OVERVIEW OF MUON COOLING*

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Abstract

Muon cooling techniques are surveyed, along with a concise overview of relevant recent R&D.

INTRODUCTION

Muon cooling enables muon colliders and neutrino factories, and enhances low-energy muon experiments. At high energies, use of muons rather than electrons substantially suppresses radiative processes ($\propto m_{\text{lepton}}^{-4}$), allowing acceleration and collision in rings — greatly reducing lepton-collider footprint and cost — as well as more-monochromatic collisions and feasibility at much higher energies (10 TeV or more) [1]. While muon decay (mean lifetime = 2.2 μs) complicates beam handling, it enables stored-muon-beam neutrino factories, the most capable technique for precision measurements of neutrino oscillation [2].

Figure 1 schematically compares these two types of high-energy muon facility, for both of which the performance and cost depend on how well a muon beam can be cooled. They are seen to have much in common:

- In both designs, a high-intensity (MW-scale), medium-energy "proton driver" illuminates a high-power capable target in a heavily shielded enclosure, copiously producing charged pions, which decay into intense broad-band muon beams.
- Bunching and "phase rotation" (reducing the energy spread by accelerating slower muon bunches and decelerating faster ones) prepare the muon beams to be cooled. The "initial cooling" stage completes the facility "front end" [3], which is similar if not identical in the two cases.
- After cooling, the beams are accelerated to the desired energy and injected into storage rings, where they circulate for $O(10^3)$ turns.

Rubbia has emphasized the importance of muon colliders for Higgs-boson studies [4]. To test for physics beyond the standard model (SM) requires sub-percent measurements of Higgs branching ratios as well as a precision scan of the resonance lineshape, possible only with s-channel production at a 125 GeV muon collider. Studies of the Higgs self-coupling are also needed, requiring a $\gtrsim$ TeV muon collider.[1] Hints are emerging for possible new physics in the $\gtrsim$ 2 TeV region [5]. Above $\approx$ 1–2 TeV, the muon collider is arguably the most capable and cost-effective lepton collider [6].

A natural muon collider staging plan thus emerges [6, 7]:

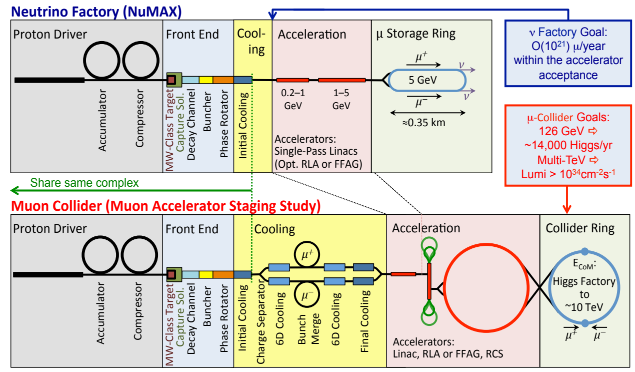

Figure 1: Neutrino factory (top) / muon collider (bottom) comparison. The "front end" (muon production, collection, bunching, phase rotation, and initial cooling) can be very similar for both. It is followed in a neutrino factory by acceleration of the muons to multi-GeV energy and injection into a storage ring, with long straight sections in which muon decay forms intense neutrino beams aimed at near and far detectors. For a muon collider, it is followed by 6-dimensional cooling, bunch coalescence, acceleration (e.g., to 62.5 GeV for a precision "Higgs Factory"), and injection into a collider ring, where μ^+ and μ^- bunches circulate for $\sim 10^3$ turns.

1. Start by building a neutrino factory,[2] which can do competitive physics with no cooling, and ultimately requires only "initial" cooling by a factor of ~ 10 in six-dimensional (6D) emittance.
2. Then upgrade the facility to a 125 GeV "Higgs Factory" muon collider, requiring $O(10^6)$ or more emittance reduction.
3. Then upgrade to a $\gtrsim$ TeV collider.

At low energies, cooling can give smaller and more intense stopping-muon beams [8, 9]. A subject of ongoing R&D at the Paul Scherrer Institute, it may enable enhanced studies of muonium spectroscopy, searches for muon–electron conversion and muonium–antimuonium oscillations, and a test of antimuon gravity [10], among other measurements [11].

BRIEF HISTORY

Muon colliders have been discussed since the 1960s [12, 13]. The key idea enabling high luminosity — ionization cooling — came later [14, 15], and its theory was not fully understood until the 1990s [16].

In the mid-1990s the ("grass roots") Muon Collider Collaboration formed, producing a report on muon colliders

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[1] As time passes and nothing below 1 TeV besides the Higgs is seen at LHC, comparable measurements with electrons seem increasingly unlikely.

[2] The nuSTORM short-baseline muon storage-ring facility, aimed at precision cross-section measurements and sterile-neutrino searches, requires no cooling and no new technology and has been proposed as an even earlier step [18].

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EXPERIMENTAL OBSERVATION OF LONGITUDINAL ELECTRON COOLING OF DC AND BUNCHED PROTON BEAM AT 2425 MeV/c AT COSY

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Abstract

The 2 MeV electron cooling system for COSY-Julich started operation in 2013 years. The cooling process was observed in the wide energy range of the electron beam from 100 keV to 908 keV. Vertical, horizontal and longitudinal cooling was tested at bunched and continuous beams. The cooler was operated with electron current up to 0.9 A. This report deals with the description of the experimental observation of longitudinal electron cooling of DC and bunched proton beam at 2425 MeV/c at COSY.

SETUP DESCRIPTION

New generation of the accelerators for study nuclear physics at range of relativistic energy 1-8 Gev/u requires very powerful cooling to obtain high luminosity. In the present time the large experience of using magnetized cooling was collected. The first experiments in BINP and further experiments in the others scientific centers show the usefulness of the idea of magnetized cooling. There are many electron cooler devices that operate now at low and middle energy (CSRm, CSRe, LEIR, ESR, e.t.c). The 2 MeV electron cooling system for COSY-Julich has the highest energy from all coolers that were made with idea of magnetized electron cooling and transport of the electron beam. The COSY cooler is designed on the classic scheme of low energy coolers like coolers CSRm, CSRe, LEIR that were produced in BINP before. It can be used for beam cooling at injection energy and for testing new features of the high energy electron cooler for COSY and HESR.

The schematic design of the setup is shown in Fig. 1. The design of the cooler and its main parameters are described in [1-2]. 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 and deuterons 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.

EXPERIMENTS SETUP

The detailed experiments with electron cooling were carried out with the proton energy 2425 MeV that corresponds to the electron energy 908 keV. This working point was investigated carefully in the previous experiments and there was a large collection of the hardware setups for the operation. Moreover the stochastic cooling was accessible at this energy. The experimental setup involves the barrier bucket and RF of 1-st harmonic. The diagnostic of the proton beam was based on IPM (ionization profile monitor), BPM and pickup of the stochastic cooling system. The proton current is measured by DCCT.

The main parameters of COSY regime at this point are listed in Table 1.

Table 1: COSY Regime Parameters

Parametere	**Value**
Gamma transition	2.26
Alpha	0.196
Proton numbers	10^8-10^9
Vacuum	10^{-9}-10^{-10} mbar
Qx	3.589
Qy	3.675
Slip-factor	-0.066
Perimeter	183.5 m
Kinetic energy	1.662 GeV
Gamma	2.771
Frequency	1.5239 MHz
Dipole field	1.156 T
Horizontal beta function in cooling section	9 m
Vertical beta function in cooling section	15 m
Dispersion in cooling section, m	0

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STOCHASTIC COOLING OF HEAVY IONS IN THE HESR

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Abstract

Due to the Modularized Start Version (MSV) of the FAIR project with the postponed New Experimental Storage Ring (NESR), the High Energy Storage Ring (HESR) became very attractive for experiments with heavy ions. Although the HESR is optimized for the storage of antiprotons it is also well suited for heavy ion beams with slight changes in the optics. Within the MSV only stochastic cooling and no electron cooling will be available, but even the main 2 - 4 GHz stochastic cooling system will be capable to fulfil the beam requirements for heavy ions. Most critical parts of the active elements are the high power amplifiers. The stochastic cooling amplifiers for the HESR will be based on new GaN devices. Nonlinearities of these devices necessitate a dedicated analysis of the use in stochastic cooling systems.

STOCHASTIC COOLING SYSTEM OF HESR

The stochastic cooling system of the HESR is based on completely new structures especially designed for the HESR [1]. Each beam surrounding slot of these so called slot-ring couplers covers the whole image current without a reduction of the HESR aperture. Each resonant ring structure is heavily loaded with eight 50 Ω electrodes for a broadband operation. The single rings are screwed together to a self-supporting structure in stacks of 16 rings. Four of these stacks will build the spindle for one tank.

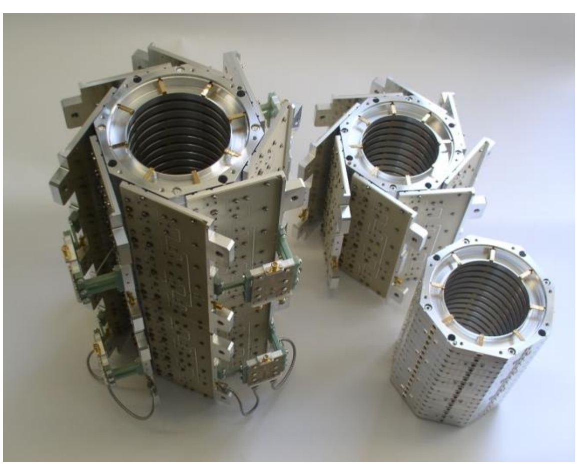

Figure 1: Stacks of slot ring couplers with and without 16:1 combiner-boards and two stacks mounted together including 2:1 combiner with heat-trap.

These structures have the great advantage that they can be simultaneously used in all three cooling planes (horizontal, vertical and longitudinal) just by skilful combining the signals of the electrodes. Another advantage in the case of the HESR is the fact that no movable parts in the vacuum are needed to obtain a good signal to noise ratio. The basic parameters of the main stochastic cooling system are summarized in table 1.

Table 1: Basic Parameters of Main System

Main system	**Based on slot-ring couplers**	
Bandwidth	2 - 4	GHz
Cooling methods	transverse, longitudinal filter cooling, longitudinal ToF cooling	
β-range	0.83-0.99	
Pickup:	**2**	**tanks**
No. of rings /tank	64	
Shunt impedance Z_{pu} / ring	9	Ohm
Total impedance	1152	Ohm
Structure temp.	30	K
Kicker	**3**	**tanks**
	2 tanks for transverse **or** longitudinal cooling, 1 tank longitudinal cooling only	
No. of rings /tank	64	
Shunt impedance Z_k / ring	36	Ohm
Impedance /tank	2304	Ohm
Installed power/tank	640 (longitudinal cooling) 320 (transverse cooling)	W W

Beside extensive test as pickup in the Cooler Synchrotron COSY Jülich [2] one small pickup and one kicker each equipped with 16 rings were installed into the Nuclotron in Dubna. This experimental stochastic cooling setup was initiated as a preparatory work for the NICA collider [3, 4]. During a few runs in 2013 and 2014 the system was commissioned and D^+ and C^{6+} beams were successful longitudinal cooled [5].

Cooling of Heavy Ions using Existing Design

The HESR stochastic cooling system was designed to cool pbars in the whole momentum range of the HESR lasting from 1.5 GeV/c to 15 GeV/c. Two operation modes have been analysed: first, the High-Resolution mode (HR) with 10^{10} pbars and a momentum spread of $\Delta p/p \approx 5\times10^{-5}$ and second, the High-Luminosity mode (HL) with 10^{11} pbars and a momentum spread of Δp/p

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STOCHASTIC COOLING SYSTEM FOR HESR: THEORETICAL AND SIMULATION STUDIES

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Abstract

The High-Energy Storage Ring (HESR) is part of the upcoming International Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt. The HESR dedicates to the field of high-energy antiproton physics to explore the research areas of charmonium spectroscopy, hadronic structure, and quark-gluon dynamics with high-quality beams over a broad momentum range from *1.5* to *15 GeV/c*. High momentum resolution beams are mandatory for internal target experiments which are prepared with the well-established filter method in stochastic momentum cooling. This cooling technique will also be applied for antiproton accumulation in the HESR as well as in heavy ion beam cooling experiments with internal targets. Fast beam cooling is achieved with a *(2 – 4) GHz* system. In cases when the momentum spread exceeds the filter cooling acceptance the Time-Of-Flight (TOF) method, which is easily set up when filter cooling is already available, is applied to pre-cool the beam prior to filter cooling. To compare both cooling methods the basics of the theory is presented. Beam experiments at COSY are outlined to verify these aspects of the cooling theory.

INTRODUCTION

The HESR [1] has been originally designed for storage and acceleration of up to 10^{11} antiprotons for internal target experiments with high momentum resolution up to $\approx 1 \cdot 10^{-5}$ in the momentum range *1.5 GeV/c to 15 GeV/c*. Since in the modularized start version [1] the storage rings RESR and NESR are postponed the accumulation of the beam delivered by the CR has to be accomplished in the HESR itself. The well-established stochastic stacking method [2] is however not applicable. Instead a different method using moving barriers and stochastic filter momentum cooling is established [3] to accumulate 10^{10} antiprotons within *1000 s*. Recently, the feasibility of the HESR storage ring for the application of heavy ion beams with the special emphasis on the experimental program of the SPARC collaboration at FAIR has been investigated in detail [4]. The magnetic rigidity range $5Tm \le B\rho \le 50Tm$ allows the storage of $^{132}Sn^{50+}$ and $^{238}U^{92+}$ ions in the kinetic energy range *165 MeV/u* up to ≈ *5 GeV/u*.

Both, transverse and longitudinal cooling is available at the HESR. Transverse cooling is mainly applied to compensate a transverse beam blow up due to the beam-target interaction. The highest demands are made on longitudinal cooling, especially in the high momentum resolution mode. To fulfil this goal the bandwidth of the cooling system will be *(2 – 4) GHz* with the extended option of *(2 - 6) GHz* in a later stage [5]. High sensitive pickup/kicker structures have been developed and tested at COSY [5]. The filter cooling technique [6] is applied for longitudinal cooling in the momentum range above *3.8 GeV/c*. Below *3.8 GeV/c* the Time-Of-Flight momentum (TOF-) cooling technique [7] will be used.

MOMENTUM COOLING METHODS

Stochastic momentum cooling is described with the Fokker-Planck Equation (FPE) [6]

$$\frac{\partial \Psi}{\partial t} = -\frac{\partial}{\partial \delta}\left[F\Psi - D\frac{\partial \Psi}{\partial \delta} \right] \qquad (1)$$

for the time evolution of the momentum distribution $\Psi(\delta,t)$ of ions with relative momentum deviation δ. The explicit expressions for the drift *F* describing cooling and diffusion *D* depend on the cooling method.

In the Filter cooling method a pickup in sum mode measures the beam current and the discrimination of particles with different momentum deviations is obtained by inserting a notch filter and a *90* degree phase shifter in the signal path before it drives a kicker in sum mode. Besides pre-amplifiers and power amplifiers a variable delay is available to adjust the signal transit time from pickup to kicker to the time-of-flight of a particle with nominal momentum. The basic system arrangement is illustrated in figure 1.

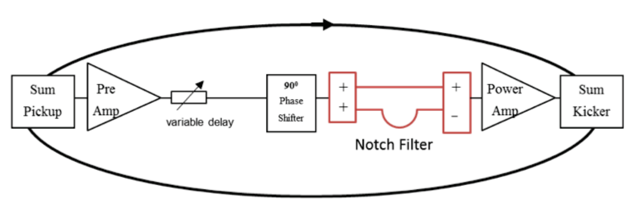

Figure 1: Basic system configuration for filter cooling.

A severe restriction in the practical cooling bandwidth comes from mixing between pickup and kicker. Large mixing from pickup to kicker will reduce the maximum momentum spread that can be cooled for a given upper cooling frequency without particle losses. Figure 2 illustrates a simulation [8] for an antiproton beam at *3.8 GeV/c* in the HESR with 10^{10} particles. The electronic gain is *110 dB*. The relative momentum spread is $5 \cdot 10^{-4}$. It shows the drift term (the energy change per second a particle receives at the kicker due to its on momentum

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STOCHASTIC COOLING DEVELOPMENTS FOR THE COLLECTOR RING AT FAIR

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Abstract

A Status report on the ongoing developments for the demanding stochastic cooling system of the Collector Ring is given. The system operates in the frequency band 1-2 GHz, it has to provide fast 3D cooling of antiproton, rare isotope (RIBs) 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. Progress in designing, testing and integrating the hardware is discussed.

INTRODUCTION

The CR stochastic cooling system is described in [1, 2]. In summary: Antiproton cooling is limited by the poor ratio Schottky signal/thermal noise, that is why it is foreseen: (i) to keep the slotline pickup electrodes at cryogenic temperatures (20-30 K), (ii) to strive for large sensitivity by moving (plunging) the pickup electrodes as the beam shrinks, (iii) for longitudinal cooling, to implement the notch filter technique, which is the best choice since it advantageously filters out the thermal noise. The chosen ring slip factor $|\eta|$=0.011 guarantees optimum momentum acceptance for the notch filter cooling, but slows down the simultaneous transverse cooling due to the high mixing M between kicker and pickup. A remedy comes from the flexibility of the CR lattice in setting different γ_{tr} values. As $\delta p/p$ shrinks during the 10 s of cooling, $|\eta|$ can be slightly increased by a factor 2-3 (decrease γ_{tr}), by small tuning of the quadrupole strength, so as to control $M(t) \sim (|\eta(t)|\delta p(t)/p)^{-1}$. At the end of cooling the beam is rebunched and extracted, then the quadrupoles must ramp fast back to their initial value ($|\eta|$=0.011) before new beam is injected. The lattice, the quadrupoles and their power supplies must be specified from the beginning for ramping in the range $|\eta| \approx 1-3\%$ within shortest time with respect to the cooling/cycle time. This $|\eta|$-ramping procedure will be optimized during commissioning with beam, at present it may be studied with cooling simulations in all 3 planes.

Heavy ion cooling is limited by the undesired mixing. In the beginning, for the hot RIBs, only the Palmer method can be applied with a dedicated pickup (pre-cooling stage). Recently, the option of time of flight (TOF) longitudinal cooling using the Palmer pickup in sum mode has been included. The TOF option can be useful for precooling the tails of hot RIB beams since it suffers less from the interplay with the horizontal betatron motion than the Palmer method. In a second stage, after δp/p has decreased, it is planned to switch to cooling with the slotline pickups and the notch filter until the final beam quality is reached.

The option of TOF longitudinal cooling for antiprotons or RIBs is useful for moderate requirements on the final $\delta p/p$ or on the cooling time (e.g. lower particle number, longer cycles) or, due to its larger momentum acceptance, as pre-cooling before the notch filter takes over.

For primary beams of stable ions coming with better quality after acceleration in the synchrotrons, one-stage cooling by the TOF or notch filter method with the slotline pickups should be sufficient.

Table 1: Required Cooling Performance in the CR. For parameters in red there is no safety margin, for those in blue larger values can be accepted with the HESR downstream.

3 GeV, 10^8 antiprotons, coasting beam		
	δp/p (rms)	$\epsilon_{h,v}$ (rms) π mm mrad
Before cooling	0.35 %	40
After cooling	0.05 %	1.25
Cooling down time	≤9 s	
Cycle time	10 s	
740 MeV/u, 10^8 RIBs, coasting beam		
	δp/p (rms)	$\epsilon_{h,v}$ (rms) π mm mrad
Before cooling	0.2 %	35
After cooling	0.025 %	0.125
Cooling down time	≤1 s	
Cycle time	≤1.5 s	

Table 1 shows the updated cooling requirements for 10^8 antiprotons and RIBs in the CR. In the present FAIR scenario the CR delivers to the HESR [3] pre-cooled antiprotons and stable ions/RIBs for accumulation and in-ring experiments. Taking into account the rebunching of the antiprotons/ions for transfer to the HESR as well as the small momentum acceptance of the HESR and its stochastic cooling systems, up to 30% lower final δp/p would be needed after cooling in the CR. On the other hand, higher emittances can be accepted in the HESR. For the most demanding case of 10^8 antiprotons in a 10 s cycle, the momentum spread budget should be within reach by optimizing the interplay among the longitudinal and transverse cooling in the CR, the rebunching/debunching procedures in the transfer as well as the longitudinal cooling in the HESR. The stable ions are less critical since they are initially not so hot as the RIBs.

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THE GREEN ENERGY TURBINE AS TURBO GENERATOR FOR POWERING THE HV-SOLENOIDS AT A RELATIVISTIC ELECTRON COOLER

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Abstract

One of the challenges in the development of a relativistic electron cooler is the powering of components, e.g. the HV-solenoids, which sit on different high potentials within a high voltage vessel and therefore need a floating power supply.

In this report we present the turbo generator "Green Energy Turbine" (GET), an assembly of a turbine and a generator, as a possible candidate for powering e.g. the HV-solenoids and give an overview over the future road map.

INTRODUCTION

In many experiments in hadron physics it is essential to keep the emittance constant, counteracting the emittance blow up e.g. due to scattering experiments. One way to prevent the emittance from increasing is the electron cooling technique [1], which will be used for example at the High Energy Storage Ring (HESR) at GSI/FAIR to permit high energy antiproton experiments [2]. The HESR has a circumference of 575 m and can operate in two modes, the "High Luminosity" (HL) and "High Resolution" (HR) mode. Some experimental demands are summarised in Table 1 [3].

Table 1: Experimental Demands of the HESR

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

To meet these requirements for the high resolution mode, magnetised electron cooling with a 4.5 MeV, 1 A electron beam is necessary. 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. In order to solve critical technical issues, the Helmholtz-Institut Mainz (HIM) promotes collaborations with other Institutes such as Forschungszentrum Juelich (FZJ), Budker Institute of Nuclear Research Novosibirsk (BINP SB RAS), Russia and Lehrstuhl fuer Technische Thermodynamik und Transportprozesse (LTTT), University Bayreuth. One of the challenges is the powering of HV-solenoids, which are located on different electrical potentials inside a high voltage vessel, which is why they need a floating power supply.

Within a design study, BINP SB RAS has proposed two possibilities to build a power supply in a modular way. The first proposal is to use two cascade transformers per module. One cascade transformer powers 22 small HV-solenoids, the second one should generate the acceleration/deceleration voltage for the electron beam. The cascade transformers themselves are fed by a turbo generator, which is powered by a gas under high pressure that could be generated outside of the high voltage vessel. The second possibility is to use two large HV-solenoids per module, which are composed of four small coils. In this proposal, the HV-solenoids are powered directly by a turbo generator [5]. Both concepts have in common that they need a suitable turbo generator which delivers a power of 5 kW. A research for proper turbo generators has identified the Green Energy Turbine (GET) from the company DEPRAG as a potential candidate [6]. At HIM, two GET were bought and tested.

GREEN ENERGY TURBINE

The GET (Figure 1) is an assembly composed essentially of a turbine and a generator. Dry compressed air enters the

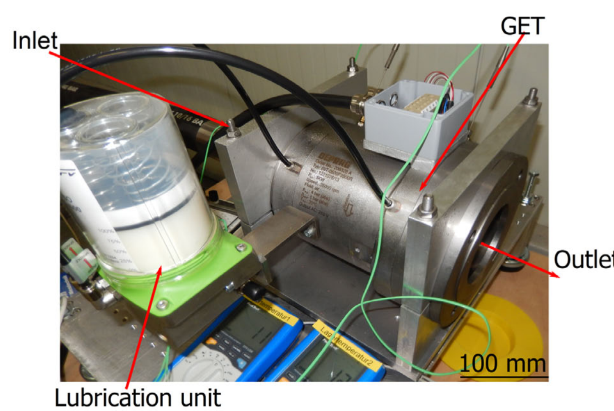

Figure 1: The turbo generator Green Energy Turbine (GET) with lubrication unit.

GET on the inlet side and is expanded through a nozzle. The resulting accelerated air drives a turbine, which in turn drives a generator. After the expansion, the air is diverted around the generator and leaves the GET on the outlet side at normal pressure. The generator is connected in delta configuration, which generates three-phase current. The turbine and the generator are supported by ball bearings, which was believed

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ELECTRON LENSES AND COOLING FOR THE FERMILAB INTEGRABLE OPTICS TEST ACCELERATOR*

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Abstract

Recently, the study of integrable Hamiltonian systems has led to nonlinear accelerator lattices with one or two transverse invariants and wide stable tune spreads. These lattices may drastically improve the performance of high-intensity machines, providing Landau damping to protect the beam from instabilities, while preserving dynamic aperture. The Integrable Optics Test Accelerator (IOTA) is being built at Fermilab to study these concepts with 150-MeV pencil electron beams (single-particle dynamics) and 2.5-MeV protons (dynamics with self fields). One way to obtain a nonlinear integrable lattice is by using the fields generated by a magnetically confined electron beam (electron lens) overlapping with the circulating beam. The required parameters are similar to the ones of existing devices. In addition, the electron lens will be used in cooling mode to control the brightness of the proton beam and to measure transverse profiles through recombination. More generally, it is of great interest to investigate whether nonlinear integrable optics allows electron coolers to exceed limitations set by both coherent or incoherent instabilities excited by space charge.

INTRODUCTION

In many areas of particle physics, such as the study of neutrinos and of rare processes, high-power accelerators and high-brightness beams are needed. The performance of these accelerators is limited by several factors, including tolerable losses and beam halo, space-charge effects, and instabilities. Nonlinear integrable optics, self-consistent or compensated dynamics with self fields, and beam cooling beyond the present state of the art are being actively pursued because of their potential impact.

In particular, the Integrable Optics Test Accelerator (IOTA, Fig. 1) is a research storage ring with a circumference of 40 m being built at Fermilab [1, 2]. Its main purposes are the practical implementation of nonlinear integrable lattices in a real machine, the study of space-charge compensation in rings, and a demonstration of optical stochastic cooling. IOTA is designed to circulate pencil beams of electrons at 150 MeV for the study of single-particle linear and nonlinear dynamics. For experiments on dynamics with self fields, protons at 2.5 MeV (momentum 69 MeV/c) will be used.

In accelerator physics, nonlinear integrable optics involves a small number of special nonlinear focusing elements added to the lattice of a conventional machine in order to generate large tune spreads while preserving dynamic aperture [3], thus providing improved stability to perturbations and mitigation of collective instabilities through Landau damping.

One way to generate a nonlinear integrable lattice is with specially segmented multipole magnets [3]. There are also two concepts based on electron lenses [4]: (a) axially symmetric thin kicks with a specific amplitude dependence [5–7]; and (b) axially symmetric kicks in a thick lens at constant amplitude function [8, 9]. These concepts use the electromagnetic field generated by the electron beam distribution to provide the desired nonlinear transverse kicks to the circulating beam.

In IOTA, the electron lens can also be used as an electron cooler for protons. In this paper, we present a preliminary exploration of the research opportunities enabled by the cooler option: beam dynamics with self fields can be studied in a wider brightness range; spontaneous recombination provides fast proton diagnostics; and, lastly, perhaps the most interesting question is whether the combination of electron cooling and nonlinear integrable optics leads to higher brightnesses than presently achievable.

NONLINEAR INTEGRABLE OPTICS WITH ELECTRON LENSES

Electron lenses are pulsed, magnetically confined, low-energy electron beams whose electromagnetic fields are used for active manipulation of circulating beams [10, 11]. One of the main features of an electron lens is the possibility to control the current-density profile of the electron beam (flat, Gaussian, hollow, etc.) by shaping the cathode and the extraction electrodes. Electron lenses have a wide range of applications [12–22]. In particular, they can be used as nonlinear lenses with tunable kicks and controllable shape as a function of betatron amplitude.

The goal of the nonlinear integrable optics experiments, including the ones with electron lenses, is to achieve a large tune spread, of the order of 0.25 or more, while preserv-

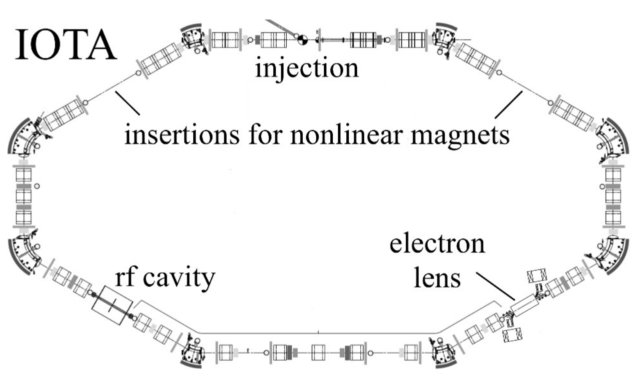

Figure 1: Layout of the IOTA ring.

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A COOLING STORAGE RING FOR AN ELECTRON-ION COLLIDER

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Abstract

Electron cooling offers performance advantages to the design of an electron-ion collider. A first design of a 6 GeV/u storage ring for the cooling of ions in MEIC is presented, along with some remarks on the particulars of electron cooling in this ring.

INTRODUCTION

Previously, we have proposed the design of a fixed-energy storage ring [1] for electron cooling as an improvement to the MEIC baseline [2], which plans for DC electron cooling at 0.1 GeV/u and 2 GeV/u in the Booster, and bunched beam cooling using an energy recovery linac (ERL) at 7.9 GeV/u and at collision energy, 100 GeV/u. Most of this cooling is aimed at suppression of IBS and maintenance of emittance during the beam lifecycle. To supplement this approach, our design aims to reduce emittance with DC cooling at the fixed energy of 6 GeV/u. The primary design criteria for the ring are: 1) accumulation of ions by momentum stacking, 2) electron cooling and stacking times commensurate with the existing MEIC structure, so as not to bottleneck the acceleration process, 3) minimization of additional cost to accommodate the ring, compared with the benefits offered.

CURRENT DESIGN

Regarding criterion (1), lab-frame longitudinal cooling force $F_{\parallel}$ scales with $1/\gamma$, lab-frame cooling rate τ^{-1} scales with $1/\gamma^2$ [3]. This motivates DC cooling at lower energies, and a lower limit is established by space charge dominance. An operating point near the top energy of the MEIC booster (~7-8 GeV/u) is a good compromise

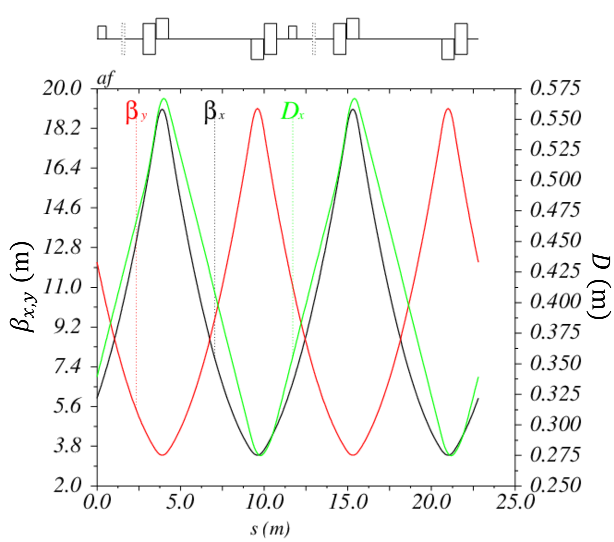

Figure 1: Arc cell optics, shown over the length of one collision ring period.

between these opposing constraints, as well as the operational flow of the machine. With this energy and electron current of hundreds of mA, the characteristic cooling time (due to Spitzer) for protons in MEIC is

$$\tau_{\text{lab}} = \frac{3}{8\sqrt{2\pi} n_e Z^2 r_e r_i c \Lambda}\left[\frac{T_e}{m_e c^2} + \frac{T_i}{m_i c^2}\right] \leq 5 \text{ min},$$

meeting the needs of criterion (2) assuming a physics time of ~1 hr in the collision ring and ~10 cycles of the Booster. With a dedicated cooling ring, once a beam has been transferred to the collision ring for final acceleration and

Figure 2: Schematic layout of placeholder cooling ring integrated above the collider ring in the same cryostat.

collision operation, preparation and storage of a new beam can begin immediately, bringing down the time needed between dumping old beam and resumption of physics operations. The integration of the arcs (Figure 2) in the same cryostat as the ion collision ring (in currently unallocated space) goes a long way to meeting criterion (3), as no addition provisions need be taken for the cryogenic systems. The magnet strengths given in Table 1 do not represent large demands on top of the existing cryogenic design.

Table 1: Cooling Ring Parameters

Arc dipole	0.245 T
Focusing gradient	9.363 T/m
Defocusing gradient	9.424 T/m
Cooling solenoid field	>1.0 T
Electron energy	3-4 MeV
Electron beam current	>250 mA

In the electron cooling section (see Figure 3), the dispersion is matched to zero to maximize the effectiveness of electron cooling. If the dispersion is non-zero, there will be some ions whose velocity is less than that of the electron beam on many turns, resulting in heating and eventual loss of these particles. Note that although the betatron function is shown in the figure, the cooling solenoids occupying the drift spaces will couple the transverse motions and provide

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QUANTIFICATION OF THE ELECTRON PLASMA IN TITAN'S COOLER PENNING TRAP*

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Abstract

Modern rare isotope facilities provide beams of short-lived radionuclides primarily for studies in the field of nuclear structure, nuclear astrophysics, and low energy particle physics. At these facilities, many activities such as re-acceleration, improvement of resolving power, and precision experimental measurements require charge breeding of ions. However, the charge breeding process can increase the energy spread of an ion bunch, adversely affecting the experiment. A Cooler Penning Trap (CPET) is being developed to address such an energy spread by means of sympathetic electron cooling of the Highly Charged Ion bunches to $\lesssim 1$ eV/q. Recent work has focused on developing a strategy to effectively detect the trapped electron plasma without obstructing the passage of ions through the beamline. The first offline tests demonstrate the ability to trap and detect more than 10^8 electrons. This was achieved by using a novel wire mesh detector as a diagnostic tool for the electrons.

INTRODUCTION

Nuclear masses serve as critical inputs in models of nucleosynthesis [1] and provide insight into nuclear structure [2], among numerous other applications. Penning trap mass spectrometry presently offers the highest precision and accuracy for mass measurements of radioactive nuclides [3].

Penning traps use a combination of static electric and magnetic fields to confine charged particles in space. A particle with charge, q, precesses in the magnetic field, B, with a cyclotron frequency given by

$$\omega_c = qB/m. \tag{1}$$

Since the cyclotron frequency is inversely proportional to the mass, we can readily determine the mass by measuring this frequency with a Penning trap.

At TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [4] the masses of short-lived isotopes are measured with precisions of 1 part in 10^7 and better. TITAN has successfully performed mass measurements at these precisions for the shortest-lived isotopes ever studied in a Penning trap (e.g. ^{11}Li at $t_{1/2}$ = 8.75 ms) [5].

At the TITAN facility, beams of singly charged, radioactive ions from the Isotope Separator and ACcelerator (ISAC) [6] are cooled and bunched in TITANs Radio Frequency Quadrupole ion trap before being delivered to TITAN's Measurement Penning Trap (MPET) [7] for precision mass measurement.

Precision in MPET is limited by

$$\frac{\delta m}{m} \propto \frac{m}{qBT_{RF}\sqrt{N}}, \tag{2}$$

where $\frac{\delta m}{m}$ is the mass uncertainty, m is the mass, q is the charge state, B is the magnetic field of the trap, T_{RF} is the period over which the ion is resonantly excited in the trap, and N is the total number of ions individually trapped and measured [8]. Therefore, in order to achieve the best possible precision, a stable and homogeneous magnetic field, a long excitation time, and a large number of ions are needed.

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FINAL MUON IONIZATION COOLING CHANNEL USING QUADRUPOLE DOUBLETS FOR STRONG FOCUSING

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Abstract

Considerable progress has been made in the design of muon ionization cooling for a collider. A 6D normalized emittance of $\epsilon_{6D} = 0.123\,\mathrm{mm}^3$ has been achieved in simulation, almost a factor of a million in cooling. However, the 6D emittance required by a high luminosity muon collider is $\epsilon_{6D} = 0.044\,\mathrm{mm}^3$. We explore a final cooling channel composed of quadrupole doublets limited to 14 Tesla. Flat beams formed by a skew quadrupole triplet are used. The low β^* regions, as low as 5 mm, produced by the strong focusing quadrupoles are occupied by dense, low Z absorbers that cool the beam. Work is in progress to keep muons with different path lengths in phase with the RF located between cells and to modestly enlarge quadrupole admittance. Calculations and individual cell simulations indicate that the final cooling needed may be possible. Full simulations are in progress. After cooling, emittance exchange in vacuum reduces the transverse emittance to 25 μm and lets the ϵ_L grow to 70 mm as needed by a collider. Septa slice a bunch into 17 parts. RF deflector cavities, as used in CLIC tests, form a 3.7 m long bunch train. Snap bunch coalescence combines the 17 bunches into one in a 21 GeV ring in 55 microseconds.

INTRODUCTION

The muon collider [1] offers several advantages, as compared to hadron colliders [2], to explore rare and massive events at the energy frontier due to the point like behavior of muons. It allows a relatively small collider ring. But, muons have to be cooled quickly and efficiently due to the short muon lifetime. Ionization cooling is the best cooling technique for muons and is being tested at the MICE [3] experiment. The equations describing the transverse and longitudinal cooling are given by [4]:

$$\frac{d\epsilon_\perp}{ds} = -\frac{g_t}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_\perp}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp^*}{2}\frac{(13.6\,\mathrm{MeV})^2}{E_\mu m_\mu c^2 L_R} \quad (1)$$

$$\frac{d\epsilon_L}{ds} = \frac{-g_L}{\beta^2 E_\mu}\frac{dE_\mu}{ds}\epsilon_L + \frac{\gamma^3\beta_L}{\beta c^2 p^2}\pi(r_e m_e c^2)^2 n_e(2-\beta^2) \quad (2)$$

where dE_μ/ds is the energy lost calculated by the Bethe-Bloch equation. $\beta_\perp^*$ and β_L are transverse and longitudinal betatron functions. g_L and g_t are partition numbers that depend on the absorber geometry. $\epsilon_{\perp,eq}$ and $\epsilon_{L,eq}$ are the equilibrium emittances which are calculated as:

$$\epsilon_{\perp,eq} \simeq \frac{\beta_\perp^*(13.6MeV)^2}{2g_t\beta m_\mu c^2 L_R\,(dE/ds)} \quad (3)$$

$$\epsilon_{L,eq} \simeq \frac{\beta_L m_e c^2\beta\gamma^2(2-\beta^2)}{4g_L m_\mu c^2\left[\ln\left[\frac{2m_e c^2\gamma^2\beta^2}{I(Z)}\right]-\beta^2\right]} \quad (4)$$

The transverse betatron function at the absorber should be small in order to keep the equilibrium emittance low and to reduce the heating due to multiple scattering. Strong focusing is required to cool the beam. Emittance evolution is estimated using the cooling characteristic equation 5, where i = x, y, z [4].

$$\epsilon_i(s) = (\epsilon_{0,i} - \epsilon_{i,equi})\exp(-s\frac{g_i(dP_\mu/ds)}{P_\mu}) + \epsilon_{i,equi} \quad (5)$$

Two muon cooling channels [5, 6] using the transverse cooling principle and emittance exchange have been simulated. Both show a large ϵ_{6D} reduction, but not quite enough for a muon collider as noted in Table 1.

Table 1: Helical and Rectilinear Cooling Channel normalized 6D emittances ϵ_{6D} from simulations and the emittance needed for a muon collider. The channels cool by over five orders of magnitude and need less than a factor of 10 more for a collider. The 21 bunches present after initial phase rotation are also merged into one bunch during cooling.

	ϵ_x mm	ϵ_y mm	ϵ_y mm	ϵ_{6D} mm^3
Initial Emittance [6]	48.6	48.6	17.0	40,200
Helical Cooling [5]	0.523	0.523	1.54	0.421
Rectilinear Cooling [6]	0.28	0.28	1.57	0.123
Muon Collider [7]	0.025	0.025	70	0.044

CHANNEL DESIGN

Channel Cell

According to equation 3, low equilibrium emittance requires low $\beta_\perp^*$. Strong quadrupole focusing [8] can achieve $\beta_\perp^*$ values within the required 0.5 to 2.0 cm range. A half cell is composed of two quadrupole magnets separated by a short drift space to avoid excessive fringe field interference [9] between magnets, as shown in Fig. 1 and 2. The bore diameter and length for the first quadrupole magnet

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SECONDARY ELECTRON MEASUREMENTS AT THE HIM ELECTRON COOLER TEST SET-UP

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Abstract

The planned advances in electron cooling technology aimed at improving the operation of future hadron storage rings include an increase in electron beam current and acceleration voltage. A test set-up has been built at Helmholtz-Insitut Mainz (HIM) to optimize the recuperation efficiency of such high-current beams in energy recovery operation, requiring a thorough understanding of their interaction with external electric and magnetic fields, such as those found in a Wien velocity filter. Beam diagnostics are carried out using a BPM and current-sensing scraper electrodes. At present, the set-up can be successfully operated at $U = 17\,\mathrm{kV}$, $I = 600\,\mathrm{mA}$, showing a relative secondary electron current of $\approx 2 \times 10^{-4}$. We present the current state of the project and its objectives for the foreseeable future.

INTRODUCTION

Electron coolers are designed for energy recuperation so that the total deposited energy is independent of the acceleration voltage. 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. Recent progress made by BINP [1] suggests that this effect can be eliminated using a Wien filter, at the same time allowing for measurement of the secondary electron current. Consequently, such a filter has been designed and successfully implemented in our cooler test set-up with the different properties of the components in mind [2].

A schematic view of the set-up is shown in Fig. 1. Using an isolating transformer, it is possible to use the same negative high-voltage power supply for the cathode and the collector, with an additional 6.5 kV, 1.5 A power supply providing the potential difference between cathode and collector to account for the finite perveance. This way, the beam pipe is at ground potential, greatly facilitating beam diagnostics. After the Wien filter, the set-up includes a moveable fluorescent screen, a beam position monitor obtained from BINP [3], and a mutually isolated double aperture to distinguish between secondary and primary current hitting the plates.

GAS DISCHARGES IN THE ELECTRON SOURCE

When operation of our test set-up started, it quickly turned out that the electron source obtained from TSL [4] could not be operated with the desired parameters ($U = 26\,\mathrm{kV}$, $B_z = 200\,\mathrm{mT}$) because of gas discharges between the electrodes [5]. In an attempt to identify the reason, CST simulations of

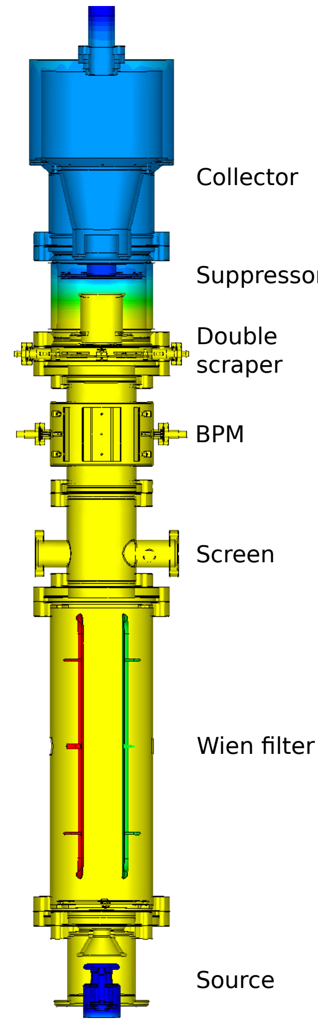

Figure 1: Schematic view of the vacuum chamber. Blue: $U < 0$. Yellow: $U = 0$.

electric fields and particle trajectories were carried out. The result of a particle simulation with the whole outer surface of the Pierce electrode emitting electrons is shown in Fig. 2. It can be seen that due to the electric field components caused by the varying distance between the outer Pierce electrode and the surrounding pipe, there are two local maximums of electric potential (indicated by arrows) along the symmetry axis of the source (vertical direction in the picture). Given a longitudinal magnetic field sufficiently high to confine the radial movement of electrons to a narrow space, all particles starting at one of the surfaces with a kinetic energy close to zero will oscillate between the potential minimums, greatly increasing the ionization probability of the residual gas. This constitutes a variety of the cylindrical magnetron where the

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SIGNALS FROM A BEAM PERFORMING BETATRON OSCILLATIONS USING AN ELECTROSTATIC ELECTRODE MODEL WITH RECTANGULAR BOUNDARIES

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Abstract

We investigate the non-linear response of a pick-up structure using electrostatic models with the formalism introduced by Bisognano and Leeman. As an example we show results from the pick-up structure at the CSRe storage ring at the IMP in Lanzhou.

ELECTROSTATIC MODELS OF AN ELECTRODE PLATE

Electrostatic Models of Relativistic Beam Response

Electrostatic models have been applied for a long time to the investigation of the response of both pick-ups and kickers. A classical overview of this subject is due to G. Lambertson [1]. He gives also an equation of the non-relativistic case, but this is meant to show that the electrostatic approximation is good for large Lorentz factors γ.

A more naive approach to the non-relativistic case is to replace the extremely short field disk of ultra-relativistic particles by the correct expressions for a free particle [2, 3]. This leads to analytical expressions of the correction, however the boundary conditions of a real vacuum chamber are not taken into account.

As this paper mainly aims at a study of the response to betatron oscillations, the electrostatic approximation is used throughout.

Parallel Boundaries without Borders

The electrostatic model with parallel boundaries was first introduced by Neuffer [4]. The underlying conformal mapping is explained in some detail in [3]. However we use here a different coordinate system where the y coordinate is zero in the center of the vacuum chamber (see Fig. 1).

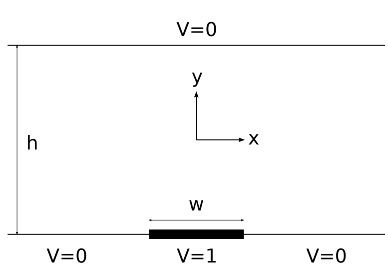

Figure 1: Electrode with parallel boundaries

The model can be calculated as follows. Take

$$z = \frac{\cos(\pi y/h)\sinh(\pi w/2h)}{\cosh(\pi x/h) + \sin(\pi y/h)\cosh(\pi w/2h)} \tag{1}$$

where w is the width of one electrode and h is the height of the chamber.

$$S(x,y) = \begin{cases} \frac{1}{\pi}\arctan z & \text{if} \quad z > 0 \\ 0.5 & \text{if} \quad z = 0 \\ 1 + \frac{1}{\pi}\arctan z & \text{if} \quad z < 0 \end{cases} \tag{2}$$

The case distinction is necessary because one has to switch between Riemann sheets of the inverse tangent function in order to get an analytic potential. The third case occurs if the point (x, y) gets vertically close to the electrode.

Rectangular Borders

To model a rectangular chamber requires a slightly more complicated conformal mapping.

A rectangular chamber in the $z = x - y$-plane extends from $-a/2$ to $a/2$ in x and from 0 to b in y (see Fig. 2). A potential V is supposed to exist from x_1 to x_2 along the x-axis.

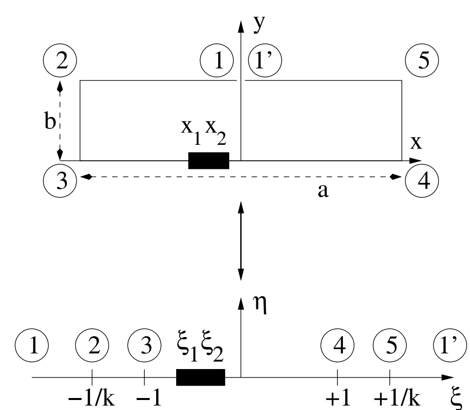

Figure 2: Conformal mapping of inner part of a rectangle to the upper half plane ($k^2 = m$).

The potential is calculated after a conformal mapping of the interiour of the rectangle to the upper complex half-plane.

$$z = x + iy \;\mapsto\; \zeta = \xi + i\eta \tag{3}$$

Such a mapping can be realized by [5]

$$\zeta = \mathrm{sn}\left(\frac{2K(m)}{a} z | m\right) \tag{4}$$

where sn is one of the Jacobian elliptic functions (using the notation from [6]) and K is a complete elliptic integral of the first kind. The parameter m depends on the aspect ratio a/b of the rectangle. It solves the equation [5]

$$\frac{a}{b} - \frac{2K(m)}{K(1-m)} = 0 \tag{5}$$

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DESIGN OF BEAM DIAGNOSTIC SYSTEM FOR OPTICAL STOCHASTIC COOLING AT IOTA RING*

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Abstract

Design of beam diagnostic system for Optical Stochastic Cooling (OSC) at IOTA ring is described in the document. Cooling parameter will be measured by the longitudinal interference pattern of synchrotron radiation lights from two undulators. Light optics and detector system are discussed.

INTRODUCTION

Damping rate of the stochastic cooling (τ^{-1}) is proportional to the bandwidth of the electromagnetic wave (W) and the beam bunch length (σ_s), i.e. $\frac{1}{\tau} \propto W\sigma_s$. It indicates that Optical Stochastic Cooling (OSC) has a great potential to cool TeV-scale proton beams, e.g. LHC and FCC because the bandwidth of radiation lights is typically $\sim 10^{14}$ Hz (wavelength of radiation lights is $\lambda \sim \mu m$) which is four or five orders of magnitude higher (shorter) than a microwave that is used in the conventional stochastic device.

Theoretical investigation of the OSC has been done [1]. Here, several critical formulae are picked up for our discussion. Damping force applies to the longitudinal phase space. The force ($\delta p/p$) is tuned by the path length (Δs) that is adjusted by a chicane,

$$\delta p/p = \kappa \sin(k\Delta s), \quad (1)$$

where κ is the undulator strength and k is the wavenumber of a radiation light. The longitudinal kick is partitioned into the horizontal phase space (x) due to dispersion. To evaluate the stochastic process, the force is averaged along the beam path in a whole ring lattice. It is given as

$$F_1(a_x, a_p) = 2J_0(a_p)J_1(a_x)/a_x, \quad (2)$$

$$F_2(a_x, a_p) = 2J_0(a_x)J_1(a_p)/a_p, \quad (3)$$

where J_0 and J_1 are the 0-th and 1-st order Bessel functions, respectively. a_x and a_p are the dimensionless amplitude that represents the phase advance of beams in the kicker undulator in horizontal (x) and longitudinal (s) phase spaces, respectively. In order to realize the positive average damping force, the phase advance between the beam and the kicker light should be $|a_x, a_p| < \mu_{01} \sim 2.405$.

Proof-of-principle experiment will be done at IOTA ring in Fermilab by using an electron beam. Figure 2 is a layout of cooling insert at IOTA ring. No optical amplifier is used in the first test. Table 1 shows the main beam parameter and the beam optics parameter in the cooling insert at IOTA ring. Dipole and quadrupole magnets are a main tuning knob to adjust the beam path length. A sextupole magnet is applied in the beam line to increase the acceptance by correcting the chromaticity. It significantly changes the path length, thus it changes the cooling condition as shown in Fig. 3. Major goal of the designed beam diagnostic system is to measure the beam path length as a function of the sextupole field strength and to observe this correlation.

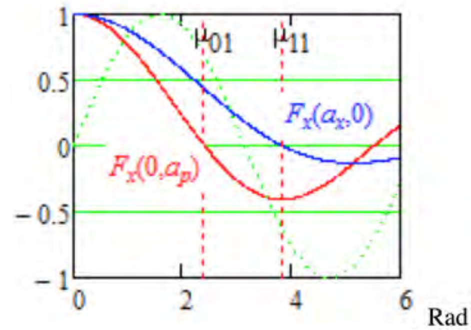

Figure 1: Averaged damping forces.

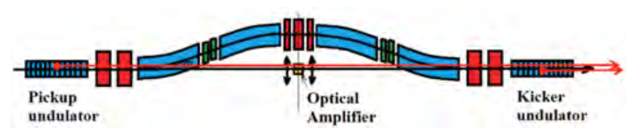

Figure 2: A cooling insert for the OSC in IOTA ring. The blue box is a bending magnet. The red and green boxes are a quadrupole and a sextupole magnets, respectively. The orange line shows a path of a synchrotron radiation light.

Table 1: Beam Parameter

IOTA ring	
Circumference	40 m
Nominal electron beam energy	100 MeV
Bending field of main dipoles	4.8 kG
Revolution	7.5 MHz
Undulators	
Radiation wavelength at zero angle, $\lambda_{\gamma,0}$	2.2 μ m
Undulator parameter	0.8
Undulator period	12.9 cm
Number of periods	6
Total undulator length	0.77 m
Peak magnetic field	664 G
Distance between centers of undulators	3.3 m
Energy loss per undulator per pass	22 meV
Optical system aperture	13 mm
Radiation spot size in the kicker, HWHM	0.35 mm
θ_{max}	4 mrad
$\gamma\theta_{max}$	0.63

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N-BODY CODE TO DEMONSTRATE ELECTRON COOLING

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Abstract

In the Electron Ion Collider (EIC), the collision between the electron beam and the proton, or heavy ion, beam results in emittance growth of the proton beam. Electron cooling, where an electron beam and the proton beam copropagate, is the desired cooling method to cool or mitigate the emittance growth of the proton beam. The pre-booster, the larger booster, and the collider ring in EIC are the major components that require electron cooling. To study the cooling effect, we previously proposed Particles' High order Adaptive Dynamics (PHAD) code that uses the Fast Multiple Method (FMM) to calculate the Coulomb interactions among charged particles. We further used the Strang splitting technique to improve the code's efficiency and used Picard iteration-based novel integrators to maintain very high accuracy. In this paper we explain how this code is used to treat relativistic particle collisions. We are able calculate the transverse emittances of protons and electrons in the cooling section while still maintaining high accuracy. This presentation will be an update on the progress with the parallelization of the code and the status of production runs.

INTRODUCTION

A set of many objects, which undergoes self-interactions and external forces, can be mathematically modeled as an N-body problem. As the number of objects, N, becomes larger, the force calculation demands remarkably high computing power.

In a charged particle beam, the mathematical formulation of the study of particles' behavior leads to an electromagnetic N-body problem. In order to calculate potential, field and Coulomb interactions among particles, we have to solve 6N differential equations (3N for x, y, z and another 3N for p_x, p_y, p_z). We have developed a code based on a novel FMM algorithm [1, 2] using certain differential algebraic techniques to solve differential equations efficiently while maintaining high accuracy.

ALGORITHM

The time taken for calculating the interaction among particles using the point-to-point or direct method exhibits quadratic growth, i.e. $O(\mathrm{N}^2)$. Even today's high-performance supercomputers cannot provide the necessary computational power to solve this problem in a reasonable amount of time. Therefore, the sheer necessity arises for finding computationally efficient and accurate methods to calculate the Coulomb interactions. From the literature review, one can find several approximate methods to calculate interactions, which are relatively efficient compared to the direct method, namely: 1. Basis function methods; 2. Particle-mesh methods; 3. Hierarchical domain decomposition methods. Due to certain drawbacks in the first and the second method, we choose the third [3]. The third group can be further divided into three sub-groups: tree, cluster and fast multipole methods (FMM). Tree and cluster groups, however, are merely special versions of the FMM. We employ a novel FMM [1] since it has many advantages over the original FMM algorithms. The FMM calculates interaction forces within a prescribed accuracy in linear time and memory usage.

In the 3D (2D) FMM, particles reside in small boxes, or octree (quadtree) nodes. The force calculation in FMM can be interpreted as the force calculation between these boxes. Due to the particle domain decomposition, the FMM enables to identify the near and far regions and calculates the far-field interactions rapidly. The near field interactions are still based on the particle–particle calculation method.

Further, we developed a code named PHAD, which is comprised of three important techniques that guarantee efficiency and accuracy. Firstly, we have shown that FMM calculates the far-field interactions with a variable but a priori guaranteed accuracy that can be adjusted by setting an appropriate FMM order. The fact that, at the optimum conditions, its calculation cost is in the order of N implies that FMM is efficient.

As the second technique, we used a variable order Picard iteration-based integrator [4, 5] to calculate the particle distributions' propagation in time. The adjustable time step size of the integrator for each particle allows investigating close encounters. In addition, the Picard integrator provides a dense output. Hence, the ability to adjust the optimum Picard order and the time step size automatically enable to calculate the near range interactions precisely, and with the appropriate number of iterations govern the efficiency.

Finally, we used a second order accurate operator splitting method, the Strang splitting, to speed up the performance of PHAD. It splits the complicated system into two simpler parts: far-range and near-range with external fields. The FMM is time-wise the most expensive procedure, thus we need to reduce the number of FMM calls. Each particle in the beam undergoes fast varying forces and slow varying forces. The fast varying forces are a result of the close encounters between the particle and its neighbors. The collective interaction due to the far away particles can be expressed as the mean field and the slow varying forces are due to this mean field. We need to select the appropriate time step size such that the slow forces stay approximately unchanged. However, in order to calculate the fast varying forces, this time interval should be split into smaller time steps. Due to this fact, we

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TAPER AND TUNER SCHEME OF A MULTI-FREQUENCY CAVITY FOR THE FAST KICKER RESONATOR IN MEIC ELECTRON CIRCULAR COOLER RING*

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Abstract

An ultra-fast harmonic kicker consisted of normal conducting resonators with high transverse shunt impedance thus less RF power consumption was designed for the proposed Medium energy Electron Ion Collider (MEIC). In the prototype design, four quarter wave resonator (QWR) based deflecting cavities are used to generate ten cosine harmonic waveforms, the electron bunches passing through these cavities will experience an integral effect of all the harmonic fields, thus every 10^{th} bunch in a continues bunch train of 10^{th} harmonic bunch frequency will be kicked while all the other bunches un-kicked. Ten harmonic waves are distributed in the four cavities with the proportion of 5:3:1:1. For the multi-frequency cavities, a great challenge is to tune each harmonic to be exact frequency. In this paper, the taper and tuning scheme for the 5-modes cavity is presented. Five taper points in the inner conductor are chosen to make the five frequencies to be odd harmonics. Five stub tuners on the outer conductor are used to tune every harmonic back to its target frequency from the manufacturing errors.

INTRODUCTION

Electron cooling is essential for the proposed MEIC to attain low emittance and high luminosity [1]. The present MEIC design utilizes a scheme of multi-stage cooling, a DC cooler in the booster and the bunched electron beam cooler in Energy Recovery Linac (ERL) in the ion collider ring. To achieve a high electron beam current in the cooling channel but a relative low current in ERL, a circulator ring is proposed as a backup scheme. The electron bunches will recirculate for 25 turns, thus the current in the ERL can be reduced by a factor of 25. Two ultra-fast kickers are required in this circulator ring, one for kick-in, one for kick-out, all with half pulse width less than 2.1ns (1/476.3MHz) and a high repetition frequency of 19.052MHz (1/25 of 476.3MHz). JLab started an LDRD proposal to develop such a kicker. Our approach is to use RF resonant cavities other than transmission line type devices. Electron bunches passing through these cavities will experience an integral effect of all the harmonic fields, thus every 25^{th} bunch in the bunch train will be kicked while all the other bunches un-kicked. Here we present a simplified design of a prototype with every 10^{th} bunch kicked, using four QWR based cavities to generate 10 harmonic modes. The generation of the flat-top kick voltage with finite harmonic modes, shunt impedance formula, cavity structure optimization, power consumption calculation, and the concept design of stub tuners and loop couplers are already presented in [2]-[3]. In addition, the harmonic voltage combining scheme have been also discussed in [4]. Here we only focused on the taper and tuning scheme design of the 5-harmonics cavity.

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CAVITY WITHOUT TAPER

The cavity model used to generate harmonic modes is quarter wave transmission line shorted at one end and a capacitor loaded at the other end, as shown in Figure 1.

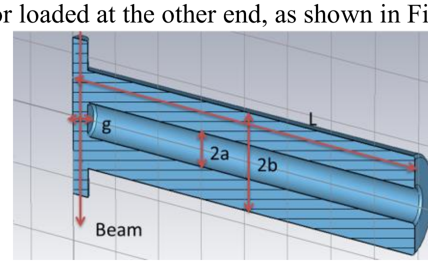

Figure 1: Cavity model without taper

Beam passes through the capacitive gap and is deflected primarily by a transverse electric field. The cavity geometry parameters for the 5-modes cavity are summarized in Tab.1.

Table 1: Cavity Geometry Parameters without Taper

Parameter	Length (mm)
Cavity Length (L)	1578
Inner Radius (a)	55
Outer Radius (b)	157
Gap Distance (g)	70
Beam Pipe Length	500

Here cavity length L is optimized to make maximum required tuning range is minimized. The relationship between the L and the required tuning range of the un-tapered cavity is shown in Fig.2.

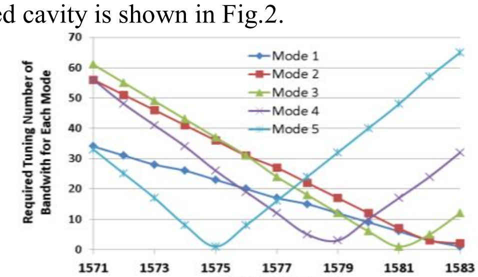

Figure 2: Required tuning range verses cavity lengths.

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STATUS, RECENT RESULTS AND PROSPECTS OF THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

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Abstract

Muon accelerators have been proposed as a means to produce intense, high energy muon beams for particle physics. Designs call for beam cooling to provide suitable beams. Existing cooling schemes cannot operate on time scales that are competitive with the muon lifetime. Ionisation cooling has been proposed as a means to achieve sufficient cooling, but it has never been demonstrated practically. In the Muon Ionisation Cooling Experiment (MICE), based at the Rutherford Appleton Laboratory (RAL), ionisation cooling will be demonstrated. MICE Step IV is currently in progress and will be completed in 2016. Muons are brought onto an absorber, resulting in a reduction of momentum and hence reduction of normalised transverse emittance. The full Demonstration of Ionisation Cooling will take place in 2017. An extra magnet module and RF cavities will be installed, as in a cell of a cooling channel. This will enable the demonstration of reduction of emittance and subsequent re-acceleration, both critical components for a realistic ionisation cooling channel.

COOLING FOR MUON ACCELERATORS

Muon accelerators have been proposed as a source for high energy neutrino beams, at the Neutrino Factory, as a source of Higgs particles in a Higgs factory and as a multi-TeV lepton collider for searches for higher energy phenomena [1, 2].

Muons are created by firing an intense beam of protons onto a high power target. Pions are produced which are captured in high field solenoids where they decay to muons. The resultant muon beam has large emittance.

In order to provide sufficient muons within the acceptance of the Neutrino Factory acceleration system, it is desirable to cool the muon beam prior to acceleration. In order to reach luminosities appropriate for a Muon Collider it is essential to cool the muon beam.

Muon cooling is performed by ionisation cooling [3–5]. This is the only technique that is competitive with the 2.2 μs muon life time. Particles are passed through an absorber where the momentum of the muons is reduced in transverse and longitudinal directions, then passed through an RF cavity where momentum is restored only in the longitudinal direction, resulting in a reduction in beam emittance.

Multiple scattering produces random momentum kicks that tend to degrade the cooling effect or even heat the beam. Low-Z materials like liquid hydrogen or lithium hydride give less multiple scattering for a given energy loss, so these are considered as absorber materials. A tight focus means that the beam has relatively high transverse momentum, so that the multiple scatters are less significant.

Muon cooling has never been demonstrated before. The Muon Ioniation Cooling Experiment (MICE) collaboration is building a section of a cooling channel in order to demonstrate the technique [6].

THE MICE PROGRAM

The MICE program is planned to operate in several installation steps [7]. Step IV is now fully installed and the equipment is being commissioned. Installation of the final step, known as the Demonstration of Ionisation Cooling, will begin in mid-2016. Schematics of Step IV and the Demonstration of Ionisation Cooling are shown in Fig. 1.

In Step IV the full diagnostics system has been installed together with a single absorber system. In this configuration MICE will study the material physics properties of the MICE absorbers and measure transverse normalised emittance reduction .

In the Demonstration of Ionisation Cooling, a cooling cell will be installed including RF equipment. This will enable the measurement of ionisation cooling with reacceleration.

In order to accommodate the characteristics of muon beams, MICE has a number of features which make it a unique accelerator physics experiment. These features are outlined below.

High resolution particle-by-particle diagnostics

MICE is similar to a small section of a much longer cooling channel, so will produce a cooling effect of only a few percent. In order to measure such a cooling effect with high precision, a high resolution detector system has been designed.

MICE will measure individual particles' position, momentum and time with respect to the RF pulse once RF is installed [8]. This enables the collaboration to make a full correlated measurement of the beam upstream and downstream of the cooling equipment.

MICE can also reject beam impurities such as undecayed pions and electrons from muon decay on a particle-by-particle basis.

The position and momentum of particles are measured using two scintillating fibre trackers upstream and downstream of the cooling region. Three 50 ps time-of-flight counters (TOFs) provide time measurement and velocity measurement. Comparison of velocity and momentum enables measurement of particle mass. Cherenkov threshold counters (Ckov), the KL pre-shower and Electron Muon Ranger (EMR) calorimeter provide additional

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STATUS OF HELICAL COOLING CHANNELS FOR INTENSE MUON SOURCES*

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Abstract

Status of the design and simulation study of a homogeneously distributed hydrogen gas-filled helical cooling channel (HCC) is presented. The helical cooling theory has been verified by numerical cooling simulations. Flexibility of cooling decrements and equilibrium emittance in the HCC were demonstrated by tuning the helical cooling lattice. Preliminary analysis of a beam-plasma interaction in a solenoid magnetic field and a gas-filled RF cavity was made. As a result, a beam-induced plasma neutralizes a space charge of the incident beam and a plasma-lens effect appears. It indicates that the beam dynamics and cooling performance in the final cooling segment will be affected by the plasma-lens.

INTRODUCTION

Ionization cooling has a great potential to shrink a muon beam phase space by factor 10^6 within their short lifetime (2.2γ μs) since the collision frequency in a cooling media is extremely high by comparing with a conventional cooling method [1]. However, a large angle scattering takes place by the Coulomb interaction with nuclei in the media, so called a multiple scattering, and grows the muon beam phase space (heating). To minimize the heating, an ionization cooling channel consists of a strong magnetic field to overcome the multiple scattering, and a high-gradient RF cavity in the magnet to immediately compensate the lost-energy via ionization process. Hydrogen is the best cooling material since it has a high energy-loss rate and a long radiation length.

Early days' designs of a cooling channel have a liquid hydrogen flask and a high gradient vacuum RF cavity in a strong magnetic field. However, soon channel designers realize a critical issue that the maximum available RF gradient is strongly limited by the magnetic field strength in the cavity [2]. One plausible model is that dark current densities in the cavity are increased due to focused by magnetic fields. It induces a RF electric breakdown at lower RF gradients in stronger magnetic fields. A possible solution is filling a RF cavity with a dense hydrogen gas [3]. Gas resists the dark current flow and, therefore suppresses RF electric breakdowns even the cavity is operated in a strong magnetic field. In addition, a dense gaseous hydrogen works as an ionization cooling media.

A helical cooling channel (HCC) is designed to maximize the advantage of utilizing the gas-filled RF cavities for a six-dimensional (6D) ionization-cooling channel [4]. Beam trajectory is a spiral by a solenoid and helical magnetic components (Fig. 1). To avoid any pressure gap on the beam path, hydrogen gas is distributed homogeneously in the channel. RF cavities are located along the helical beam path without any spatial gap. A thin RF window is located between adjacent cavities to electrically isolate each other. A solenoid and helical dipole components are applied to generate a continuous dispersion. An emittance-exchange occurs during the cooling process with the dispersion, therefore it induces 6D phase space cooling. A helical field gradient continuously focuses the beam and stabilizes the phase space. Large acceptance of the channel is achieved since there is no betatron resonance in the continuous focusing channel. Thus, the channel length is shorter than other ionization cooling channels.

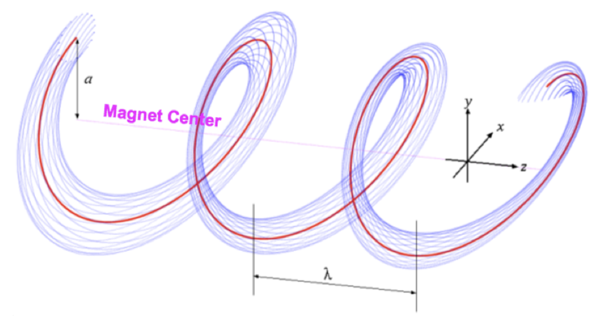

Figure 1: Beam path in a helical lattice. A red line is a reference orbit and a blue line is an orbit of an envelop particle.

Dense hydrogen gas-filled RF cavity is a unique device for beam applications. Particularly, a beam-induced gas-plasma in a dense hydrogen gas opens many interesting subjects. Ionization electrons are quickly thermalized by momentum exchange interaction with molecular hydrogens. The plasma regains kinetic energy from RF fields. The energy is transferred into hydrogen gas via the thermalization. As a result, RF power is transformed into the gas temperature. The rate is proportional to the plasma density in the cavity. It is called plasma loading effect [5]. The effect can be mitigated by doping a small amount of electronegative gas in the cavity. From experiment, 0.2 % Oxygen was sufficient to be ineffective the plasma loading for beam acceleration. Plasma parameters were measured in experiments [6]. These are used in a numerical plasma simulation to evaluate the collective effect in the cavity for intense muon beam applications. As a result, the space charge of beam is neutralized by plasma motions excited by the space charge fields and the tail of the bunched beam is strongly focused by the self-induced axial magnetic field [7, 8]. This phenomenon is similar as the plasma lens that has been developed for the electron-positron collider at SLAC [9]. Since the HCC is a positive energy transition

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PROGRESS ON PARAMETRIC-RESONANCE IONIZATION COOLING*

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Abstract

Proposed next-generation muon collider will require major technical advances to achieve the rapid muon beam cooling requirements. Parametric-resonance Ionization Cooling (PIC) is proposed as the final 6D cooling stage of a high-luminosity muon collider. In PIC, a half-integer parametric resonance causes strong focusing of a muon beam at appropriately placed energy absorbers while ionization cooling limits the beam's angular spread. Combining muon ionization cooling with parametric resonant dynamics in this way should then allow much smaller final transverse muon beam sizes than conventional ionization cooling alone. One of the PIC challenges is compensation of beam aberrations over a sufficiently wide parameter range while maintaining the dynamical stability with correlated behavior of the horizontal and vertical betatron motion and dispersion. We explore use of transverse coupling to reduce the dimensionality of the problem and to shift the dynamics away from non-linear resonances. PIC simulations are presented.

MOTIVATION

Experiments at energy-frontier colliders require high luminosities of order 10^{34} cm^{-2} sec^{-1} or more in order to obtain reasonable rates for events having point-like cross sections. High luminosity colliders require intense beams with small transverse emittances and a small beta function at the collision point. For muon colliders, high beam intensities and small emittances are difficult and expensive to achieve because muons are produced diffusely and must be cooled drastically within their short lifetimes. The muon does not interact by the strong interaction, and its high mass relative to the electron means that it can pass through matter without hadronic or electromagnetic showers. Thus, it is the perfect candidate for ionization cooling. Muons lose energy by passing through a low-Z material and only the longitudinal component is replaced by an RF cavity. This technique allows the angular spread of a beam of muons to be reduced in a very short time close to the limit determined by multiple scattering.

Ionization cooling as it is presently envisioned will not cool the beam sizes sufficiently well to provide adequate luminosity without large muon intensities. For example, a muon-collider s-channel Higgs factory, a logical prerequisite to an energy-frontier muon collider, would be compelling if the luminosity were high enough. The 4 MeV energy resolution needed to directly study the Higgs width is only possible with such a machine. Also, the mass-dependent muon-Higgs coupling gives a factor of over 40,000 cross-section advantage relative to an electron collider. Numerical simulations of muon cooling channels based on technical innovations made and experimentally tested in this millennium have shown 6D emittance reductions of almost 6 orders of magnitude. Parametric-resonance Ionization Cooling (PIC) can achieve an additional two orders of emittance reduction for an additional factor of 10 in luminosity.

In addition, to the extent that the transverse emittances can be reduced further than with conventional ionization cooling, several problems can be alleviated. Lower transverse emittance allows a reduced muon current for a given luminosity, which implies:

- a proton driver with reduced demands to produce enough proton power to create the muons,
- reduced site boundary radiation limits from muons decaying into neutrinos that interact with the earth,
- reduced detector background due to electrons from muon decay,
- reduced proton target heat deposition and radiation levels,
- reduced heating of the ionization cooling energy absorber,
- less beam loading and wake field effects in the accelerating RF cavities,
- reduced space charge effect.

Smaller transverse emittance has virtues beyond reducing the required beam currents, namely:

- smaller higher-frequency RF cavities with higher gradient can be used for acceleration,
- beam transport is easier with smaller-aperture magnetic and vacuum systems,
- stronger collider interaction point (IP) focusing can be used, since that is limited by the maximum achievable beam extension prior to the IP.

PARAMETRIC-RESONANCE IONIZATION COOLING (PIC)

Concept and Analytic Theory

The limit on the minimum achievable emittances in muon ionization cooling comes from the equilibrium between the cooling process and multiple Coulomb scattering in the absorber material. The concept of

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PROJECT OF ELECTRON COOLER FOR NICA

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Abstract

The problems of development of high energy electron coolers are discussed on the basis of the existing experience. Necessities of electron cooling application to NICA collider are considered and the project parameters of the electron cooler at NICA collider are presented.

Electron cooler of the NICA Collider is under design and development of its elements at JINR. It will provide the formation of an intense ion beam and maintain it in the electron energy range of 0.5–2.5 MeV. To achieve the required energy of the electrons all the elements of the Cooler are placed in the tanks filled with sulfur hexafluoride (SF_6) gas under pressure of 6 atm. For testing the Cooler elements the test bench «Recuperator» is used and upgraded. The results of testing of the prototypes of the Cooler elements and the present stage of the technical design of the Cooler are described in this paper.

INTRODUCTION

The first question to be answered is: "Why do need HV E-Cooler for the NICA collider?" This Collider will have to operate at the energy of heavy ions like $^{197}Au^{79+}$ in the range of 1÷4.5 GeV/u. To reach the project luminosity one needs to form short and high intense ion bunches and maintain their parameters during a long time, of the order of 1 hour at least. In NICA project two energy ranges of the Collider and two its regimes are considered.

A) Space charge (SC) dominated regime:
E_{ion} = 1–3 GeV/u. Electron cooling is mandatory here when acceptance is filled with ions up to the Laslett tune shift $\Delta Q = \Delta Q_{max} = 0.05$. Then beam intensity and Collider luminosity are limited (see details in [1]):

$$L \le L_{max} = (0.01\text{–}1)\times 10^{27}\ \text{cm}^{-2}\cdot\text{s}^{-1}.$$

B) Intrabeam scattering (IBS) dominated regime:
E_{ion} = 3–4.5 GeV/u. With energy increase SC effect becomes small, luminosity can be increased up to

$$L = 1\times 10^{27}\ \text{cm}^{-2}\cdot\text{s}^{-1}$$

and is maintained constant. However, to keep bunch parameters one has now to suppress IBS. It can be done by application of stochastic and electron cooling. At the energy above 3 GeV/u luminosity is artificially limited by max event rate acceptable for detector MPD. In this energy range electron and stochastic cooling are supposed to be used in the NICA Collider simultaneously providing a long life time of the Collider luminosity.

Nowadays electron coolers are demanded in the energy range up to tens MeV. There are several well advanced projects. In general one can divide then in two groups: high voltage (HV) and high energy (HE) electron coolers. The first ones use conventional DC HV schemes. These coolers can be used, practically, up to 10–15 MeV electron energy. Such projects are under development at COSY (FZJ), NICA (JINR), HESR (FAIR), HIAF (Lanzhou). The second group — HE electron coolers are developed on basis of several different novel approaches, like coherent e-cooling, optical e-cooling, and some others. Most feasible of them looks option of "energy recovering linac" (ERL) [2] that is under development at RHIC BES (BNL) and MEIC (JLab) projects.

THE EXPERIENCE WE HAVE

Presently we have only two examples of HV electron cooler. One is well known electron cooler at Recycler storage ring at Fermilab that was designed and constructed by the team led by S. Nagaitsev [3]. The cooler had electron energy up to 4.3 MeV at working electron current of 0.1–0.5 A (max electron current 1.6 A). The cooler design was based on the Pelletron scheme — a version of electrostatic accelerator. It had unmagnetized electron beam. Presently the machine is dismantled.

The second electron cooler was designed by original scheme and constructed by the team of V. Parkhomchuk at Budker INP [4, 5]. The cooler has maximum design electron energy of 2 MeV at the Electron beam current of 3.0 A. HV generator is made by the cascade transformer scheme, electron beam is magnetized. The "COSY cooler" is under commissioning presently [4], [5].

These two machines characterize the level of technical development in this field today.

THE CONCEPTS OF A HV E-COOLER FOR AN ION COLLIDER

The First Consideration

The NICA electron cooler is the very first experience of design and construction of such cooling system with two cooling electron beams. Therefore some consideration of a general character has been done.

An evident scheme based on two independent cooling electron beams has been proposed in the NICA project (see below). More sophisticated scheme — one (common) electron beam to cool two ion beams was

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FORMATION OF BUNCHED ELECTRON BEAM AT THE ELECTRON COOLER OF CSRm*

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Abstract

The motivation for formation of bunched electron beam at the electron cooler of CSRm is based on the three requirements. Firstly, the high energy electron cooling, especially, the ion beam with TeV energy, the bunched electron beam for cooling would be easier than the DC operating mode. Secondly, the electric field induced by the intensity modulated electron beam will be used for the suppression of instability developed in the high intensity ion beam after accumulation with the help of electron cooling, Thirdly, the electron beam was required to turn on and off in the different period of the atomic physics experiments. Some initial design and consideration were presented in this paper. And also the current situation and condition of CSRm electron cooler were described here. An off-line testbench will be established in the laboratory, and the test and the optimization will be explored in this experimentation. The validity of this system will be verified in the near future. The procedure of the modulation on the voltage of control electrode in the electron gun of the CSRm cooler was discussed. The scheme of off-line measurement was devised according to the progress.

INTRODUCTION

The electron coolers of HIRFL-CSR have operated for ten years from 2005. The performance and upgrade was reported in the paper [1]. The latest experiments and results can be found in the report [2]. During the routine operation, especially in the case of higher accumulated ion beam intensity, the instability of ion beam was observed [3, 4], some information can be found in the references [5]. It is an essential problem to find the way to suppress the instability in order to obtain the higher accumulated and stored ion beam in HIRFL-CSR.

As the described in reference [6], the conventional way to suppress the instability was adopting the feedback system. From the report [7] the feedback system was helpful to increase the accumulated ion beam intensity, the action on the instability was not clear. Another solution was proposed in the paper [8], in order to avoid the overcooling, additional heating on the electron beam was used to suppress the instability. The results were presented in the reference [9].

A more efficient way [10] to suppress the instability was increasing the energy spread with the help of modulation.

A new method was proposed in this paper, the idea came from the electron beam as 3d kicker for stochastic cooling [11,12]. The intensity of the electron beam was modulated transversely and longitudinally. The distribution of electron became asymmetrical and inhomogenous, as a result, the electron beam becomes the electron bunches. The space charge field between the bunches acts as the kicking on the ion beam. These actions can be used to suppress the instability of ion beam.

The electrostatic field produced by the space charge of electron beam in the cooler by means of modulation on the voltage of control electrode in the electron gun will act as a travelling wave in the cooling section. This action will be attempted to suppress the ion beam instability in the presence of electron cooling device.

Another application of this work can be used to demonstrate the cooling effects of bunched electron beam [13,14].

SOME CONSIDERATIONS

Generally, the bunched electron beam was easily produced by the pulse electron gun. Unfortunately, the electron gun in the CSR coolers was direct current. On the other hand, the limitations come from the normal routine operation and heavy load beamtime in CSR.

From the technical point of view, the cathode of electron gun of the electron cooler was thermic cathode. It was continuously heated during the operation. The configuration of electrodes in the electron gun presents capacitive feature. The charge and discharge rate of the electron gun should be taken into account. Due to lack of the diagnostic instruments in the electron cooler, the measurement of the bunch should be solved offline.

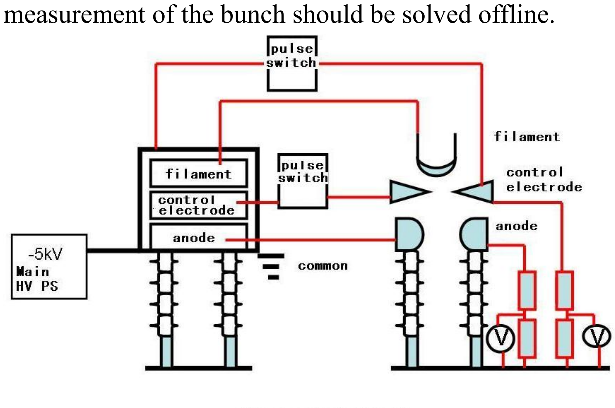

Figure 1: Layout of offline testbench.

A simplified solution was derived in this plan. The DC voltage of control electrode in the gun which was used to extraction of electron from the surface of cathode will be replaced by a new bipolar pulse power supply, in additional, a fast switch among the positive, negative and

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DEVELOPMENT OF AN ULTRA FAST RF KICKER FOR AN ERL-BASED ELECTRON COOLER

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Abstract

The staged approach to electron cooling proposed for Jefferson Lab's Medium Energy Electron-Ion Collider (MEIC) utilizes bunched beam electron cooling with a single-pass energy recovery linac (ERL) for cooling in the ion collider ring. Possible luminosity upgrades make use of an ERL and full circulator ring and will require ultra-fast kickers that are beyond current technology. A novel approach to generating the necessary ultra fast (ns-level) RF kicking pulse involves the summation of specific subharmonics of the cooling electron bunch frequency; the resultant kicking pulse is then naturally constrained to have rise and fall times equal to the electron bunch frequency. The uniformity of such a pulse and its effects on the beam dynamics of the cooling electron bunch are discussed.

INTRODUCTION

JLab's proposed MEIC requires bunched beam cooling of ions at collision energy to maintain design emittances for high luminosity. In the baseline design [1], the bunched electron beam is accelerated and decelerated using an energy recovery linac (ERL) to reduce the active beam power at the beam dump. More intense electron cooling provides a path to a luminosity upgrade, with the required higher average electron current provided by a full circulator cooler ring. Figure 1 shows a schematic of the ERL and circulator cooler ring concept. Use of the circulator ring relaxes the current requirement from the injector by allowing each electron bunch to cool multiple ion bunches. The circulator cooler ring concept requires ultra fast transverse beam kickers to deflect electron bunches into and out of the circulator ring. For a cooler ring frequency of 476 MHz, the bunch spacing is 2.1 ns and the kicker must be able to deflect a single bunch without disturbing the preceding or following bunches in the bunch train. Each pass that a single bunch makes in the circulator ring reduces the required current from the injector by the same amount; for n passes in the circulator ring, the injector current is reduced by a factor 1/n. The transverse beam kicker should then operate at a frequency of 476/n MHz, kicking every n-th bunch in the bunch train into or out of the ring. Thus a suitable kicking pulse will have rise and fall times on the order of the bunch spacing, with MHz repetition rates. A kicking pulse of this type is beyond current driver technology. We describe a novel method for generation of such a suitable kicking pulse and discuss the effects of the kicking pulse on the quality of the cooling electron bunches.

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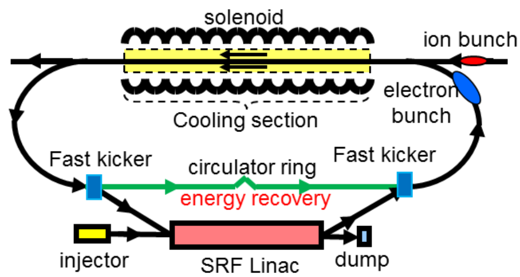

Figure 1: Schematic of an ERL-based electron cooler with full circulator ring.

CONCEPT

The ultra fast RF kicking pulse required for use in the circulator cooling ring concept can be generated by summing subharmonics of the bunch frequency with appropriate phases and amplitudes. A similar concept using the Fourier series representation of a periodic delta function with higher harmonics of the bunch frequency has been explored for the TESLA damping ring [2]. The use of subharmonics of the bunch frequency allows for adjustment of the kicker waveform according to the desired characteristics of the waveform, particularly at intermediate positions between kicking pulses at which circulating bunches should be left undisturbed. The constraints of zero amplitude and zero gradient of the kicking pulse at these undisturbed bunch positions result in the kicking pulse described by

$$f(\theta;\vec{a}) = \sum_{i=0}^{n-1} a_i \cos i\theta \qquad (1)$$

where

n = number of bunches in the bunch train
θ = bunch frequency/n = 476/n MHz
a_i = amplitude coefficients of the subharmonics

$$a_0 = \frac{1}{n} \qquad (2)$$

$$a_j = \frac{2(n-j)}{n^2}, j = 1,2,\ldots,n \qquad (3)$$

The resultant kicker waveform and the subharmonics required for the case of n=25 bunches in the bunch train is plotted in Figure 2. The peaks of the kicking pulse occur with a frequency of 476/25=19.04 MHz, and both the amplitude and gradient of the kicking pulse are zero for non-kicked bunches in the bunch train. The rise and fall time of the pulse is exactly equal to the bunch spacing.

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SIMULATION STUDIES OF INTENSITY LIMITATIONS OF LASER COOLING AT HIGH ENERGY

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Abstract

Within the FAIR project, laser cooling of highly intense, ultra relativistic ion beams will be attempted for the first time, and in a large (circumference 1084 m) and strong (max. magnetic rigidity 100 Tm) synchrotron, called "SIS100".

Laser cooling of such ion beams should result in a further increase of the longitudinal phase space density and in non-Gaussian longitudinal beam profiles. For stable operation of such ion beams, and for optimization of the cooling process, both the laser force and the high-intensity effects have to be studied numerically in advance. The efficiency of laser cooling has been analyzed for different synchrotron frequency regimes. At high beam intensities, intra-beam scattering and space-charge effects have been found to counteract the laser cooling force. We will discuss how they influence the laser cooling efficiency and thus affect the cooling time.

INTRODUCTION

Laser cooling of stored coasting and bunched ion beams has been investigated experimentally at the TSR in Heidelberg (Germany) [1, 2], and at ASTRID in Aarhus (Denmark) [3,4]. At the ESR in Darmstadt (Germany), first laser cooling experiments with stored "bunched relativistic" ion beams were conducted [5]. In the future laser cooling will be applied to highly intense and ultra relativistic ion bunches within the FAIR project [6].

The principle of laser cooling is, especially after the Nobel Prize in 1997, very well known. Here, we consider an ion with a fast atomic transition, e.g. 2s - 2p (electric dipole), of a particular wavelength λ, and a well-defined velocity $v = \beta c$. When the ion moves towards a counter-propagating photon from a laser beam, both the energy and the momentum of the photon are absorbed in a single scattering event, see Fig. 1. This brings the ion in an excited state, which, however, de-excites almost instantaneously by fluorescence emission. The corresponding recoil then occurs in a random direction. After many scattering events, the random recoils average out to zero, but photon absorption always came from one direction, thus decelerating the ion. A pure deceleration force is highly unwanted here, but a strong reduction of the velocity spread of the ions is. Therefore, a counter-balancing force is required, which comes from bunching the ion beam: the rf-bucket force. The laser must thus address ions orbiting with relativistic velocities and performing synchrotron oscillating in the rf-bucket.

Since the Doppler-width of the transition is usually much smaller than the particle distribution, the laser light can only interact with a certain velocity class of ions in the beam. To address the full range of velocities, the laser must be scanned over a large range.

In this work, we analyze the dynamics of an ion beam during the laser cooling process, using a one dimensional particle-in-cell code. The transverse plain is assumed to be unaffected by the laser force. By using "macro particles" the modeling of direct coulomb interactions between single particles is not possible. The results at very low momentum spreads might therefore not be very exact, but the focus of this work lies on the cooling process and the intensity limitations of laser-cooled ion beams.

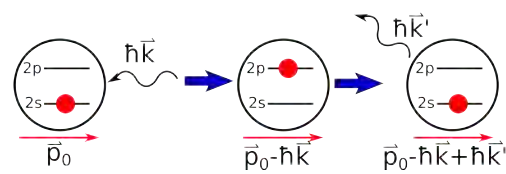

Figure 1: A single scattering event: The ion (traveling to the right) absorbs a photon from the laser beam (traveling to the left) followed by a spontaneous emission. After many scattering events, the momentum transfer of the random recoils average out to zero, but the momentum of the absorption always decelerate the ion.

The laser particle interaction is a statistical process. The probability of a spontaneous emission in a time interval Δt is given by

$$\rho_{emit} = \frac{\Delta t}{\tau} \cdot \rho_{ee} \tag{1}$$

where τ is the lifetime of the exited state and ρ_{ee} is the excitation probability. For a saturated transition the excitation probability is given by (see ref. [7])

$$\rho_{ee} = \frac{1}{2} \frac{S}{1 + S + (2\Delta\nu \cdot \tau)^2} \tag{2}$$

where S is the Saturation parameter and $\Delta\nu$ the detune between the frequency of the photon and the transition. For arbitrary excitations the optical Bloch equations have to be solved as described in [8]. The momentum kick of one spontaneous emission is given by

$$\Delta p_{lab} = \frac{\hbar\omega_{lab}}{c_0} \cdot \gamma^2(1 + \beta) \cdot 2U_j \tag{3}$$

where ω_{lab} is the frequency of the incoming photons in the laboratory frame and U_j a random number between 0 and 1, describing the projection of the randomly emitted photon.

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COOLING FOR A HIGH LUMINOSITY 100 TeV PROTON ANTIPROTON COLLIDER

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Abstract

A 10^{34} cm^{-2} s^{-1} luminosity 100 TeV proton-antiproton collider is explored. The cross section for many high mass states is 10x higher in $p\bar{p}$ than pp collisions. Antiquarks for production can come directly from an antiproton rather than indirectly from gluon splitting. The higher cross sections reduce the synchrotron radiation in superconducting magnets and the vacuum system, because lower beam currents can produce the same rare event rates. Events are also more central, allowing a shorter detector with less space between quadrupole triplets and a smaller β^* for higher luminosity. To keep up with the antiproton burn rate, a Fermilab-like antiproton source would be adapted to disperse the beam into 12 different momentum channels, using electrostatic septa, to increase antiproton momentum capture 12x. At Fermilab, antiprotons were stochastically cooled in one debuncher and one accumulator ring. Because the stochastic cooling time scales as the number of particles, 12 independent cooling systems would be used, each one with one debuncher/momentum equalizer ring and two accumulator rings. One electron cooling ring would follow the stochastic cooling rings. Finally antiprotons in the collider ring would be recycled during runs without leaving the collider ring, by joining them to new bunches with snap bunch coalescence and longitudinal synchrotron damping.

INTRODUCTION

With the recent discovery of the Higgs boson [1] the standard model of particle physics is complete, but exploration will continue to search for beyond the standard model (BSM) physics. Colliders beyond $\sqrt{s}$ =14 TeV are necessary to fully explore new BSM physics, and this provides a great motivation for the future construction of a high energy $p\bar{p}$ collider [2, 3]. A 200 km circumference ring with 8 T NbTi magnets is chosen [4]. The tunnel is 2.5× longer than the twin 40 km tunnels proposed for the International Linear Collider. The center of mass energy considered would be 100 TeV with a luminosity of 10^{34} cm^{-2} s^{-1}. Energy frontier pp [5, 6] and $\mu^+\mu^-$ [7] colliders have also been proposed.

Synchrotron radiation of about 2 Megawatts per ring becomes a problem with circular 100 TeV pp colliders [8]. A $p\bar{p}$ collider represents a large advantage with respect to a pp collider in the point that the cross section for higher mass is around 10 times larger, which allows the collider to run with lower beam currents while still producing the same high mass event rate as pp. See Figs. 1 and 2. Synchrotron radiation in superconducting magnets and the vacuum system is reduced as well as detector radiation damage.

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Some important aspects to achieve high luminosity are identified in this study, such as increased momentum acceptance in a Fermilab-like antiproton source, and studies of higher antiproton cooling rates.

PROTON ANTIPROTON COLLIDERS

Proton antiproton colliders have been used at CERN [9], Fermilab [10], and GSI Darmstadt [11].

In $p\bar{p}$ collisions, antiquarks for production can come directly from an antiproton rather than indirectly from gluon splitting as is observed in Fig. 1, which shows the main process for W′ production in $q\bar{q}$ and qq collisions.

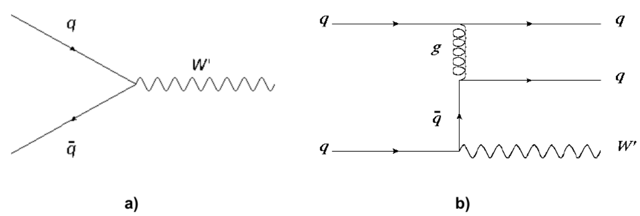

Figure 1: Feynman diagrams for W′ production in (a) $q\bar{q}$ collision, and (b) qq collision (t channel). The two final state quarks cross in the u channel, which is not shown.

In $p\bar{p}$ collisions, the cross section for most high mass states is greater than in pp collisions [2], as can observed in the Fig. 2, where the cross section is around 10x higher in $p\bar{p}$ collisions in W′ production as an example. It is important to note that the higher cross sections allow the collider to be run at lower beam currents and luminosities, which reduces synchrotron radiation in the collider's superconducting magnets and vacuum system. In addition, one beam pipe of magnets is shared by both beams, reducing costs with respect to the two beam pipes required for a pp collider, as well as simplifying the interaction region.

LUMINOSITY REQUIREMENTS

A main goal is to achieve a luminosity of 10^{34} cm^{-2} s^{-1}. As a starting point, take as reference the Tevatron collider. The luminosity can be scaled as:

$L_{scaled} = E_{increased}$ x $f_{decreased}$ x $L_{current}$ =
(50 TeV / 0.98 TeV) x (6.28 km/200 km) x (3.4 x 10^{32} cm^{-2} s^{-1}) =
5.2 x 10^{32} cm^{-2} s^{-1}
where f is collision frequency.

Thus, with 20 times more bunches a luminosity of 10^{34} cm^{-2} s^{-1} is achieved. The antiproton burn rate for a 100 TeV $p\bar{p}$ collider, with total cross section σ = 150 mbarn, is σL = 540 x 10^{10} /hr. The Fermilab Debuncher ring cooled 40

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DEVELOPMENT OF THE ELECTRON COOLING SIMULATION PROGRAM FOR MEIC*

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Abstract

In the medium energy electron ion collider project at Jefferson Lab, the traditional electron cooling technique is used to reduce the ion beam emittance at the booster ring, and to compensate the intrabeam scattering effect and maintain the ion beam emittance during collision at the collider ring. A DC cooler at the booster ring and a bunched beam cooler at the collider ring are proposed. To fulfil the requirements of and the cooler design for MEIC, we are developing a new program, which allows us to simulate the following cooling scenarios: DC cooling to coasting ion beam, DC cooling to bunched ion beam, bunched cooling to bunched ion beam, and bunched cooling to coasting ion beam. The new program has been benchmarked with existing code in aspect of accuracy and efficiency. The new program will be adaptive to the modern multicore hardware. We will present our models and some simulation results.

MEIC COOLING SCHEME

At Jefferson Lab, the medium energy electron ion collider (MEIC), to reach the frontier in Quantum Chromodynamics, will provide an electron beam with energy up to 10 GeV, a proton beam with energy up to 100 GeV, and heavy ion beams with corresponding energy per nucleon with the same magnetic rigidity. The center-of-mass energy goes up to 70 GeV. Two detectors, a primary one with full acceptance and a high-luminosity one with less demanding specification, are proposed. To achieve the ultrahigh luminosity close to 10^{34} $cm^{-2}s^{-1}$ per detector with large acceptance, the traditional electron cooling will be implemented strategically. [1]

The MEIC ion complex consists of ion sources, an SRF linac, a booster ring and a medium energy collider ring, as shown in Fig. 1. Since the electron cooling time is in proportion to the energy and the 6D emittance of the ion beam, which means it is easier to reduce the emittance at a lower energy, a multi-stage cooling scheme has been developed. A low energy DC cooler will be installed at the booster ring, which will reduce the emittance to the desired value for ion beams with the kinetic energy of 2 GeV/u. A bunched beam cooler will be installed at the collider ring, which helps to compensate the intrabeam scattering (IBS) effect and maintain the emittance of the ion beam during the injection process and during the collision.

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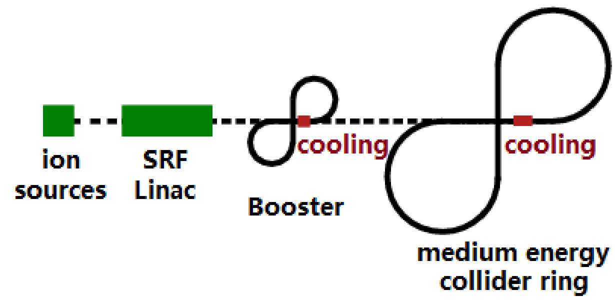

Figure 1: Components of MEIC ion complex.

CODE DEVELOPMENT GOALS

The DC cooler is within the state-of-art. [2] But the bunched beam cooler is out of the state-of-art and needs significant R&D. Numerical simulation is inevitable for the design and optimization of the MEIC electron cooling system. BETACOOL has been used in our preliminary study and it has successfully supported the MEIC design. As the study goes more in-depth, it will be beneficial to have a more efficient and more flexible tool to fulfil some specific needs of MEIC.

The goal of this new simulation program is to enhance the simulation capability for electron cooling in MEIC project. It will preferentially fulfil the needs of MEIC design. The program simulates the evolution of the macroscopic beam parameters, such as emittances, momentum spread and bunch length, in different electron cooling scenarios: DC cooling, bunched electron to bunched ion cooling, bunched electron to coasting ion cooling, etc.

Since BETACOOL has provided a collection of physical models for various electron cooling simulations [3], we decided to follow the models in BETACOOL, whenever they are applicable, and revise them when necessary. We also want to improve the efficiency by strategical arrangement of the calculation and/or by implementation of the models on modern multicore platform.

INTRABEAM SCATTERING

The intrabeam scattering (IBS) effect can cause significant increase of the emittance of the ion beam, due to the high intensity of them, in MEIC in a short time, which ruins the luminosity of the collider. The emittance change rate due to the IBS effect can be calculated using several different formulas under different assumption of the ion beam profile and lattice parameters. [4-7] Here we choose Martini model [5] for the IBS rate calculation for MEIC. Martini model assumes Gaussian distribution for the ion beam, which is reasonable at least for the first

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MICE DEMONSTRATION OF IONIZATION COOLING*

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Abstract

The goal of the international Muon Ionization Cooling Experiment (MICE) is to demonstrate transverse emittance reduction of a muon beam through use of absorber materials, RF cavities, and focusing solenoids. Low emittance muon beams are basic to Neutrino Factory and Muon Collider studies. In summer 2014, following the P5 report, a revised project plan for MICE was approved with a cooling lattice consisting of one central (primary) and two secondary LiH absorbers for energy loss, two 201 MHz RF cavities for beam re-acceleration, two solenoidal spectrometers for emittance measurement, and two focus coils to focus the muon beam. The superconducting magnets, absorbers and detectors necessary for the final stage of the experiment are already in hand and a 201 MHz prototype RF cavity module is under test at Fermilab's MuCool Test Area. We describe the muon ionization cooling concept, the redesigned cooling lattice of the MICE Demonstration of Ionization Cooling, and the cooling performance of the redesigned lattice.

INTRODUCTION

Stored low emittance muon beams lay the foundation for intense, well-parameterized neutrino beams at the Neutrino Factory and high-luminosity Muon Colliders [1]. Typical muon beams produced at the front ends of these facilities have an emittance range of 15-20 π·mm·rad. The desired muon beam emittance range at the Neutrino Factory is 2-5 π·mm·rad [2]. The Muon Collider needs further cooling with a desired transverse emittance of 0.025 π·mm·rad and longitudinal emittance of 72 π·mm·rad [3]. In order to produce a muon beam at such facilities, a high power proton beam collides and interacts with a target to produce pions, which in turn decay to muons. Such muon beams occupy a large phase space volume and in order to optimize muon yield, fit the beam into small apertures, and achieve the required luminosity, one would need to reduce the phase space volume occupied by the beam [4]. Given the muon's large mass and short lifetime, the traditional cooling techniques—synchrotron radiation and stochastic or electron cooling—are inefficient in cooling the muon beam.

Taking advantage of the muon's long interaction length, ionization cooling is suitable (and is the only feasible technique) for reducing the muon beam emittance in a time comparable to the muon lifetime [5].

In order to accomplish sustainable ionization cooling, the muon beam transverse and longitudinal momenta must be reduced via energy loss in an absorber material, with its longitudinal momentum subsequently restored in RF cavities. The rate of change of the normalized transverse emittance is

$$\frac{d\varepsilon_{in}}{ds} \cong -\frac{\varepsilon_{in}}{\beta^2 E_\mu}\left\langle\frac{dE}{ds}\right\rangle + \frac{\beta_\perp (13.6\text{MeV})^2}{2\beta^3 E_\mu m_\mu X_0}. \quad (1)$$

where βc, E_μ, and m_μ are the muon velocity, energy, and mass, dE/ds the energy loss rate through ionization, X_0 the absorber radiation length, and $\beta_\perp$ the transverse beta function at the absorber. The first term in Eq. 1 describes cooling via energy loss and the second term heating due to multiple Coulomb scattering. When the heating term and the cooling term are equal, the cooling channel is said to be at "equilibrium emittance". Setting $\frac{d\varepsilon_{in}}{ds}$ equal to zero yields

$$\varepsilon_{in} \cong \frac{\beta_\perp (13.6\text{MeV})^2}{X_0 2\beta m_\mu}\left\langle\frac{dE}{ds}\right\rangle^{-1}. \quad (2)$$

A smaller equilibrium emittance leads to a more effective emittance reduction which from Eq. 2 can be achieved by minimizing $\beta_\perp$ and maximizing X_0 and dE/ds [2]. Experimentally, use of a solenoid focusing channel leads to small transverse betatron functions, and use of low-*Z* absorber materials such as LiH (lithium hydride) leads to large radiation length and energy loss. The muons passing through low-*Z* absorber material lose energy due to electromagnetic interactions with the atomic electrons of the material and in general for the cooling effect to dominate, the low-*Z* materials are placed in strong focusing fields [2]. The MICE cooling lattice components make use of the muon ionization cooling concept, and they are described in the following section.

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PROGRESS OF THE RF-SYSTEM DEVELOPMENTS FOR STOCHASTIC COOLING OF THE FAIR COLLECTOR RING

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Abstract

An overview of the recent developments regarding the RF signal processing for the stochastic cooling system of the Collector Ring is given. In focus are the developments of RF components which can be used at different locations within the signal paths between the pickup and kicker tanks in the frequency band (1-2 GHz). Two of these components are discussed in detail, a directional power meter with high dynamic range (9 dBm to −68 dBm) , low phase distortion (±0.75 °(max)) and low attenuation (≤0.4 dB) and a variable phase shifter with exceptionally flat amplitude (±0.4 dB(max)) and linear phase response (±3.5 °(max)). Furthermore, we present the status and the newest enhancements of other components with stringent specifications, such as optical notch filters, pickup module controllers and the power amplifiers at the kickers.

INTRODUCTION

The main components of a stochastic cooling system are certainly the pickup and kicker devices. The signal processing between the pickup and kicker tanks has a great influence on the cooling performance as well. To achieve a high cooling efficiency a precise phase and amplitude control of the signals is necessary. Therefore it is crucial to monitor and affect these values according to the requirements of the integral system. The need to monitor and adjust certain values in the signal processing paths is typically not bounded to one particular point, instead there are multiple locations where phase and amplitude correction can be necessary. Standard RF components available at the market often do not fulfill crucial requirements (i.e. bandwidth, linear phase response etc.) for stochastic cooling. Therefore, the approach is to develop own RF components which meet our requirements and can be used at different locations without changing the design parameters of the respective devices. The next two sections cover the status of two in-house RF developments: a directional embedded power meter and a variable phase shifter. The subsequent sections present the development status of non-universal (i.e. fixed position, specialized purpose etc.) stochastic cooling components: notch filter, pickup module controller and power amplifies at the kickers.

EMBEDDED POWER METER

The embedded power meter consists out of two main components, a 20 dB broadband directional coupler with low insertion loss and low phase distortion and a power level detector with a high accuracy and wide dynamic range. The power level detector is a true RMS (Root Mean Square) device with a linear and temperature-compensated output voltage. It can measure any broadband signal with arbitrary waveform and crest factor changes over time [1]. The power meter should be used as a feedback to adjust the power levels and prevent gain compression. Additionally, a diagnostic I/O port was incorporated into the design, therefore the power meter can not only be used for measuring the power level of the input signal, but also to direct diagnostic signals into/out of the signal path. The diagnostic I/O port can be used to determine beam and system parameters which affect the cooling setup and performance. All components were dimensioned to work within the 1-2 GHz band of the stochastic cooling system. However, the system is also somewhat sensitive to out of band signal components in the 0.7 – 2.3 GHz range, therefore the power meter must also fulfill less stringent specifications within this extended band. Figure 1 shows a schematic of the power meter. To guarantee a reliable operation of the device several selftest circuits are embedded: a 10 MHz test signal generator which can be used to perform RF tests of the 20 dB amplifier, the Wilkinson power divider (resistive splitter), the RMS power detector and the "RF1" and "RFC" connection of the solid state relay. Three DC test points can be used to perform resistance and leakage current measurements. They can be used to check the DC characteristics of the 15 MHz low pass filter, directional coupler and "RF" connections of the solid state relay.

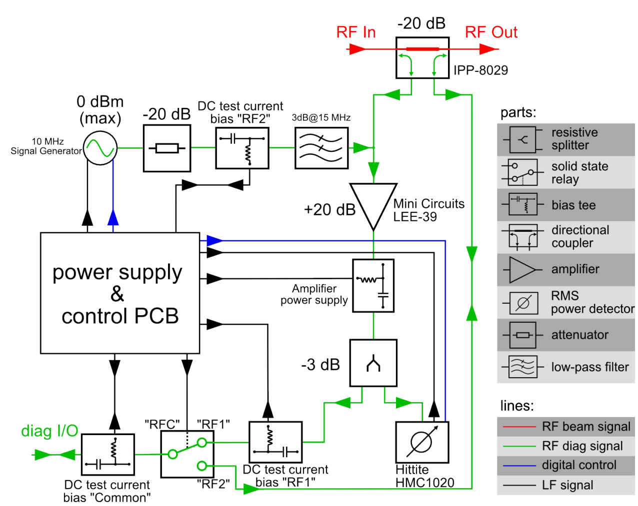

Figure 1: Block diagram of the embedded power meter.

A prototype (Fig. 2) of the power meter was build and the S-parameters were recorded. The determined electrical parameters of the prototype are given in Table 1[1].

[1] Phase distortion is defined as the deviation from the ideal linear phase response.

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HIGH EFFICIENCY ELECTRON COLLECTOR FOR THE HIGH VOLTAGE ELECTRON COOLING SYSTEM OF COSY

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Abstract

A high efficiency electron collector for the COSY high voltage electron cooling system was developed. The main feature of the collector is usage of special insertion (Wien filter) before the main collector, which deflects secondary electron flux to special secondary collector, preventing them fly to the electrostatic tube. In first tests of the collector in COSY cooler efficiency of recuperation better then 10^{-5} was reached. Before assembling of the cooler in Juelich upgrades of the collector and electron gun were made. After the upgrade efficiency better then 10^{-6} was reached. Design and testing results of the collector are described.

INTRUDUCTION

In electron cooling method the process of heat exchange between ions and electrons occurs in the beam reference system. As a result the process almost doesn't change electron beam energy. It means that after interaction with ion beam electrons with sufficiently high energy must be utilized. Utilization of the beam on full energy is serious technical task, because stored power in the beam is very large. Moreover, such approach means that high voltage power supply (PS) must be constructed for big load current (about 1 A). 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 that is connected to the same high voltage 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 keV and it is defined by a special collector PS.

Using recuperation method one can decrease maximum load current of the high voltage power supply to the value of about several mA, or even less, because its consumption is determined only by high voltage divider, which distributes voltage along acceleration column, and by leakage current from the high voltage terminal to the ground. Load current for collector PS is equal to beam current but its operation voltage is several kV. Moreover, stability of collector PS voltage can be much worse.

Power consumption in divider is determined during system design and doesn't change during operation. 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 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]. These method allows 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.

Efficiency limit of the axially symmetric collector with electrostatic and magnetic closing of secondary electrons, which are usually used in electron cooling devices, was estimated in [2] and its value is about 10^{-4}. For COSY high voltage electron cooler [3] such efficiency is not enough because needed value is about 10^{-5} [4]. In order to satisfy the requirement a new collector with suppression of secondary electrons by Wien filter was designed.

WORK PRINCIPLE

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).

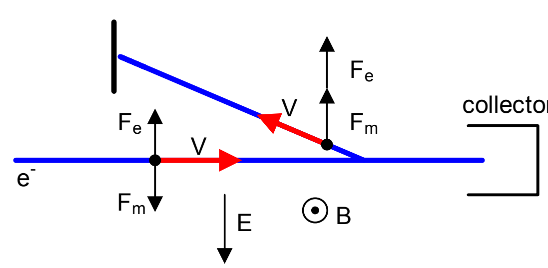

Figure 1: Principle of the collector with Wien filter work.

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 [3]. Because of the field, secondary electrons move not to electrostatic plates in but in direction parallel to them that protects the plates and their PS.

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DECOUPLING AND MATCHING OF ELECTRON COOLING SECTION IN THE MEIC ION COLLIDER RING*

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Abstract

To get a luminosity level of 10^{33} $cm^{-2}sec^{-1}$ at all design points of the MEIC, small transverse emittance is necessary in the ion collider ring, which is achieved by an electron cooling. And for the electron cooling, two solenoids are used to create a cooling environment of temperature exchange between electron beam and ion beam. However, the solenoids can also cause coupling and matching problem for the optics of the MEIC ion ring lattice. Both of them will have influences on the IP section and other areas, especially for the beam size, Twiss parameters, and nonlinear effects. A symmetric and flexible method is used to deal with these problems. With this method, the electron cooling section is merged into the ion ring lattice elegantly.

INTRODUCTION

The MEIC ion ring has cooling requirement from injection to the final collision stage. To realize ion beam cooling, a solenoid element is inserted in the ion ring to create an environment for heat extraction from the ion beam by an electron beam [1]. However, the solenoids can introduce coupling and matching problems which should be carefully dealt with.

ELECTRON COOLING SECTION IN MEIC ION RING

The MEIC ion collider ring accelerates protons from 9 to up to 100 GeV/c or ions in the equivalent momentum range and is designed to provide luminosity above 10^{33} $cm^{-2}s^{-1}$ in the momentum range from 20 to 100 GeV/c [2, 3, 4]. The overall layout of the ion collider ring is shown in Figure 1.

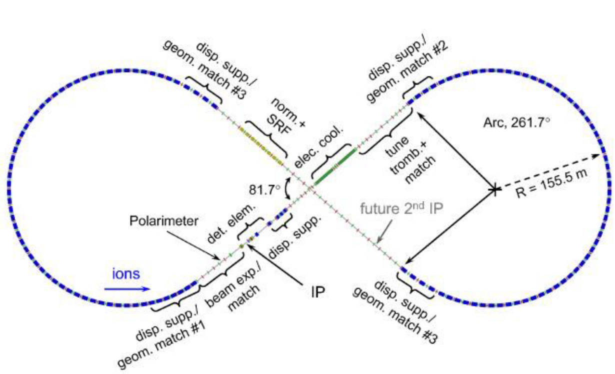

Figure 1: Layout of the MEIC ion collider ring. Main components are shown including IP and electron cooling section.

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The ring consists of two 261.7° arcs connected by two straight sections intersecting at an 81.7° angle. The two arc sections are composed mainly of FODO cells and a Chromaticity Compensation Block (CCB) section with larger beta and dispersion parameters. The lattice and Twiss parameters are shown in Figure 2. Including the two straight sections, the circumference of the overall ion collider ring is 2153.89 meters.

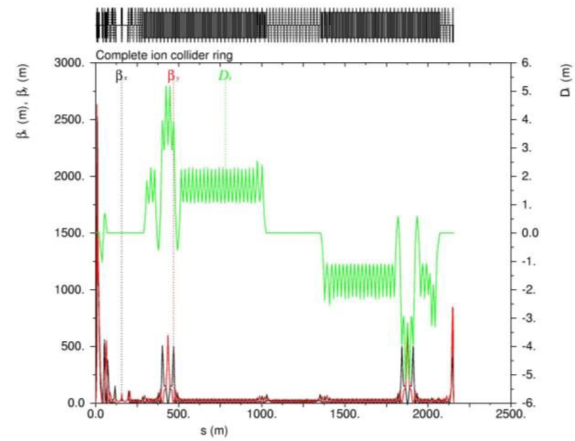

Figure 2: Lattice and twiss parameters of the MEIC ion collider ring.

As can be seen from Figure 2, between the 2 arc sections, one straight section houses an Interaction Point (IP) region, tune trombone matching section, election cooling section just 100 meters downstream of IP, and many matching sections. The maximum horizontal and vertical betas of 2574/2640 meters are located in IP region of Final Focus Quadrupoles. The second straight is mostly filled with FODO cells, while equipping with SRF system and retaining the capability of inserting a second interaction region.

Detailed lattice and Twiss parameters of the cooling section are shown in Figure 3. It has two main drifts of 30 meters which are reserved for placing a large solenoid each one and assistant equipment. Optics based on triplet focusing is used to provide such long drifts. There is a matching segment at each end of the cooling section connecting it the interaction region on one side and a straight FODO of a tune trombone on the other side.

Spin dynamics considerations require that the net solenoid field integral is compensated. Therefore, our proposed solution is to have the fields in the two solenoids opposite to each other so that one cooler solenoid serves as an anti-solenoid for the other as discussed below.

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HARMONIC STRIPLINE KICKER FOR MEIC BUNCHED BEAM COOLER*

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Abstract

In the current design of JLab's Medium-energy Electron-Ion Collider (MEIC), the ion collider ring needs to be cooled by a bunched electron beam of up to 200 mA 55 MeV, with the possibility to upgrade to 1.5 A. To reduce the technical risk and cost associated with such an ERL, a scheme was proposed to recirculate the electron bunches in a ring for up to 25 turns until the bunch's beam quality is degraded, reducing the beam current in the ERL by a factor of 25. This scheme requires one or a pair of fast kickers that kick one in every 25 bunches. In this paper, we will analyze the efficiency of a harmonic stripline kicker for this circulator ring, and compare to the harmonic resonator kicker.

INTRODUCTION

In the MEIC design, bunched electron beam cooling of the ion beam is essential to achieve and maintain low emittance and small beam size in the colliding ion beam, reaching the luminosity goal [1]. In MEIC's bunched beam cooler, a 200mA 55MeV electron beam with a repetition rate of f_0=476.3MHz will be used to cool the ion beam, with the possibility to be upgraded to 1.5A and/or 952.6MHz. In the baseline design, an ERL will be used to provide such a beam, recovering 80%-90% of the electron beam energy. To reduce the technical risk and cost in such an ERL, especially the beam current and RF power in the booster and gun, a circulator ring scheme [2] has been proposed, as shown in Fig. 1. In this scheme, the electron bunches will be injected from the ERL into the ring with a fast kicker, circulate for N turns in a ring until the beam quality degrades, and then kicked out into ERL for energy recovery. The proposed scheme chose N=25 nominally, but we use the example of N=10 in part of this paper for simpler demonstration. This scheme reduces the bunch repetition rate and the beam current in the ERL by a factor of N, but requires one or two faster kickers with sub-nanosecond rise/fall time and repetition rate of f_0/N, or 19MHz, and a kicking voltage of 55kV to achieve 1mrad deflecting angle for a 55MeV beam. This set of parameters will be prohibitive for switching DC pulse kickers, but could be achieved by harmonic RF kickers, in which the kicking waveform is constructed by a series of CW RF harmonics, plus a DC bias.

There are several different approaches to implement the harmonic kicker. One is the resonant cavity kicker [3], which would be more efficient, but requires a number of bulky cavities to generate the desired waveform. Another option is the stripline kicker, which can be very compact in the system.

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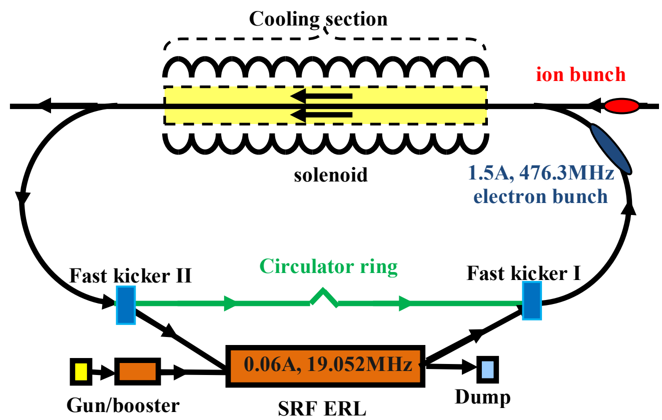

Figure 1: Layout of the MEIC bunched beam cooler, with the option of circulator upgrade.

EFFICIENCY OF STRIPLINE KICKERS

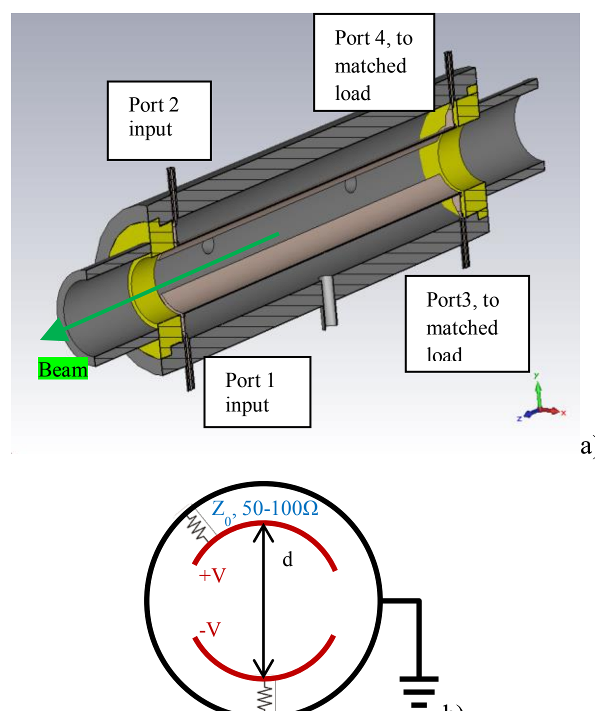

Figure 2. a) 3D model of the stripline kicker; b) cross-section model of the stripline kicker

A typical stripline RF kicker represented by the PEP-II coupled bunch feed-back kicker [5] is shown in Fig. 2. It utilizes the TEM mode travelling wave propagating from the input ports to the terminated ports, between two oppositely biased electrode plates and the grounded outer cylinder. The beam needs to travel in the direction

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OPTICAL STOCHASTIC COOLING AT IOTA RING*

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Abstract

The optical stochastic cooling (OSC) represents a promising novel technology capable to achieve fast cooling rates required to support high luminosity of future hadron colliders. The OSC is based on the same principles as the normal microwave stochastic cooling but uses much smaller wave length resulting in a possibility of cooling of very dense bunches. In this paper we consider basic principles of the OSC operation and main limitations on its practical implementation. Conclusions will be illustrated by Fermilab proposal of the OSC test in the IOTA ring.

INTRODUCTION

The stochastic cooling [1 - 4] has been successfully used in a number of machines for particle cooling and accumulation. Cooling rates of few hours required for luminosity control in hadron colliders cannot be achieved in the microwave frequency range (~10^9-10^{10} Hz) usually used in stochastic cooling. Large longitudinal particle density used in such colliders requires an increase of cooling bandwidth by few orders of magnitude. To achieve such increase one needs to make a transition to much higher frequencies. A practical scheme operating in the optical frequency range was suggested in Ref. [5]. The method is named the optical stochastic cooling (OSC). It is based on the same principles as the stochastic cooling but uses much higher frequencies. Consequently, it is expected to have a bandwidth of ~10^{13}–10^{14}Hz and can create a way to attain required cooling rates.

Fermilab plans to make an experimental test of the OSC in IOTA ring [6]. Details of the project have been changing with improved understanding of the experiment. In particular, the basic wave length of the wiggler radiation was changed from 0.8 to 2.2 μm to achieve reasonably large cooling and dynamic apertures. The reasons of this transition will be discussed in the following sections.

In the OSC a particle emits e.-m. radiation in the first (pickup) wiggler. Then, the radiation amplified in an optical amplifier (OA) makes a longitudinal kick to the same particle in the second (kicker) wiggler as shown in Figure 1. A magnetic chicane is used to make space for the OA and to delay a particle so that to compensate for a delay of its radiation in the OA resulting in simultaneous arrival of the particle and its amplified radiation to the kicker wiggler. A particle passage through the chicane has a coordinate-dependent correction of particle longitudinal position which, consequently, results in a correction of relative particle momentum, $\delta p/p$, with amplitude ξ_0 so that:

$$\delta p / p = -\xi_0 \sin\left(k\,\Delta s\right) . \tag{1}$$

Here $k = 2\pi/\lambda$ is the radiation wave-number,

$$\Delta s = M_{51}x + M_{52}\theta_x + M_{56}\left(\Delta p / p\right) \tag{2}$$

is the particle displacement on the way from pickup to kicker relative to the reference particle which experiences zero displacement and obtains zero kick, M_{5n} are the elements of 6x6 transfer matrix from pickup to kicker, x, θ_x and $\Delta p/p$ are the particle coordinate, angle and relative momentum deviation in the pickup.

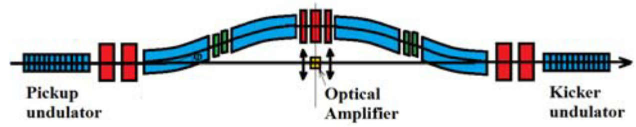

Figure 1: OSC schematic; blue – dipoles, red quadrupoles, green - sextupoles.

For small amplitude oscillations the horizontal and vertical cooling rates per turn are [7]:

$$\begin{bmatrix} \lambda_x \\ \lambda_s \end{bmatrix} = \frac{k\xi_0}{2}\begin{bmatrix} M_{56} - S_p \\ S_p \end{bmatrix} , \tag{3}$$

where $S_p = M_{51}D_p + M_{52}D'_p + M_{56}$ is the partial slip-factor introduced so that for a particle without betatron oscillations and with momentum deviation $\Delta p/p$ the longitudinal displacement relative to the reference particle on the way from pickup to kicker is equal to $S_p\Delta p / p$, and D_p and D'_p are the dispersion and its derivative in the pickup. Eq. (3) assumes an absence of *x-y* coupling in the chicane. Introduction of *x-y* coupling outside the cooling area redistributes the horizontal cooling rate between two transverse planes but does not change the sum of cooling rates which is equal to: $\Sigma\lambda_n = k\xi_0 M_{56}/2$, $n = x, y, s$.

Although M_{56} and, consequently, the sum of cooling rates depend only on focusing inside the chicane, S_p and the ratio of cooling rates depend on the dispersion at the chicane beginning, *i.e.* on the ring dispersion. Eq. (3) yields the ratio of cooling rates:

$$\lambda_x / \lambda_s = M_{56} / S_p - 1 . \tag{4}$$

A non-linear dependence of kick on Δs in Eq. (1) results in a dependence of cooling rates on amplitudes [7]:

$$\begin{aligned} \lambda_x(a_x, a_s) &= \left(2\,J_0(a_s)J_1(a_x)/a_x\right)\lambda_x \quad , \\ \lambda_s(a_x, a_s) &= \left(2\,J_0(a_x)J_1(a_s)/a_s\right)\lambda_s \quad , \end{aligned} \tag{5}$$

where a_x and a_s are the amplitudes of longitudinal particle displacement relative to the reference particle on the way from pickup to kicker due to betatron and synchrotron oscillations expressed in the units of e.-m. wave phase:

$$\begin{aligned} a_x &= k\sqrt{\varepsilon_1\left(\beta_p M_{51}{}^2 - 2\alpha_p M_{51}M_{52} + \left(1+\alpha_p{}^2\right)M_{52}{}^2\right)} , \\ a_p &= k\left|S_p\right|\left(\Delta p / p\right) \quad , \end{aligned} \tag{6}$$

ε_1 is the Courant-Snyder invariant of a particle, β_p and α_p are the horizontal beta-function and its negative half derivative in the pickup, and $(\Delta p/p)$ is the amplitude of particle synchrotron motion. As one can see from Eqs. (5) each cooling rate changes its sign if any of amplitudes

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SINGLE-PASS-AMPLIFIER FOR OPTICAL STOCHASTIC COOLING PROOF-OF-PRINCIPLE EXPERIMENT AT IOTA*

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Abstract

Test design of a single-pass mid-infrared Cr:ZnSe optical amplifier for an optical stochastic cooling (OSC) proof-of-principle experiment foreseen at the Integrable Optics Test Accelerator (IOTA) ring part of Fermilab Accelerator Science & Technology (FAST) facility. We especially present an estimate of the gain and evaluate effects of thermal lensing. A conceptual design of the amplifier and associated optics is provided.

INTRODUCTION

Optical stochastic cooling is a promising technique to mitigate luminosity degradation in hadron colliders [1]. In OSC, the beam information is obtained via electromagnetic-radiation process (pick-up) and the required correction is applied by coupling back the amplified radiation to the beam (kicker). In Ref. [1] considered the use of pick-up and kicker quadrupole-wiggler magnets. The OSC was subsequently extended to enable cooling of beams with large initial emittances [2]. In the latter case, the pick-up and kicker are conventional dipole-type undulator magnets. The electron beam and undulator radiation are physically separated between the two undulators to permit amplification of the radiation and to delay the electron beam using a four-dipole chicane beam line. Fermilab is planning a proof-of-principle experiment of OSC in IOTA located at FAST [3]. The experiment will employ a 100-MeV electron beam so that sufficient undulator-radiation flux from the pick-up undulator reaches the kicker undulator with or without an optical amplifier (OA) to yield to an observable cooling effect.

The design of OA is considerably constrained. The longitudinal and transverse cooling ranges are respectively defined as $n_s = (\frac{\Delta P}{P})_{max}/\sigma_p$ and $n_x = \sqrt{(\epsilon_{max}/\epsilon)}$. Here P is the design momentum, σ_p is the rms momentum and ϵ is the horizontal beam emittance. $(\frac{\Delta P}{P}_{max})$ and ϵ_{max} represent boundaries for which particles that fall within will be cooled.

In case of equal damping rates in both planes it can be shown [4] that the cooling ranges reduce to

$$n_s \approx \frac{\mu_{01}}{\sigma_P k \Delta S}, \qquad n_x \approx \frac{\mu_{01}}{2k\Delta S}\sqrt{\frac{D^{*2}}{\epsilon\beta^*}}, \tag{1}$$

with $\mu_{01} \approx 2.405$ being the first zero of the Bessel function, $k = 2\pi/\lambda$ the wavenumber of the radiation (determined by the wavelength λ of the OA), ΔS is the electron-beam path-length delay introduce by the chicane and sets the optical delay of the OA system, and D^* and β^* are the respectively the dispersion and beta functions at the center of the chicane. From Eq. (1) we note that a longer operating wavelength for the OA allows for a larger delay and thus a longer crystal (resulting in a higher gain). A review of the available lasing media prompted us to choose Cr:ZnSe as our gain medium (center wavelength of $\lambda \simeq 2.49\,\mu$m) resulting in a delay ΔS of a few millimeters.

Previous OA designs for OSC were based on Ti:Sp ($\lambda \simeq 0.8\,\mu$m) as the gain medium [5, 6] because of its excellent bandwidth (95 THz FWHM [7]) and ability to produce high gain. Cooling rate is inversely proportional to the amplifier bandwidth and for Cr:ZnSe it is just 50 THz [8]. However to keep the same cooling range Eq. (1) indicates a Ti:Sp crystal would need to be 0.6 the length of a Cr:ZnSe crystal [the signal delay of an amplifier with a crystal of length L and index of refraction n is given as $\Delta S = L(n-1)$]. Furthermore even if both crystals could have the same delay it was shown in Ref. [9] that Cr:ZnSe is expected to produce superior gain at lower pump intensities.

Another advance of Cr:ZnSe is the large number of pumping options in the mid-IR range. Therefore we investigated how the pumping wavelength will affect the amplifier performances. Optical parametric amplification has been ruled out as it would require pulses long enough to cover the length of a bunch in IOTA (~ 14 cm corresponding to 470-ps duration) at a repetition rate of 7.5 MHz. Instead we concentrate on the design of a single-pass amplifier with CW pumping.

GAIN EQUATIONS

In this section we demonstrate how to calculate the gain of a signal passing through a pumped medium. We start with the population rate equation for a 4-level system. Let N_0 be the population density of the ground state and N_i, $i = 1, 2, 3$ be population densities of the excited states. If we only allow for spontaneous emission to occur between nearest energy levels the rate equations are given as

$$\frac{dN_3}{dt} = -\kappa_3 N_3 - \frac{\sigma_{pa} I_p}{h\nu_p}(N_3 - N_0), \tag{2}$$

$$\frac{dN_2}{dt} = \kappa_3 N_3 - \kappa_2 N_2 - \frac{\sigma_s I_s}{h\nu_s}(N_2 - N_1) - \frac{\sigma_{pe} I_p}{h\nu_p}(N_2 - N_0), \tag{3}$$

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EMITTANCE GROWTH FROM MODULATED FOCUSING AND BUNCHED ELECTRON BEAM COOLING*

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Abstract

The low energy RHIC electron cooling (LEReC) project at Brookhaven employs a linac to supply electrons with kinetic energies from 1.6 to 2.6 MeV. Along with cooling the stored ion beam the electron bunches create a coherent space charge field which can cause emittance growth. This process is investigated both analytically and through simulation.

INTRODUCTION AND THEORY

The low energy RHIC electron cooling project is currently under construction at BNL. We are using an electron linac with bunch lengths of a few centimeters to cool gold beams with lengths of several meters. Let γ be the Lorentz factor of the ions, α_{p} be the momentum compaction factor, σ_{p} be the rms fractional momentum spread, $\eta = 1/\gamma_t^2 - 1/\gamma^2$, and T_0 be the revolution period. The rms longitudinal slip per turn is $\sigma_{\mathrm{slip}} = T_0|\eta|\sigma_{\mathrm{p}}$. Table 1 shows this and other RHIC parameters.

Table 1: Gold Beam Parameters

parameter	$\gamma = 4.1$ value	$\gamma = 6.0$ value
σ_{tg}(ns)	11.7	9.6
σ_{p}	3.5×10^{-4}	3.8×10^{-4}
N_{ion}	6×10^8	1×10^9
emittance μm	2.5	2.5
f_0 (kHz)	75.8	77.2
σ_{slip}(ps)	280	127

Table 2: Electron Beam Parameters

parameter	$\gamma = 4.1$ value	$\gamma = 6.0$ value
σ_{te}(ps)	100	67
σ_{p}	$4 - 8 \times 10^{-4}$	$4 - 8 \times 10^{-4}$
Q_{e}(pC)	65 – 130	78-156
emittance μm	1-2	1-2
bunch spacing (ns)	1.42	1.42
bunches per train	31	25

The electron parameters are still under discussion but ranges are shown in Table 2. In the tables σ_{tg} and σ_{te} are the root mean square (rms) bunch durations, Q_{e} is the electron bunch charge, and N_{ion} is the number of ions per bunch.The emittance is the rms normalized emittance. There is a train of electron bunches of length $\sim 4\sigma_{\mathrm{tg}}$ as illustrated in Figure 1. For all cases one has $\sigma_{\mathrm{te}} < \sigma_{\mathrm{slip}}$ which means that if an ion is subjected to a maximal space charge force on one turn it will not be subject to a significant force on the next turn. Unpublished work by Gang Wang and Vladimir Litvinenko has shown that it is critical that the electron bunches not slip with respect to the ion bunches. We assume this is the case but this still leaves the possibility of synchrobetatron resonances.

To study these resonances assume the cooling section is centered on β^* with $\alpha^* = 0$ and take the transverse ion coordinates to be x and $p = \beta^* x'$ so that the one turn matrix is just a rotation with phase advance $\psi_0 = 2\pi Q_x$. As a first approximation assume a single electron bunch centered on the ion bunch so that an ion interacts with it twice per synchrotron oscillation. Assuming the electron bunch has focusing strength k the map for half a synchrotron oscillation is

$$\begin{bmatrix} x_{n+1} \\ p_{n+1} \end{bmatrix} = \begin{bmatrix} \cos\frac{\pi Q_x}{Q_s} & \sin\frac{\pi Q_x}{Q_s} \\ -\sin\frac{\pi Q_x}{Q_s} & \cos\frac{\pi Q_x}{Q_s} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \beta^* k & 1 \end{bmatrix} = \begin{bmatrix} x_n \\ p_n \end{bmatrix}, \tag{1}$$

where Q_s is the synchrotron tune. When Q_x/Q_s is close to an integer the map is unstable. Taking $\sin(\pi Q_x/Q_s) = \epsilon$ and assuming an eigenvalue $\lambda = 1 + \delta$ one finds $\delta \approx \sqrt{\beta^* k\epsilon - \epsilon^2}$. The resonances for LEReC are typically very weak with $\beta^* k \sim 10^{-5}$. When coupled with the small fraction of time the ions interact with the electrons one expects a very small fraction of the beam would be harmed by these resonances. However there is another important dynamical effect. Longitudinal intrabeam scattering causes the longitudinal action to wander and with it the synchrotron tune. This causes individual particles to wander back and forth through resonances, usually increasing betatron amplitude with each passage. If we look at it in terms of statitical averages the average increase in amplitude will be proportional to the maximum growth and the fraction of time growing is proportional to the resonance width. Since both terms are linear in the charge of the electron bunch one expects the emittance growth rate to scale as the square of the electron bunch charge.

A better model can be obtained using perturbation theory. Since we only consider a matrix and a thin lens cooling region we take $|Q_x| < 1/2$. The equations of motion are generated by the hamiltonian

$$H(x, p; \theta) = \frac{Q_x}{2}\left(p^2 + x^2\right) + \delta_p(\theta) F_e(\tau) \ln\left(1 + x^2/a^2\right), \tag{2}$$

* Work supported by United States Department of Energy

ELECTRON COOLING AT GSI AND FAIR - STATUS AND LATEST ACTIVITIES

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Abstract

The status, function and operation parameters of the existing and future electron coolers at GSI and FAIR are presented. We report on the progress of the ongoing recommissioning of the former CRYRING storage ring with its electron cooler at GSI. First systematic results on the cooling of a 400 MeV proton beam during the last ESR beamtime are discussed. Motivated by the demands of the experiments on high stability, precise monitoring and even absolute determination of the velocity of the electrons i.e. the velocity of the electron- cooled ion beams, high precision measurements on the electron cooler voltage at the ESR were carried out towards the refurbishment of the main high-voltage supply of the cooler. Similar concepts are underway for the CRYRING cooler high-voltage system.

INTRODUCTION

Following machines with electron coolers are available at GSI (Table 1) or foreseen within the FAIR project:

- SIS18 (18 Tm, electron cooling), in operation [1]: accumulation of stable ions.
- ESR (10 Tm, stochastic and electron cooling, internal target), in operation [1]: accumulation, storage, deceleration, experiments with stable ions / rare isotope beams (RIB).
- CRYRING (1.44 Tm, electron cooling), under installation and commissioning: storage, deceleration, experiments with stable ions/RIB (also antiprotons as a future option).

CRYRING AND ITS ELECTRON COOLER

Initially, CRYRING was the designated storage ring for FLAIR [2]. It was moved into a cave behind the ESR [3] to benefit from an earlier realisation of a working machine for ions. Activities concentrate around this CRYRING@ESR project as it also serves as a test bench for FAIR developments (control system, beam diagnostics, vacuum etc.).

CRYING@ESR is dedicated to low-energy experiments with highly-charged heavy ions like collision spectroscopy at the electron cooler, a transverse electron target and a laser spectroscopy setup [4]. The electron cooler is the most important device for preparation of (decelerated) stored beams and most experiments. In particular, for electron-ion recombination studies: (i) The adiabatic magnetic expansion by a factor 100 offers a transversally very cold electron beam with $k_B T_\perp = 1.5 - 3.5$ meV [5, 6] (compared to $k_B T_\perp \approx$ 200 meV in the ESR). The expected longitudinal electron beam temperature $k_B T_\parallel = 0.05 - 0.20$ meV is as usual determined by the longitudinal-longitudinal relaxation. (ii) The electron beam energy has to be ramped in a small range

Table 1: Basic Operation Parameters of the Electron Coolers at GSI. Typical values are in brackets.

Parameter	SIS18	ESR	CRYRING
main HV power supply (kV)	≤ 35	≤ 320	≤ 20
e^- energy/HV (kV)	[≤ 7]	[2-220]	[≤ 8]
e^- current (A)	[0-1.5]	[0-1]	[0-0.15]
gun perveance (μperv)	2.9	2	1.68
cathode diameter (inch)	1	2	0.16
adiab. exp. factor	1-8	1	10-100
guiding B field (T)		[0.02-0.1]	
in gun	≤ 0.4 [0.18]		≤ 4 [3]
in cool. section	≤ 0.15 [0.06]		≤ 0.3 [0.03]
cool. section length/eff. (m)	3.4/2.8	2.5/1.8	1.1/
ring circumference (m)	216	108	54
vacuum (mbar)	10^{-11}	10^{-12}-10^{-11}	10^{-12}-10^{-11}

around the nominal electron energy which is matched to the ion velocity. Fast and precise ramping of the cooler voltage will be realised by a special HV amplifier in the range ± 2 kV installed on the HV platform [4].

In 2015 considerable efforts were made to rebuild the CRYRING machine and provide the associated infrastructure (Fig. 1). In parallel, the cooler had to undergo repairs because of damage to the gun toroid vacuum chamber, which occured after the transport from Sweden (complete disman-

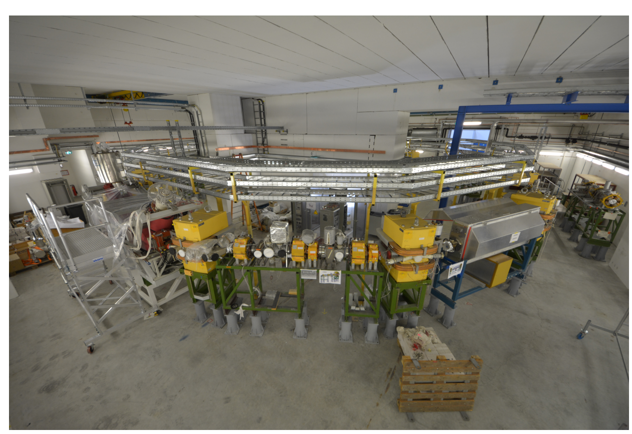

Figure 1: CRYRING in the cave behind the ESR.

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THE SNS LASER STRIPPING EXPERIMENT AND ITS IMPLICATIONS ON BEAM ACCUMULATION

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Abstract

The laser assisted H^- charge exchange concept is under development at the SNS as on option for replacing traditional carbon-based foil technology in future HEP accelerators. A laser based stripping system has the potential to alleviate limiting issues with foil technology, specifically radiation from beam scattering and foil survivability, paving the way for accumulation of higher density proton beams. This paper discusses the advantages and limitations of a laser-based stripping system compared with traditional foil-based charge exchange systems for various beam accumulation scenarios, scaling from SNS experience with high power beam injection and calculations of laser stripping parameters. In addition, preparations for an experimental demonstration of laser assisted stripping for microsecond long 1 GeV, H^- beams are described.

INTRODUCTION

The standard method for accumulating intense beams of protons is through H^- charge exchange from a linac into a synchrotron. In this scheme, an H^- beam from a linear accelerator is merged with a circulating proton beam in a ring. The merged beam is subsequently passed through a thin (~µm) carbon foil that strips the electrons from the H^- ions to yield a proton beam [1]. While in principle this non-Liousvillian technique can yield indefinitely dense proton beams, in practice the beam density is limited by the stripping mechanism.

The presence of the foil in the beamline introduces two major performance limitations. First, energy deposition in the foil leads to foil heating. Foils suffer vulnerabilities in their structural integrity when thermal effects are high causing warps, holes and tears. The primary failure mechanism for foils is sublimation above a certain temperature threshold, which translates into constraints on the achievable beam power densities. Existing high power machines such as the SNS accelerator are already estimated to operate just below this limit [2]. Second, particle scattering in the foil leads to large levels of beam loss and activation. This issue is pervasive across machines that utilize H^- charge exchange injection, and results in residual radiation levels typically an order of magnitude greater than the rest of the accelerator [3].

While schemes such as injection painting can be used to minimize beam foil trav0ersals and their subsequent effects, they are not infinitely scalable because they result in progressively larger beam emittances and machine apertures. An interesting question to consider is what a proton accumulation scenario would look like if the charge exchange process could be accomplished without the use of a foil. This paper will explore this question through a set of experiments in the SNS proton accumulator ring. Following this, the development of laser stripping method, a foil-free alternative stripping scheme, will be described.

HIGH DENSITY EXPERIMENT AT SNS

Experimental Configuration

The SNS accumulator ring accumulates up to 1.5e14, 1 GeV protons during a 1 ms, 1000 turn accumulation cycle. The injection process utilizes 400 µg/cm2 nanocrystalline diamond foils. Correlated dual plane injection painting is employed via a set of injection kickers which fall off by 52% over 1000 turns in a $\sqrt{turns}$ fashion.

The purpose of the experiment was to approximate what beam parameters could be accomplished in the absence of injection foil limitations. While the injection foil can not in reality be removed from the system, the beam can be run in a configuration with reduced repetition rate, i.e., 1 Hz instead of the 60 Hz, to avoid foil heating and allow for temporarily higher levels of beam loss. Besides the repetition rate, the remainder of the beam parameters were fixed at nominal production values, with 1.43e14 ppp accumulating over 1000 turns. This produces a "1.4 MW equivalent" beam in a per pulse sense.

The effects of three injection painting scenarios were explored: 1) No painting, 2) Nominal painting, and 3) Shallow painting with an injection kicker amplitude fall of 30% (compared with the nominal 52%). For each of these scenarios, the initial injection kicker amplitudes were varied to alter the beam emittance, up until the point where injection losses exceeded acceptable values even at 1 Hz. For each setting, the beam loss in the ring and the final beam emittance was recorded. Due to constraints on the allowable peak beam density on target, the emittances were only measured directly for the nominal production configuration. The remainder of the emittances were derived from ratios of the rms beam sizes with the production case at a common wirescanner location.

Results

Fig. 1 shows the results of the measured emittances for the various beam configurations. The upper right point, with emittance (ε_x=29 mm*mrad, ε_y=36 mm*mrad), represent the nominal configuration. By contrast, the smallest emittance achieved was (ε_x=12 mm*mrad, ε_y=17 mm*mrad), roughly a factor of two smaller in each plane.

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RF TECHNOLOGIES FOR IONIZATION COOLING CHANNELS *

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Abstract

Ionization cooling is the preferred method of cooling a muon beam for the purposes of a bright muon source. This process works by sending a muon beam through an absorbing material and replacing the lost longitudinal momentum with radio frequency (RF) cavities. To maximize the effect of cooling, a small optical beta function is required at the locations of the absorbers. Strong focusing is therefore required, and as a result normal conducting RF cavities must operate in external magnetic fields on the order of 10 Tesla. Vacuum and high pressure gas filled RF test cells have been studied at the MuCool Test Area at Fermilab. Methods for mitigating breakdown in both test cells, as well as the effect of plasma loading in the gas filled test cell have been investigated. The results of these tests, as well as the current status of the two leading muon cooling channel designs, will be presented.

INTRODUCTION

Ionization cooling appears to be the only method of significantly reducing the emittance of a muon beam within the lifetime of a muon. The Muon Ionization Cooling Experiment (MICE) will validate simulation codes and demonstrate ionization cooling with reacceleration of a muon beam, and is currently underway [1]. The change in normalized transverse emittance with path length is given by

$$\frac{d\epsilon_n}{ds} = \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0} - \frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} \qquad (1)$$

where $\beta = v/c$, $\beta_\perp$ is the transverse optical beta function, E_μ and m_μ are the energy and mass of the muon, respectively, and X_0 and $\left\langle\frac{dE_\mu}{ds}\right\rangle$ are the radiation length and stopping power of the absorbing material, respectively. The first term in Eq. 1 is the heating term, due to multiple scattering, and the second is the cooling term. To minimize the effect of multiple scattering, a small beta function at the location of the absorbers and a large absorber radiation length are ideal. Hydrogen and lithium hydride have been selected as absorbing materials, due to their radiation length and stopping powers.

A small beta function dictates strong focusing, and as longitudinal momentum lost in the absorbers is replaced by radio frequency (RF) cavities, these cavities are subject to external magnetic fields larger than 1 T. This immediately rules out the use of superconducting cavities, and an experimental program set out to determine how normal conducting RF cavities performed in such an environment at Lab G and currently the MuCool Test Area (MTA), both at Fermilab.

BREAKDOWN IN RF CAVITIES

High voltage breakdown in both vacuum and gas has been studied extensively. The presence of a multi-tesla external magnetic field provided a new variable, however. As ionization cooling depends on RF cavities operating in such an environment, the performance of said cavities must be understood and characterized.

Early experiments focused on 805 MHz vacuum RF cavities. Both a six cell standing wave cavity and a single cell pillbox cavity were tested. The pillbox cavity allowed for different materials (copper, beryllium, molybdenum) and endplate structures (flat, curved, electrode) to be studied. The results of each indicated that there was a strong negative correlation between maximum accelerating gradient in the cavity and applied external magnetic field [2–5]. Plots from these experiments are shown in Figures 1 and 3.

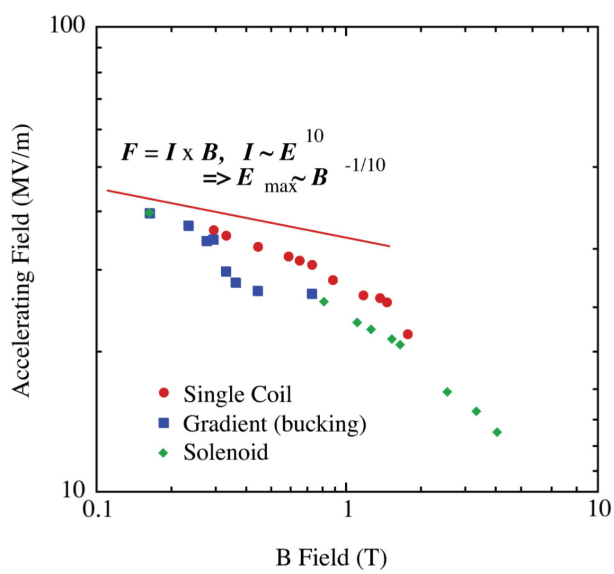

Figure 1: Maximum accelerating gradient as a function of external magnetic field from Ref. [3]. The data were collected with an 805 MHz vacuum pillbox cavity. Various coil configurations of the solenoid are shown.

A model to explain breakdown of RF cavities in external magnetic fields was proposed [6]. In this model, the mag-

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FRONT END AND HFOFO SNAKE FOR A MUON FACILITY*

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Abstract

A neutrino factory or muon collider requires the capture and cooling of a large number of muons. Scenarios for capture, bunching, phase-energy rotation and initial cooling of μ's produced from a proton source target have been developed, for neutrino factory and muon collider scenarios. They require a drift section from the target, a bunching section and a ϕ-δE rotation section leading into the cooling channel. The currently preferred cooling channel design is an "HFOFO Snake" configuration that cools both μ^+ and μ^- transversely and longitudinally. The status of the design is presented and variations are discussed.

INTRODUCTION

Scenarios have been developed for using muons in a storage ring based neutrino source or "neutrino factory" and in a high-energy high-luminosity "muon collider". [1, 2] The scenarios are outlined in Figure 1. In both scenarios high intensity proton bunches from a proton source strike a production target producing secondary particles (mostly $\pi^{\pm}$'s). The π's decay to μ's and the μ's from the production are captured, bunched, cooled and accelerated into a storage ring for neutrinos or high energy collisions. The present paper discusses the section of the scenarios labelled the "front end" in figure 1, between the target and the accelerator for the neutrino factory and between the target and "6-D" cooling section of the muon collider.

In the Front End, pions from the production target decay into muons and are focused by magnetic fields and bunched by time-varying electric fields into an initial cooling system that forms the muons into a beam suitable for the following acceleration and/or cooling.

μ's from the target and decay are produced within a very broad energy spread and length. Initially, capture within a single bunch was considered, but that requires either very low frequency rf (<20MHz) or novel induction linacs. The scale and cost of such a system would be uncomfortably large. Instead a novel system of higher frequency rf cavities (~200—500 MHz) was developed that forms the μ's into a train of manageable bunches, using current-technology rf cavities and power sources.[3,4] The same system can be used for both neutrino factory and collider scenarios.

The rf bunching naturally forms the beam for an initial cooling section. For the IDS neutrino factory design study, this uses a simple solenoidal focusing system with LiH absorbers that provides only transverse cooling (4-D phase-space cooling). More recently a 6-D initial cooling system (the "HFOFO Snake") using tilted solenoids and LiH wedge absorbers was developed,[5] and is currently considered somewhat superior, particularly for a collider scenario. The initial cooling concepts are discussed and compared.

FRONT END OVERVIEW

The Front End concept presented here was generated for the Neutrino Factory design studies,[6] and subsequently extended and reoptimized for the Muon Accelerator Program (MAP) muon collider design studies. The Front End system takes the π's produced at the target, and captures and initiates cooling of the resulting decay μ's, preparing them for the μ accelerators. Figure 2 shows an overview of the system, as recently developed for the MAP studies. In this figure, the transport past the target is separated into drift, buncher, rotator and cooling regions.

Drift

The multi-GeV proton source produces short pulses of protons that are focused onto a target immersed in a high-field solenoid with an internal beam pipe radius r_{sol}. The proton bunch length is 1 to 3 ns rms (~5 to 15 ns full-width), B_{sol} =20 T, and r_{sol} = 0.075 m, at initial baseline parameters. Secondary particles are radially captured if they have a transverse momentum p_T less than $\sim ecB_{sol}r_{sol}/2$ = 0.225 GeV/c. Downstream of the target solenoid the magnetic field is adiabatically reduced from 20T to 2T over ~14.75 m, while the beam pipe radius increases to ~0.25 m. This arrangement captures a secondary pion beam with a broad energy spread (~50 MeV to 400 MeV kinetic energy).

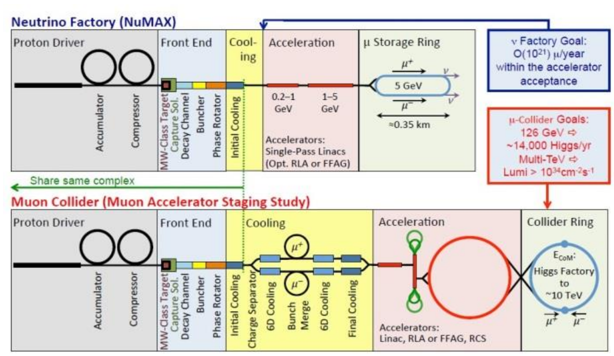

Figure 1: Block diagrams of neutrino factory and muon collider scenarios. The present paper discusses the "Front End" section from the Target to the Cooling/Acceleration, including "Initial Cooling". The same Front End can be used in both scenarios.

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CRYSTALLINE BEAM STUDIES WITH ANDY SESSLER*

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Abstract

For more than two decades since 1992, Andy Sessler worked with us as a hobby on the topic of crystallization of charged ion beams and cooling methods. In this paper, we review the studies jointly performed with Andy highlighting major findings and challenges, and discuss current status and possible future topics and directions.

INTRODUCTION

Beam crystallization has been a topic of interests since first evidence of experimental anomaly was observed on an electron-cooled proton beam at the storage ring NAP-M in 1980 [1]. Starting 1985, J. Schiffer and co-workers studied the properties of one-component, non-relativistic charged particles in the external potential of a simple harmonic oscillator using the molecular dynamics method [2]. Since then, strong space-charge dominated phenomena and one-dimensional (1-D) ordering states were reported with both proton and heavier ions at storage rings TSR [3], ASTRID [4], ESR [5], CRYRING [6], and S-LSR [7] (Table 1).

In 1992, A.G. Ruggiero introduced A.M. Sessler and J. Wei (JW) to the discussion of studying crystalline beams in realistic storage ring conditions. The study immediately involved X.-P. Li (XPL) who is a condensed matter physicist by training. We realize that the most straightforward and rigorous approach is to derive the equations of motion in the so-called beam rest frame where the reference particle is at rest. In this frame, the conventional method of condensed matter physics can be readily applied.

It took JW six month to adopt the formalism of general relativity to derive the equation of motion in the beam rest frame using numerical algebra methods [8]. In another month, XPL developed the beam dynamics algorithms as well as other relevant condensed matter analysis algorithms. Together we created the codes SOLID that can be used to rigorously study beams at ultra-low temperature regime [9].

To attain an ordered state, effective beam cooling is needed to overcome beam heating caused by coherent resonance crossing and intra-beam scattering. Furthermore, the cooling force must conform to the dispersive nature of a crystalline ground state in a storage ring for 3-D structures. To reach the state of crystalline beams in numerical simulations, we used artificial cooling methods enforcing periodicity of the particle motion in the beam rest frame. H. Okamoto (HO) led the analysis of actual beam cooling methods including coupled cooling and tapered cooling [10]. Thus, the entire theoretical approach on beam crystallization was developed.

For more than two decades since 1992, Andy worked closely with us on all major topics of beam crystallization from the derivation of equations of motion to numerical simulation and then to realization with practical cooling methods. Figures 1 to 6 show various occasions associated with Andy during the past 20 years. Andy hosted our extended visits to Lawrence Berkeley National Laboratory (LBNL) in formulating the study approaches and identifying major directions of breakthrough (Fig. 1). He led the interaction with major experimental groups at Aarhus, Denmark and Heidelberg, Germany, providing insights in experimental benchmarking (Fig. 2). Starting from 1997, Andy visited Kyoto University, Japan, for extended periods of time stimulating both experimental and theoretical beam cooling and crystallization work in Japan. Later, he stayed at Hiroshima University collaborating with H. Okamoto and his students (Fig. 4).

Andy has been our mentor, role model, colleague, and friend. He was always fresh with new ideas and passionate about physics, life, and friendship. During early years of study at Berkeley, he often came up with a dozen new ideas a day as we explored the fascinating physics of beam crystallization. Even though most did not survive the subsequent trial and error, some most important findings originated from Andy's imagination.

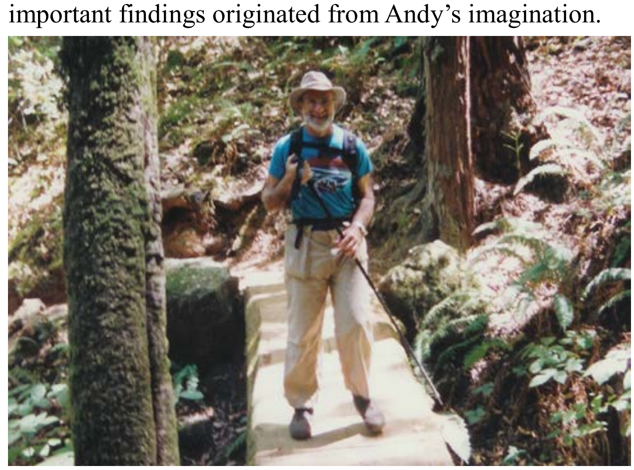

Figure 1: A.M. Sessler in Muir Woods, California, USA, 1993 (photo taken by J. Wei). Andy hosted extended visits to LBNL at multiple stages of beam crystallization studies.

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STOCHASTIC COOLING EXPERIMENTS AT NUCLOTRON AND APPLICATION TO NICA COLLIDER*

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Abstract

Stochastic cooling is the key element for the NICA accelerator facility that is presently under development at JINR, Russia. Beam cooling will work with the high-intensity bunched beams in the 3-4.5 GeV energy range; all three degrees of freedom will be treated simultaneously. The preparatory experimental work on stochastic cooling is carried out at accelerator Nuclotron (JINR, Dubna) since 2010. During this work hardware solutions and automation techniques for system adjustment have been worked out and tested. Based on the gained experience the overall design of the NICA stochastic cooling system was also developed. The report presents the conceptual design of the NICA stochastic cooling system and overviews the results of cooling experiments at Nuclotron and the developed adjustment automation techniques.

INTRODUCTION

Nuclotron-based Ion Collider Facility (NICA) is an intensively developing flagship project of Joint Institute for Nuclear Research (JINR) [1]. Stochastic cooling will be used in the collider ring during experiments with heavy ions for beam accumulation and intra-beam scattering (IBS) suppression to avoid luminosity reduction, which implies full 3D cooling of intense bunched beams. Beam accumulation process requires only longitudinal cooling and implies almost coasting beam with reduced intensities, therefore primary requirements for stochastic cooling systems arise from the IBS counteraction.

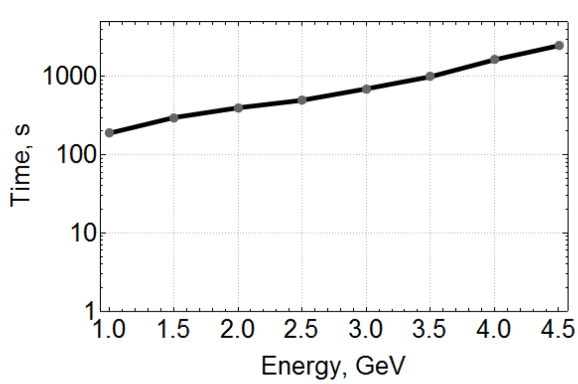

Figure 1: IBS heating times for Au^{79+}.

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Stochastic cooling must provide cooling times lower than corresponding IBS heating times to prevent beam emittance growth and keep the luminosity, Figure 1 shows expected IBS heating times in the energy range of the collider operation.

At lower energies IBS process becomes much faster and accompanied with significant phase slip factor growth, which makes stochastic cooling hardly feasible at this region and therefore here electron cooling is foreseen. Nevertheless, it's highly advantageous to cover as wide as possible energy range with stochastic cooling, because it doesn't have additional beam losses unlike electron cooling (due to ion recombination).

The parameters of NICA collider are listed in Table 1:

Table 1: Parameters of the NICA Collider

Circumference, *m*	503		
Ions	Au^{79+}		
Number of bunches	22		
RMS bunch length, *m*	0.6		
γ_{cr}	7.088		
Energy, *GeV/u*	1	3	4.5
Bunch intensity × 10^9	0.2	2.4	2.3
$\Delta p/p$ × 10^{-3}	0.55	1.15	1.5
$\varepsilon_x, \pi \cdot mm \cdot mrad$	1.1	1.1	1.1
$\varepsilon_y, \pi \cdot mm \cdot mrad$	0.95	0.85	0.75
Phase slip factor η	0.215	0.037	0.009
IBS heating time, *s*	160	460	1800

LONGITUDINAL COOLING

There are three experimentally tested techniques to achieve longitudinal stochastic cooling – time-of-flight, Palmer and notch-filter methods. Further we shortly review the possibilities of implementation of these methods in the NICA collider.

Time-of-flight method provides the largest momentum spread acceptance for cooling system compared to the other methods. Time-of-flight method uses longitudinal pick-up and 90° phase shifter (which acts like differentiator) to make the signal to be proportional to the beam's momentum deviation. This method was recently experimentally tested at Forschungszentrum Jülich (FZJ) [2]. Unfortunately, time-of-flight method provides best

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FOKKER-PLANCK APPROACH TO THE DESCRIPTION OF TRANSVERSE STOCHASTIC COOLING

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Abstract

A Fokker-Planck equation for transverse stochastic cooling is presented, based on some simplifying assumptions. The calculation of the drift and diffusion coefficients is derived from the signal theory of the pick-up response and the dynamics of the kicker response. The equilibrium transverse action (emittance) distribution turns out to be exponential. Furthermore there is a special solution of the time-dependent equation for the case that the initial action distribution is exponential, as well. The distribution remains exponential, and the average action decreases exponentially towards equilibrium. The cooling rate is equal to the standard textbook rate.

THEORETICAL PRELIMINARIES

Fokker-Planck Equation

Let $2J$ be the usual one-particle emittance. J is an action variable in Hamiltonian theory. ϕ is the betatron angle, conjugate to J. The betatron phase advance between pick-up and kicker is denoted $\mu_k - \mu_p$. The beta functions are β_p and β_k.

The Fokker-Planck equation describes the evolution of the distribution function $\Psi(J_x, J_y, \delta p/p)$. It is a continuity equation with a flux Φ in action space

$$\frac{\partial \Psi}{\partial t} + \mathrm{div}\Phi = 0 \quad (1)$$

The flux is

$$\Phi = F\Psi - \frac{1}{2} D \,\mathrm{grad}\Psi \quad (2)$$

The drift coefficient F describes the average cooling. It generally has three components, e.g.

$$F_x = \lim_{\tau\to 0} \left\langle \frac{\delta J_x}{\tau} \right\rangle \quad (3)$$

The limit $\tau \to 0$ always leads to physical interpretation problems, as a rule of thumb one might say that no essential change of the distribution function should happen during τ. The diffusion tensor D describes the diffusion, its components are

$$D_{mn} = \lim_{\tau\to 0} \left\langle \frac{\delta J_m \delta J_n}{\tau} \right\rangle \quad (4)$$

The Fokker-Planck equation is frequently used for the calculation of the longitudinal momentum distribution (see [1] and references therein). In this work the transverse case is presented. All details of the calculations of the drift and diffusion coefficients are not given, they can be derived along the lines presented in [1].

Simplifying Assumptions

In the following we make the assumption that longitudinal cooling works independently of transverse cooling, and that the longitudinal momentum distribution is given somehow. Then the transverse cooling is decoupled and both cooling pcrocesses can be described by one-dimensional Fokker-Planck equations.

1. All kickers and pick-ups are placed at locations of zero dispersion.
2. All electrodes can be described by a simple linear response model.
3. There is no overlap between different Schottky bands.
4. Chromaticity is neglected.

Because of the decoupling between phase spaces, we derive here a separate Fokker-Planck equation for horizontal cooling, where the horizontal distribution is simply called $\Psi(J)$. We normalize it to 1. We also need the longitunal distribution $\psi(\delta p/p$ which we define to be normalized to the number of particles N.

SIGNALS AND BEAM RESPONSE

Sensitivity and Single Particle Signals

The sensitivity $S(\Omega)$ is used for the description of the quality of delivering accelerating voltages to a beam paricle in a kicker electrode.

It is the ratio between the effective accelerating voltage $U(\Omega)$ and the voltage $V_k(\Omega)$ at the input port of the kicker:

$$U(x, y, \Omega) = S(x, y, \Omega)V_k(\Omega) \quad (5)$$

S depends on the beam velocity and on the position of the particle with respect to the electrode.

In the following it will be assumed that S is linear in x over the full range of betatron amplitudes.

$$S(x, y, \Omega) = xS'(\Omega) \quad (6)$$

The formalism becomes much more complicated if this simplification is abandoned [2].

If such an electrode is used as a pick-up electrode and if it is reciprocal, a particle with revolution frequency ω produces a signal at the betatron sidebands

$$\omega_{m,\pm} = \omega(m \pm Q_x) \quad (7)$$

where ω is the revolution frequency (which depends on the longitudinal momentum via the well-known relationship

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DESIGN OF THE PALMER PICKUP FOR STOCHASTIC PRE-COOLING OF HOT RARE ISOTOPES AT THE CR

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Abstract

We report on the design of a Faltin type pickup for the stochastic pre-cooling of rare isotope beams at 740 MeV/u, using a bandwidth of 1-2 GHz, for the Collector Ring (CR) in the FAIR project at GSI. The design difficulties inherent in Faltin rails at these frequencies are described. Measurements of prototypes and HFSS simulations are compared, to check the simulations, and show good agreement. The pickup impedance and signal output phase with respect to ions traveling at 0.83c are simulated and presented for the final design both with and without the use of damping material, showing the need to damp unwanted modes present in the beam chamber.

INTRODUCTION

The CR is designed for 6D stochastic cooling of antiprotons at 3 GeV or rare isotopes beams (RIBs) at 740 MeV/u [1]. The CR stochastic cooling system will operate in a frequency band of 1-2 GHz. For the noise-limited antiproton cooling, slotline pickups and kickers are foreseen [2]. RIB cooling in the CR is limited by the undesired mixing for which the Schottky bands overlap, so that only the Palmer method [3] can initially be applied. 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. The RIBs must be cooled from $\varepsilon_{xy} = 35$ 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 σ values) within 1.5 s.

6D Cooling at the Palmer Pickup

The Palmer pickup is 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 so as to extract vertical error signals and combined horizontal and longitudinal error signals as shown in Fig. 1. Figure 1 also shows an added time of flight (TOF) option for longitudinal cooling.

The Palmer pickup tank will be equipped with Faltin type pickups which are favorable due to their low number of feedthroughs, robustness and ease of manufacture.

Faltin Electrode

The Faltin electrode [4] is a rectangular coaxial waveguide with slots which couple to the beam. Figure 2 shows a diagram of a section of the Palmer pickup tank containing four Faltin rails intended for horizontal and vertical difference measurements. Figure 2 also shows the horizontal and vertical beam apertures of 400mm and 132mm respectively, and the position ferrite absorbing material needed to damp unwanted modes in the beam chamber.

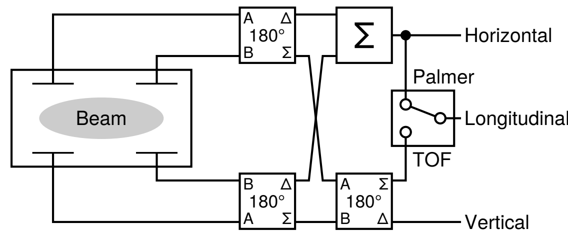

Figure 1: Diagram of the Palmer cooling method (including an optional TOF method) as foreseen in the CR showing the combination of signals in sum and difference modes.

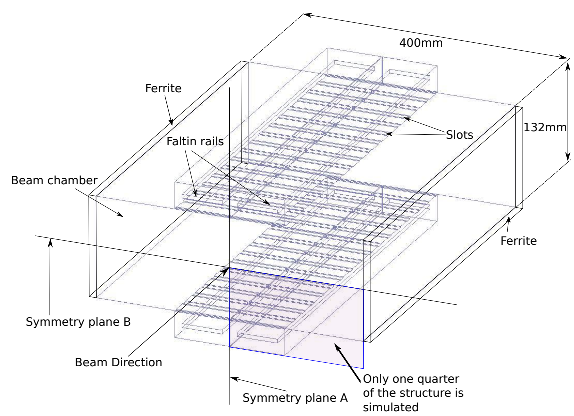

Figure 2: Diagram of a section of length of the Palmer pickup showing Faltin rails, beam chamber, ferrite absorbing material and symmetry planes used during simulations.

The wave in the pickup induced by the beam travels parallel to the beam and at the same velocity such that induction from beam to waveguide through each slot adds constructively. Therefore, in a Faltin type pickup (or any traveling wave pickup), it is crucial that the phase velocity in the waveguide approximately equals the particle velocity across the desired frequency band of operation.

Previous work on these type of pickups has included analytical approaches to calculating the coupling and the characteristics of induced waves [5, 6]. Experimental results were later published for a slot to TEM type pickup [7]. In addition, simulations using HFSS have been performed on similar structures for use in the SPS at CERN [8].

Pickups for stochastic cooling require an output signal with a large but flat amplitude over the band, and a linear phase with respect to the particle. The larger the amplitude

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LEPTA - THE FACILITY FOR FUNDAMENTAL AND APPLIED RESEARCH

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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 POSITRON INJECTOR

Positron injector consist of cryogenic slow positron source, positron trap and positron transfer channel (Figure 1).

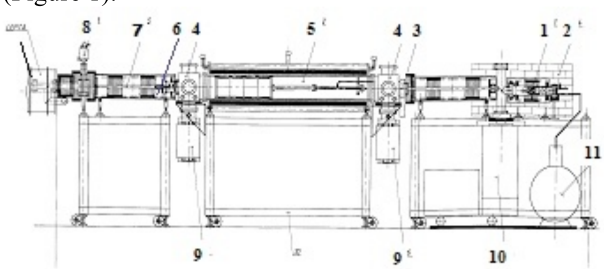

Figure 1: The positron injector. 1 – positron source 22Na, 2 – radioactive shield, 3 – vacuum valve, 4 – vacuum chamber for pumping out and diagnostic tools, 5 – positron trap, 6 – vacuum isolator, 7 – positron vacuum channel, 8 – vacuum "shatter", 9 – ion pump, 10 – turbo pump, 11 – liquid He vessel.

The solid neon is uses as a moderator in the positron source. The positrons lose energy passing thought neon layer and wide energy spectrum of 22Na the thin line of slow positrons is formed.

From the source slow positrons move to the positron trap. We use so called Penning-Malnberg-Surko (PMS) trap. The trap consists of the solenoids, of the vacuum chamber and of the electrodes which form static electric field (Figure 2).

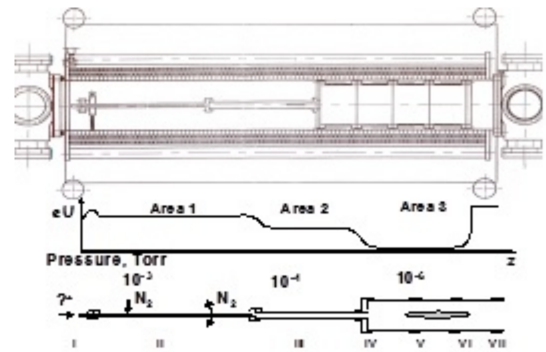

Figure 2: Assembly drawing of the positron trap (upper picture), potential and pressure distributions along the electrode system.

The trap of the LEPTA facility has the traditional geometry of the PMS trap [2]. In 2014, the trap pumping speed was significantly enhanced by implementation of turbo-molecular and cryogenic pumps. The choice of the potentials distribution on the electrodes 1-8 and pressure of the buffer gas (high-purity molecular nitrogen) is critical. At optimal allocation of potentials and pressure positrons, "jumping" on the atomic and molecular levels, very quickly overcome the energy region where the probability of annihilation is maximal (the so-called Ore gap [1]).

Rotating electrical field (RW) is generated in the electrode 4, cut into 4 sectors, which have permanent and (in pairs) alternative potentials. This method allows us to compress bunch and to increase number of particles in the bunch. The accumulation process is well described by the dependence of the number of accumulated particles N_{trap} on accumulation time at fixed values of the efficiency of the particle capture ε, the flux of the injected positrons $\dot{N}$ and the lifetime of the trapped particles τ:

$$N_{trap}(t) = \varepsilon \dot{N} \tau \left(1 - e^{\frac{t}{\tau}}\right) \Rightarrow \begin{cases} \varepsilon \dot{N} \tau, t << \tau \\ \varepsilon \dot{N} \tau, t >> \tau \end{cases} \quad (1)$$

At known flux $\dot{N}$ the, first of the asymptotics in formula (1) allows us to determine the value of the efficiency ε, and the second asymptotics - the value of the τ. Both these values are dependent of buffer gas pressure: ε is increases, τ is decreases but their product increases up to some optimal value of gas pressure. Experimental results are presented in the Table 1.

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COMMISSIONING OF THE RARE-RI RING AT RIKEN RI BEAM FACTORY

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Abstract

The Rare-RI Ring is an isochronous storage ring to measure masses of short-lived rare nuclei by using relative TOF measurement method. The expected precision of the measured mass is of the order of ppm.

We examined the basic performance of the devices, i.e. injection line, septum magnets, dipole magnets with trim-coils, and fast-kicker system by using α-source in 2014. We demonstrated that trim-coils, which are fixed on the dipole magnets of the ring, can adjust the isochronous condition of the ring. An α-particle was injected into the ring individually by using self-trigger mechanism and was extracted from the ring several turns after the injection.

In June 2015, a commissioning run using a ^{78}Kr beam was performed and basic performances of the Rare-RI Ring were verified. We succeeded in injecting a particle, which was randomly produced from a DC beam using cyclotrons, into the ring individually with the fast-kicker system, and in extracting the particle from the ring less than 1 ms after the injection with same kicker system. We measured time-of-flight (TOF) of the ^{78}Kr particles between the entrance and the exit of the ring to check the isochronism. Through the first-order adjustment with trim-coils, the isochronism on the 10-ppm order was achieved for the momentum spread of ±0.2%. Higher-order adjustment employed in future will lead us to the isochronism on the order of ppm. In addition, we confirmed that a resonant Schottky pick-up successfully acquired the frequency information of one particle in storage mode.

In this paper, the technical aspects of the Rare-RI Ring and the preliminary results of the beam commissioning will be described.

INTRODUCTION

Systematic mass measurements, especially for neutron-rich exotic nuclei very far from the stability, are essential for solving the *r*-process path. However, nuclei in such regions have very short half-lives and have a very low production rate even with the powerful accelerator complex in RI Beam Factory, therefore, very fast and sensitive apparatus is needed. To this end, we have proposed a unique apparatus, the so called "Rare-RI Ring" about 10 years ago [1], to precisely measure masses of such rare-RIs.

Figure 1 shows the conceptual design of mass measurement by using the Rare-RI Ring. When a produced secondary particle passes through the timing detector at F3 of the BigRIPS separator [2], a trigger signal is generated. The trigger signal is transmitted to a fast-kicker system via a high speed coaxial tube. Kicker magnets are then immediately excited by thyratrons. In the meanwhile, the particle goes through the BigRIPS separator, the SHARAQ spectrometer [3], and an injection line. The particle that arrives at the entrance of the ring is injected into an equilibrium orbit of the ring using septum and kicker magnets. After the particle revolves in the ring about 700 μs, it is extracted using another septum and the same kicker magnets to measure TOF. In the end, it is identified by ΔE-E detectors. In addition to the short measurement time, this method enables us to measure the mass of even one particle which is suited to measure masses in the *r*-process region.

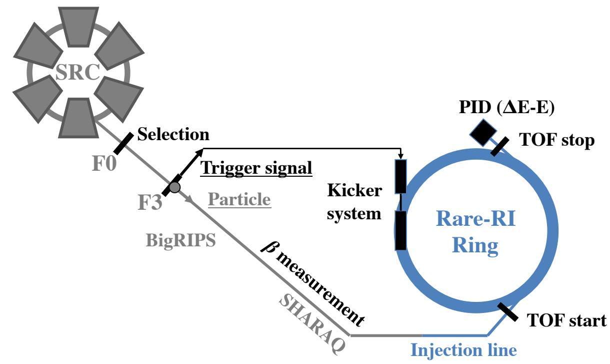

Figure 1: Conceptual design of mass measurement with the Rare-RI Ring.

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PRINCIPLE OF MASS MEASUREMENTS

We adopted the relative mass measurements with references in Isochronous Mass Spectrometry (IMS). In IMS, orbital of the particle is determined by its rigidity. If the rigidity of the particles to be obtained the mass (m_1/q) is the same as that of the reference particle (m_0/q), the flight-pass lengths are identical and the following equations are fulfilled:

$$\frac{m_0}{q}\gamma_0\beta_0 = \frac{m_1}{q}\gamma_1\beta_1, \quad (1)$$

$$\beta_0 T_0 = \beta_1 T_1, \quad (2)$$

where $m_{0,1}/q$ are mass-to-charge ratio, $T_{0,1}$ and $\beta_{0,1}$ are the revolution time and the velocity of the particles with $m_{0,1}/q$ and $\gamma_{0,1} = 1/\sqrt{1-\beta_{0,1}^2}$. By using Eq. (1) and (2), the m_1/q can be expressed as

$$\frac{m_1}{q} = \frac{m_0}{q}\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \frac{m_0}{q}\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-(\frac{T_1}{T_0}\beta_1)^2}}. \quad (3)$$

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