, which ultimately must be capable of operation at 4 MW of incident proton power. The MERIT experiment has demonstrated the ability of a liquid Hg jet target to operate at up to 8 MW of incident beam power [6].
- [NF+MC] A ***Front End*** where the muon beam is bunched and phase rotated to provide a bunch train containing both species. For the NF application, an initial stage of 4D ionization cooling channel is the last accelerator system of the front end. For an MC, a full 6D cooling channel begins at this point. It should be noted that, in a dual-use facility, incorporation of the 6D cooling channel could also benefit NF performance.

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# MUON BEAM HELICAL COOLING CHANNEL DESIGN*

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## *Abstract*

The Helical Cooling Channel (HCC) achieves effective ionization cooling of the six-dimensional (6d) phase space of a muon beam by means of a series of 21st century inventions. In the HCC, hydrogen-pressurized RF cavities enable high RF gradients in strong external magnetic fields. The theory of the HCC, which requires a magnetic field with solenoid, helical dipole, and helical quadrupole components, demonstrates that dispersion in the gaseous hydrogen energy absorber provides effective emittance exchange to enable longitudinal ionization cooling. The 10-year development of a practical implementation of a muon-beam cooling device has involved a series of technical innovations and experiments that imply that an HCC of less than 300 m length can cool the 6d emittance of a muon beam by six orders of magnitude. We describe the design and construction plans for a prototype HCC module based on oxygen-doped hydrogen-pressurized RF cavities that are loaded with dielectric, fed by magnetrons, and operate in a superconducting helical solenoid magnet.

## OVERVIEW

Much of the ionization cooling technology included in the conceptual design discussed here did not exist before this millennium. Below we describe these new technologies and their verification by calculations, simulations, and experiments. We present a conceptual design of a module of an HCC that demonstrates how to marry the new concepts into a practical cooling channel to enable muon colliders and to make muon beams for neutrino factories and precision experiments affordable.

The design incorporates the HCC theory with emittance exchange using a continuous absorber [1], hydrogen-pressurized RF cavities [2] loaded with dielectric [3] and doped with oxygen [4], Helical Solenoid (HS) magnets [5], phase and frequency-locked magnetron power sources [6], and optimizations using G4beamline [7] muon beam cooling simulations. The innovations that were developed with support from the DOE SBIR-STTR program are combined to provide a practical engineering solution for a muon-beam cooling channel. The references above indicate the many contributors and institutions to the conception, development, and verification of the HCC and its components.

In the description that follows, six segments, each with the same parameters, form a 233 m long linear magnetic channel. Each segment is composed of modules that are similar to the prototype module described here.

## HCC THEORY

The theory of the Helical Cooling Channel, extended to include a continuous homogeneous absorber, provides a framework to develop practical devices and techniques. The forces generated by particle motion in combined solenoid and Siberian-snake helical dipole fields are used to construct a Hamiltonian that is solved by moving into the rotating frame of the helical dipole where stability requirements determine the need for a helical quadrupole.

In an HCC, solenoid and transverse helical dipole field components provide a constant dispersion along the channel for emittance exchange to allow longitudinal cooling. The helical dipole component creates an outward radial force due to the longitudinal momentum of the particle while the solenoid component creates an inward radial force due to the transverse momentum of the particle:

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

where $B$ is the solenoid component, the axis of which defines the $z$ axis, and $b$ is the transverse helical dipole field component. Figure 1 shows the motion of particles around the equilibrium orbit (red).

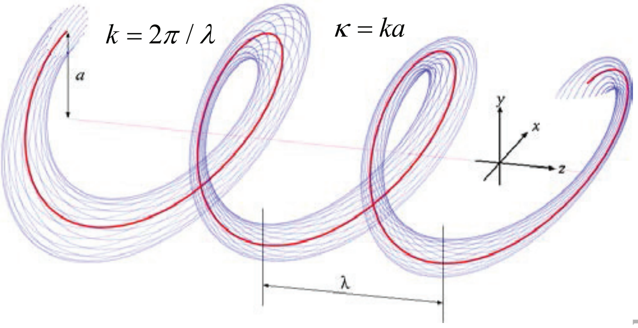

Figure 1: Schematic of beam motion in an HCC. Unlike cooling in a solenoid, the radius, a, does not diminish.

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

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

The dispersion factor $\hat{D}$ is determined by the field components $B$, $b$, and the transverse magnetic field radial gradient $\partial b/\partial a$ on the particle orbit:

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

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

The magnetic field ratio on the equilibrium trajectory satisfies the condition

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

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# 6D COOLING IN PERIODIC LATTICES INCLUDING A PLANAR SNAKE*

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## *Abstract*

A Muon Collider requires 6 dimensional (x, x',y, y', t, E) cooling down to a transverse emittance of 240 µm and a longitudinal emittance of the order of 2 mm [1]. Ionization cooling in absorbers, together with emittance exchange is used. Previously known lattices, using vacuum rf, are discussed. All use solenoid focusing combined with weak dipoles to generate dispersion. Three of the examples use bi-periodic focusing, known as SFOFO or RFOFO, in different geometries: a) rings [2]; slow helices (known as Guggenheims) [3]; and linear [4]. These lattices all require wedge shaped absorbers and work for only one muon sign at a time. The Helical FOFO Snake lattice [5], based on simple alternating solenoids, together with a weak rotating dipole, uses flat slab absorbers and works for both signs simultaneously. But this solution would require unreasonably high magnetic fields for cooling to the required transverse emittance.

A new lattice, the Planar RFOFO Snake [6] is then discussed. Like the Helical FOFO Snake, it uses slab absorbers and cools both signs simultaneously. But this Planar RFOFO lattice is based on bi-periodic solenoid focusing and allows cooling to lower emittances without excessive fields.

## INTRODUCTION

This work is part of the Muon Accelerator Program (MAP) [7] that is studying Muon Colliders over a range of energies (approximately 125 GeV for a 'Higgs Factory' as well as energies of several TeV. All of these require 6 dimensional (x, x',y, y', E, t) cooling down to a transverse emittance of approximately 240 µm, and a longitudinal emittance of the order of 2 mm (lower longitudinal emittances give undesirable space charge effects). Transverse ionization cooling is achieved by passing the muons though a low Z absorber, typically liquid hydrogen, in which both transverse and longitudinal momentum are lost. An rf cavity (only vacuum rf is considered in this paper) restores the lost longitudinal momentum, leaving the reductions of the transverse components. Multiple scattering leads to a minimum (equilibrium) emittance that is proportional to the betatron $\beta_\perp$ divided by the muon momentum. This $\beta_\perp$, and thus minimum emittance, can always be reduced by scaling all dimensions down, with the magnetic field scaled up ($B \propto 1/L$). It can also be decreased if the lattice focuses the muons to a lower $\beta_\perp$ at the absorber: something that cannot be done in a non-periodic lattice like the Helical Cooling Channel [8].

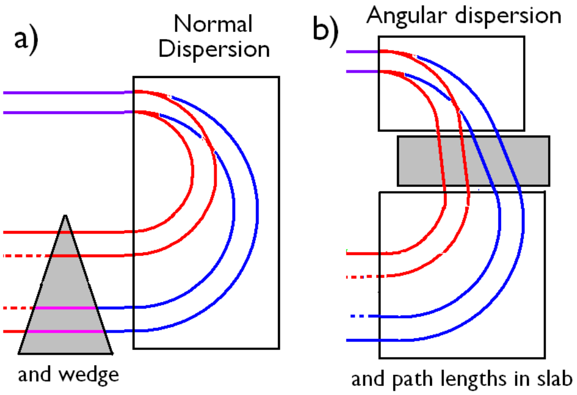

Figure 1: Emittance Exchange: a) using dispersion and wedge absorbers; b) using angular dispersion and slab absorbers.

For cooling in the longitudinal (Energy and time) dimensions, emittance exchange is required. The two methods applicable here are illustrated in Figure 1. In method a), a wedge absorber is placed in a region with dispersion so that the higher momenta see more energy loss than the lower. The same result can be achieved in a plane slab absorber, given angular dispersion, as shown in b). Emittance exchange can also be achieved in a non-periodic lattice like the Helical Cooling Channel [8] in which the absorbing material is everywhere and the higher momenta have longer paths.

Periodic lattices allow the possibility of lower transverse betatron lengths $\beta$ at the absorbers, but have inevitable integer and half integer resonances that define the regions of momentum where they operate. The lattices types can be grouped by the region of phase advance used. Figure 2 illustrates the options.

Simple lattices consisting of equi-spaced alternating solenoids (known as FOFO lattices) operate above the single $\pi$ resonance (see Figure 2a). Bi-periodic lattices [9], with pairs of coils of opposite polarities, are spaced by longer drifts, known as SFOFO (super FOFO) or RFOFO, (see Figure 2b). These lattice operate between the $2\pi$ and $\pi$ resonances and have an attractively level $\beta$ over their acceptance. There are also systems that look like FOFO or RFOFO lattices, but have small dipole fields that are different of some finite number of the basic FOFO or RFOFO cells. The effective phase advances now double, together with the number of resonances. Both cases considered here operate between the $3\pi$ and $4\pi$ stop bands (see Figure 2c).

Cooling channels are formed by sequences of lattice cells, arranged in differing geometries (see Figure 3). Examples of these differing channels will now be discussed in more detail.

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# LEIR OPERATIONS FOR THE LHC AND FUTURE PLANS

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*Abstract*

LEIR, CERN's Low Energy Ion Ring, is an essential part of the LHC ion injection chain. In addition, since 2010 the accelerator complex is also delivering ions to the fixed target programme of the SPS North Area. We review the operation of the machine during the recent runs, and we detail the plans for the coming years with Pb and other species.

## THE LHC ION INJECTOR CHAIN

The ion injector chain of the LHC consists of six machines [1]:

- The ECR source [2] provides $Pb^{29+}$ at 2.5 keV/u. It is followed by a spectrometer which filters out the other species and charge states.
- The Radio-Frequency Quadrupole bunches, focuses and accelerates the ions to 250 keV/u.
- The Interdigital Linear Accelerator (Linac3) accelerates the ions to 4.2 MeV/u. It is followed by a momentum ramping cavity which ac-/de-celerates part of the beam by 0.4%. At the exit of Linac3, a 0.3 µm carbon foil strips the $Pb^{29+}$ ions to $Pb^{54+}$.
- LEIR, the Low Energy Ion Ring, (Fig. 1) accumulates one or several Linac3 pulses at 4.2 MeV/u; after cooling and bunching, the ion beam is accelerated to 72 MeV/u and extracted to the Proton Synchrotron (PS).
- The PS accelerates the ions to 5.9 GeV/u, and defines the bunch spacing by RF gymnastics. At the exit of the PS, a 1 mm aluminium plate fully strips the $Pb^{54+}$ ions to $Pb^{82+}$.
- The Super Proton Synchrotron (SPS) defines the train structure, hence the collision pattern, and accelerates the ions to 177 GeV/u, the injection energy of the LHC, on a non-integer harmonic [3].

## THE LOW ENERGY ION RING, LEIR

The role of LEIR is to transform a series of 200 µs long, low-intensity ion pulses from Linac3 into high-brightness, short (~200 ns) bunches using multi-turn injection, accumulation and phase-space cooling. After accumulating six such pulses, the resulting coasting beam is adiabatically captured on $h = 2$, and accelerated to 72.2 MeV/u. Figure 2 shows a typical cycle where the electron current is first established, then six Linac3 pulses are injected with a 200 ms repetition time. At the end of the flat bottom, the electron current is switched off and the ion beam is accelerated.

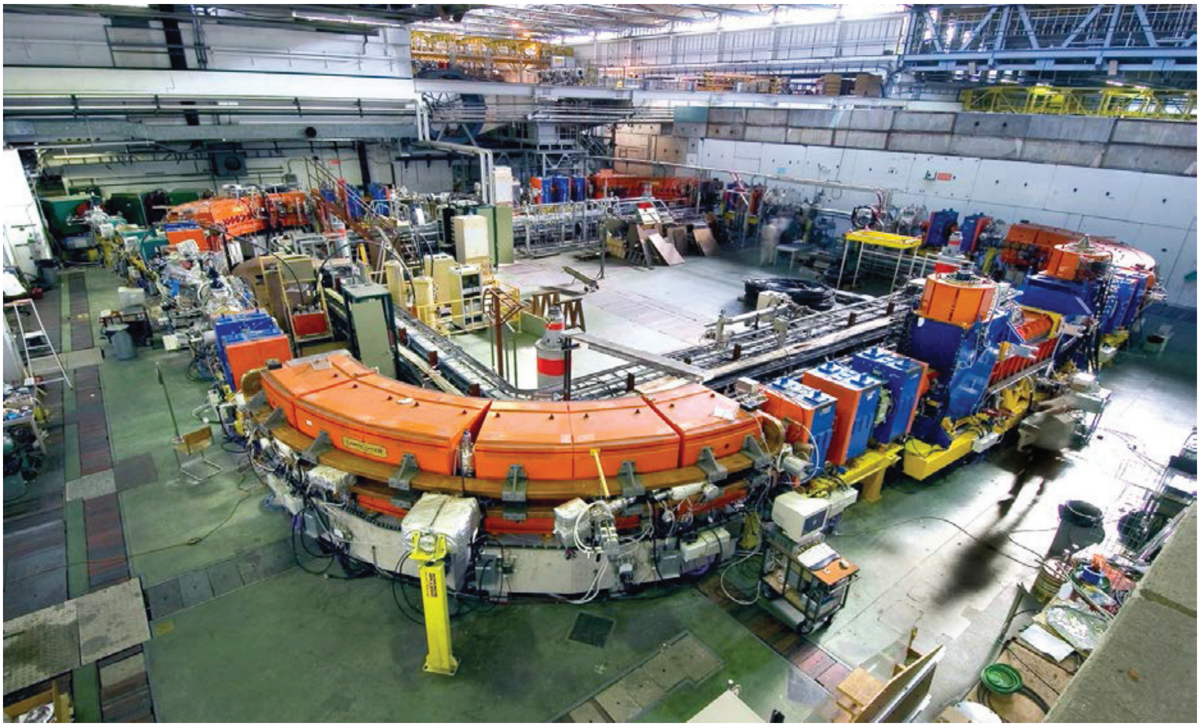

Figure 1: The LEIR machine is situated in CERN's South Hall.

# AD STATUS AND CONSOLIDATION PLANS

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## *Abstract*

The CERN Antiproton Decelerator (AD) has now completed its 12th year of supplying low-energy antiproton beams for the successful physics program.

Most of the machine's key components are in operation since more than 25 years and prompted by the approval of the ELENA project, a substantial consolidation program is now being launched to ensure continued reliable operation. Over the course of the next few years a progressive renovation of the AD-Target area and the AD-ring with all the associated systems will take place.

Status and performance of the AD are presented along with an overview of planned and ongoing consolidation activities with emphasis on stochastic and electron beam cooling.

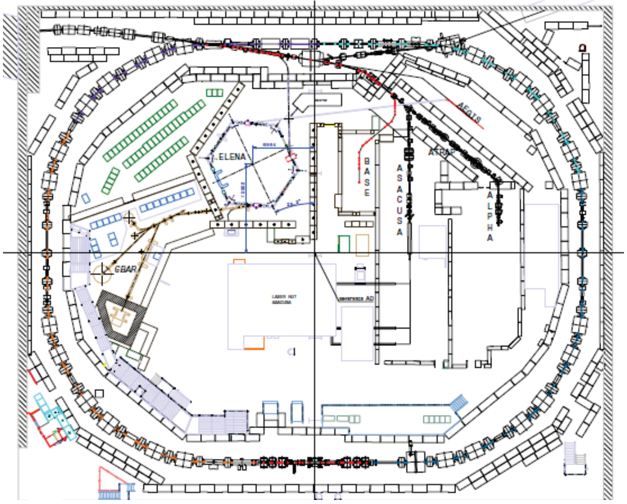


Figure 1: Layout of AD, ELENA and experimental areas.

## INTRODUCTION

With 5360 realized physics hours and a beam availability of 90%, 2012 was the best year ever for the CERN Antiproton Decelerator (AD) with antiprotons at 100 and 500 MeV/c supplied to the ALPHA, ACE, ATRAP, ASACUSA and AEGIS experiments.

For the medium and long-term future, several options exist for upgrades and consolidation of the facility as well as for extension of the physics program.

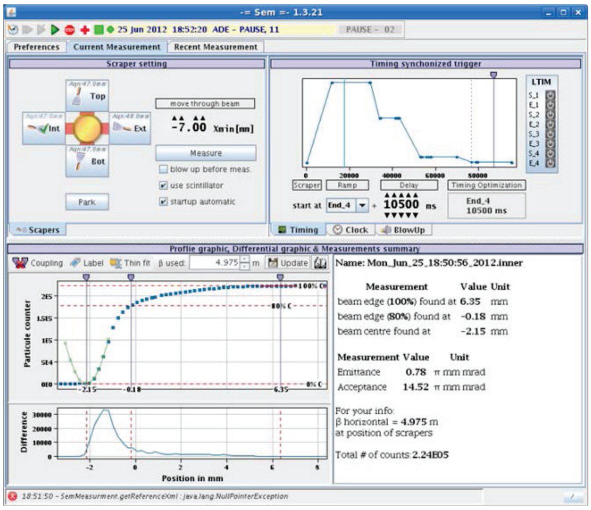
A major improvement to the facility, the recently approved ELENA ring [1], is a small post-decelerator which will be installed in the existing AD building. ELENA will greatly increase ejected beam density and intensity thereby increasing the number of trapped antiprotons at the experiments by up to two orders of magnitude.

To reliably produce antiprotons and deliver them to ELENA for the next 10–20 years, all AD sub-systems have to be renovated or renewed. In total, a budget of some 18 MCHF has been allocated for AD consolidation during the period 2013 to 2020.

Layout of AD, the future ELENA ring and the experimental areas can be seen in Fig.1.

## AD PERFORMANCE

Deceleration efficiencies of around 85% (3.57 GeV/c to 100 MeV/c) were maintained throughout the year with beam intensities of 3.5 to $4.0*10^7$ ejected in one single bunch at 100 MeV/c per 100s machine cycle. Machine performance in terms of quality and stability of the ejected beam was in 2012 more constant than during previous years. Length of the ejected single bunch stayed quite constant over the year at around 150 ns. At 100 MeV/c after final cooling, transverse emittances of less than 1 pi.mm.mrad were obtained for 80 and 95% of the beam in the horizontal and vertical planes respectively. During the start-up, a significant amount of time was spent setting-up the machine for efficient beam-ccoling at low energies. As a result, emittances of the extracted beam remained small throughout the run and previously observed degradations needing re-tuning could be avoided. Problems with long tails and halo-like structures in the horizontal beam profile were also reduced. Measured horizontal beam profile after cooling at 100 MeV/c can be seen in Fig. 2.



move through beam
-7.00 Xmin[mm]
☐ blow up before meas.
☑ use scintillator
☑ startup automatic
start at End_4 + 10500 ms
End_4
10500 ms
β used: 4.975 m

Name: Mon_Jun_25_18:50:56_2012.inner

| Measurement | Value | Unit |
|---|---|---|
| beam edge (100%) found at | 6.35 | mm |
| beam edge (80%) found at | -0.18 | mm |
| beam centre found at | -2.15 | mm |

| Measurement | Value | Unit |
|---|---|---|
| Emittance | 0.78 | π mm mrad |
| Acceptance | 14.52 | π mm mrad |

For your info:
β horizontal = 4.975 m
at position of scrapers

Total # of counts:2.24E05

```
18:51:50 - SemMeasurment.getReferenceXml : java.lang.NullPointerException
```

Figure 2: Horizontal beam profile after cooling at 100MeV/c as measured with scraper and scintillating detector.

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# PROGRESS OF THE STOCHASTIC COOLING SYSTEM OF THE COLLECTOR RING

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### *Abstract*

An overview of the recent achievements and ongoing developments for the stochastic cooling system of the Collector Ring is given. In focus are the hardware developments as well as the progress in predicting the system performance. The system operates in the frequency band 1-2 GHz, it has to provide fast 3D cooling of antiproton, rare isotope and stable heavy ion beams. The main challenges are (i) the cooling of antiprotons by means of cryogenic movable pick-up electrodes and (ii) the fast two-stage cooling (pre-cooling by the Palmer method, followed by the notch filter method) of the hot rare isotope beams (RIBs). Recently, a novel code for simulating the cooling process in the time domain has been developed at CERN. First results for the momentum cooling for heavy ions in the CR will be shown in comparison with results obtained in the frequency domain with the Fokker-Planck approach.

## INTRODUCTION

The overview of the CR stochastic cooling system, its design criteria and the required physics performance, especially for the antiprotons, are described elsewhere [1].

Heavy ion cooling is limited by the undesired mixing. After injection and bunch rotation of the hot RIBs only the Palmer method can be applied with a dedicated pick-up (pre-cooling stage). In a second stage, after the momentum spread has decreased, it is planned to switch to cooling with the slotline pick-ups and the notch filter until the final beam quality is reached. For stable ion beams coming with better quality after acceleration in the synchrotrons, one-stage cooling by the TOF or notch filter method with the slotline pick-ups should be sufficient.

Table 1: Cooling Requirements for RIBs in the CR

| 740 MeV/u, $10^8$ ions, coasting beam | | |
|---|---|---|
| | $\delta$p/p (rms) | $\epsilon_{h,v}$ (rms) $\pi$ mm mrad |
| Before cooling | 0.2 % | 45 |
| After cooling | 0.025 % | 0.125 |
| Cooling down time | $\leq$1 s | |
| Cycle time | 1.5 s | |

The design value for the maximum stored beam current in the CR corresponds to $10^9$ $U^{92+}$ ions. The cooling requirements for $10^8$ ions are given in Table 1. Originally, the phase space reduction in Table 1 was dictated by the need for fast electron cooling in the NESR. At present, the experiments envisaged in the HESR are the only users of heavy ion beams from the CR: in this case, the final beam phase space requirements are rather $\delta$p/p(rms)=0.025 % and $\epsilon_{h,v}$(rms)$\approx$1 $\pi$ mm mrad, taking into account the rebunching for transfer from the CR to the HESR and the matching to the acceptances (momentum acceptance $\pm$ 2.5$\cdot 10^{-3}$, transverse 7 $\pi$ mm mrad) of the HESR [2].

## PICK-UP ELECTRODES AND TANKS

### *Developments at the Prototype Pick-up Tank*

The prototype pick-up tank (Fig. 1) has been modified in the mechanical workshop in order to accommodate the two novel water-cooled linear motor drive units (Fig. 1). Their synchronous operation remains to be tested after reassembly in the tank. These units are easier to maintain and are made of aluminium which is lighter and cheaper to manufacture than the previously used stainless steel. Their maximum range of plunging is now 70 mm so as to follow the size of the shrinking beams during cooling. After cooling, the motor drive units must move out back to the initial maximum aperture within 200 ms, before new beam is injected.

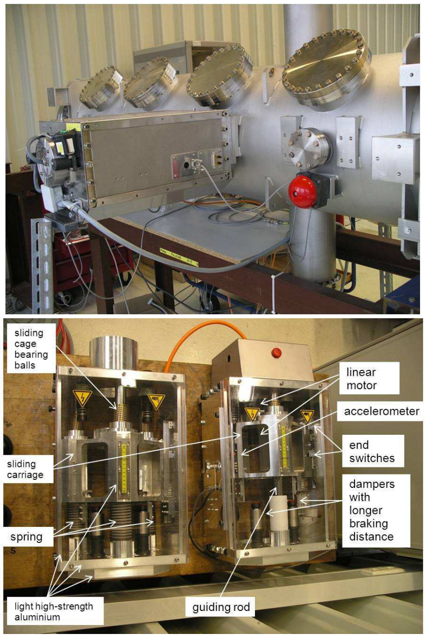

Figure 1: The prototype pick-up tank where the mechanical and thermal concepts will be tested. The new linear motor drive unit.

# STOCHASTIC COOLING OF A POLARIZED PROTON BEAM AT COSY

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## *Abstract*

Future experiments at COSY with vertically polarized proton beams and internal targets at beam momentum larger than 1.5 GeV/c require stochastic cooling and barrier bucket operation to compensate the strong mean energy loss and beam momentum dilution due to the beam-target interaction. At the same time a long beam polarization life time is mandatory in these experiments. Albeit the electromagnetic fields in the kicker of the stochastic cooling system are small the question arises whether they can lead to de-polarization specifically in long time experiments. To investigate this question is also of great importance for the future challenging program at COSY to search for electric dipole moments of protons and deuterons.

## INTRODUCTION

COSY is a COoler SYnchrotron and storage ring for medium energy physics [1]. The cooler ring delivers polarized or unpolarized protons and deuterons in the momentum range 270 to 3300 MeV/c. The COSY facility consists of an ion source, an injector cyclotron, a 100-m-long injection beam line, a 184-m-circumference ring and extraction beam lines. It has an electron cooling system that operates at injection, and a stochastic cooling system that operates at momenta between 1500 and 3300 MeV/c. A new 2 MeV electron cooler now being installed [2] will provide high energy cooling in future experiments.

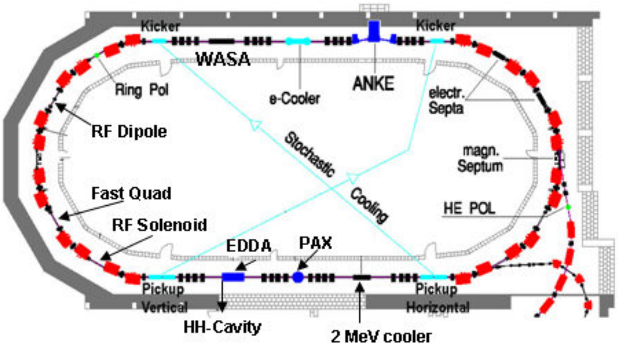

Figure 1: COSY layout.

Internal target experiments using gas jet targets, pellet targets or internal target cells are carried out at COSY. Stochastic cooling is necessary to improve the beam quality during these experiments and a barrier bucket cavity is used to compensate the strong mean energy loss induced by the beam-target interaction. Transverse stochastic cooling and Time-Of-Flight or Filter momentum cooling are routinely used [3].

Upcoming experiments with vertically polarized proton beams require long polarization life times. Since radial magnetic fields can depolarize the beam it is therefore necessary to investigate stochastic cooling as a source of depolarization through its electromagnetic fields in the kicker. In this experiment vertical cooling is applied since then radial magnetic fields in the kicker are present.

The COSY stochastic cooling system simultaneously works in two bands: Band I: 1 to 1.8 GHz, Band II: 1.8 to 3 GHz, and has separate signal paths for horizontal and vertical cooling, Figure 1. The electrode-bars of the pickups and corrector structures can independently be moved and allow an aperture change from 140 mm during the injection and a minimum of 20 mm during cooling. The design of the CERN AC tanks [4] had been adapted to the COSY requirements. The pickups consist of two tanks each equipped with 24 quarter wave electrode loops in band I and 32 loops in band II. Each of the two kickers consists of one tank each for band I and II. The interior of the PUs including the electrode terminations are cooled down to 40 K.

In this experiment vertical cooling with band II has been used. The distance between pickup and kicker is 94 m and the betatron phase advance is $\mu \approx 7/3 \cdot \pi/2$. The installed electronic power is 500 W/plane. The maximum voltage gain is 150 dB. Table 1 summarizes important parameters for the present experiment.

Table 1: SC Parameters

| $\lambda/4$ **electrodes** | | |
|---|---|---|
| Gap height d | 50 | mm |
| Loop width w | 20 | mm |
| Loop length $l_P$ | 22 | mm |
| loop impedance $Z_L$ | 50 | Ω |
| **Pickup**<br>number of loops $n_P$ | 32 | |
| Beta function $\beta_P$ | 11 | m |
| **Kicker**<br>number of loops $n_K$ | 8 | |
| Beta function $\beta_K$ | 13 | m |
| System temperature $T_R + T_A$ | 40 | K |

## EXPERIMENT

During acceleration to the maximum flat top energy up to sixteen depolarizing resonances have to be cured for polarized protons in COSY. The strongest resonance occurs if the spin tune is $\gamma G = 8 - Q_z$. The gyromagnetic anomaly $G$ is 1.79 for protons. During acceleration the vertical tune is kept at $Q_z = 3.62$ and the resonance

# STOCHASTIC COOLING OF BUNCHED IONS SIMULATED IN THE TIME DOMAIN

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## *Abstract*

To include the influence of synchrotron oscillations, beam feedback and IBS a particle by particle and turn by turn treatment in the time-domain has been tried out. – Complete pickup, amplification and kicker characteristics, defined in the frequency domain, are introduced via inverse Laplace transformation, and so is the Dirac function representing the single ion. – The computation time is kept within reasonable limits thanks to the rule that cooling times scale proportionally with the particle number [1]. Typically 10000 simulation particles are cooled in 1200 turns. A recent proposal [2], based on signal binning and FFTs, offers the potential for at least one order of magnitude more ions and turns.

## INTRODUCTION

The usual arrangement of radial pickup, preamplifier, phase equalizer, power amplifier and longitudinal kicker is shown in Fig. 1 for momentum cooling.

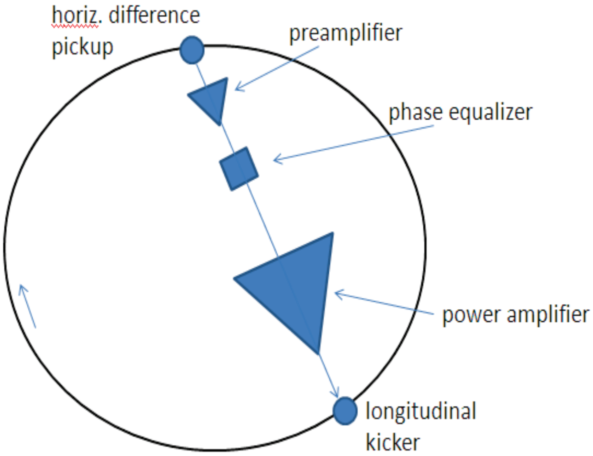

Figure 1: Palmer momentum cooling lay-out.

The method consists in cascading all loop components in the complex frequency plane and to perform the inverse Laplace transformation on the product of the cascaded elements, integrating over the frequency range (in our case 3 to 6 Ghz). There are thus 6 elements, the first one being the Dirac function, representing the single particle. Optimum pickup and kicker loop geometries, both with the usual frequency dependency sin(2πf/4.5e9) (amplitude) are included. - The system gain is defined as the fraction of the ion energy error (E) removed per turn (coherent effect and assuming no unwanted mixing). Considering the high charge/ion, the preamplifier noise is neglected and the amplification chain (benefiting from the phase equaliser) is assumed to have ideal phase.
Due to the high momentum compaction factors (eta) of most low-energy ion rings, only a Palmer cooling set-up (based on radial pickups) with simultaneous betatron cooling has been considered.

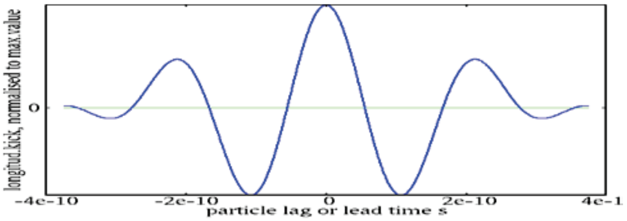

Figure 2: Single-particle correction pulse from an octave-band difference pickup obtained via the inverse Laplace transformation of the Dirac function followed by the 5 cooling components shown in Fig. 1.

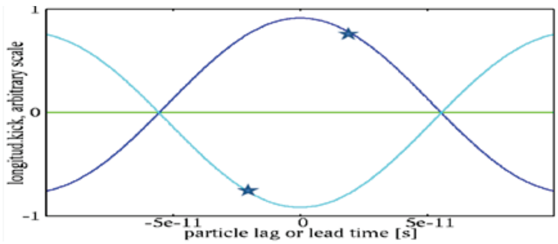

Figure 3: Expanded single particle coherent kick pulses for 3-6 GHz bandwidth. The dark blue curve represents the pulse created by a high energy ion grazing the outer pickup loop; this particle arrives in advance (with respect to the peak) by about 19 ps due to its high energy E=3sigmaE, whereas an ion with E= - 3sigmaE grazing the inner loop (light blue curve) will arrive late by the same amount. The moments of correction are indicated by stars.

The correction that particle N exerts on itself via the system (coherent cooling effect) will be reduced by the unwanted mixing between pickup and kicker which is introduced as a time-lead or lag with respect to its passage at the kicker, depending on the particle energy, see Fig 3.
Kicks from all other particles (incoherent heating effects) are also applied, taking into account their arrival times at the kicker. Furthermore, since we simulate step by step what actually happens in a real cooling process, the treatment inherently also includes:

a) the beam feedback effect: change of Schottky signals when the feedback loop is closed (a potential source of instabilities).
b) the synchrotron motion due to the bunching cavity: synchrotron resonances are not neglected.
c) IBS, introduced via its rms kick value, using a randomly changing sign between particles and turns.
d) betatron cooling results are obtainable for 2 separate distributions (2 betatron phase spaces), taking into account the evolving longitudinal distribution.

# SIMULATION STUDY OF STOCHASTIC COOLING OF HEAVY ION BEAM AT THE COLLECTOR RING OF FAIR

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## *Abstract*

In the modularized start version of the FAIR project, the New Experimental Storage Ring is not included and therefore the task of the stochastic cooling system at the Collector Ring (CR) is now focused on the 3 GeV anti-proton beam. On the other hand, recently the SPARC collaboration has proposed to perform the high energy atomic physics experiments in the HESR ring with stable ions, typically a $^{238}U^{92+}$ beam, employing an internal target. Furthermore the future possibility of the nuclear physics experiments with rare isotope beams (RIBs), typically a $^{132}Sn^{50+}$ beam, in the HESR is envisaged. In the present report, the beam dynamics, mainly the longitudinal motion from the fragment separator SuperFRS to the end of beam cooling in the CR are described emphasizing the process of stochastic cooling of the rare isotope beam.

## INTRODUCTION

Nuclear and atomic physics experiments with heavy ions are envisaged at the High Energy Storage Ring (HESR) of which the primary goal has been planned to perform the anti-proton beam experiment with the internal target at the PANDA detector. Through the optimization process of the anti-proton beam experiment, the acceptance of HESR ring for the lattice of gamma transition=6.2, is as follows. The transverse acceptance is 7 π mm.mrad and the momentum acceptance $\Delta p/p$ is +/-$2x10^{-3}$. Then the rms value of the transverse emittance of the injected beam has to be less than 1.1 π mm.mrad considering that the full acceptance should be larger than the 6 times the rms value. The momentum spread of the injected beam should be less than $7x10^{-4}$ (rms).

The transverse and longitudinal emittances of the RI beam produced through the beam fragmentation process at the superFRS are estimated using the simulation code MOCADI. [1] The relative momentum spread is $\Delta p/p$ (rms)=$1.25x10^{-2}$, and the horizontal and vertical emittance (rms) are 90.7 and 44.3 π mm.mrad, respectively. They should be scraped and matched to the acceptance of Collector Ring (CR) of +/- 1.5% (momentum spread) and 45 π mm.mrad (rms) (transverse emittance). As the rare isotope beam has much larger transverse and longitudinal emittances which cannot be accepted by the HESR ring, the cooling of RIBs in the CR is indispensible.

Details of the recent progress of stochastic cooling system for the CR are presented in a separate report emphasizing the hardware development [2].

In the present report numerical results of the stochastic cooling process investigated with the Fokker Planck approach for the longitudinal cooling are described.

## BUNCH ROTATION

The bunch length of the primary ion beam from the SIS100 is estimated as around 12 nsec (rms). Thus the bunch length of the injected beam is short enough compared with the revolution period in the CR and then the bunch rotation is effective to reduce the relative momentum spread. The parameters of bunch rotation are as follows: ion beam energy is 740 MeV/u, RF voltage 200 kV, harmonic number 1, momentum slip factor 0.178, initial $\Delta p/p$ +/-1.5 % (the acceptance limit of CR) and initial bunch length +/-37.5 nsec (truncated Gaussian at the value of +/- 3 rms value), respectively.

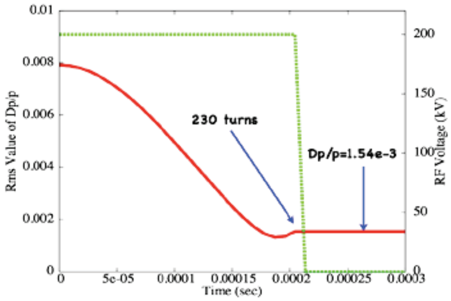

Figure 1: The variation of $\Delta p/p$ (rms) (red) and the RF voltage (green) as a function of time.

During the bunch rotation the momentum slip factor varies according to the change of their momentum spread. This effect is included in the present calculation. The RF voltage is applied during 1/4 synchrotron period and then switched off. In Fig. 1 the variation of the rms value of $\Delta p/p$ and the RF voltage are given as a function of time. The rms value of $\Delta p/p$ is reduced to $1.54x10^{-3}$ after the 1/4 bunch rotation corresponding to 230 turns in the ring. The momentum distribution has a quasi uniform shape.

## STOCHASTIC COOLING OF RI BEAM

The overall layout of the stochastic cooling system at the CR is presented in [2]. It is foreseen to use the three cooling methods for the heavy ion cooling, Palmer, Time Of Flight (TOF) and notch filter cooling. The Palmer pickup is located at the drift section with the finite dispersion of 6.58 m while the PUs of the notch filter cooling system are located at the dispersion-free section. The kicker systems are all located at the dispersion-free section. To apply the TOF cooling the notch filter system is removed from the cooling chain and the phase is

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# NOVEL IDEAS IN ELECTRON COOLING

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*Abstract*

The development of electron cooling started in 1966 from proposal by G.I.Budker. He used this system for proton-proton colliders. Now electron cooling is used for many ions accelerators for shrinking ion beam emittance and for accumulation of rare ions beam at a very broad energy range. Many ideas were used for increasing the cooling power and many problems were opened at the time of this development. The new ideas for extended the energy of cooled beam will be discussed in this report. The energy of cooler up to 8 GeV is still required for HESR to suppress the scattering antiproton in inner target. The experience of commissioning a 2 MeV cooler is used. These results are a practical test bench for estimating different solutions for the cooling systems.

## INTRODUCTION

The history of the development of electron cooling began at the Institute of Nuclear Physics (Novosibirsk) just after the first successful experiments there with electron-electron and electron-positron colliding beams. Radiation cooling plays a decisive role in the achievement of high luminosity in electron and electron-positron colliders. Cooling based on ionization losses in matter was suggested but interaction with the target nuclei did not allow the application of this method because it makes the beam lifetime too short

The idea of using electron cooling, proposed by G.I. Budker in 1965 [1], was to shift from cooling with a stationary target to the use of a pure beam of electrons (without nuclei). Electron cooling work began in 1967 with theoretical studies [2] and the development of an electron beam facility [3]. These were aimed at verification of the electron cooling concept. The electrons would travel with the same average velocity as the proton beam. Of course, the electron beam density is much smaller than the electron density in condensed matter, but in this case, electrons are traveling together with the proton beam and the interaction efficiency between the two beams depends only on the spread of relative velocities of the protons and the electrons. For suppressed drift motion by the electrons beam space charge repulsion the high value magnet field B along the electrons trajectory used. After cooling the ions temperature tend to temperature of electron beam. The electron beam emitted from the cathode has a temperature close to the cathode temperature $T_к$ – about 1000 $^{o}$К ~0.1 eV. After acceleration in the electrostatic field the longitudinal velocity spread becomes very small since the energy spread is in the laboratory system $\delta V = T_c / (m_e V_0)$. This simple effect (practically 0 longitudinal electron beam temperature) was experimentally discovered at study longitudinal cooling force versus relative velocity ion electron beam. The strong magnet fields keeps the transverse motion electrons inside small Larmor cycle. As results the effective electron beam temperature becomes very small and ions beam can cool to temperature of about 1K. Already in the first experiments at NAP-M, after appear magnetized cooling, it was experimentally demonstrated that the increase in the electron beam transverse temperature caused a weak decrease of the cooling rate but noticeably reduced recombination between protons and electrons. For the project of incorporating electron cooling in the RHIC collider, this effect turned out be rather important. Special experiments have been carried out to verify the effect of reducing recombination by high electron temperature for the highly charged ions at GSI in the ESR storage ring. In the RHIC collider, the lifetime of ion beams should be of many hours with rather fast cooling. For suppression of recombination, it was suggested using a “transversely hot” electron beam in a strong magnetic field. The temperature of transverse motion of an electron beam should be increased up to 100 eV but the cooling time should not be substantially longer.

## IDEAS THAT WAS REALIZED AT COOLERS

**1** An electron gun was put into a solenoid producing the longitudinal guiding magnetic field, which accompanies the beam until it reaches the collector [4]. As initially and up to now continues the discussion of the other alternative systems magnetic optic with using quadruples or wigglers magnets. But the all operated coolers have solenoid field at cooling section. The strong magnet field suppressed transverse motion of electrons.

**2** The effect of magnetization the own transverse motion of the electrons help to reach the Kelvin range of the ion beam temperature [5,6]. The nice features solenoid field is the free motion the light electrons along magnet lines. It help to have the fast cooling by absorbing the kinetik energy of the moving ions. The kinematic suppression longitudinal motion of electrons after acceleration gives temperature close to 0 at the cooling section. The transverse motion by the space charge of electron beam should be suppressed the high longitudinal field (B).

$$V_{\perp} = c\frac{2\pi n_e e x}{B}$$

For testing cooling force for the magnetized electrons beam was designed cooling section with strong magnet field up to 4 kG show Figure 1 [7]. The proton or $H^-$ 1MeV beam after single pass the electron beam send at spectrometers for measure losses energy. Results measuring cooling force versus magnet fields shows Fig. 2. From this figure clear see that increasing magnet field open space for increasing the electron beam density (op-

# FERMILAB'S EXPERIENCE WITH A HIGH-ENERGY ELECTRON COOLER*

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## Abstract

The Recycler ring at Fermilab served as a repository of 8 GeV antiprotons destined for collision in the Tevatron, a proton-antiproton collider. From 2005 to 2011, the world's only relativistic electron cooling system was used to cool the antiprotons for accumulation and preparation of bunches before injection into the collider ring.

With a 4.3-MeV, 0.1-A DC electron beam, a weak continuous longitudinal magnetic field in the cooling section and lumped focusing elsewhere, this unique electron cooler allowed for significant improvements in the Tevatron luminosity, yet also presented numerous challenges, such as achieving reliable operation of a high-voltage, high-power electrostatic accelerator in a high-current recirculation mode. In this paper, we discuss the experience of running this unique machine.

## INTRODUCTION

The missions for the cooling systems in the Recycler were to neutralize multiple Coulomb scattering (IBS and residual gas), neutralize the effects of heating due to the Main Injector ramps (stray magnetic fields), reduce the emittances of the stored antiprotons between transfers from the Accumulator and reduce the phase space of the stored antiprotons in preparation for a Tevatron store. To this end, an electron cooler was envisioned as an important part of the Recycler ring upgrade and discussed in the original Recycler Technical Design Report [1].

Installation of the Recycler Electron Cooler (REC) was completed in February 2005, relativistic electron cooling demonstrated within 6 months [2], and put into operation days later. By the end of the Tevatron collider Run II in October 2011, electron cooling had significantly contributed to the several-fold increase of the luminosity production.

## CHOICE OF THE SCHEME

All coolers that had been built previously worked at non-relativistic energies ($E_e < 300$ keV). They used a strong (~1 kG) longitudinal magnetic field to transport the electron beam and enhance the cooling force. With a typical requirement of tens of minutes for the cooling time, a scheme without a strong magnetic field in the cooling section (a.k.a. non-magnetized cooling) was shown to be satisfactory at a reasonable electron beam current (~0.5 A).

The non-magnetized approach is a clear deviation from the way coolers are being built, and it brought up serious questions about the stability of the electron beam transport and ability to provide low transverse electron velocities in the cooling section. A novel approach was devised [3] in which the electron gun and the cooling section are both immersed in a longitudinal magnetic field but beam focusing in between is provided by separate solenoid lenses. However, a beam generated inside a solenoid and extracted into free space acquires an effective rms normalized emittance (in the paraxial ray approximation):

$$\varepsilon_{B,eff} = \frac{eB_{cs}R_{cs}^2}{8m_e c^2}$$

where $B_{cs}$ is the magnetic field in the cooling section, $R_{cs}$ is the beam radius, $e$ and $m_e$ are the electron charge and mass, and $c$ the speed of light. This emittance arises from the conservation of the canonical angular momentum, which in turn results in a coherent angular rotation of the beam and needs to be taken into consideration in the design of the transport beam lines optics. To accommodate lumped focusing at low $\gamma$ during acceleration, the beam size, $R_{cs}$, and magnetic field, $B_{cs}$, in the cooling section were limited to 2-4 mm and 100-200 G, respectively.

Based on preliminary cooling scenarios and estimations of the cooling rates, design parameters were specified [4] (they are partly reproduced in Table 1). Table 1 assumes a scheme with a DC electron beam, a longitudinal magnetic field at the cathode and in the cooling section, and lumped focusing in the beam transport lines (description of the cooler setup can be found in Ref [5] for instance). Table 1 also shows typical beam parameters during regular operation (when the electron beam was fully optimized).

Table 1: Parameters of the Cooler

| Parameter | Unit | Design | Operation |
|---|---|---|---|
| Electron energy | MeV | 4.33 | 4.33 |
| Beam current, DC | A | 0.5 | 0.1 |
| Terminal voltage ripple (rms) | V | 500 | ~150† |
| Magnetic field at the cathode | G | ≤ 600 | 86 |
| Magnetic field in the cooling section | G | ≤ 150 | 105 |
| Electron beam divergence | μrad | 80 | ~100† |
| Pressure | nTorr | 0.1 | 0.3 |
| Cooling section length | m | 20 | 20 |

† Inferred from indirect measurements

It should be noted that the electron beam current used for normal operation, 0.1 A, is not an intrinsic limitation of the cooler, but was found sufficient to provide adequate

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* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

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# ELECTRON COOLER R&D AT HELMHOLTZ-INSTITUT MAINZ

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Helmholtz-Institut Mainz, Germany

## *Abstract*

Helmholtz-Institut Mainz conducts research related to critical design aspects of relativistic magnetized electron coolers. This comprises on the one hand accelerator physics issues such as minimally invasive beam diagnostics and optimization of energy and particle recovery. On the other hand, the realization of power supplies at several different Megavolt potentials is an important problem that we hope to attack with a new concept, namely using turbo generators. A status report of the different research subjects is given.

## INTRODUCTION

The HESR (High Energy Storage Ring) will be erected as a contribution of Forschungszentrum Jülich to the Facility of Antiproton and Ion Research (FAIR). Several planned experiments at HESR require cooling of the stored ions with a magnetized relativistic electron beam. Cooling of antiprotons for the antiProton ANnihilation at DArmstadt (PANDA-) experiment [1] would represent the most significant application during the first operational phase of FAIR, which is expected to begin at the end of this decade. Furthermore, it is discussed to use the HESR as an ion-storage ring in a double polarized collider facility, the Electron Nucleon Collider at FAIR (ENC@FAIR), a machine which could become operational in the 2020 decade [2]. ENC@FAIR is a project of considerable importance for the hadron physics community, which is strongly represented at the new Helmholtz Institute Mainz (HIM). ENC@FAIR with both its machine and experimental aspects is therefore a long-range project pursued by HIM. While several of the planned experiments at PANDA can be performed with stochastic cooling alone, the presence of relativistic magnetized cooling is mandatory for ENC@FAIR. First calculations of the cooling power needed to compensate for the beam heating effects in collider operation indicate that a current of several amperes would be needed [2]. Furthermore, it is evident that the desire for maximum center of mass energy of the collider favors operation at the highest proton momentum possible at HESR (BR=50 Tm), which corresponds to an $e^-$energy of 8 MeV. No device of comparable performance exists so far. The former Fermilab cooler parades the highest energy of all electrostatic cooling devices (4.5 MV) but it was not operating in a completely magnetized fashion [3] and it ran at currents well below 1 A since it could fulfill its task with very low cooling rates. Though a design based on an extrapolation of established technology was developed by a team at the university of Uppsala [4] it is by no means clear if such an approach is feasible.

The realization of the magnetized multi MeV cooler for HESR requires a very considerable investment. Several critical design issues are pending for which promising solutions should be provided before investment starts. We have identified several tasks where we hope to be able to contribute:

1. A first issue arises from the need of floating power supplies. The power needed for maintaining the longitudinal field in the acceleration stage and for operating the high current collector at the terminal will be of the order of 100 kW. The power will have to be distributed on many different potentials in the multi-MV range. Traditional concepts–such as transformers or shaft driven generator/pelletron combinations-could prove unsuitable for the increased demands.
2. Particle losses, especially from the collector, are even less tolerable if compared to sub-MV devices due to the high ionization rate associated with a loss process. We therefore investigate efficient loss-minimization concepts for high intensity beams.
3. Given the enormous beam power, it seems worthwhile to investigate new concepts of minimally invasive beam diagnostics.

## TURBO GENERATORS

Cascaded transformers allow to transfer electrical power to many different potentials (stages). After rectification this power can be used to power the solenoids which create the longitudinal magnetic field in the acceleration column. Furthermore, small HV power supplies can provide the potential difference from stage to stage. The 2 MV cooler at COSY Jülich [5] will be one of the most sophisticated applications of the transformer principle. So far it is not clear if an extension towards higher voltages is technologically feasible. The group at Uppsala proposed to use a more conventional approach based on generators driven by insulating shafts and generation of HV by a pelletron, as it was the case in the Fermilab cooler. However, this mechanical system has to be distributed over many stages, which leads to a somewhat clumsy design that will become less attractive if one extends this approach from the initially proposed 4.5 MV to 8 MV. A new concept was proposed by BINP for the 2 MV cooler project at COSY in its initial stage. The suggestion was to use compressed gas which drives an expansion turbine, the mechanical energy of which is converted into electrical energy. This turbo generator may then sit on any desired potential. Each individual 60 kV transformer stage would therefore have been replaced by such

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# ADVANCE IN MEIC COOLING STUDIES*

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## *Abstract*

Cooling of ion beams is essential for achieving a high luminosity for MEIC at Jefferson Lab. In this paper, we present the design concept of the electron cooling system for MEIC. In the design, two facilities are required for supporting a multi-staged cooling scheme; one is a 2 MeV DC cooler in the ion pre-booster; the other is a high electron energy (up to 55 MeV) ERL-circulator cooler in the collider ring. The simulation studies of beam dynamics in an ERL-circulator cooler are summarized and followed by a report on technology development for this cooler. We also discuss two proposed experiments for demonstrating high energy cooling with a bunched electron beam and the ERL-circulator cooler.

## INTRODUCTION

An electron-ion collider with both highly polarized electron and ion beams is considered a perfect probe for the study of QCD. At Jefferson Lab, a polarized medium energy electron-ion collider, MEIC, was proposed to answer this science call. Over the last twelve years, the MEIC design has been actively pursued; as a result of this effort, a comprehensive report summarizing the design concept and accelerator R&D was released [1].

The electron-ion collider science program demands high luminosities over a broad CM energy range with a peak value above $10^{33}$ /cm$^2$/s. This is a very challenging goal since it is 100 times above the highest luminosity ever archived in HERA, the only electron-proton collider ever built and operated. It is evident that, to achieve this goal, a form of efficient cooling of ions must be realized, given the fact there is no radiation damping in this medium energy range.

The MEIC proposal is based on the conventional electron cooling [2,3,4]. It is designed for achieving a significant reduction of beam emittance and maintaining the high phase space density during the store of the ion beam. While it is a fully developed technology at low energies, the MEIC proposal extends electron cooling to much higher energies for the cooling beam. In addition, the design demands a high brightness electron beam with a high repetition rate and average current. An advanced cooler design [1] based on an energy recovery linac and a circulator ring has been developed to meet several technical challenges. In the following, we first outline the MEIC cooling scheme and the cooler design concept [1,5,6,7], next present progress of an R&D program, both in simulations and in technology developments. We further discuss the proof-of-concept experiment utilizing facilities at Jefferson Lab or our collaborating institutes.

## MULTI-STAGED COOLING SCHEME

Presently, MEIC is designed as a ring-ring collider [1]. The proposal requires the construction of two storage-collider rings and an ion complex at the Jefferson Lab site. The ion collider ring can accommodate protons with energy up to 100 GeV and light to heavy ions with energy up to 40 GeV per nucleon. The ion complex consists of sources, a linac and two booster rings, and is responsible for the formation and acceleration of ion beams. The top kinetic energies of protons in the pre- and large booster are 3 and 25 GeV respectively, while energies of ions vary, subject to the same magnetic rigidity, according to their masses and charges. The injection energies of the pre-booster are 285 MeV for protons and 100 MeV/u for lead ions. The pre-booster also serves as an accumulation ring for ion beams.

The MEIC proposal aims to deliver high luminosities up to above $10^{34}$ /cm$^2$/s. Its accelerator design has adopted a luminosity concept which has already been proven in lepton-lepton colliders. It has three equally important tiers, namely, (1) two colliding beams with ultra short bunch lengths and high repetition rates; (2) interaction regions with an unusually small beta-star for strong final focusing and also crab crossing of colliding beams, and (3) a fast damping mechanism for achieving very low 6D beam emittances. An expanded discussion of this luminosity concept and its application to MEIC--the first time to a collider involving a hadron beam--can be found in [7]. Regarding the last tier of the concept, for the lepton beams in electron-positron or electron-ion colliders, it is the synchrotron radiation that provides a rapid damping. For medium energy ions, there is no synchrotron radiation. Thus, a cooling of ion beams must be introduced in the MEIC to provide damping.

Conventional electron cooling is adopted for the MEIC design. We believe such a technology would most likely meet the MEIC requirement, and carry the least amount of technical uncertainty in the project time frame. Further, in order to achieve an adequate cooling efficiency, a multi-staged cooling scheme [1,5,6] has been adopted:

- *Stage 1*: A DC electron cooling (up to 100 keV electron energy) in the pre-booster for assisting accumulation of positive ions after being injected from the ion linac;
- *Stage 2*: Pre-cooling at the top energies of the ion pre-booster utilizing a 2 MeV DC electron cooler for the initial stage of ion emittance reduction;
- *Stage 3*: A final electron cooling in the collider ring and at the ion collision energies for achieving the designed low 6D emittance and short bunch length;

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# STUDY FOR STOCHASTIC COOLING AT NUCLOTRON, JINR

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### *Abstract*

The experiment on stochastic cooling at Nuclotron, initiated two years ago as a preparatory work for the NICA collider, is progressing. New scheme of cooling system, which includes ring-slot couplers as pick-up and kicker (designed at FZJ), an optical notch-filter and a full remote-controlled automation of measurements and adjustments, was set in operation in autumn 2012. This report presents first results of the beam cooling achieved at Nuclotron in March 2013.

## INTRODUCTION

A unique heavy-ion collider NICA is under construction at JINR (Joint Institute for Nuclear Research) [1]. One of the challenging technologies of the collider project is the stochastic cooling. Since the stochastic cooling had never been used before in JINR, it was decided to perform an experiment at Nuclotron, superconducting synchrotron at JINR, for the NICA team to get familiar with the cooling technique.

The stochastic cooling experiment started in 2010. During the first two years design of the cooling scheme, ordering the required equipment, assembling and adjusting the system components were completed. The present working system was set in operation in 2012.

As the pick-up is located in the straight section with small dispersion, the scheme utilizing the sum signal from the pick-up is advantageous. Thus notch-filter scheme was implemented for the first stage of the experiment.

## COOLING SYSTEM

Main parameters of the Nuclotron and stochastic cooling system are presented in Table 1.

Table 1: Parameters of the Cooling System at Nuclotron

| | |
|---|---|
| Circumference, m | 251.5 |
| Ions | D+ |
| Intensity, particles | $2\times10^{9}$-$10^{10}$ |
| Energy, GeV | 3 |
| Rev. frequency, MHz | 1.158 |
| Flattop time, s | 480 |
| Phase slip factor, $\eta$ | 0.034 |
| Initial $(\Delta p / p)_{RMS}$ | $0.55\times10^{-3}$ |
| Cooling system | Long., notch filter |
| Bandwidth, GHz | 2-4 |
| ToF P-K, ns | 431.88 |
| Pick-up impedance, Ohm | 144 |
| Kicker impedance, Ohm | 576 |
| Power for the kicker, W | 18 |

The design of cooling system is described precisely in [2]. Here are described only major features.

**The pick-up and kicker** are located at the opposite straight sections of accelerator ring (Fig. 1).

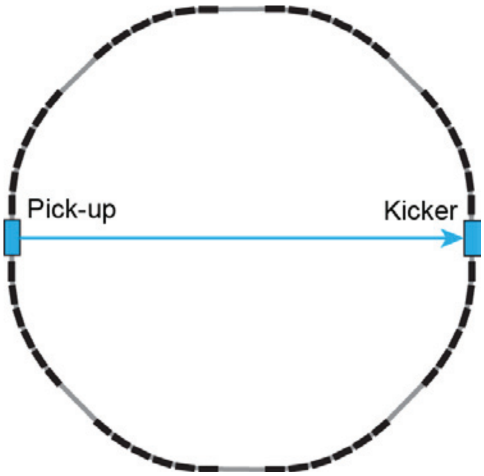

Figure 1: Pick-up and kicker location at the Nuclotron.

The pick-up is installed inside the cryostat at ~10 K, while kicker is in the section at room temperature. Both structures are of ring-slot couplers type (developed in FZ Jülich [3]) consisting of 16 rings with electrodes. Each ring has 8 electrodes, placed uniformly over the perimeter. Signals from each of 8 electrodes are transferred to combiner boards. It is possible to switch remotely between sum and difference modes by rearranging the outputs. In the experiment transverse signals were obtained by combination of 8 electrodes of pick-up in opposite pairs and further subtraction of appropriate signals in vertical or horizontal planes (Fig.2).

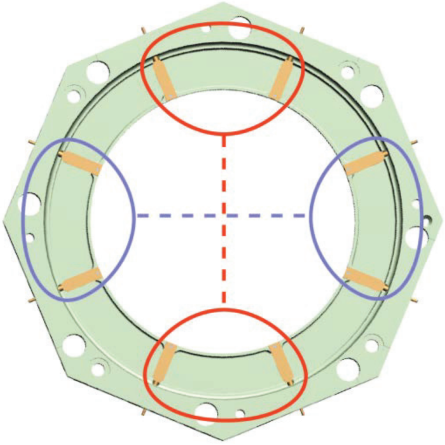

Figure 2: Combination of electrodes for horizontal (blue) and vertical (red) signals.

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# POTENTIAL OF STOCHASTIC COOLING OF HEAVY IONS IN THE LHC

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### *Abstract*

The dynamics of the high intensity lead beams in the LHC are strongly influenced by intra-beam scattering (IBS), leading to significant emittance growth and particle losses at all energies. Particle losses during collisions are dominated by nuclear electromagnetic processes and the debunching effect arising from the influence of IBS, resulting in a non-exponential intensity decay during the fill and short luminosity lifetimes. In the LHC heavy ion runs, 3 experiments will be taking data and the average fill duration will be rather short as a consequence of the high burn-off rate. The achievements with stochastic cooling at RHIC suggest that such a system at LHC could substantially reduce the emittance growth and the debunching component during injection and collisions. The luminosity lifetime and fill length could be improved to optimize the use of the limited run time of 4 weeks per year. This paper discusses the first results of a feasibility study to use stochastic cooling on the lead ion beams in the LHC. The present and expected future performance without cooling is presented and compared to preliminary simulations estimating the improvements if stochastic cooling is applied.

## SIMULATION

The simulations presented in this paper are done with two related simulation programs [1, 2]: the Collider Time Evolution (CTE) program [2], used regularly for LHC, was built on a previous version of [1]. These programs perform a 6D tracking of initial particle coordinates, taking into account intra-beam scattering (IBS) and beam population burn-off from luminosity production. Moreover, [2] additionally takes into account radiation damping and quantum excitation. On the other hand, [1] includes a treatment of stochastic cooling.

Both require data on the initial beams, like the particle type, no. of particles per bunch, $N_b$, transverse emittances, $\varepsilon_{N,x,y}$, rms bunch length, $\sigma_z$, total RF voltage, $V_{\mathrm{RF}}$, that are taken from measurements in the following. The program in [1] also requires the definition of the stochastic cooling system to be used (bandwidth, gains).

## LHC HEAVY-ION BEAMS

The lead ion bunches cannot be injected into the LHC directly from the source. The particles have to pass several pre-accelerators (LINAC3, LEIR (Low Energy Ion Ring), PS (Proton Synchrotron), SPS (Super Proton Synchrotron)) to be fully stripped and pre-accelerated up to the LHC injection energy of $450Z$ GeV.

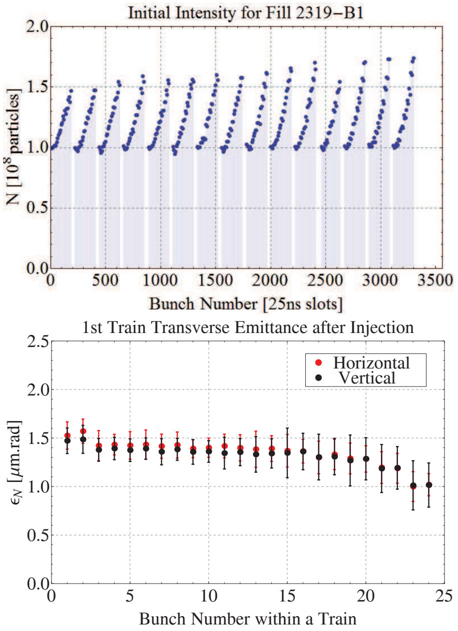

Figure 1: Initial intensity (top) and emittance (bottom) data after injection into the LHC.

Table 1: Typical Bunch Parameters in 2013

| Parameter | | head | average | tail |
|---|---|---|---|---|
| $N_b$ | [$10^8$ ions] | 1 | 1.4 | 2 |
| $\varepsilon_n = \varepsilon\gamma$ | [$\mu$m rad] | 1.2 | 1.5 | 1.8 |
| $\sigma_z$ | [m] | 0.08 | 0.10 | 0.11 |

### *Bunch-by-Bunch Differences*

Because of the shorter length of the machines down the chain, a certain number of bunches will be accumulated in each pre-accelerator before their energy ramp and transfer to the next. The bunches injected earliest have to wait at the low injection energy, where they are more strongly affected by IBS (which scales with $\propto \gamma^{-3}$) [3] than those arriving later. Thus IBS introduces significant bunch-by-bunch differences in emittance and intensity. This effect occurs mainly while forming trains in the SPS and again when assembling them into the full beam in the LHC.

In Fig. 1 the intensity and transverse emittances are shown right after injection to the LHC as a function of the bunch number. The intensity plot shows the whole beam of 15 trains (injections from the SPS) with 24 bunches each. The emittance data are only displayed for the first injected train. In both cases a clear pattern within the trains is observable, arising from the IBS at the injection plateau of the SPS. Table 1 summarises the parameters of 3 typical bunches along a train.

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# COMMISSIONING COSY COOLER WITH ELECTRON BEAM AT NOVOSIBIRSK

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## *Abstract*

The electron cooler of a 2 MEV for COSY storage ring FZJ is assembled in BINP [1]. Results of experiments with high voltage, with electron beam, cascade transformer for distribution power along acceleration tube will be discussed in this report. The COSY cooler is designed on the classic scheme of low energy coolers like cooler CSRm, CSRe, LEIR that was produced in BINP before. The electron beam is transported inside the longitudinal magnetic field along whole trajectory from an electron gun to a collector. This optic scheme is stimulated by the wide range of the working energies 0.025÷2 MeV. The electrostatic accelerator consists of 33 individual unify section. Each section contains two HV power supply (plus/minus 30 kV) and power supply of the magnetic coils. The electrical power to each section is provided by the cascade transformer. The cascade transformer is the set of the transformers connected in series with isolating winding.

## SETUP DESCRIPTION

A new generation of accelerators to study nuclear physics in the range of relativistic physics 1-8 Gev/u will require very powerful cooling to obtain high luminosity. For example the experiments with 15 GeV antiprotons for investigation of meson resonances on PANDA detector require an internal hydrogen target with effective thickness $4\times10^{15}$ hydrogen atoms per $cm^2$ and $10^{10} – 10^{11}$ antiprotons circulating in HESR. In this case the peak luminosities ranging from $2\times10^{31}$ to $2\times10^{32}$ $cm^{-2}s^{-1}$ are achievable. Resolution of the experiments is limited only by momentum spread in antiproton beam, which must be better than $10^{-4}$. These experiments demand the strong system of the “cooling” of the antiproton beam for suppression of the internal target influence. The electron cooler for COSY storage ring may be prototype of such system.

The basic idea of this cooler is to use high magnetic field along all orbit of the electron beam from the electron gun to the electron collector. At this case we have chance to have high enough the electron beam density at cooling section with low effective temperature. For example the electron beam density $2*10^8$ $cm^{-3}$ (beam diameter 6 mm and current 1.5 A) magnetized with longitudinal magnetic field 2 kG will have at beam reference system drift velocity $2.7*10^6$ cm/sec. This velocity lets (at principle) to have cooling time near 0.1 sec for the beam with low angular spread $\Delta p_{\perp} / p = 10^{-5}$.

The schematic design of the setup is shown in Fig.1. The electron beam is accelerated by an electrostatic generator that consists of 33 individual sections connected in series. Each section has two high-voltage power supplies with maximum voltage 30 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 protons of COSY storage ring. After interaction the electron beam returns to electrostatic generator where it is decelerated and absorbed in the collector.

The optics of 2 MeV cooler for COSY is designed close to the classical low-energy coolers. The motion of the electron beam is magnetized (or close to magnetized conditions) along whole trajectory from a gun to a collector. This decision is stimulated by requirement to operate in the wide energy range from 25 keV to 2 MeV. So, the longitudinal field is higher then transverse component of the magnetic fields. The bend magnets and linear magnets of the cooler are separated by a section with large coils for the location of the BPMs, pumps and a comfort of the setup assembling. The length of the linear magnets is defined by the necessity to locate the electrostatic generator outside the shield area of the storage ring.

The vacuum chamber is pumped down by ion 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 subsystem of the electron cooler are 1 electrostatic accelerator, 2 high voltage terminal, 3 main magnetic system, 4 Corrector magnetic system, 5 Interlock system, 6 Cascade Transformer power supply, 7 BPM system, 8 Oil system, 9 SF6 system, 10 Magnetic probe system

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# INFLUENCE OF ELECTRON ENERGY DETUNING ON THE LIFETIME AND STABILITY OF ION BEAM IN CSRM*

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## *Abstract*

The energy spread of electron beam was artificially increased with the help of the detuning system in the electron cooler. The Influence of electron energy detuning on maximum accumulated intensity, the lifetime and stability of ion beam were experimentally investigated with the beam of 3.7MeV/u $^{112}Sn^{35+}$ in CSRm. The lifetime was derived from the signals of ion beam intensity from DCCT varying with time, and the instability was observed by mean of the longitudinal frequency signals from Schottky probe. The experiments results show that no significant influence of electron energy detuning on the maximum accumulated intensity and lifetime. Due to the limitation of beam intensity from injector, the space charge limitation and saturation condition was not approached, and the obvious evidence for instability suppression by the detuning has not observed in such detuning frequency range.

## INTRODUCTION

The accelerator facility HIRFL-CSR [1] is operated for nuclear physics experiments, atomic physics experiments, cancer therapy and other research area. Over 3000 hours beam time was provided in last year, which was mainly used on the research topics of nuclei mass measurements, electron-ion recombination and heavy ion therapy [2-4].

However, the extremely heavy ion beam like Bi and U were successfully cooled and accumulated with very low injection energy and weak intensity [5].

A few times commission for accumulation of proton with the help of electron cooling were performed in CSRm, including instead of proton with $H_2^+$, these commission were not successfully completed carried out up to now due to the mismatching parameters between injector and storage ring. The accelerator staff was puzzled by this phenomenon. The lifetime of proton beam became shorter when the electron beam was turned on, ulteriorly the proton beam disappeared in the storage ring. No any obvious cooling and accumulation was happened. This was ascribed to the “electron heating” [6, 7]; in this case, the proton beam was not cooled, but heated by the electron beam.

The proton beam disappeared after turn on the electron cooler and electron beam. There was no obvious cooling and accumulation. The lifetime of $H_2^+$ is very short comparing with the results from TSR and CELSIUS [8, 9].

The instability of high intensity cooled ion beam and electron heating problem were studied in several e-cooler storage rings [10-12]. These are also a challenge of CSRm [13]; the related experimental research work was published on the proceedings of RuPAC 2012 [5]. In order to satisfy higher request on beam intensity, quality and stability, we attempted to improve beam intensity by detuning the matched energy of electron beam.

The motivation of this experiment was to increase the accumulated ion intensity and suppress the ion beam instability after cooling.

Based on the easily implemented experimental methods in literature [14], this paper studied the experimental affect of electron beam energy detuning on ion beam accumulation, lifetime, and instability.

## EXPERIMENTS AND PARAMETERS

The Sn beam was generated by the superconductive ECR ion source SECRAL with charge state 26+, turned into about 1ms length bunches after the chopper, rise its energy to 3.7MeV/u by a cyclotron SFC and stripped to $^{112}Sn^{35+}$ by a 33mg/cm$^2$ carbon film before injected into CSRm. The beam intensity reached approximately 1μA at the injection point of the main synchrotron (CSRm).

$^{112}Sn^{35+}$ beam was injected into the synchrotron through the falling process of four Bumps that have the setting of rising time 1.8ms, platform time 0.7ms, and falling time 1.2ms. Each injection cycle composed of 200 pulse injections with the time interval of 150ms. During the injection, CSRm was set as rigidity 0.889Tm, revolution frequency 0.166MHz, transverse acceptance 200πmmmrad and 30πmmmrad at both directions, longitudinal acceptance ±0.125%, and Betatron function 10m and 16m in horizontal and vertical direction respectively at electron cooling section.

The electron cooling parameters are listed below. The magnetic field at gun section is 1562Gs and 365.5Gs at cooling section. The adiabatic expansion factor is 4.275. The electron beam diameter is 60mm at the cooling section. The electron beam current was 110mA. The hollow profiled electron beam was controlled with the potential ratio between control electrode and anode 0.188kV/1.3129kV.

The lifetime of cooled $^{112}Sn^{26+}$ ion beam was about 7.2 seconds without electron energy modulation. The maximum beam current was 90 μA after 10-second stacking with electron cooling and multiturn injections; the corresponding particle number was $1\times10^8$.

The lifetime of cooled $^{112}Sn^{35+}$ ion beam was about 5.7 seconds and the maximum stacking current was 39 μA with electron energy modulation, the corresponding particle number was $3\times10^7$.

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# COOLING ACTIVITIES AT THE TSR STORAGE RING

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## *Abstract*

In ring experiments at the heavy ion storage ring, using a reaction microscope, require highly charged bunched ion beams with bunch length below 5 ns. Small longitudinal ion profiles can be obtained by bunching the ion beam with electron cooling. The measured short bunch lengths are determined by the space charge limit. To over come the space charge limit and to further minimize the bunch lengths, the TSR was operated at a momentum compaction factor 1.58, a mode in which the revolution frequency at higher energies decreased. This reduced the bunch length by up to 3.5 times compared to the standard mode. During this beam time, self-bunching of the ion beam was observed for the first time in the TSR. To provide highly charge ions at the TSR deceleration is required. Deceleration experiments are mainly carried out with $^{12}$C$^{6+}$ ions to investigate the behavior and evolution of the beam during deceleration. To explore the deceleration cycle, $^{12}$C$^{6+}$ ions are decelerated from 73.3 MeV to 9.77 MeV with an efficiency of about 90 %. To achieve this low energy two cooling steps at the initial and final beam energies are applied. Electron pre-cooling results in a dense ion beam where IBS has to be taken into account to describe the development of the beam size during deceleration. An approximated model of IBS is proposed to interpret the experimental data.

## SHORT ION BUNCHES

Small longitudinal bunch lengths are necessary for experiments with a reaction microscope in a storage ring. Tests therefore were performed with 50 MeV $^{12}$C$^{6+}$ ion beams using the $6^{th}$ harmonic for bunching. A bunched ion beam profile obtained with simultaneous electron cooling, measured with a capacitive pick-up, is shown in Figure 1. The intensity of the $^{12}$C$^{6+}$ ion beam with $E = 50$ MeV used for this measurements was $I = 45$ µA. The resonator voltage was set to 795 V. Also shown in Fig. 1 is a parabola fit function (red line), which represents the data very well. A bunch length,defined in Fig. 1, of $w = 20$ ns can be obtained from the fit. This bunch length is space charge limited. In the space charge limit the voltage of the resonator $U_i(\Delta\phi) = U\sin(\Delta\phi + \phi_s)$ each ion is passing through is compensated by the longitudinal space charge voltage of the ion beam. For bunching, in the TSR standard mode, where the slip factor $\eta = \frac{\Delta f_0/f_0}{\Delta p/p}$ is positive, the synchronous phase used for bunching is $\phi_s = 0$, where $f_0$ is the revolution frequency of an ion and $p$ describes its momentum. Because the synchrotron oscillation is a very slow process compared to the revolution time, the longitudinal electrical field $E_{\|}(\Delta\phi)$, seen by one ion, can be assumed to be constant during one turn and the space charge voltage can be defined by $U_s(\Delta\phi) = E_{\|}(\Delta\phi)\cdot C_0$, where $C_0$ denotes the circumference of the storage ring. The ion phase $\Delta\phi$ is related to the longitudinal position $s$ in the bunch: $\Delta\phi = -\omega\frac{s}{v_s}$, where $\omega$ is the angular frequency of the resonator and $v_s$ the velocity of the synchronous particle, located in the center of the bunch at s=0. Ions in front of the synchronous particle ($s > 0$) arrive at the resonator gap earlier than the synchronous one, therefore there is a negative sign in the formula. The longitudinal electrical field $E_{\|}(s)$ can be calculated from the charge line density $\lambda(s)$ of the bunch by the following formula [1]:

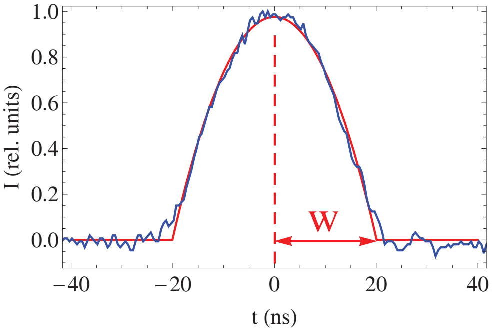

Figure 1: Measured electron cooled longitudinal ion beam ($^{12}$C$^{6+}$, $E = 50$ MeV ) profile. The width of the parabola profile is defined by $w$.

$$E_{\|}(s) = -\frac{1 + 2\ln(\frac{R}{r})}{4\pi\epsilon_0\gamma^2}\frac{\partial\lambda(s)}{\partial s}. \qquad (1)$$

The constant $\epsilon_0$ is the absolute permittivity and $\gamma$ is the relativistic mass increase (for TSR energies $\gamma = 1$). $R$ denotes the radius of the beam tube ( $R = 0.1$ m) and $r$ is the average beam radius, defined by twice the two $\sigma_r$ value ($r = 2\sigma_r$) of the transverse beam width. A parabola density profile is the only longitudinal charge line distribution, for an electron cooled ion beam with $\Delta\phi \ll 2\pi$ ($\sin(\Delta\phi) = \Delta\phi$) , which compensates the resonator voltage $U_i(\Delta\phi)$ for each ion, independent of its phase $\Delta\phi$. The parabola charge line density $\lambda(s)$ can be calculated from the number $N_B$ of particle in the bunch:

$$\lambda(s) = \frac{3N_BQ}{4w_s}(1 - \frac{s^2}{w_s^2}) \qquad (2)$$

for $|s| \le w_s$, with $\int_{-w_s}^{w_s}\lambda(s)ds = N_B\cdot Q$ . The charge of an ion is $Q$ and $w_s$ describes the bunch length in meters, re-

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# FAST LASER COOLING OF LONG LIVED ION BEAMS

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## *Abstract*

Some peculiarities of fast laser cooling of long-lived ion beams in storage rings are discussed. Selective interaction of ions and broadband laser beam with sharp frequency and geometric edges is used while laser and ion beams are partially overlapped. The rates of change of the ion beam density in different regions of the phase space and at different moments of time in this scheme of cooling differ. That is why the generalized Robinson theorem valid for the infinitesimal phase space regions of non exponential cooling in turn is used to interpret the results.

## INTRODUCTION

Laser ion cooling (LIC) is a well-known technique now [1-4]. Basic idea of this method is in irradiation of moving ion beam with a laser, having frequency which if transformed into the moving frame becomes close to the transition levels. As the ion is moving, the photon radiated after the ion jumps into the ground state will carry substantial momenta directed along the instant direction of motion, while transformed into the Lab frame.

Other well-known technique is so called Enhanced Optical Cooling (EOC). Its basic idea is in application the cooling procedure to the fraction of the beam, first- to the particles with the highest deviation from equilibrium and further on to the ones with lower deviations. To manipulate with amplified optical signal from pick-up undulator we suggested an electro-optical deflection device or even mechanical system for slower processes [5].

In this report we considered the benefits of implementation of EOC technique to the LIC. More exactly we suggest irradiating just fraction of the moving ion beam at a time and further on expanding illumination area to ~ half of the cross section of ion beam. Below we describe this idea in detail.

The trajectory of a particle in external fields is described by the equation $d\vec{p}/dt = \vec{F}_{ext} + \vec{F}_{fr}$, where $\vec{p} = m\gamma\vec{v}$ is the particle momentum, $\vec{F}_{ext} = e(\vec{E}_{ext} + (1/c)[\vec{v}\vec{H}_{ext}])$ is the external force, $\vec{F}_{fr} = F_{fr}(\vec{r},\vec{v})\vec{n}_v$ is the frictional force, $m$ is the particle rest mass (the mass depends on its state: excited, non excited), $\gamma = \varepsilon / mc^2$ is its relativistic factor, $\vec{n}_v = \vec{v}/v$ is the unit vector in the direction of the particle velocity, $\varepsilon$ is the total energy of the particle , $\vec{r}$ is the radius vector, $\vec{v}$ is the vector of particle velocity, $v = |\vec{v}|$, $F_{fr} = |\vec{F}_{fr}|$, $\vec{E}_{ext}$ and $\vec{H}_{ext}$ are the external electric and magnetic fields. In this case the six dimensional infinitesimal volume of an ensemble of particles in a 6D phase space region gathered round some selected particle is decreased by the law $\rho = \rho_0 \exp[-\int \alpha_{6D}(\vec{r},\varepsilon,t)\; dt]$ with the instantaneous decrement determining the rate of cooling

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

where $P_{fr} = \vec{F}_{fr}\vec{v} = F_{fr}v$ is the power of the particle energy loss [1].

In synchrotrons or storage rings the energy losses of ions can be recovered by their RF systems (cooling in a bucket). The 6D increment of such beam in this case is the sum of radial, vertical and longitudinal increments: $\alpha_{6D} = 2\alpha_x + 2\alpha_z + 2\alpha_s$. In the relativistic case:

$$\alpha_x = \frac{1}{2}\left[\frac{\overline{P}_s}{\varepsilon_s} + \frac{\partial\overline{P}}{\partial\varepsilon}|_s - \frac{d\overline{P}}{d\varepsilon}|_s\right], \quad \alpha_z = \frac{1}{2}\frac{\overline{P}_s}{\varepsilon_s}, \quad \alpha_l = \frac{1}{2}\frac{d\overline{P}}{d\varepsilon}|_s, \qquad (2)$$

where the over lined values are the values averaged over many periods of the particle revolution in the ring, $\varepsilon_s$ is the equilibrium ion energy in the ring [1]. The first and second terms in (2) are related to the damping of the radial and vertical betatron oscillations in the transverse plane and the third one $\overline{\alpha_l}$ is related to the damping of the phase oscillations in the longitudinal plane. It is supposed that partial increments (2) are valid inside all area of the corresponding planes. The six dimensional (6D) damping time of the ion beam in this case is:

$$\tau_{6D} = 1/\overline{\alpha_{6D}}. \qquad (3)$$

If relativistic particle beam emits synchrotron and undulator radiation then the power $\overline{P}_{Fr}(\varepsilon) = k_{fr}\varepsilon^2$, the radiative damping decrement $\overline{\alpha_{6D}} = 4\overline{P}_{fr}(\varepsilon)/\varepsilon|_{\varepsilon=\varepsilon_s}$, where $k_{fr}$ is a constant. The decrement for the ionization cooling based on the energy loss of particles in a matter targets has more complicated nonlinear form [2]. Cooling based on such energy losses has the partial derivatives $\partial\overline{P}_{fr}(\varepsilon)/\partial\varepsilon \sim \overline{P}_{fr}(\varepsilon)/\varepsilon$ and small decrements $\alpha_{6D}$.

In the case of radiative cooling of ion beams in storage rings by broadband lasers [3], [4] the target is the contra propagated laser beam, where the backward Rayleigh scattering of laser photons takes place. The spectral distribution of the intensity of the laser beam $\overline{I}_{\omega,l}$ determines the partial derivative $\partial\overline{P}_{fr}(\varepsilon)/\partial\varepsilon$ and hence the rates of the ion beam cooling. For ordinary radiative ion beam cooling [3] the spectral distribution of the laser beam intensity is uniform in the frequency band $\Delta\omega_l = \omega_{l,\max} - \omega_{l,\min}$. It corresponds to the resonance conditions for the excitation of the ion beam in the limits of its energy spread $\Delta\varepsilon_b$. In this case the derivative $\partial\overline{P}_{fr}(\varepsilon)/\partial\varepsilon \sim \overline{P}_{fr}(\varepsilon)/\varepsilon$ is small. For stimulated radiative cooling of ion beam the spectral distribution of the laser beam intensity is increased from zero to maximum value

# STACKING MODES WITH BARRIER BUCKETS METHOD IN NICA COLLIDER

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## *Abstract*

A new accelerator complex NICA is under construction at JINR. The main goal of this project is to reach a luminosity of $10^{27}$ [$cm^{-2}$ $s^{-1}$] in the colliding experiments with gold ions in the energy range of 1 ÷ 4.5 GeV/u. Both electron and stochastic cooling methods are planned to be used to provide the required beam parameters. The comparison of the beam stacking in the longitudinal phase space with stationary and moving barrier buckets under action of electron cooling or without cooling are presented in this report.

## BEAM STACKING IN LONGITUDINAL PHASE SPACE

The beam accumulation in the collider was proposed to be realized in longitudinal phase space with application of RF barrier bucket (BB) technique. If no cooling applied, the minimum longitudinal emittance of the beam after accumulation cannot be less than the sum of the injected bunch emittances:

$$\left(\frac{\Delta p}{p}\right)_{stack} L_{stack} \geq \left(\frac{\Delta p}{p}\right)_{inj} L_{inj} N_{cycles}\,, \qquad (1)$$

where $(\Delta p/p)_{stack}$ and $(\Delta p/p)_{inj}$ – momentum spreads, $L_{stack}$ and $L_{inj}$ – lengths of the stacked and injected regions correspondingly, $N_{cycles}$ – number of injected cycles.

The maximum rms momentum spread of the stack cannot exceed the longitudinal acceptance which can be estimated as the barrier height in units of $dp/p$ divided by 3 (±3σ include 95% particles). Thus the rms momentum spread of the injected bunch has to be less then:

$$\left(\frac{\Delta P}{P}\right)_{inj} \leq \frac{1}{3} \times \left(\frac{\Delta P}{P}\right)_{barrier} \times \frac{L_{stack}}{L_{inj} N_{cycles}}\,. \qquad (2)$$

This condition (2) shows the limit where accumulation without cooling is possible in principle. Otherwise the implementation of cooling is necessary.

Simulations of the particle accumulation for NICA collider with the stationary barrier buckets and the electron cooling system [1, 2] show that the efficiency of accumulation is good at low ion energies and is not sufficient at higher energies (Table 1). These simulations were made for the following parameters: the rms momentum spread of the injected beam - $5\times10^{-4}$, injection and stacking regions - 2π/3, interval between injections - 10 s, barrier voltage - 2 kV and length – π/3.

Table 1: Stacking Efficiency with Stationary Barriers

| Ion energy, GeV/u | 1.5 | 2.5 | 4.5 |
|---|---|---|---|
| Electron cooling rates, $s^{-1}$ | 0.32 | 0.08 | 0.013 |
| Stacking efficiency, % | 92 | 65 | 20 |

There is serious disadvantage of using stationary barriers. Particles are injected into unstable region (potential "top"). Their phase motion is slow in comparison to that of in stack. The time then particles are in injected region is lost for cooling. In addition while travelling through barriers from injection zone into stack, particles experience positive energy kick if their energy is above synchronous one and negative - if below. That means that momentum spread in stack is more than in injection region, as a result the time of cooling increases.

## STACKING WITH MOVING BARRIERS

The simple scheme of stacking [3] with moving barriers can be proposed if the parameters of the injected beam satisfy to the condition (2). The pulse of the injection kicker is designed to be no less than 800 ns i.e. it occupies 1/2 of the Collider's perimeter in phase space. So the injection zone cannot exceed 1/2 of the circumference. But this difficulty can be circumvented because phase space occupied by barrier pulses can be used for the leading and trailing edges of the kicker pulse. That means that injection zone can be diminished up to π/5.

For simulations (Fig. 1) the following parameters were taken: ion energy - 4.5 GeV/u, the barrier rf amplitude - 5 kV, barrier phase width - π/10. In addition, the initial momentum spread of injected beam was chosen to be $1\times10^{-4}$ that meets well the expected parameters of the NICA collider (Table 2). The barrier height of 5 kV corresponds to $(\Delta p/p)_{barrier} = 2\times10^{-3}$, so the injected beam is well satisfied to the condition (2).

Table 2: Parameters of the Injected Bunch [4]

| Ion Energy, GeV/u | 1.0 | 4.5 |
|---|---|---|
| RMS bunch length, m | 5.9÷17.5 | 2.5÷6.2 |
| Momentum spread, $10^{-4}$ | 2.8÷0.95 | 2.1÷0.85 |

Particles are injected into the stable region (Fig. 1a). 1st and 4th barriers are moving during 3 sec more close to the injection region (Fig. 1b). Amplitudes of 3rd and 4th barriers are decreasing during 4 sec to zero value (Fig. 1c). 1st barrier is moving during 3 sec to the own initial position and 2nd barrier is moving to the initial position of the 4th barrier (Fig. 1d). Just before the next injection cycle all barriers jump back to their initial positions (Fig. 1a) and procedure repeats.

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# OPERATIONAL EXPERIENCE WITH THE HESR ELECTRON COOLER TEST SET-UP

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## *Abstract*

The electron cooler test set-up built at Helmholtz-Institut Mainz as a feasibility study for the electron cooling device at the High Energy Storage Ring (HESR) at FAIR has been set in operation. One of the main goals of the test set-up is to evaluate the gun design proposed by TSL (Uppsala) with respect to vacuum handling, EM fields and the resulting beam parameters. Another purpose of the set-up is to achieve a maximum relative collection loss of $10^{-5}$. To measure this quantity, a Wien filter will be employed, which will also prove capable of mitigating collection losses. Recent developments and operational experiences with the test set-up are presented.

## INTRODUCTION

At the proposed High Energy Storage Ring (HESR) at FAIR in Darmstadt, it is planned to store antiproton beams at energies up to 15 GeV. Since the internal experiment PANDA [1] increases the emittance of the stored beam, beam cooling mechanisms have to be employed. One possible way of reducing the emittance of the stored beam is to employ an electron cooling device as depicted in Fig. 1.

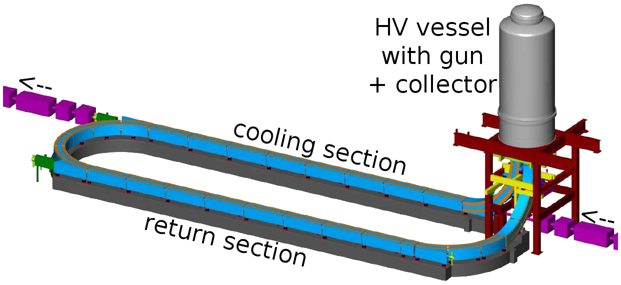

Figure 1: Proposed design of the HESR electron cooler [2].

In this device, a high-intensity electron beam moves coincidentally along the axis of the hadron beam, allowing for unwanted momentum components to be shifted into the phase space of the electrons, which are subsequently extracted and dumped in a collector. In order for the electron plasma to appear at rest from the perspective of the hadron beam, one has to ensure that the beams meet the requirement

$$v_e = v_{\overline{p}} \quad \Rightarrow \quad E_e = \frac{m_e}{m_{\overline{p}}} E_{\overline{p}}. \tag{1}$$

Therefore, an electron beam with an energy of up to 8 MeV is needed. Calculations done by FZJ [3] show that the current should be of the order of 3 A for maximum cooling rate. Additionally, the demand for magnetized cooling requires the beam to be constrained within a solenoidal magnetic field.

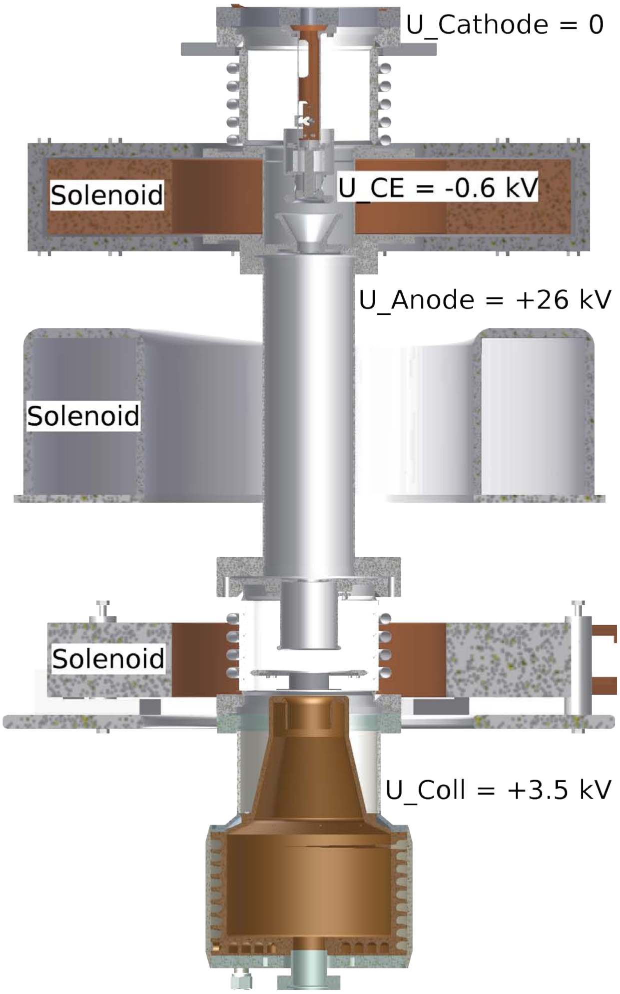

Figure 2: Schematic view of the complete test bench.

The device is designed for energy recuperation such that the total deposited energy is independent of the beam power. However, the electrostatic symmetry induced by this approach leads to the problem that secondary electrons reflected from the collector surface can traverse the beam pipe in the wrong direction. This effect can be reduced by using a suppressor electrode in front of the collector aperture so the low-energy tail of the secondary electron spectrum is reflected back into the collector. However, as high-energy secondaries cannot be reflected in this geometry, we are planning to investigate whether a Wien filter is sufficient to completely suppress this effect.

# COLLECTOR FOR ELECTRON COOLING SYSTEMS WITH SUPPRESSION OF REFLECTED ELECTRON FLUX

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## *Abstract*

Results of testing of the collector with Wien filter in the 2 MeV electron cooling system for COSY synchrotron are presented. Efficiency of a collector in high voltage electron cooling devices is important from the point of view of the load on high voltage power supply, radiation safety and vacuum conditions in the system. The collector for 2 MeV COSY cooler is supplemented with Wien filter which allows increase efficiency of the system by deflection secondary electron flux in crossed transverse electric and magnetic fields. Results of tests show that such solution provides efficiency of recuperation in the cooler up to $10^{-5}$. After tests some changes were made in the construction of the Wien filter to improve quality of the collector performance.

## INTRODUCTION

Feature of the electron cooling is that during cooling process electron beam almost doesn't change its energy. It means that after interaction with ion beam electrons with sufficiently high energy must be utilized, that is serious technical task. To avoid this problem the method of recuperation of electron beam energy is used in electron cooling devices. An idea of the method is to decrease electron beam energy in electrostatic tube which is connected to the same high voltage power supply (PS) which is used for acceleration of electrons. After that electron beam is directed to a special collector where they are absorbed by its surface. Usual energy of electrons absorbed in a collector is 1÷5 kV and it is defined by a special collector PS.

The method allows decrease power consumption of the high voltage PS because it determined only by leakage current from the high voltage terminal to the ground. As a result it allows simplify construction of the high voltage PS Collector PS usually is more powerful but its operation voltage is several kV.

The most important cause of appearance of the leakage current from high voltage terminal is losses of full energy electrons ($I_{leak}$). The most part of such electrons are secondary particles reflected from a collector. The ratio of $I_{leak}/ I_{beam}$ (where $I_{beam}$ – main beam current) is called efficiency of recuperation.

Besides increasing of load to high voltage PS bad efficiency of recuperation in electron cooling systems can cause other problems. Full energy electrons which hit wall of vacuum chamber are source of radiation. Besides worsen of radiation safety it can cause problems in reaching good vacuum conditions and decrease electric strength of the cooler.

In coolers EC-35, EC-40 and EC-300 produced in BINP for IMP (China) and CERN the efficiency was improved with the help of special electrostatic bending plates installed in toroid parts of the coolers [1]. Electrons reflected from collector move from collector to gun solenoid and then back to collector where it can be absorbed. These plates allow to increase efficiency of cooler recuperation from $10^{-3}$ to $10^{-6}$. But in 2 MeV cooler for COSY shape of magnetic system and high energy of electrons make using of such method very complicated. In this case one should improve collector efficiency.

In the work [2] the best efficiency of ordinary axially symmetric collector with electrostatic and magnetic closing of secondary electrons was estimated and its value is about $10^{-4}$. For high voltage electron coolers such efficiency is not enough and for the 2 MeV cooler needed value is about $10^{-5}$ [3]. For this a new collector with suppression of secondary electrons by Wien filter was designed [4].

## COLLECTOR WITH WIEN FILTER

The main idea of the collector with Wien filter is to install a special insertion with crossed transverse electric and magnetic fields before ordinary collector (Fig. 1).

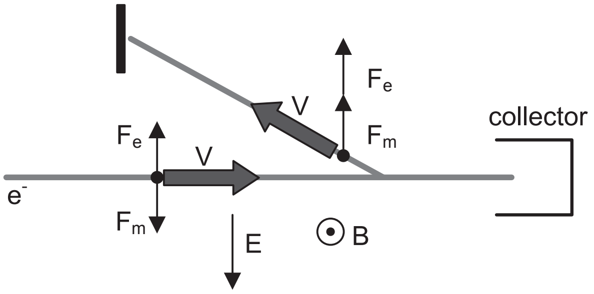

Figure 1: Principle of the collector with Wien filter work.

For main beam action of fields compensate each other but for secondary beam, which moves back, magnetic field acts in opposite direction and secondary beam is deflected to a special electrode (secondary collector).

In the 2 MeV cooler the collector with Wien filter is placed in longitudinal magnetic field that is related with features of the cooler. The field makes the secondary beam move in direction parallel to electrostatic plates protecting them from electrons of the beam.

The sketch of the collector with Wien filter for the 2 MeV cooler is shown in Fig. 2. Collector itself (i.e. collector without Wien filter) is based on construction used in previous coolers produced in BINP.

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# POWERING OF THE HV-SOLENOIDS AT THE HESR ELECTRON COOLER

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## *Abstract*

Many experiments at the planned High Energy Storage Ring (HESR) require magnetised electron cooling [1]. One of the challenges in the future HESR electron cooler is the powering of HV-solenoids, which need a floating power supply.

In this report we discuss the possibility of using turbo generators. We give an overview, including an introduction, status report and a road map.

## INTRODUCTION

An essential part of the Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt is the HESR project, which is dedicated to the field of high energy antiproton research. The HESR is a storage ring with a circumference of 575 m and can operate in two modes, the “High Luminosity” (HL) and “High Resolution” (HR) mode. The experiments occur in the PANDA detector [2]. Some experimental demands are summarised in Table 1 [3]. To meet these requirements for the high resolution mode, magnetised electron cooling with a 4.5 MeV, 1 A electron beam is necessary to counteract the emittance blow up due to scattering processes.

Table 1: Experimental Demands of the HESR

| | HL | HR |
|---|---|---|
| Momentum range | $1.5 - 15\ \frac{\mathrm{GeV}}{\mathrm{c}}$ | $1.5 - 9\ \frac{\mathrm{GeV}}{\mathrm{c}}$ |
| Peak luminositiy | $2 \cdot 10^{32}\ \frac{1}{\mathrm{cm}^2\mathrm{s}}$ | $2 \cdot 10^{31}\ \frac{1}{\mathrm{cm}^2\mathrm{s}}$ |
| Momentum resolution | $\frac{\Delta p}{p} = 10^{-4}$ | $\frac{\Delta p}{p} = 10^{-5}$ |

An intention for the HESR is an upgrade to the Electron Nucleon Collider (ENC). The ENC will allow experiments with polarised electrons and protons [4], which also need magnetised electron cooling. In that case, an 8 MeV, 3 A electron beam is needed.

The Helmholtz-Institut Mainz (HIM) promotes a collaboration with other institutes such as Forschungszentrum Juelich (FZJ) and Budker Institute of Nuclear Physics Novosibirsk (BINP), Russia, in order to solve critical design issues for the HESR electron cooler. One of the challenges is the powering of HV-solenoids, because they are located on different electrical potentials inside a high voltage vessel. As a consequence, the HV-solenoids need floating power supplies. A concept that is currently being discussed to power them is the usage of cascaded cascade transformers, powered by turbo generators. The turbine is powered by gas under high pressure, consequently driving the generator.

The paper is organised as follows. In the first section, we show an overview of the HESR/ENC electron cooler and define the problem. In the following section, we present the concept currently under discussion and in the last part, the further road map is given.

## HESR ELECTRON COOLER

The design of the HESR electron cooler as it was originally planned by the Svedberg Laboratory, Uppsala University, is shown in Figure 1 [5]. The cold electron beam is generated and accelerated within the high voltage vessel and is directed into the interaction straight, where the cooling process takes place. At the end of the interaction straight, the cooled antiproton beam is separated from the electron beam, which is returned to the high voltage vessel and deposited in a collector in order to restore energy [6]. Along the entire path from the source to the collector, the electron beam is guided in a homogeneous magnetic field generated by solenoids. Inside the high voltage vessel the magnetic field strength is 0.07 T, in the interaction and return straight 0.2 T. To prevent discharges, the high voltage vessel is filled with sulphur hexafluoride ($SF_6$) at an absolute pressure of 6 bar.

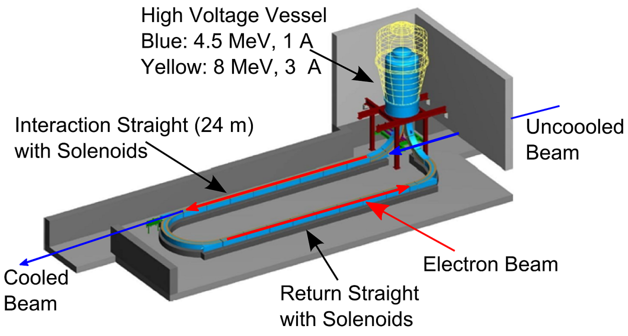

Figure 1: Proposed design of the HESR electron cooler.

The interior of the high voltage vessel is illustrated in Figure 2. The main components are the DC-thermionic electron source, the collector, the acceleration and deceleration tube. The accelerating/decelerating voltage is provided by a high voltage column. It is built in a modular way and consists of decks. Every deck has a defined electrical potential. The potential difference between two decks should be in the range of 60 kV, which is a presently available technology already used in the 2 MeV COSY cooler (Forschungszentrum Juelich) [7]. The potential difference of 750 kV between the decks, as proposed in the swedish design, is not pursued further. The solenoids generating the homogeneous magnetic field inside the high voltage ves-

# MATCHING OF MAGNETIC FIELD WITH ENERGY OF ELECTRONS IN 2 MeV COSY COOLER

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*Abstract*

In the high energy electron cooler for COSY the beam energy range is wide (24keV- 2MeV). Maximal guiding magnetic fields are 0.5kG in accelerating tube, 1kG in transport channels and 2kG in cooling solenoid and 45° toroids. As result we have two sections with longitudinal gradient of field, three 90°bends and 45° toroid before beam pass to solenoid.

Transition of beam energy to transverse degrees of freedom is possible in such conditions. Chances to minimize this transition (named further “heating“) are discussed. Also the results of using of correctors and pick-up system are considered.

## MATCHING OF GUIDING & BENDING FIELDS

The magnetic measurements on the assemblies of cooler magnetic elements are shown good agreement with calculated magnetic fields for such assemblies [1]. Therefore optimization of magnetic fields $B_S$ and $B_B$ for different electron energy was produced by trajectories computations. Computations were done for fragments of system (see Fig. 1). Each fragment includes potential “heating” element (bend, matching section and etc.). Field along of magnetic system are constructed from such fragments

Functionally five high-current power supplies are used in system.

- cooling solenoid – PS-1, (566)
- 45° toroids – PS-2, (173).
- guiding field of bends and lines-17 – PS-3, (349, 331)
- lines-05 and lines-10 – PS-4, (358, 348).
- all bending coils – PS-5, (17βγ).

Fields at currents 100A are recorded in brackets.

PS currents for series values of electron energy are contained in Table 1. Currents correspond with optimal fields for these energies.

Table 1: Electron Energy and PS Current Correspond with Optimal Fields

| T<br>MeV | PS – 1<br>A | PS – 2<br>A | PS – 3<br>A | PS – 4<br>A | PS – 5<br>A |
|---|---|---|---|---|---|
| 0.5 | 286.0 | 792.0 | 302.0 | 302.0 | 115.0 |
| 1.0 | 260.0 | 720.0 | 265.0 | 265.0 | 187.0 |
| 1.5 | 251.0 | 714.5 | 281.0 | 279.3 | 255.6 |
| 2.0 | 246.9 | 565.0 | 254.1 | 250.0 | 323.0 |
| 2.0 | 317.3 | 933.0 | 254.1 | 250.0 | 323.0 |

Currents for others energies may be converted from these as γβ relations. Geometric parameters (bend’s radii, number of turns around field $B_S$ on bend length and etc.) keep in this case

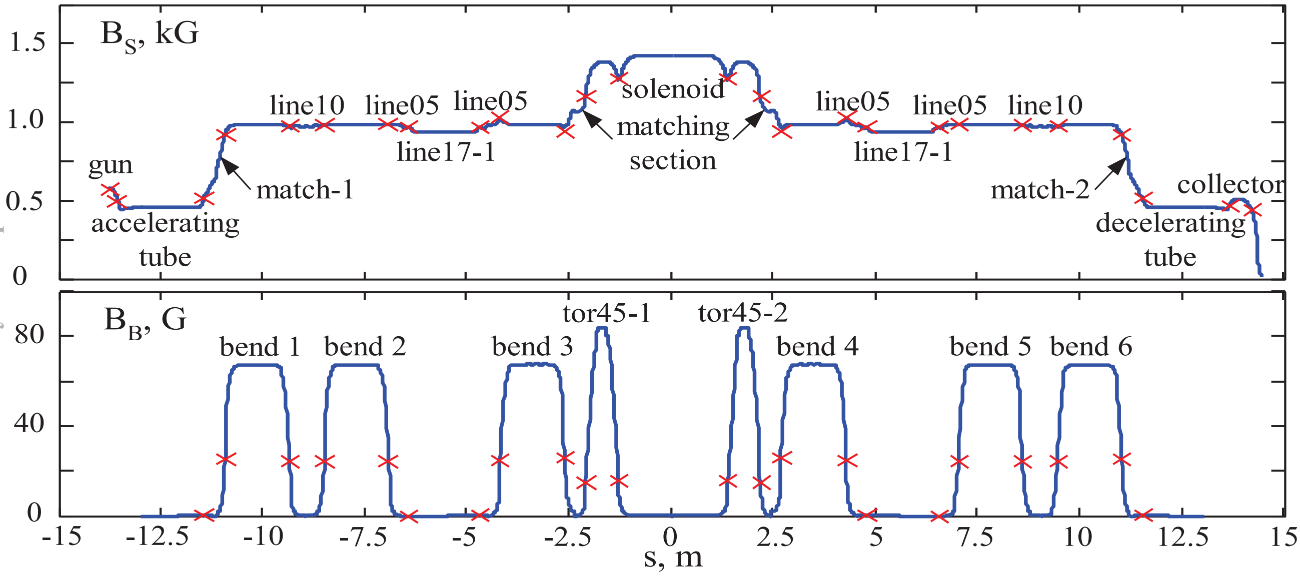

Figure 1: Calculated guiding magnetic field $B_S$ and transverse bending magnetic field $B_B$ along axis of magnetic system of cooler. Fields are optimal for 1.5MeV electrons. Junctions of magnetic element are marked by symbol ×.

# ELECTRON COOLER FOR THE NICA COLLIDER

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## *Abstract*

The goal of the cooling system of the NICA collider is to meet the required parameters for ion beams in energy range of 1 ÷ 4.5 GeV/u that corresponds to 0.5 ÷ 2.5 MeV of electron energy (Table 1). The electron cooler is developed according to existing world knowledge of manufacturing of similar systems. The main peculiarity of the electron cooler for the NICA collider is use of two cooling electron beams (one electron beam per each ring of the collider) that never has been done. Two versions of design of the cooling system are under consideration presently. In one scheme the acceleration and deceleration of the electron beams is produced by common high-voltage (HV) generator (Fig. 1). The cooler consists of three tanks. Two of them contain acceleration/deceleration tubes and are immersed in common superconducting solenoids. The third one contains HV generator. The second scheme has two coolers (one per each ring of the collider) (Fig. 4). The coolers have own high voltage systems. The electron cooler consists of two tanks. One tank contains acceleration/deceleration tubes which immersed in own magnetic field created by separated coils accommodated inside the tank.

## CONCEPTUAL DESIGN OF THE FIRST COOLER VERSION

Three tanks of the electron cooler (Fig. 1) are filled with SF6 gas under pressure of 0.8 MPa (≈8at) [1]. Tanks 1 and 3 contain acceleration tube and electron gun for one of the electron beam and deceleration tube and electron collector for another one. The tank 2 houses the HV generator. The magnetic field is formed by a set of straight and toroidal superconducting solenoids. The solenoids forming the magnetic field in the region of acceleration/deceleration tubes are placed outside of the tanks that resolve the problem of HV insulation.

Table 1: Cooler Parameters

| | |
|---|---|
| Electron energy, MeV | 0.5 ÷ 2.5 |
| Electron beam current , A | 0.1 ÷ 1,0 |
| Beam diameter, cm | 1,0 |
| solenoid magnetic field, T | 0.1 ÷ 0.2 |
| HV PS current, mA | 1 |
| Collector PS, kW | 2×2 |
| HV PS stability, ΔU/U | $1\times10^{-4}$ |
| $SF_6$ gas pressure, at | 5 ÷ 8 |

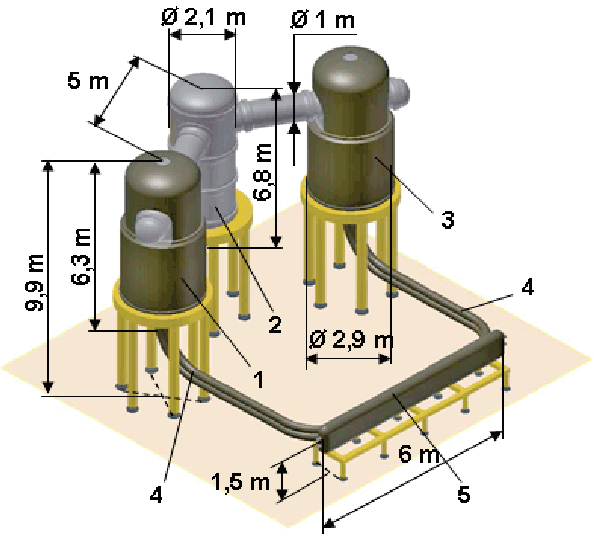

Figure 1: General view of the electron cooler. 1, 3 – the tanks with electron gun and acceleration tube and deceleration tube + collector for electron beam of opposite direction , 2 – tank with HV generator, 4 – beam transportation solenoids, 5- electron cooling section.

## HIGH VOLTAGE GENERATOR OF THE FIRST COOLER VERSION

High voltage (HV) generator placed in one of the tank of the cooler (Fig. 2) is based on the principle of the cascade scheme [2]. The power transmission to the high

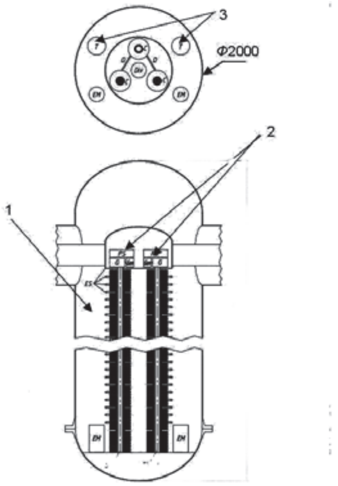

Figure 2: Design of power supply of 2.5 MV. 1 - cascade generator, 2 - gun and collector power supply, 3 - power transmitters to high potential (“shafts”).

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# BEAM PROFILE MEASUREMENTS FOR MAGNETIZED HIGH ENERGY COOLING DEVICES

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## *Abstract*

Recent developments in the field of high intensity electron beams in the regime below 10 MeV, e.g. energy recovery linacs or magnetized high energy electron coolers [1], have led to special demands on the beam diagnostics. Since commonly used diagnostic tools like synchrotron radiation and scintillation screens are ineffective or not able to withstand the beam power without being damaged, new methods are needed. Hence a beam profile measurement system based on beam induced fluorescence (**BIF**) was built. This quite simple system images the light generated by the interaction of the beam with the residual gas onto a PMT. A more elaborated system, the Thomson Laser Scanner (**TLS**) — the non-relativistic version of the Laser Wire Scanner — is proposed as a method for non-invasive measurement of all phase space components, especially in the injector and merger parts of an ERL. Both methods are implemented in a 100 keV photo gun.

## INTRODUCTION

The new high energy cooling devices easily reach several MWs of beam power. Due to high voltage breakdowns and the energy recuperation in the collector, they allow only a very small beam loss, which is not compatible with normal destructive diagnostics.

There are already several non-destructive beam diagnostic methods established, which are used in different accelerators, such as a scintillation profile monitor [2] at COSY, [3] at GSI or the laser wire scanner at the synchrotron source PETRA III [4]. These methods can be adapted for the profile measurement of high intensity electron beams.

## BEAM INDUCED FLUORESCENCE

For protons and ions, beam profile measurement based on beam induced fluorescence is a common technique [5]. The idea is to image the fluorescing residual gas on a photo detector with a spatial resolution. Instead of a detector with a spatial resolution, a photomultiplier tube (PMT) with a slit in front of it can be used. The slit cuts out a small slice of the electron beam image at the PMT as indicated in Fig. 1. By moving the slit up and down, a beam profile can be measured.

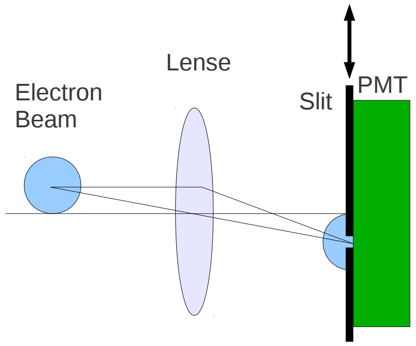

Figure 1: Schematic view of the beam induced fluorescence profile measurement done with a PMT and a slit.

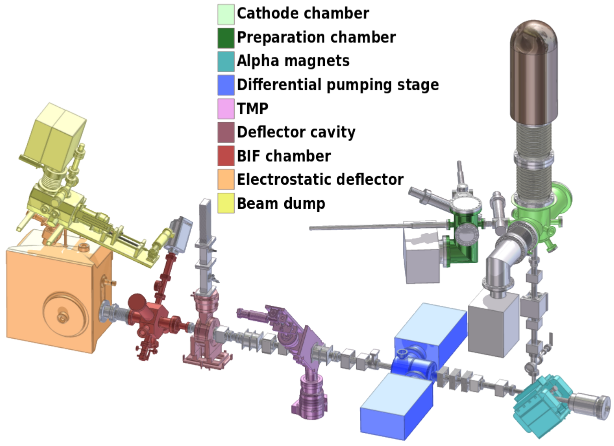

Figure 2: The polarized test source PKAT.

To measure the beam induced fluorescence, a new vacuum chamber has been installed at the polarized test source (PKAT) [6] shown in Fig. 2 at the Mainzer Mikrotron (MAMI). In this source, a NEA-GaAs [7] photo cathode is used, which requires a pressure much lower than $10^{-10}$ mbar for stable operation. Therefore, this chamber is separated from the cathode chamber by two differential pumping stages. The first one consists of a turbo molecular pump (purple) and the second one of two ion getter pumps (blue). This allows local pressure bumps of up to $10^{-5}$ mbar while maintaining the XHV condition at the cathode. These high pressures are necessary to achieve a significant amount of fluorescent light because the beam current of the photo gun is limited to a few 100 $\mu$A.

With this setup, first beam profiles have been measured. The conditions during the measurement are listed in Table 1. Since the light yield scales linearly with pressure and current, these conditions are comparable to the conditions in an electron cooling device. There a residual gas pressure of $10^{-9}$ mbar in combination with a current of 1 A generates the same amount of photons as in our measurements.

A typical measurement is shown in Fig. 3. In this case the laser was pulsed with a pulswidth of 2 ms and a spacing between the pulses of 20 ms. The resulting duty factor of 0.1 and the average beam current of 50 $\mu$A measured at the beam dump results in a peak current of 500 $\mu$A. A convolu-

# LEPTA PROJECT: TOWARDS POSITRONIUM

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### *Abstract*

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

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

## LEPTA RING DEVELOPMENT

The Low Energy Particle Toroidal Accumulator (LEPTA) is designed for studies of particle beam dynamics in a storage ring with longitudinal magnetic field focusing (so called "stellatron"), application of circulating electron beam to electron cooling of antiprotons and ions and positronium in-flight generation.

For the first time a circulating electron beam was obtained in the LEPTA ring in September 2004 [1]. First experience of the LEPTA operation demonstrated main advantage of the focusing system with longitudinal magnetic field: long life-time of the circulating beam of low energy electrons. At average pressure in the ring of $10^{-8}$ Torr the life-time of 4 keV electron beam of about 170 ms was achieved that is by several orders of magnitude longer than in usual strong focusing system. However, experiments showed a decrease of the beam life-time at increase of electron energy. So, at the beam energy of 10 keV the life time was not longer than 12 ms. The possible reasons of this effect are the magnetic inhomogeneity and resonant behavior of the focusing system.

### *Diagnostic System Development*

Previous PU system was connected to amplifier by using the cable of near 3 meters length. That reduced significantly sensitivity for all system. New amplifier was designed, manufactured and mounted (Fig. 1). It locates directly at connector exits from vacuum chamber. Sensitivity of new system is of 1,1 mV/μA.

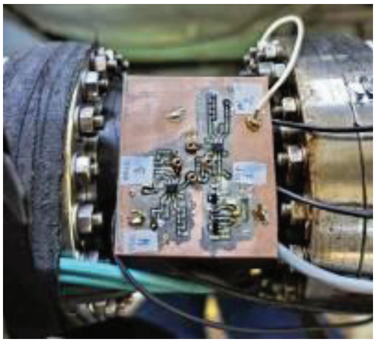

Figure 1: The new PU amplifiers.

For fine tuning of the trajectory and control of circulating positron beam aperture probe based on semiconductor gamma detector has been designed (Fig.2), fabricated, mounted and tested with positrons injected into the ring.

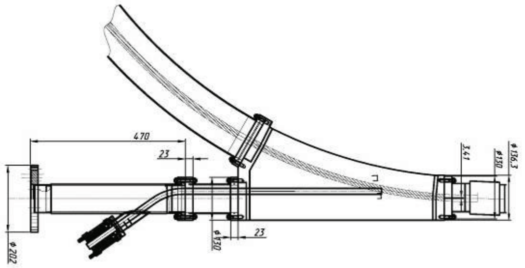

Figure 2: The circulating $e^+$ beam detector.

## THE POSITRON INJECTOR

In summer 2010 the slow positron source and the trap have been assembled. The first attempts of slow positron storage were performed and stored positrons were extracted to the diagnostic collector.

### *Vacuum System Development*

New vacuum chamber for transport channel was manufactured and mounted to minimize losses during injection. Aperture was increased from 3,2 cm to 6,5 cm.

The vacuum conditions in the accumulation space of the positron trap have been improved by the application of a cryogenic screen (Fig 3). that was designed, manufactured, mounted and tested. It has effected in an increase of stored positron life time by a three times.

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# COMPASS FOR MEASURING THE MAGNETIC LINES STRAIGHTNESS AT THE COOLING SECTION IN VACUUM

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## *Abstract*

The 2 MeV cooler is currently under construction at the COSY synchrotron. Due to high energy it is a very strict requirement for the magnetic field homogeneity at the cooling solenoid. Since the magnetic field has to be adjusted during the accelerator operation, the measurement system is installed inside vacuum chamber. The design and features of this system are described in the article, as well as preliminary results are discussed.

## INTRODUCTION

Magnetic field homogeneity at the cooling section is quite important for electron cooling as it increases effective velocity of electrons. For high energy electron cooling transverse temperature of electrons is strongly depended on magnetic field nonstraight linearity [1].

In the first experiments on determination of the quality of magnetic field at BINP [2], an optical automatic autocollimator was used as the measuring system. As the magnetic sensor it was used a construction composed of the mirror, laid down in the gimbal suspension with jewels from clock as the bearing supports, and of steel rod penetrating the mirror axis. In 2000, a measurement system for a prototype of electron cooling system for the Tevatron (Fermilab, USA) was designed [3]. The magnetic sensor was made of two cylinder of NdFeB material that provided required sensitivity at relatively low guiding magnetic field. Electronic circuit contained a low power semiconductor laser as light source, four quadrant photodiode, source of compensating current and the feedback loop, allowing return reflected from the mirror compass beam to the starting position for fixing the value of the compensation current.

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

All those designs of the sensors showed very high sensitivity and were successfully used for different coolers commissioning. But such a type of compass can not be used in the COSY cooler because of following disadvantages:

- The suspension wire is rather weak to overcome the tension caused by transverse field. This is important as long as sensor must be hidden inside special parking place to release accelerator's aperture. Increasing the strength of wire by increasing its thickness is also limited because of rapid growth of the elastic forces.
- The sensors contain incompatible to UHV materials those determine some of their features.
- Some of details are not heat resistant that doesn't correspond to the requirement that all components have to be back able up to 300°C

So a device which meets UHV requirements and allows to measure straightness without disassembling of vacuum chamber was constructed. The sensor design is similar to the device which was used on electron cooler for NAP-M storage ring [2] except some peculiarities. On the other hand measurement system is based on the same ideas, used in "air type" measurements [4].

## SENSOR DESIGN

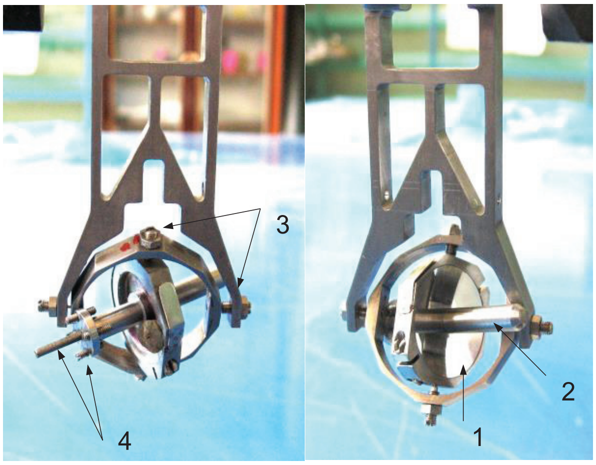

Figure 1: Compass with gimbals suspension. (1 – mirror, 2 – compass needle, 3 – jewel bearings, 4 – balancing screws).

Compass needle (fig. 1) is made from low carbon steel with high permeability to provide its complete saturation. It is attached to the mirror which is made of polished tantalum disk. Gimbals suspension has two axes formed by two couples of precise jewel bearings. The bearings type was chosen as conical bore that provide low friction in it. On the other hands this type requires precise alignment of the bearings axis in the bore to avoid any backlash which may result in measurement hysteresis [5]. On the needle back part five balancing screws are placed, one at the compass axis and two couples along bearings axes. One couple is made from low carbon steel but another one from stainless steel. The idea is to eliminate misbalance of the compass in gravity force as well as in magnetic force due to needle discontinuity since it has a screw

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# SIMULATION STUDY OF BEAM COOLING WITH ELECTRON ENERGY MODULATION*

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## *Abstract*

The electron cooling is less efficient for hot ion beam because that the cooling force reduces rapidly at high electron-ion relative velocity. A possibility scheme of electron cooling for ion beam with large velocity spread was studied by simulation method. In this scheme, the average electron beam velocity was modulated through the ion velocity distribution during cooling procedure. Therefore the average friction force at high electron-ion relative velocity range will be increased. The results show that the hot ions can be captured and cooled. A fast beam momentum spread shrinking could be achieved through this electron energy modulation method. The capture rate dependence on the modulation parameters was investigated. The simulation results also show different ion beam longitudinal velocity distribution can be produced via electron energy modulation.

## INTRODUCTION

The electron cooling method is an important technique to produce high quality ion beams in storage rings. Based on energy transfer between the ions and a cold external electron beam, the heat is transferred from ions to electrons and the phase space of ions is reduced.

The experiments and theory research work on the electron cooling showed that the "magnetized" electron cooling has an extremely sharp dependence of the drag force on the difference relative velocity of ions and electrons. In the small relative velocities range, the drag force is a linear function of the relative velocity. The ions in this region will be attracted by cold electron beam and cooled down fast. In the relative velocities out of this linear range, the drag force decreases very fast as scale as $F \sim v^{-2}$ . Therefore, the electron cooling is less efficient and not well suited for cooling the hot ions.

One of the most important applications of the electron cooling is used to cool the ion beam after injection, in order to increase the number of ions in a storage ring by a combination with multi-injection. Generally, the ion beam after multi-turn injection has large momentum spread and emittance. In order to cool down the ion beam as fast as possible, especially for the hot ions in the tail of phase space, a possibility of efficient electron cooling of ion beams with wide velocity spread has been investigated experimentally [1]. The results show that the reduction of the cooling time could be achieved by the electron energy modulation method. In this paper, the cooling effect with electron energy modulation scheme was studied by simulation method.

## PRINCIPLE

The basic parameter describing this energy transfer in electron cooler between ions and electrons is the cooling force. A useful practical formula of the cooling force was written by Parkhomchuk by fitting to the experimental data [2]. The cooling rate for ion originated from this formula can be described as below:

$$\lambda_{cool}(v) = \frac{-4Z^2 n_e m_e c^2 r_e^2 L_c}{m_{ion}} \frac{1}{\eta} \frac{1}{\left(v^2 + v_{eff}^2\right)^{3/2}} \quad (1)$$

Here $v$ is the ion electron relative velocity. $v_{eff}$ is the effective electron velocity. $L_c$ is the coulomb logarithm of the impact parameters. $\eta$ is the part of cooling section at the ring circumference. $r_e$ is the electron classic radius.

The intra-beam scattering (IBS) is another important effect in the cooling process. The final cooled-down ion beam parameters are mainly determined by the equilibrium between the cooling effect and IBS effect. Usually, the growth rate caused by IBS is much less than the cooling rate of hot ions, therefore it's not a significant role for our calculation. Here we used a simple gas relax model for IBS diffusion coefficient calculation [3].

$$D_{IBS} = \frac{2}{(\beta\gamma)^3} \frac{1}{\left(\varepsilon_{h,v}\right)^{3/2}} \frac{N_{ion} c}{\sqrt{\beta_{h,v}}} r_{ion}^2 \frac{1}{C_{ring}} Lc \quad (2)$$

According to the Fokker-Planck equation and stochastic dynamics principle [4], the momentum transfer of each particle after once integration step can be described as:

$$\theta_{final} = \theta_{start} \exp\left(\frac{1}{\gamma^2} \lambda_{cooling} t\right) + \sqrt{D_{IBS} t}\,\xi \quad (3)$$

Here $\xi$ is a Gaussian random number. The integration step $t$ is much shorter than the cooling time in the calculation.

Additionally, the beam dynamics in synchrotron was also considered. Since the momentum changing in each integration step was very small, and we assumed the particle position was constant in each integration step. We applied the matrix with a stochastic tune number after once step.

Based on principle above, a compute code was written for simulating the cooling process with electron beam

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# PRESENT STATUS OF COHERENT ELECTRON COOLING PROOF OF PRINCIPLE EXPERIMENT*

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## *Abstract*

We conduct a proof-of-the-principle experiment of coherent electron cooling (CEC), that potentially wil significantly boost the luminosity of high-energy, high-intensity hadron colliders [1]. Herein, we discuss the current status of the experimental equipment, detailing our first tests of the electron gun and the results of magnetic measurements of the wiggler prototype. We describe the current status of the design, and our near-future plans.

## PROJECT OVERVIEW

Figure 1 shows the overall layout of our experiment [2]. We will generate the electron beam by a CsSb photocathode inside the 2 MeV 112 MHz SRF gun. Two 500 MHz copper cavities will provide energy chirp for the ballistic compression of the electron beam. The compressed bunches will be accelerated further to 22 MeV by the 704 MHz 5-cell superconducting RF linac.

The electron beam will merge with 40 GeV/u gold ion beam after passing through a dogleg. The ions will “imprint” their distribution on to the electron beam by modulating its density in their locations. This modulation will be amplified in a high-gain FEL comprising of three 2.5-m-long helical undulators.

The ions will co-propagate with electron beam through the FEL. Therein, the ion’s average velocity is matched to that of the group velocity, e.g., to the propagation speed of the wave-packet of the e-beam’s density modulation. We will use a three-pole wiggler at the exit of the FEL to tune the phase of the wave-packet such that the ions with the nominal energy experience zero longitudinal electric field.

The dependence of time-of-flight on the ion’s energy will insure that the off-energy ions will be accelerated or decelerated, depending on the sign of their energy error. Such interaction will lessen the energy spread in the ion beam [1].

The used electron beam will be bent away from the ions’ path and then dumped.

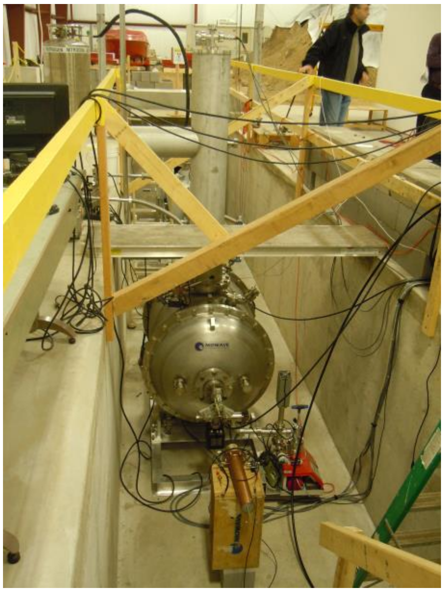

Figure 2: The 112 MHz cavity in the trench during the test at Niowave.

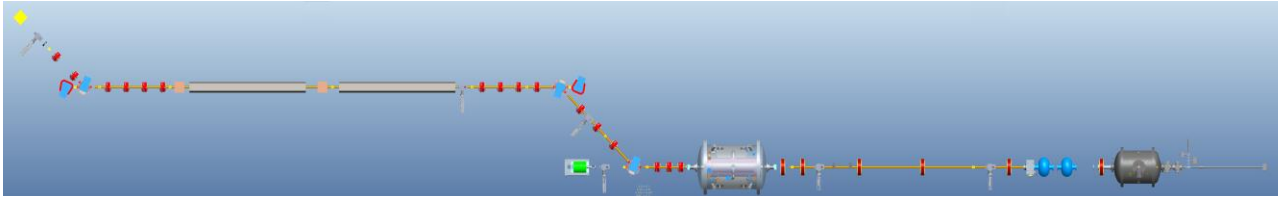

Figure 1: The layout of the CeC Proof-of-Principle experiment. On the right there is a electron gun with a cathode launcher. Between the gun and an accelerating cavity (gray) the electron beam is focused by solenoids (red). 500 MHz cavities (blue) modulate beam energy for ballistic bunching. After the accelerator the electron beam is transported with dipoles (red-blue) and quadrupoles (red). Two dumps are used: low power (green) and high-power (yellow).

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# ELENA: FROM THE FIRST IDEAS TO THE PROJECT

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*Abstract*

Successful commissioning of the CERN Antiproton Decelerator (AD) in 2000 was followed by significant progress in the creation of anti-hydrogen atoms. The extraction energy of the decelerated antiprotons is nevertheless very high compared to that required by the experiments and results in a trapping efficiency of only 0.1% to 3%. To improve this value by an order of magnitude the study of an Extra Low ENergy Antiproton ring (ELENA) started in 2003 and was approved as a CERN construction project in 2011. During these years the choice of the main machine parameters such as the beam extraction energy, emittance and bunch length were defined, taking into account requests from the physics community. The main challenges were also identified, such as dealing with the large space charge tune, the ultra-high vacuum required and the tight requirements for the electron cooler. Housing the ELENA ring within the AD hall significantly reduced the project cost as well as simplifying the beam transfer from AD to ELENA and from ELENA to the existing experimental areas. This contribution will follow ELENA from its beginnings to the final, approved project proposal.

## INTRODUCTION

CERN has provided experiments with antiprotons since 1980 and is the world's unique source of low energy antiprotons. In the shadow of the discovery of the W and Z bosons in the SPS, the Low Energy Antiproton Ring (LEAR) contributed to a number widely recognised scientific successes that include:

- The most precise comparison of the charge-to-mass ratio for the proton and antiproton resulting in the most stringent test to date of CPT invariance with baryons.
- Some of the most precise studies of CP violation.
- First observation of fast anti-hydrogen atoms.

LEAR was stopped in 1996 for its conversion to an ion accumulator ring (LEIR) but since 2000 the Antiproton Decelerator (AD) has continued to deliver low energy antiproton beams to experiments mainly concerned with the production, trapping and spectroscopy of anti-hydrogen atoms. Large numbers of anti-hydrogen atoms are now routinely produced and more recently the collaborations have managed to trap these antiatoms for sufficiently long periods such that ALPHA has been able to perform the first microwave spectroscopy studies.

## FIRST IDEAS ON ELENA

Already in the LEAR era many experiments requested a facility which would provide antiprotons at energies much lower that the extraction energy of the LEAR ring [1,2]. They all required a resonant extraction system to make more efficient use of the available beam. The first proposal for such a ring was made in 1982 [3] and was baptised "ELENA" for Extra Low ENergy Antiproton ring. Figure 1 shows the proposed layout consisting of four 90º bending D-magnets and four straight sections of 1.4 length each. The ring circumference of 7.85 m corresponded to 1/10 the LEAR circumference and all magnets were to be equipped with pole face windings to allow the fine tuning of the ring parameters. One of the straight sections would also be equipped with an electron cooler to ensure a small beam emittance at the low energy plateau of 200 keV. The length of the deceleration cycle was to be about 7 seconds, in which the beam would be cooled, decelerated to 200 keV and then resonantly extracted during 100 ms.

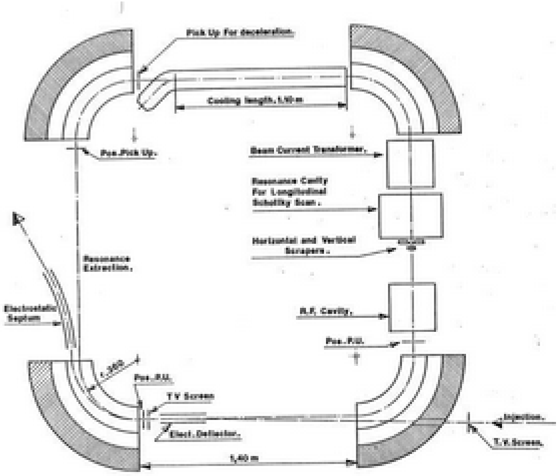

Figure 1: The first ELENA proposal (1982).

Table 1: Main Parameters

| | | |
|---|---|---|
| Kin. Energy range | 5 Mev | 200 keV |
| Momentum range | 100 MeV/c | 20 MeV/c |
| Circumference | 7.85 m | |
| Bending radius | 0.37 m | |
| Magnetic field | 0.9 T | 0.18 T |
| Tune | $Q_h = 1.63$ | $Q_v = 1.43$ |
| e gun voltage | 2870 V | 113 V |
| e current | 20 mA | 0.16 mA |
| Magnetic guiding field | 380 G | 76 G |
| Cooling length | 1.1 m | |

# THE ELENA ELECTRON COOLER: PARAMETER CHOICE AND EXPECTED PERFORMANCE

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### *Abstract*

Electron cooling will be central to the success of the ELENA project which aims to increase by a factor of up to 100 the number of antiprotons available for the trap experiments. Because of the tight space constraints, the design of the device will be based on the compact electron cooler in operation on the S-LSR ring in Kyoto.

The biggest challenge will be to generate a cold and stable electron beam at an energy of just 55 eV in order to cool the 100 keV antiprotons. The use of photocathodes is excluded because their relatively short lifetime would require too many vacuum interventions during operation. We present the design parameters of our cooler as well as the results of the cooling performance simulations made with BetaCool and on-going work into "cold" cathodes.

## INTRODUCTION

The Extra Low ENergy Antiproton ring (ELENA) project is aimed at substantially increasing the number of antiprotons delivered to the Antiproton Decelerator (AD) physics community. ELENA will be a small machine that receives antiprotons from AD at a kinetic energy of 5.3 MeV and decelerates them further down to 100 keV [1]. Electron cooling will be essential in ELENA in order to reduce or eliminate the emittance blow-up caused by the deceleration process and obtain the small emittance antiproton beams needed for further deceleration and extraction to the trap experiments.

Right after injection into ELENA at 100 MeV/c the beam is decelerated to 35 MeV/c where electron cooling is applied in order to eliminate losses caused by injection mismatch and beam blow up during the deceleration process [1]. Cooling is applied a second time after deceleration to the extraction momentum of 13.7 MeV/c (100 keV kinetic energy) in order to achieve required values of the beam emittances and momentum spread (See Fig.1).

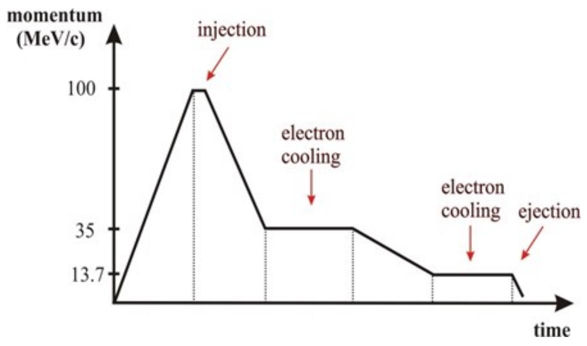

Figure 1: ELENA cycle

## THE ELECTRON COOLING DEVICE

The cooler will be installed in long straight section 4 of the machine and will take up almost half the available space. The rest of the section will accommodate the orbit correctors and the compensation solenoids of the cooler. Due to the size limitations of the straight sections in ELENA, the space available for the electron cooler is 1930 mm flange to flange. This makes room for a drift solenoid with a length of 1000 mm. The cooler will have a beam height of 1200 mm as is the standard for the ELENA/AD complex. The electron cooler is envisaged to be mounted horizontally for easier maintenance and access.

Due to the space constraint, we have decided to base our design on the device built by Toshiba Corp. for the S-LSR project at Kyoto University [2]. This compact cooler was also built for use at relatively low energies with very high field uniformity and utilising the latest advances in cooler design (Fig. 2). The main cooler parameters are summarised in Table 1.

Table 1: Main Electron Cooler Parameters

| Momentum | 35 MeV/c | 13.7 MeV/c |
|---|---|---|
| Electron beam energy | 355 eV | 55 eV |
| Electron current | 5 mA | 2 mA |
| $B_{gun}$ | 1000 G | |
| $B_{drift}$ | 100 G | |
| Toroid bending radius | 0.25m | |
| Cathode radius | 8 mm | |
| Electron beam radius | 25 mm | |
| Twiss parameters | $\beta_h$=2.103m, $\beta_v$=2.186m, D=1.498m | |
| Cooling (drift) length | 1.0 m | |
| Total cooler length | 1.93 m | |

The vacuum system will be similar to the one used for the LEIR cooler, namely; NEG cartridges at the gun and collector where the gas load is the highest, NEG coating of the vacuum chambers and NexTorr ion pumps in the cooling section.

For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the magnetic field guiding the electrons from the gun to the collector.

# RESULTS FROM STEP I OF MICE AND PHYSICS PLAN FOR STEP IV

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on behalf of the MICE collaboration

## *Abstract*

The Muon Ionisation Cooling Experiment (MICE) will demonstrate ionisation cooling, an essential technology for a Neutrino Factory and/or Muon Collider, by measuring a 10% reduction in emittance of a muon beam. A realistic demonstration requires beams closely resembling those expected at the front-end of a Neutrino Factory, *i.e.* with large transverse emittance and momentum spreads.

The MICE muon beam line at ISIS, Rutherford Appleton Laboratory, was built to provide beams of different momenta and emittance so that the performance of the cooling channel can be fully explored. During Step I of MICE, a novel technique based on time-of-flight counters was used to establish that the beam emittances are in the range 0.6–2.8 $\pi$ mm-rad, with central momenta from 170–280 MeV/$c$, and momentum spreads of about 25 MeV/$c$.

The emittances of the beams will initially be increased by scattering in high-$Z$ material. Low-$Z$ absorbers, such as liquid hydrogen and LiH will be used to reduce the emittance of the beam. The physics program of Step IV of MICE is discussed, including all stages necessary for a first demonstration of ionisation cooling.

## INTRODUCTION

Muons produced at the front-end of a Neutrino Factory occupy a large area of phase space, which must be reduced before they are stored and accelerated. For example, the Neutrino Factory requires a large transverse emittance beam of $\varepsilon_N \approx$12–20 $\pi$ mm-rad to be reduced to 2–5 $\pi$ mm-rad. Conventional cooling techniques are inapplicable to reducing the emittance of muon beams due to the short muon lifetime. A different technique is required to maximise the muon flux delivered to a storage ring.

Ionisation cooling is the only possible method of reducing the emittance of a muon beam. Muons pass through a low-$Z$ material, losing energy by ionisation, which reduces their momentum components. They are then re-accelerated, which restores longitudinal momenta, resulting in a net reduction in the divergence of the beam and therefore the transverse emittance. The reduction in emittance, $\frac{d\varepsilon_N}{ds}$, is given by

$$\frac{d\varepsilon_N}{ds} = \frac{\varepsilon_N}{\beta^2 E_\mu}\left\langle\frac{dE}{ds}\right\rangle + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}, \qquad (1)$$

where $\varepsilon_N$ is the normalised transverse emittance, $\beta$ the relativistic velocity, $E_\mu$ the energy, $\frac{dE}{ds}$ the energy lost by ionisation, $m_\mu$ the mass of the muon, $X_0$ the radiation length of the absorber material, and $\beta_\perp$ the transverse beta function.

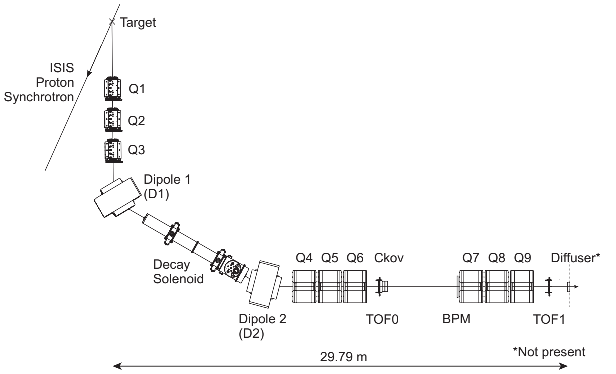

Figure 1: The MICE upstream beam line during Step I in 2010–11.

The first term describes "cooling" by ionisation, and the second describes "heating" by multiple scattering. Hence, a small $\beta_\perp$ and large $X_0$ are necessary features of an ionisation cooling channel.

The Muon Ionisation Cooling Experiment (MICE) will measure the cooling efficiency of one "SFOFO" lattice cell based on the cooling channel design of Neutrino Factory Feasibility Study 2 [1]. The cooling channel will accept beams with a momentum spread of $\approx$ 20 MeV/$c$ about central momenta in the range 140–240 MeV/$c$, and transverse emittances of 3–10 $\pi$ mm-rad. The beam will pass through a sequence of liquid hydrogen absorbers and RF cavities, contained within a solenoidal focussing channel, where its emittance is reduced by $\approx$ 10%. This reduction will be measured to 1% precision using single-particle measurements with scintillating fibre trackers inside a 4 T solenoid field (the "spectrometer solenoids"). Particle identification is provided upstream by threshold Cherenkov and time-of-flight (TOF) detectors, and by a pre-shower detector and muon ranger downstream.

## CHARACTERISATION OF THE MICE BEAM LINE

A realistic demonstration of cooling requires beams resembling those expected at the front-end of a Neutrino Factory. The new muon beam line at the ISIS proton synchrotron, Rutherford Appleton Laboratory, has been designed to produce beams of variable emittance and momenta. The beam line is described in [2] and is shown in Figure 1. The ISIS proton beam is sampled by a titanium target, creating pions that are captured by the upstream quadrupoles (Q1–3). The pions are momentum-selected at the first dipole, D1, and transported to the Decay Solenoid which captures the decay muons.

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# PROGRESS TOWARDS THE COMPLETION OF THE MICE APPARATUS

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*on behalf of the MICE Collaboration*

## *Abstract*

MICE aims to demonstrate 10% ionisation cooling of a synthesised beam of muons by its interaction with low Z absorber materials followed by restoration of translational momentum in RF linacs. Extensions to the apparatus required to achieve Step IV, including the first absorber cell, of either liq. $H_2$ or LiH, and the two particle tracking spectrometers shall be described. Two very large superconducting spectrometer solenoids and one focus coil solenoid will provide a magnetic field of up to 4 T in the volume of the two trackers and the absorber cell respectively. The development, testing and integration of these challenging components will be reported. Progress towards Steps V & VI will be presented: tests of the RF cavities to demonstrate the required 8 MV/m gradient in a strong magnetic field; the RF drive system to deliver 2 MW, 1ms pulses of 201 MHz frequency at a PRF of 1 Hz; the distribution network to deliver 1 MW to each cavity with correct RF phasing; diagnostics to determine the gradient and transit phase of the muons and the development of the very large diameter magnets required for the accelerators.

## INTRODUCTION

The Muon Ionisation Cooling Experiment (MICE), Fig. 1, is being created to demonstrate that ionising interactions with low Z 'absorber' materials, specifically LiH and Liq. $H_{2,}$ followed by re-acceleration can reduce the emittance of a muon beam in the momentum range of 140-240 MeV/c [1]. Future muon accelerators would have a 'front end' with a repeating lattice of such devices to reduce the emittance to the level demanded by the application. In MICE, the muon beam is formed by the decay of pions generated by the impact between a fraction of the high power proton beam in the ISIS synchrotron and a dynamically inserted target [2]. The experiment aims to measure a 10% reduction in emittance to 1% accuracy in a set up consisting of 3 'absorber' and 2 RF acceleration cells, see Fig 1.

MICE is being conducted in stages, referred to as 'steps'. Step I is complete and the apparatus is now being prepared for the imminent Step IV measurements (which incorporate Steps II and III) and finally Step VI where sustainable cooling will be tested. The staging is illustrated in Fig 2.

## EXPERIMENTAL APPROACH

To measure emittance to the required levels, MICE uses a single particle technique, where the behaviour of a real beam will be reconstructed from precision measurements of the behaviour of individual particles.

The muons are first momentum selected by the magnets in the transport system from the ISIS synchrotron hall into the MICE hall. The particle species is identified to select the muons for analysis using a range of detectors: time of flight (ToF); threshold Cherenkovs and sampling calorimeter [3]. These have been used in Step I to analyse the constitution of the beam and to perform, using a novel technique, preliminary measurements of the emittance.

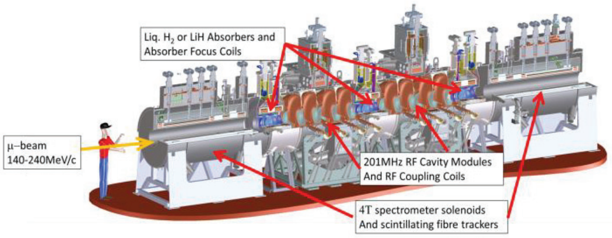

Figure 1: The MICE Step VI Cooling channel.

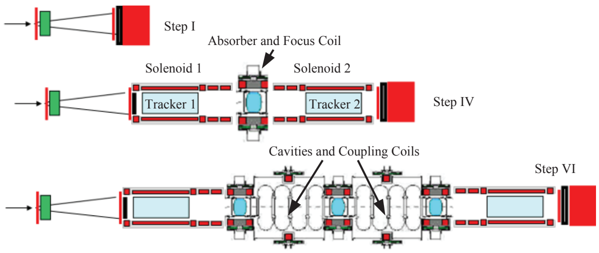

Figure 2: The MICE phased construction project.

In Step IV, the first studies will be undertaken of the effect of transporting the muons through the absorbers [4]. This requires the addition of the first absorber cell and absorber focus coil, along with a much augmented suite of detectors, specifically a pair of scintillating fibre trackers [5] to provide precision phase space measurements of each muon at the entrance and exit of the absorber cell. The measurements will be compared to predictions and simulations of the ionisation cooling process. Enhanced particle identification will be enabled by the electron muon ranger (EMR) detector which will stop all particles and identify muons by the distribution of their energy deposition. Step VI adds two further absorber units, the three absorber cells bracketing a pair of RF accelerators to restore the electron translational momentum. The 8 individual cavities are separated by beryllium windows and are driven by 4 high power 201MHz amplifier chains, with 1MW delivered to each cavity. This will allow a study of the cooling process in an energy sustaining system. An option remains to perform a 'Step V' experiment as an intermediate stage, which would use four RF cavities (i.e. one linac module) sandwiched by 2 absorber cells.

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# THE NOVEL OPTICAL NOTCH FILTER FOR STOCHASTIC COOLING AT THE ESR

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### *Abstract*

In the frame of the development for the FAIR facility at GSI, notch filter cooling is essential for the stochastic cooling system of the CR (Collector Ring). A prototype notch filter based on optical components has been developed and assembled. The focus was to achieve sufficient notch depth and low periodicity error of the filter transfer function. The compact optical notch filter was integrated into the ESR stochastic cooling system. Longitudinal cooling of heavy ion beams was successfully demonstrated. The layout of the notch filter and the experimental results are presented.

## INTRODUCTION

The principle of a correlation notch filter consists of splitting the input signal into two lines with different electrical lengths. The short line is the direct connection and the long line is the connection with additional delay T. Both branches should have the same attenuation. If the basic propagation delay time of the short line is $t_0$, for the long one it should be $t_0$+T. The signals of both lines are subtracted from each other. This ideal notch filter with the transfer function given by equation (1) has zero transmission at all harmonics $nf_0$ (notches spaced by $f_0=1/T$ in frequency) and maximum transmission at frequencies $(n+1/2)f_0$, $n=0,1,...\infty$. The phase jumps by 180° at each notch.

$$S_{21,ideal} = \frac{S_0}{2}(1-\mathrm{e}^{j\omega T}) = -j\,|S_0|\sin\left(\frac{\omega T}{2}\right)\mathrm{e}^{j\omega\left(t_0+\frac{T}{2}\right)} \qquad (1)$$

$$S_0 = |S_0|\,\mathrm{e}^{j\omega t_0}$$

When the notch filter is used for longitudinal stochastic cooling of the ion beam in the storage ring (Thorndahl's method [1]), the delay T (notch distance $f_0=1/T$) should be exactly equal to the nominal revolution period (frequency) of the beam. Also, $\omega=2\pi\cdot n(f-f_0)$, where f is the revolution frequency of each beam particle. Physically, the notch filter response combined with an additional 90° phase-shift pushes particles with wrong revolution frequency to the nearest notch and does not affect particles with the nominal revolution frequency. The time of flight (TOF) longitudinal cooling method [2] uses only the short line of the filter combined with a -90° phase shift [3]. In practice, the TOF method is applied by opening the long branch of the notch filter (e.g. switching off the lower detector in Fig. 1) and shifting the phase by 180° with respect to the notch filter setting.

The optical notch filter was developed, measured in the lab and then integrated into the ESR stochastic cooling system which operates in the bandwidth 0.9-1.7 GHz and at the nominal ion beam kinetic energy of 400 MeV/u (velocity β=0.71), corresponding to a revolution frequency of 1.96 MHz.

## THE OPTICAL NOTCH FILTER

The classic approach is to use a long coaxial cable as delay line. This has different problems. The long cable has large frequency-dependent losses and dispersion. Also, a low-loss cable longer than 100 m is very bulky. In an optical notch filter, an optical fibre is used instead of the coaxial cable. Instead of a baseband signal on a coaxial cable, which has a high relative bandwidth, the signal on an optical fibre is modulated on a 1550 nm (i.e. THz range) carrier. This signal has a small relative bandwidth and, as a result, frequency-dependent losses and dispersion are negligible. Mechanically the optical filter is very compact; the setup presented here was built on a 0.84 $m^2$ plate.

### *Components of the Notch Filter*

At the input of the notch filter the electrical RF signal is amplitude-modulated on light by a laser modulator (Mitec LBT-10M3G-25-15-M14 FA). The optical output power is measured to be 6.8 dBm. The optical signal is split by a single mode wideband coupler 1x21551 FC APC in two branches. Each output level is 3.5 dBm. The short branch contains a fixed attenuator of 6 dB, type PLK-FA-DW 2 dB connected in series with a 4 dB attenuator. The power level after both attenuators is -3.1 dBm. The short branch determines the propagation delay $t_0$ (i.e. the electrical length) of the filter. In our case $t_0$= 5.44 ns.

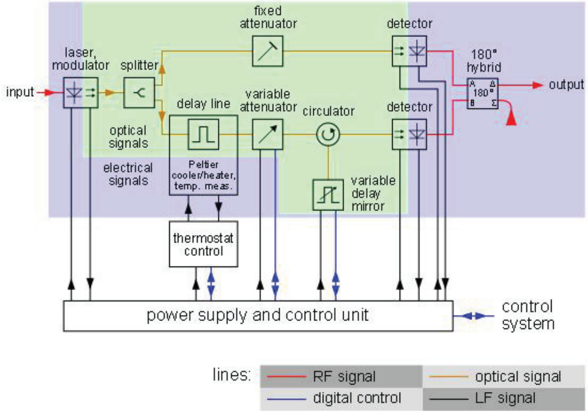

Figure 1: Block diagram of the optical notch filter.

# RF-SYSTEM FOR STOCHASTIC COOLING IN THE FAIR COLLECTOR RING

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## *Abstract*

The collector ring (CR) of the FAIR project is designed for fast stochastic cooling of rare isotope and antiproton beams injected at different velocities. A flexible RF signal processing scheme for the stochastic cooling system will be presented. It includes cooling with time of flight (TOF), notch filter and Palmer methods. A Palmer pick-up with Faltin electrodes is foreseen for pre-cooling of hot rare isotope beams. For TOF and notch filter methods, a horizontal and a vertical pick-up tank with movable cryogenic slotline electrodes for ions with two different velocities is under development. The layout of this slotline pick-up tank will also be presented.

## INTRODUCTION

The signal processing for the stochastic cooling has to be very flexible. The rare isotope beams (RIBs) or stable heavy ions will have a relativistic $\beta$=0.83 and the antiprotons ($\bar{p}$) will have $\beta$ =0.97. The stored beam current varies from 21 nA ($10^5$ $\bar{p}$) to 17 mA ($10^9$ $U^{92+}$ions). The stochastic cooling system should achieve a 6D phase space volume reduction of $9*10^3$ in 9 s for $1*10^8$ $\bar{p}$ and $1*10^6$ in 1 s for $1*10^8$ $U^{92+}$ions. The beam diameter at the pick-up will be up to 160 mm at injection and will shrink to $\leq$20 mm after cooling.

For cooling of $\bar{p}$ and RIBs there will be two cryogenic pick-up tanks with movable slotline electrodes located at zero dispersion. For hot RIBs, the unwanted mixing from this position to the kicker is too large. Therefore, there will be an additional pick-up with Faltin type electrodes at a high dispersion position nearer to the kicker for Palmer precooling of RIBs. The Faltin type pick-up is discussed in another paper at this workshop [1]. The frequency band of the system is 1-2 GHz in the start version. For an upgrade to a frequency band of 2-4 GHz, space for one additional pick-up tank and one additional kicker tank for $\bar{p}$ cooling is reserved in the ring.

## SLOTLINE PICK-UP TANK

The slotline pick-up tanks will be used for cooling in all three planes of $\bar{p}$ and RIBs. The notch filter or the TOF method will be applied for longitudinal cooling. A group of eight coupling slots in a row with 25 mm spacing will be integrated together with the first Wilkinson combiner on a common alumina printed circuit board (PCB) [2]. The eight signals from this PCB will be combined to a single vacuum feedthrough. The seven Wilkinson combiners and the delay lines are integrated on a second PCB. The delay lines are dimensioned for $\bar{p}$. The RIBs deliver much stronger signals compared to the antiprotons. The slight performance degradation due to the fixed delay lines is acceptable. Two of these modules will be mounted together on a linear motor- driven support. So, the modules can follow the decreasing beam envelope from ±80 mm to ±10 mm during the cooling process [3].

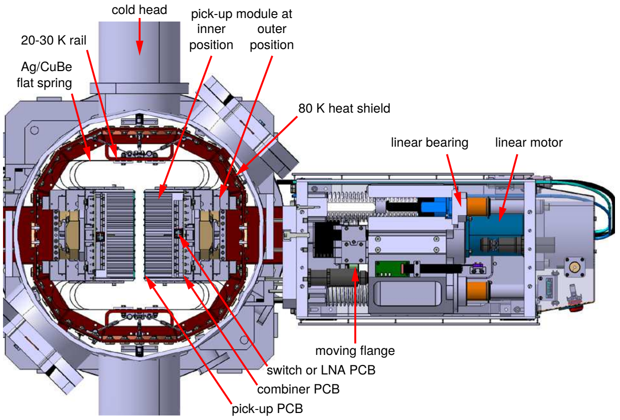

Figure 1: Sectional view of the prototype cryogenic slotline pick-up tank.

Fig. 1 shows a sectional view of the tank. The modules are thermally coupled by silver plated BeCu flat springs to the second stage of two cold heads. These cryogenic coolers will bring down the temperature to 20-30 K. The first stages of the cold heads will cool down a heat shield and the support rods to 80 K. In the start version, one low noise amplifier (LNA) per module, directly behind the vacuum feedthrough at the movable flange is foreseen. As an ugrade, a cryogenic LNA can be installed inside the module between the pick-up and the combiner PCB. A LNA at this point would not see the losses of the internal combiners and RF lines. The slotline coupler with the first Wilkinson combiner has an high reflection factor. Therefore, this LNA would see its own electrically cold input as terminator. These two benefits can significantly increase the signal to noise ratio. Additionally, each module will have a test signal input, which can be switched to each slot individually or phase correct to all slots in order to simulate a $\bar{p}$ beam. This input can be used for commissioning and self test without beam.

The signals from eight modules per side will be combined to one signal. The combiner will have integrated switchable delay lines ($\beta$ switch). A 180° hybrid combines the signal from the two sides to a sum signal (longitudinal) and a difference signal (transversal). There will be one tank for horizontal and one for vertical cooling. Behind the hybrids, the signals go to the pick-up signal processing inside the radiation shielded inner part of the building. The longitudinal signals from the two tanks will be combined through a $\beta$ switch to a common sum signal.

# DESIGN OF THE PALMER PICKUP FOR STOCHASTIC PRE-COOLING OF HEAVY IONS IN THE CR

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### *Abstract*

We report on the design of a Faltin type pickup for the stochastic cooling of rare isotope beams (RIBs), using a bandwidth of 1–2 GHz, for the Collector Ring (CR) at GSI. Through HFSS simulations using an eigenmode solver, the impedance and signal output phases are calculated and presented.

## INTRODUCTION

The CR is designed for the efficient collection and fast 3D stochastic cooling of antiprotons at 3 GeV or rare isotopes (RIBs) at 740 MeV/u [1]. The CR stochastic cooling system will operate in the frequency band 1–2 GHz.

For the noise-limited antiproton cooling, slotline pickups are foreseen [2]. In the CR, the notch filter method [3] is indispensable for longitudinal cooling.

Heavy ion cooling in the CR is limited by the undesired mixing, and for the hot RIBs, the Schottky bands overlap, so that only the Palmer method [4] can be applied initially. After the momentum spread is decreased so as to fit into the acceptance of the notch filter, cooling will proceed with the slotline pickups down to the final beam quality.

At present, slotline kickers, reciprocal to the slotline pickups are planned, but their current design may change if they cannot withstand the high microwave power (250 W/ 8 slots).

The RIBs have to be cooled from $\varepsilon_{xy}$= 45 mm·mrad and $\delta p/p = 0.2\%$ to $\varepsilon_{xy}$=0.125 mm·mrad and $\delta p/p = 0.025\%$ (all values are 1 $\sigma$ values) within 1.5 s.

The Palmer pickup tank will be equipped with Faltin type pickups which are favorable due to their robustness, ease of manufacture and the fact that combiner boards are not needed in principle. A good signal to noise ratio is envisioned due to the high charge of the RIBs, therefore cryogenics or plunging is not foreseen.

### *3D Cooling at the Palmer Pickup*

The Faltin pickups are placed at a point of high dispersion in the ring so as to fulfill momentum cooling as envisioned by R. Palmer in 1975, private communication. The signals at the pickup are combined to extract a vertical error signal and a combined horizontal and longitudinal error signal as shown in Fig. 1.

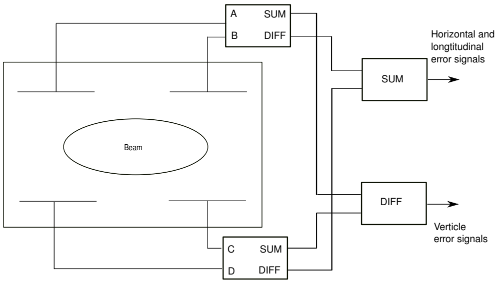

Figure 1: Diagram of the Palmer cooling method showing the combination of signals in sum and difference modes.

### *Faltin Electrode*

The Faltin electrode [5] is a rectangular coaxial waveguide with slots which couple to the beam as shown in Fig. 2. Figure 2 shows a diagram of four Faltin rails installed in a beam chamber in the configuration envisioned for Palmer cooling in the CR.

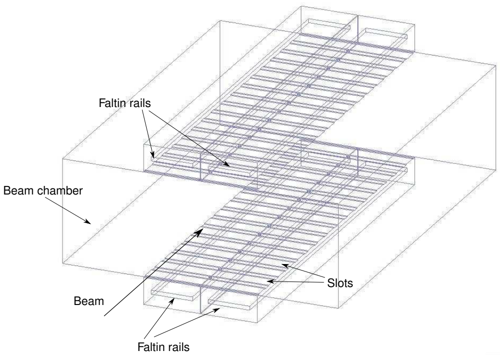

Figure 2: Diagram of a section of the beam chamber at the Palmer pickup with the Faltin rails.

The wave in the pickup induced by the beam travels parallel to the beam direction such that every time a particle passes a slot it induces an additional wave which adds to the existing wave. Therefore, in a Faltin type pickup, it is crucial that the waveguide be designed such that the phase velocity approximately equals the particle velocity so that all waves induced by a particle passing a slot interfere constructively to produce a good output signal.

Previous work on these type of pickups has included analytical approaches to calculating the coupling and the characteristics of induced waves [6, 7]. Experimental results were later published for a slot to TEM type pickup [8].

The primary mode in the waveguide is TEM due to its coaxial structure. However, in addition to slowing down the wave, the slots in the top of the waveguide have the effect of creating a quasi TEM mode which is subject to some dispersion.

Both the dispersion and the mismatch between particle velocity and phase velocity in the waveguide will result in

# BEAM CRYSTALLIZATION — ARE WE THERE YET?*

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## *Abstract*

A brief review is made of Coulomb crystallization of a charged particle beam circulating in a storage ring at high speed. An ideal crystalline state is reached when the beam is cooled to near the absolute zero temperature. The corresponding emittance is also nearly zero, which means that the crystalline beam has the highest quality achievable in principle. Through past theoretical studies, it has been revealed that beam crystallization is feasible only in a storage ring that satisfies several physical conditions. This paper summarizes those necessary conditions and illustrates why they are so important in establishing the ultimate state of a beam.

## INTRODUCTION

In any practical applications of particle beams, we certainly care about the beam quality, or in other words, the *emittance* that represents the phase-space volume occupied by the beam. A beam has better quality and is thus more useful as the emittance becomes smaller. Since the emittance cannot be negative, its ultimate limit is zero. An interesting question is whether such an ultimate state is physically allowable. If it is, we might raise more questions including "what conditions are required to stabilize the zero-emittance state?", "how can we reach there in practice?", etc.

To the best of the author's knowledge, the phase transition of a charged particle beam toward an ultralow emittance state was first discussed by Russian researchers when they tried to explain an anomalous behavior of electron-cooled ion beams in the NAP-M storage ring [1]. Later, John Schiffer and his co-workers performed systematic molecular dynamics (MD) simulations demonstrating that a one-component plasma confined by a uniform external restoring force can form a spatially ordered structure at very low temperature [2]. This seminal work was followed by further MD studies by Wei, Li, and Sessler who incorporated effects from realistic alternating-gradient (AG) lattice structures of modern accelerators into their simulations [3]. It is now believed that the periodic and dispersive nature of a cooler storage ring imposes severe restrictions upon the realizability of beam crystallization [3, 4]. In fact, nobody has succeeded in generating a crystalline beam while very low-energy, moving Coulomb crystals were produced in a tabletop circular Paul trap [5].

This paper focuses on the dynamics of crystalline beams, outlining past theoretical progress. After clarifying the definition of beam crystallization, we show several conditions essential to establish such an ultimate low-emittance state. We then consider possible cooling schemes toward beam crystallization.

## COULOMB CRYSTALS

In Paul traps [6], it is straightforward to make a variety of Coulomb crystals by employing the laser cooling technique. Figure 1 shows the fluorescence images of actual Coulomb crystals produced in a compact linear Paul trap at Hiroshima University. Each bright spot corresponds to a single $^{40}\mathrm{Ca}^{+}$ ion Doppler cooled by a semi-conductor laser system to a mK range. The upper panel is a picture of the so-called *string* crystal where cooled ions are aligned along the trap axis at almost equal intervals. By adding more ions, this simple string formation converts into a *zigzag* structure. Above a certain density threshold, the zigzag formation is eventually transformed to a *shell* structure as shown in the lower panel. The number of the ion shells increases as the line density becomes higher. The structural transitions of infinitely long Coulomb crystals can be well explained by the Hasse-Schiffer theory [7].

The phase transition of a one-component plasma is often characterized by the Coulomb coupling constant defined as the ratio of the average Coulomb potential energy to the thermal energy:

$$\Gamma = \frac{q^2}{4\pi\varepsilon_0 d}\cdot\frac{1}{k_B T}, \qquad (1)$$

where $q$ and $2d$ are the charge state and the average distance of particles, $k_B$ is the Boltzmann constant, and $T$ denotes the plasma temperature [8]. Regular *gaseous*

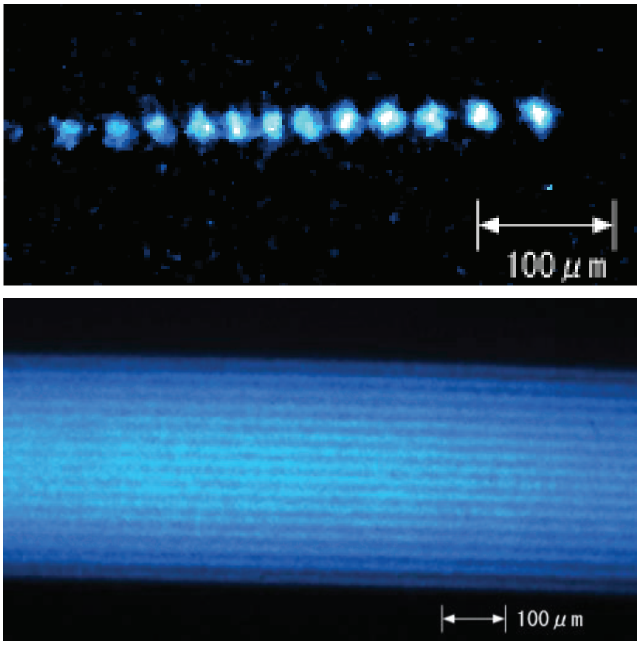

Figure 1: Fluorescence images of a string (upper) and multi-shell (lower) Coulomb crystals produced in a linear Paul trap by Doppler laser cooling.

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# LATEST RESULTS OF EXPERIMENTAL APPROACH TO ULTRA-COLD BEAM AT S-LSR*

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## *Abstract*

Utilizing S-LSR which has a super-periodicity of 6 and is designed to be tough against resonant perturbation to the circulating beam, we have tried to approach as low as possible temperature with laser cooled 40 keV $^{24}Mg^+$ ion beam. With the use of theoretically proposed Synchro-Betatron Resonance Coupling scheme, we have experimentally demonstrated the capability of active indirect transverse laser cooling. At first, the achieved transverse cooling efficiency was limited due to heating caused by intra-beam scattering (IBS). For the purpose of reduction of IBS heating, we have established a scheme to control the circulating ion beam intensity down to ~$10^4$ by scraping the outskirt of the beam with the use of a horizontally moving scraper, which enabled us to cool down the transverse beam temperatures down to 20 K and 29 K for horizontal and vertical directions, respectively for the operation tune without H-V coupling. They were modified to be 40 K and 11 K by the horizontal and vertical coupling with the difference resonance with an excitation of a solenoid of 22.5 G, which were further improved to 7.0 K and 2.1 K adding deceleration by an induction accelerator of 6 mV/m using a -26 MHz detuned laser.

## INTRODUCTION

S-LSR has a high super-periodicity of 6 in order to realize a good performance for the beam dynamical point of view, which had been already demonstrated by 1D ordering realized at S-LSR for single charged 7 MeV proton beam [1]. Applying such characteristics of S-LSR, we have tried to realize a very low temperature ion beam with the use of laser cooling. According to computer simulations utilizing Molecular Dynamics [2], it is expected that a crystalline string of 1D or 2D will be created for ion numbers up to $10^3$ if enough power and number of lasers are utilized. In real S-LSR experiments, however, only a single laser co-propagating with the 40 keV $^{24}Mg^+$ ion beam could be utilized. Because of the heating effect caused by intra-beam scattering (IBS), the efficiency of indirect transverse laser cooling was found to be poor as is described below for the ion beam intensity of ~$10^7$. We have applied beam scraping to reduce the IBS effect and found the fact that the efficiency of the transverse indirect laser cooling has been improved so much as the computer simulation expects [3] by reducing ion beam intensities down to $10^4$, where we could attain needed S/N ratio to measure the transverse beam size, although attainment of crystalline string might need further one order of magnitude reduction of the ion beam intensity.

## INDIRECT TRANSVERSE LASER COOLING

### *Synchro-Betatron Resonance Coupling (SBRC)*

Among various cooling schemes, laser cooling has the strongest cooling force for the direction parallel to the beam path. The cooling effeciency in the transverse directions reported so far, however, is rather poor mainly due to heat transfer between the longitudinal and transverse directions caused by IBS [4] or parallel displacement of the laser from the ion beam orbit at a finite dispersion position [5].

An active indirect transverse laser cooling scheme which utilizes “Synchro-Betatron Resonance Coupling (SBRC)” has been proposed by H. Okamoto, A.M. Sessler and D. Möhl [6]. It utilizes a resonance coupling of the synchrotron and betatron motions in the longitudinal and horizontal phase spaces under the condition that

$$\nu_H - \nu_s = l \quad (l\text{: integer}) , \tag{1}$$

where $\nu_H$ and $\nu_s$ are the numbers of horizontal betatron oscillation and synchrotron oscillation, respectively. Furthermore a coupling of the horizontal and vertical directions is required, leading to the condition

$$\nu_H - \nu_V = m \quad (m\text{: integer}), \tag{2}$$

where $\nu_V$ represents the vertical betatron tune. Horizontal-vertical coupling can be realized by using a solenoidal magnetic field.

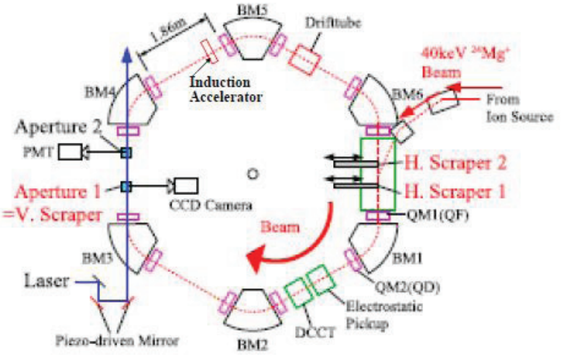

Figure 1: Layout of S-LSR and laser cooling equipments.

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# SIMULATION STUDY ON TRANSVERSE LASER COOLING AND CRYSTALLIZATION OF HEAVY-ION BEAMS AT THE COOLER STORAGE RING S-LSR

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*Abstract*

Multi-dimensional laser cooling of heavy-ion beams at the cooler storage ring S-LSR in Kyoto University is studied numerically using the molecular dynamics simulation technique in which the stochastic interaction between ions and laser photons is incorporated. The purpose of the study is to find out how low-temperature we can achieve using actual experimental parameters and to verify the observation result in the experiment. In these proceedings, the characteristics of the ion beam laser-cooled in S-LSR are reported. It has been confirmed that, in spite of the limitation in the experimental conditions such as a single laser beam, low power, fixed detuning and short laser-cooling section, the three-dimensionally low-temperature beam is obtained through resonant coupling at a low intensity of $10^4$ ions in the ring, which is consistent with the experimental result. It is also demonstrated that a string crystalline state of the beam can be formed at a further lower intensity.

## INTRODUCTION

Laser cooling is the most promising technique for achieving an ultralow-temperature ion beam or even crystallization since its lowest attainable temperature is very low, usually on the order of milli-Kelvin in principle. Actually, the performance of laser cooling in a storage ring was proven experimentally in 1990s [1, 2]; an ultralow beam temperature of 1 mK was attained in the longitudinal direction. However, the effective transverse laser cooling of the ion beam for beam ordering or crystallization failed practically, while indirect laser cooling in the transverse directions was achieved to some extent through intra-beam scattering of an ion beam pre-cooled by electron beams [3] and through dispersive coupling [4]. Theoretical studies have proven that the biggest reason of this failure is that the focusing lattice structures of the storage ring were not appropriate to generating a low-temperature space-charge-dominated beam [5].

It is now well-known that an operating point of a storage ring must be chosen properly for the formation of an ultralow-temperature beam including a crystalline beam [5]: The kinetic energy of the beam must be below transition energy of the ring and the average bare betatron phase advance must be less than 127 degrees per lattice period. The latter criterion "maintenance condition" is required to avoid the linear resonance at ultralow temperature. Practically, crossing linear resonances must be avoided in the cooling process of the beam: For this purpose, the betatron phase advance must be less than 90 degrees per period [6]. Note that, when the line density of the beam is very low, these criteria on betatron tunes may not always be met for the stability of ultralow-temperature beams [7].

A compact cooler storage ring S-LSR was newly built at Kyoto University in 2005 [8]. S-LSR can satisfy the above lattice conditions toward the realization of beam crystallization, and is equipped with a laser-cooling system of a $^{24}\mathrm{Mg}^{+}$ ion beam as well as with an electron-cooling system. Several stable operating points can be chosen for efficient transverse cooling. Transverse laser cooling has been investigated experimentally to attain ultralow-temperature ion beams in the ring [9-13]. Recently, efficient transverse laser cooling has been accomplished for a low-current beam through the resonant coupling [14].

Molecular dynamics (MD) simulations have been performed in parallel with the experiments to clarify how the beam is laser-cooled at S-LSR. In these proceedings, MD simulation results are shown to reveal the characteristics of laser-cooled Mg beams in S-LSR. In addition, the feasibility of one-dimensional (1D) beam crystallization is explored.

## MOLECULAR DYNAMICS SIMULATION CODE

A dedicated MD simulation code CRYSTAL is employed for the present study [15-17]. The three-dimensional (3D) equation of motion derived from the Hamiltonian in the beam rest frame is integrated in a symplectic algorithm in the code. The focusing effects from skew quadrupole and solenoid magnets as well as

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# LASER COOLING OF RELATIVISTIC $C^{3+}$ ION BEAMS WITH A LARGE INITIAL MOMENTUM SPREAD

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## *Abstract*

We present results on laser cooling of stored relativistic $C^{3+}$ ion beams at the Experimental Storage Ring (ESR) in Darmstadt. For the first time, laser cooling of bunched relativistic ion beams using a continuous-wave UV-laser that was widely tunable over a large frequency range has been demonstrated. This new scheme allows to address the complete, initially broad momentum distribution of the ion beam without the need of additional electron cooling. Most importantly, this new method can be directly adopted to future high-energy ion storage rings where a previous scheme, based on varying the bunching frequency, can no longer be employed. As conventional beam diagnostics reach their limit at the ultra-low momentum spreads achievable with laser cooling, we show that with in-vacuo detectors the fluorescence emitted by the laser-cooled ions can be used instead for optical beam diagnostics.

## INTRODUCTION

Future accelerator facilities, such as FAIR (Germany) [1] and HIAF (China), will provide high-energy beams of stable and rare (heavy) ions for fundamental research. Many of the experiments planned at these facilities, such as in-ring mass spectrometry of short-lived rare nuclei, tests of strong-field quantum electrodynamics with highly-charged ions, or in-beam x-ray spectroscopy of atomic transitions in heavy nuclei, will greatly benefit from ion beams with ultra-low momentum spread. Most of the existing storage ring facilities employ electron cooling to obtain ion beams with a low momentum spread ($\Delta p/p$) and a small diameter. However, at highly-relativistic energies or high $\gamma$ ($\gamma^2=1/(1-\beta^2)$, $\beta=v/c$), there are two major challenges to achieve electron cooling. The first challenge deals with the creation of high-current electron beams of several hundred mA and energies of several MeV [1, 2]. The second challenge comes from the fact that the cooling time increases as $\tau_e \propto \gamma^{3/2}$ [3]. For an electron beam energy of 8 GeV and a beam current of 1 A, this can lead to cooling times of above one minute to reach $\Delta p/p \approx 10^{-5}$ [4]. The high cost and the demanding technical efforts to perform electron cooling at such high energies are the main reasons why other methods are sought for. Schramm *et al.* [5] have suggested laser cooling as a promising alternative, and listed several advantages. Most importantly, for appropriate cooling transitions in highly charged ions, the laser cooling force scales with $\gamma^3$ and thus becomes very strong, yielding cooling times as short as milliseconds. Many different ion species can be laser-cooled due to the large Doppler-shift of the cooling transition frequency $f_0$ in the ion rest frame ($f=f_0\gamma(1-\beta)$, $f=c/\lambda$) and state-of-the-art laser systems of appropriate power [6]. Furthermore, at high $\gamma$-values, the fluorescence photons from the ions are emitted into a Lorentz-boosted cone of opening angle $\theta=1/\gamma$ [7]. This yields high photon rates and supports fluorescence detection of the laser-excited cooling transition, which, in turn, can be used for optical beam diagnostics and spectroscopy.

## ESR EXPERIMENT

After several years of planning [8], development [9], and tests [10], in August 2012 a laser cooling experiment using a cw laser system with a broad detuning range has been performed at the ESR [11]. The first goal of this beamtime was to demonstrate that the initially 'hot' ions in the bucket can be cooled by a single laser with a relative frequency scanning range surpassing the rf bucket acceptance, *i.e.* without changing the bucket frequency and without initial electron cooling. A second goal was to demonstrate *in-vacuo* optical detection of the UV-fluorescence from the laser-excited ions. Finally, systematic studies of the 'dynamics of laser cooling' with varying bunch lengths, rf-bucket amplitudes,

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# BEAM ACCUMULATION AND BUNCHING WITH COOLING

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*Abstract*

The accumulation of antiproton beam in the storage ring was successfully performed at CERN and FNAL with the use of a stochastic stacking system. In the original version of the FAIR project such a concept was envisaged at the accumulator ring named RESR. However in the modularized start version of FAIR, the RESR was postponed and the new concept of antiproton accumulation in the High Energy Storage Ring (HESR) was strongly demanded. The barrier bucket (BB) system with stochastic cooling was found with simulation work to have enough capabilities to accumulate the pre-cooled 3 GeV antiproton beam in the HESR. The Proof Of Principle (POP) experiment was performed at the GSI storage ring ESR with ion beams employing both the stochastic and electron cooling. The experimental results were in good agreement with the prediction of the simulation study. The concept of BB accumulation could be applied to the planned Collider of the NICA project at JINR. In the present paper the concept of BB accumulation and the short bunch formation including the space charge effects are presented as well as the analysis of the POP experiment.

## RF STACKING & COOLING

It is imperative to accumulate the hadron beam in the storage ring to perform the colliding experiment or the experiments with the use of an internal target. The first hadron collider was the CERN Intersecting Storage Ring, ISR [1] where the 25 GeV proton beam was injected from the PS and was RF stacked in the longitudinal phase space. It culminated in the maximal luminosity of $\sim 3\times10^{29}$ /cm$^2$/sec during the physics run with the accumulated circulating current of ~ 10 A. During the operation of ISR the first observation of Schottky signals was tried successfully and immediately the stochastic cooling (transverse cooling) was demonstrated. This discovery, stochastic cooling, brought out the decisive strategy of beam accumulation of secondary beams like antiproton or Rare Isotope Beam after that.

The low energy ion storage ring, TARN was constructed at the INS, Univ. of Tokyo where 28 MeV *He* ions were RF stacked from the Sector Focus cyclotron. The injected beam was adiabatically captured by RF and was accelerated (or decelerated) to the stack top energy where the RF was switched off and the beam was deposited there. Thus RF stacked ion beam had a large momentum spread and the stochastic cooling was subsequently applied to the stacked ion beam to reduce the momentum spread [2].

## STOCHASTIC STACKING

The accumulation of antiproton beam in the storage ring was performed at CERN with the stochastic stacking system. It was based upon the exponentially decaying cooling force in the horizontal direction employing several pickups, named Tails and Core, at the large dispersion section of the ring. In the FAIR project the storage ring, RESR was designed to accumulate the 3 GeV antiproton beam with stochastic stacking system following the successful CERN results.

A simplified theoretical model of the stochastic stacking process was developed by S. van der Meer [3] where the diffusion terms by electronic noise and intra-beam scattering are neglected and beam feedback effects are not taken into account. While these assumptions are not fulfilled in the real stacking system, this simplified approach could give some basic parameters of the stacking system.

Realistic parameters were determined by the numerical analysis with the use of the Fokker Planck code including the electronic noise, intra-beam scattering, notch filter characteristics and other effects. In Fig.1 the simulation results of the antiproton distribution of RESR after the optimization of many parameters such as positioning of PUs, Gain and notch-filter are illustrated [4].

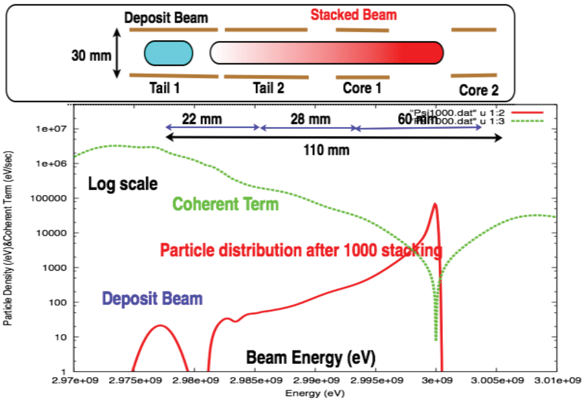

Figure 1: The layout of Tail1, Tail2, Core1 and Core2 PUs. Attained coherent term (green) and beam profile (red) of the 1000 times stacked 3 GeV anti-proton beam for RESR. The cycle time is 10 sec and the deposited particle number is $1\times10^8$/shot.

The frequency band of the two Tail's system are chosen as 1-2 GHz while for the Core system the wider band width 2-4 GHz is selected. The positioning of PUs, Tails

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# ADVANCES IN COHERENT ELECTRON COOLING*

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*Abstract*

Cooling techniques are required for improving the quality of hadron beams and increasing the luminosity in hadron- and electron-hadron-colliders. In contrast to light leptons that have very strong radiation damping via synchrotron radiation, the hadrons radiate very little (even in a 7-TeV LHC) and require an additional cooling mechanism to control the growth or reduce their emittances. In this paper, we focus on the advances in, and challenges of Coherent Electron Cooling (CeC) that promises to be an effective method of cooling of high-energy hadron beams, and potentially even ultra-relativistic muon beams.

Specifically, we describe the underlying physics principles, and the advances in this revolutionary, but yet untested, technique: viz., CeC. While we described physics principles in an earlier paper [1], our comprehensive studies revealed several other important factors affecting the CeC's performance [2-5]. In this paper, we summarize our main findings as well as presenting current advances and novel CeC schemes. We also briefly describe the CeC demonstration experiment under preparation at Brookhaven National Laboratory; its detailed description is part of these proceedings [6].

## INTRODUCTION

In contrast to electron- and positron-beams, hadron beams in all present-day storage rings and colliders do not have strong loss mechanism, such as synchrotron radiation and, therefore, there is no natural mode of damping to reduce their energy spreads and emittances. Cooling hadron beams transversely and longitudinally at the energy of the collision may greatly increase the luminosity of high-energy hadron colliders and future electron-hadron colliders, such as the RHIC [7] eRHIC [8], ELIC [9], and even the LHC/LHeC [10]. The high luminosity of these colliders is critical for high-energy physics and in high-energy nuclear physics.

Presently, two techniques are used for efficiently cooling hadron beams; electron cooling [11], and stochastic cooling [12]. Unfortunately, the efficiency of traditional electron cooling rapidly falls with the increase in the beam's energy. Detailed studies of this technique for RHIC demonstrated that its efficiency declines as hadron energy to the power 2.5. Consequently, the cooling time for 250 GeV protons in RHIC would exceed 30 hours, a time that is too long, and the strength of this cooling is too feeble to affect luminosity in RHIC, eRHIC, or in ELIC. It also will not suffice for reducing the beam's emittance and the bunch length of hadron beams envisioned eRHIC.

The efficiency of traditional stochastic cooling, while independent of the particles' energy, rapidly falls with the particles' number and their longitudinal density [12]. Hence, while this technique has been very successful with ion beams, it is ineffective for proton beams with a typical linear density ~$10^{11}$-$10^{12}$ protons per nanosecond. The eRHIC relies upon a very high longitudinal- and transverse-density of ions, with the growth times of intra-beam scattering (IBS) ranging from a few seconds to a few minutes. Present-day stochastic cooling [13] has cooling time ~10-100 hours, and cannot offer the cooling required to attain high luminosity.

Accordingly, it is impossible to assure the cooling of protons with energies from about 100 GeV in RHIC (or eRHIC) with conventional techniques. However, two potential candidates might be up to the task; viz., optical stochastic cooling (OSC) [14], and coherent electron cooling (CeC) [1].

The OSC technique is very interesting but highly inflexible; it is based on a fixed wavelength laser amplifying undulator radiation from the hadron beam. Hence, it is hardly useable, if at all, for hadron colliders operating at various energies. For example, operating the RHIC at 50 GeV and 250 GeV with the same OSC system would necessitate changing the amplifier wavelength by a factor of 25, i.e., well beyond the capabilities of current lasers.

In contrast, the CeC technique is based on the fully adjustable optics-free FEL-amplifying mechanism [1]. Furthermore, it does not necessitate our making any changes in the system, neither to support a large range of the operational energies nor for cooling different species. In addition, the amplifier's wavelength naturally scales with the particles' energy.

Finally, there are CeC schemes that do not require the FEL as an amplifier, the so-called hybrid and bunching/micro-bunching schemes [15-19] that we discuss briefly in next session; however, they await a detailed evaluation of their performance.

## COHERENT ELECTRON COOLING

The CeC scheme is based on the electrostatic interactions between electrons and hadrons that are amplified ether in a high-gain FEL or by other means. The CeC mechanism bears some similarities to stochastic cooling, but with the enormous bandwidth of the amplifier. Here, we briefly review the fundamental principles of physics involved in coherent electron cooling (CeC). Figure 1 is a schematic of a classical coherent electron-cooler, comprising a modulator, a FEL-amplifier, and a kicker. It also illustrates some aspects of the process of CeC.

Figures 2-4 depict three other schematics of the CeC using approaches other than an FEL amplifier [15-19]. These schemes are developed conceptually, and detailed studies still are essential, similar to that of the classical

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# NOISE SUPPRESSION IN RELATIVISTIC ELECTRON BEAMS*

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## *Abstract*

A brief rerview is presented of the various schemes which have been proposed for removing shot noise from a beam that will be used as a driver for a free electron laser. Attention is focused on just one of these schemes; namely that proposed in Ref. [1]. We begin with a general discussion of shot noise properties and their mathematical formulation. An analysis is developed which expresses noise suppression in terms of the longitudinal impedance in the region where interaction is taking place. The impedances of a number of different interaction regions are presented with numerical examples that demonstrate their efficacy for noise suppression. Comments are made about the application of noise suppression to real systems.

## INTRODUCTION

In a beam of randomly distributed particles, the longitudinal density exhibits uncorrelated fluctuations, commonly called shot noise. In free electron lasers (FEL), shot noise provides the start-up radiation for Self-Amplified Spontaneous Emission (SASE). There are situations, however, where the same density fluctuations may adversely affect FEL operation. For example, the microbunching instability incapacitates diagnostics of the beam and can lead to degradation of the FEL performance [2–7]. In seeded FELs shot noise competes with external modulations of the beam being amplified in the process of the seeding [8, 9]. In these situations suppression of the shot noise in the beam would lead to improved performance of the FEL and allow for a lower seed power in seeded machines. Suppressing shot noise could also allow controlling instabilities and increasing efficiency in cooling relativistic beams [10]. Suppression of shot noise is the subject of this paper.

Suppression of long wavelength shot noise was observed in microwave tubes as early as the 1950s, [11]. In the last few years, several groups have independently proposed suppressing shot noise at short wavelengths in relativistic electron beams [1, 12–14]. The first experimental observation of shot noise suppression at sub-micron wavelengths were recently reported in [15, 16].

We have to point out that noise suppression is not a cooling of the beam. As we will show below it involves the reactive part of the impedance associated with the particle interactions. One can say that it transfers the shot noise in the longitudinal ($z$) direction to the energy coordinate, where it is relatively benign for applications of interest. We will discuss how noise suppression can improve FEL performance, but also, as well, the difficulties associated with its application.

## APPROACHES TO SUPPRESS THE SHOT NOISE

One method for shot noise suppression (also chronologically first) was presented in Refs. [12, 13] where it was pointed out that the density fluctuations in a beam oscillate in time with the plasma frequency. If the beam is prepared in such initial state that there is only density fluctuation, and no energy, or velocity, fluctuation, after a quarter of the plasma period it will be fully converted to velocity fluctuation and the initial density fluctuation disappears.

This suppression method can be useful for beam energies that are not very large because the length required for a relativistic beam to execute a plasma oscillation increases with the beam energy. The beam plasma frequency, in the laboratory frame, is

$$\omega_p = c\left(\frac{4\pi}{\gamma^3 S}\frac{I}{I_A}\right)^{1/2}, \qquad (1)$$

where $I$ is the beam current, $I_A = mc^3/e \approx 17.5$ kA is the Alfven current, and $S$ is the transverse cross section area of the beam. As an example, consider the following beam parameters: beam energy 1 GeV, $I = 1$ kA, $S = 100\ \mu$m $\times 100\ \mu$m, which give for the quarter plasma period length $\pi c/2\omega_p \approx 16$ m. Lower currents or higher beam energies make this distance longer and, hence, less atractive.

Another approach, which seems more attractive in the limit of high energies, was proposed in [1]. In this paper we will focus only on the second approach, for it has the promise of a more compact setup. In this approach a relatively short interaction region is used followed by a dispersive element, see Fig. 1. Of course it is an approximation to confine the interaction to a particular region but for conceptual purposes it is convenient to think this way. A complete calculation would be needed to quantify this approach.

Figure 1: Schematic of noise suppression system. A beam with shot noise is injected into an interaction region of length $L$, followed a dispersion region with a proper value of $R_{56}$.

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# THE LOW ENERGY STORAGE RING CRYRING@ESR

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## *Abstract*

The Swedish in-kind contribution to the FAIR facility in Darmstadt, the heavy-ion storage ring CRYRING, has been transported to Darmstadt recently. Instead of warehousing until installation at the Facility for Antiproton and Ion Research, FAIR, the immediate installation behind the existing Experimental Storage Ring, ESR, has been proposed. CRYRING can decelerate, cool and store heavy, highly charged ions that come from the ESR down to a few 100 keV/nucleon. It provides a high performance electron cooler in combination with a gas jet target and thus opens up a very attractive physics program as a natural extension of the ESR, which can only operate down to about 4 MeV/nucleon. CRYRING@ESR also provides beams of low charged ions independently on the GSI accelerator. All this makes CRYRING@ESR the perfect machine for FAIR related tests of diagnostics, software and concepts, and atomic physics experiments with heavy, highly charged ions stored at low energy. Perspectives are also opened up for low-energy nuclear physics investigations. CRYRING@ESR is a first step towards atomic physics with low-energy, highly charged ions at FAIR as planned within the SPARC and APPA collaborations.

## 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.

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.

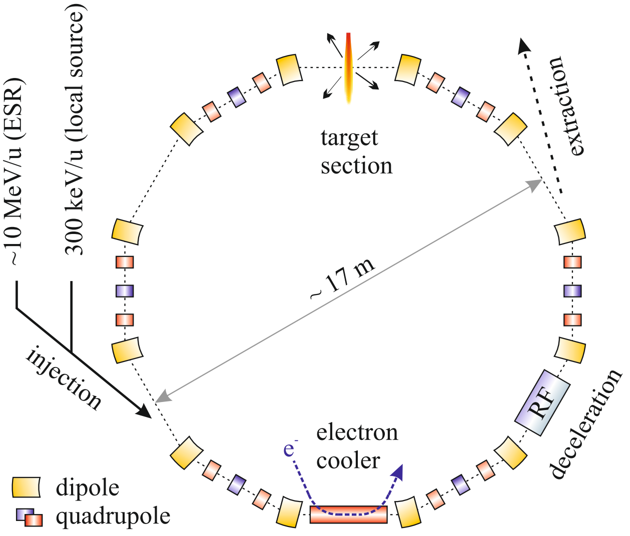

Figure 1: Overview of the storage ring CRYRING as it will be installed at the ESR at GSI in Darmstadt.

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# ELENA PROJECT STATUS

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## *Abstract*

The Extra Low Energy Antiproton ring (ELENA) is a small ring at CERN which will be built to increase substantially the number of usable antiprotons delivered to the experiments for studies with antihydrogen and antiprotonic nuclei. The project is now at stage of finishing the technical design. This presentation reviews the major features of ELENA: the ring, transfer lines and experimental area layout, the choice of the basic machine parameters and the main challenges. Electron cooling plays a key role in ELENA both for efficient deceleration as well as for preparing extracted beam with parameters defined by the experiments. The choice of machine optics as a tool for achieving the required parameters and fitting the available space is discussed. The important systems like the magnets, vacuum, beam instrumentations and others are reviewed as well.

## INTRODUCTION

The construction of ELENA ring will allow significantly increase intensity of antiproton beam which is now delivered to experiments. The AD beam extracted energy is 5.3 MeV, while most experiments need antiprotons at 3-5 keV which is defined by trap voltage. Further deceleration is done with degrading foils where particles lose energy and straggle (see Fig.1). As result only 0.3% of antiprotons are captured into trap.

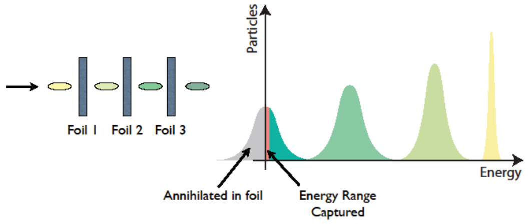

Figure 1: Antiproton deceleration after AD.

With much lower extracted beam energy in ELENA compared with that in AD, the degrading foil still needed, but very thin (Fig.2). The capture efficiency is very high (~30%) because straggling spread is of order of kV.

The particular choice of extraction energy E=100 keV is defined by space charge limit due to incoherent tune shift, strong IBS (intra-beam scattering), high vacuum about $3 \cdot 10^{-12}$ Torr is required for good lifetime [1]. Extra advantage is a possibility to equip ELENA extraction lines with electrostatic elements. Finally, the foil between extraction line and trap is mandatory to separate high vacuum in trap from lower in line, and its thickness of 1μm is a technology limit.

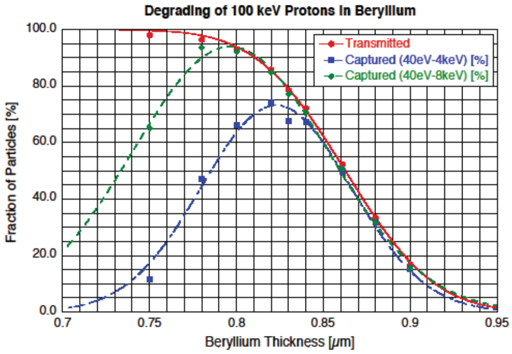

Figure 2: Antiproton deceleration in foil after ELENA.

## RING LAYOUT

The ELENA machine will be installed in the AD hall which allows keeping existing experimental areas in place. Its position and orientation inside of AD ring is chosen to make the beam injection and two beam extractions in the most efficient way [2], with minimal strength of kickers and septum (Fig.3). The extraction towards the existing experiments (ASACUSA, ALPHA, ATRAP, ACE and AEGIS) and one coming soon (BASE) is made from the top right of the ring, and towards future experiments one of which (GBAR) is approved, is made from the bottom left part of the ring.

An 800 mm thick concrete shielding around the new machine and the new experimental areas is sufficient to ensure radiation levels in case of total beam loss of below 3 μSv/h at any point in the hall and below 0.5 μSv/h on the planned visitor platform.

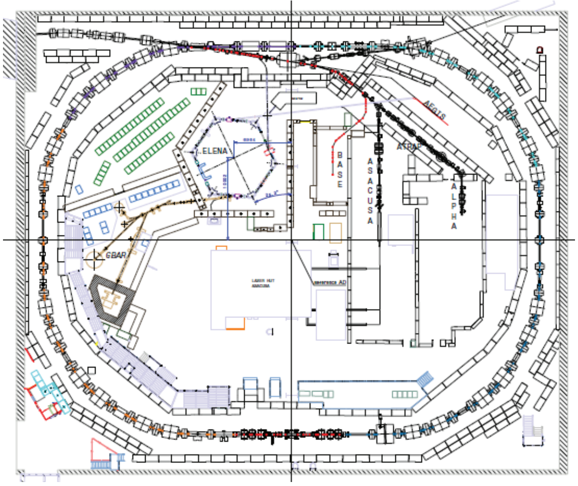

Figure 3: AD hall layout with ELENA and experimental areas.

# PRESENT STATUS OF NICA PROJECT

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## *Abstract*

Nuclotron-based Ion Collider fAcility (NICA) is the new accelerator complex being constructed in Joint Institute for Nuclear Research. General goal of the project is to start experimental study of hot and dense strongly interacting QCD matter and search for possible manifestation of signs of the mixed phase and critical endpoint in heavy ion collisions. In this report the present status of the NICA accelerator complex are presented.

## PROGRESS IN NICA CONSTRUCTION

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

- heavy ions $^{197}\mathrm{Au}^{79+}$ at $\sqrt{s_{NN}}$ = 4÷11 GeV (1÷4.5 GeV/u ion kinetic energy) at average luminosity of $1\cdot10^{27}$ $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ (at $\sqrt{s_{NN}}$ = 9 GeV);
- light-heavy ions colliding beams of the same energy range and luminosity;
- polarized beams of protons $\sqrt{s}$ = 12÷27 GeV (5÷12.6 GeV kinetic energy) and deuterons $\sqrt{s_{NN}}$ = 4÷13.8 GeV (2÷5.9 GeV/u ion kinetic energy) at average luminosity ≥ $1\cdot10^{31}$ $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$.

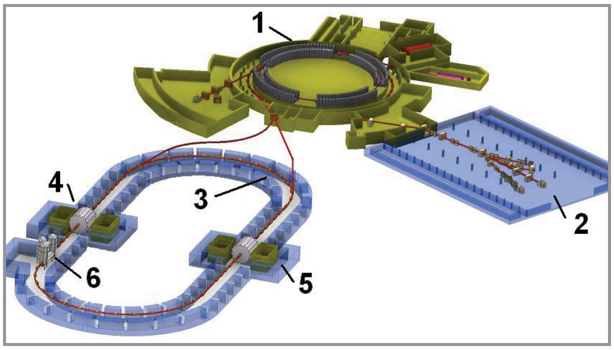

Figure 1: The NICA facility: 1 - Existing building with KRION-6T, SPP, LU-20, HILac, booster synchrotron and Nuclotron, 2 - fixed target experimental hall; 3 – Collider rings; 4 and 5 - the Multy Purpose Detector (MPD) and Spin Physics Detector (SPD); 6 – high voltage electron cooling system.

As the first step in the realization of the NICA heavy-ion program, Baryonic Matter at Nuclotron (BM@N) - a new fixed-target experiment developed in cooperation with GSI, Darmstadt - has been approved by JINR's Program Advisory Comittee and Scientific Council and is now under construction [2].

Presently in parallel with the existing accelerator complex development the technical design of the NICA collider had been prepared for the State expertise in Governmental authorities that is planned at 2013.

The development of NICA injection complex is actively performed [3]. New ESIS-type heavy ions source KRION-6T with 6 Tesla solenoid is assembled and at the stage of commissioning with electron beam now. New source of polarized particles SPP had been assembled and tested in 2013, we plan to perform several experimental runs for polarimetry measurements on it during 2013-2014 at the test bench. Construction of new 3.2 MeV/u heavy-ion linear accelerator (HILac) is now under way in cooperation with the BEVATECH Company, its commissioning in Dubna is scheduled for the beginning of 2014.

RF stations for the Booster manufactured at BINP are scheduled for commissioning at Dubna in the end of 2013. Electron cooling system to the Booster had passed TDR phase and it's construction will start in 2013 at BINP.

The full-scale Nuclotron–type superconducting model dipole and quadrupole magnets for the NICA booster and collider were manufactured during 2010 – 2012 [4]. First magnets for the Booster have successfully passed the cryogenic test on the bench. Serial production of the booster magnets is expected start in early 2014. To construct the Booster and collider rings, it is necessary to fabricate more than two and half hundreds of the dipole magnets and lenses during a short period of time. Special Test Facility for the magnet assembly and full-scaled tests required for the magnet commissioning is currently constructed. This Facility is planned to be used also for assembly and cold testing of quadrupole magnets for SIS100 (FAIR project).

The NICA cryogenics [5] will be based on the modernized liquid helium plant that was built in the early 90's for the Nuclotron. The main goals of the modernization is increasing of the total refrigerator capacity from 4000 W to 8000 W at 4.5 K and construction a new distribution system of liquid helium. These goals are achieving now by construction of a new 1000 l/hour helium liquefier, "satellite" refrigerators located near the accelerator rings, and a liquid nitrogen system that will be used for shield refrigerating at 77 K and at the first stage of cooling down of three accelerator rings with the total length of about 1.5 km and "cold" mass of 220 tons.

Application of the cooling methods is a key feature of the NICA project. The project realization requires elaboration of novel cooling systems that can be done

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# A COOLER PENNING TRAP TO COOL HIGHLY CHARGED AND SHORT-LIVED ISOTOPES AT TITAN

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## *Abstract*

The low-energy regime of nuclear physics can provide a tremendous insight into the realm of subatomic physics. Precision mass measurements of short-lived isotopes is one such endeavour that can probe the unitarity of the CKM matrix, test the CVC hypothesis, understand the nucleosynthesis path, nuclear structure and help improve nuclear mass models [1, 2]. TITAN at TRIUMF is a facility where precision mass measurement of short-lived isotopes is carried out. The unique feature of TITAN is the combination of three online ion traps that enables mass measurement of short-lived isotopes with very high precision. Presently an EBIT increases the charge state to improve the precision [3]. However, the charge breeding process causes a large energy spread. Accuracy of measured mass is linearly dependent on charge state, while the increased emittance of the beam has a negative impact on trapping efficiency and hence on precision. To overcome this drawback, a cooler Penning trap has been constructed. The trap is designed to use charged particles to reduce the beam emittance by sympathetic cooling, and it is currently undergoing off-line tests. Working principles and updates on the status of the TITAN cooler trap are presented in this paper.

## INTRODUCTION

The TITAN experiment at TRIUMF was commissioned with the goal of investigating nuclear landscape's short-lived members. Production, manipulation and mass measurement of these short-lived isotopes within a very short time span is extremely challenging. Only a few facilities worldwide have the necessary expertise to accomplish this goal [4]. TITAN has measured masses of isotopes with half-lives as short as 8.8 ms ($^{11}$Li) [5] (and [6] for a list of recent achievements at TITAN). The source of radioactive beam at TRIUMF is a solid target which is bombarded with 500 MeV protons. The Isotope Separator and ACcelerator (ISAC) facility separates the isotopes with a resolution of $m/\Delta m = 3000$ [7]. This continuous beam then enters TITAN's Radio Frequency Quadrupole (RFQ) trap. RFQ is a Paul trap with the facility of sympathetic cooling by He gas. As shown in Fig. 1, for mass measurement of singly charged ions, the cooled and bunched beam is then sent directly to the Measurment Penning Trap (MPET). To perform measurement with highly charged ions, ions from the RFQ are sent to an Electron Beam Ion Trap (EBIT). The charge-bred ions are then sent to MPET for precision mass measurement. The cooler Penning Trap (CPET) will be inserted at the space shown in Fig. 1.

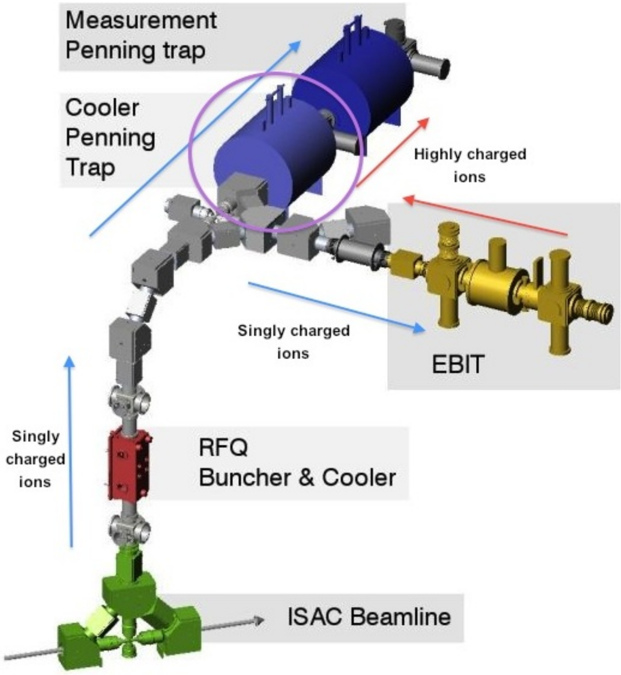

Figure 1: TITAN beamline. The Cooler Penning trap's final position when included in the beam-line is indicated in the circle.

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