CURRENT PLANS FOR BEAM COOLING AT FAIR

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Abstract

The improvement of the quality of secondary beams by beam cooling is an essential component in the scenario of the Facility for Antiproton and Ion Research (FAIR). Beam Cooling is applied to match the secondary beams, antiprotons and rare isotopes, which are produced in thick solid targets, to the needs of experiments. Pre-cooling in the Collector Ring, accumulation and preparation for experiments in the High Energy Storage Ring are the main tasks of the Cooling Systems. Many of the beam cooling concepts for FAIR are studied experimentally in the existing Experimental Storage Ring ESR which has been operated at GSI over more than two decades and which will also be available for beam physics experiments in the coming years.

INTRODUCTION

The construction of the international Facility for Antiproton and Ion Research (FAIR) [1] is presently focussed on the Modularized Start Version (MSV). The funding of this first stage of the project is secured and the goal is to provide beams for all major experimental programs. The scientific programs cover research with high energy antiprotons in the PANDA experiment, Compressed Baryonic Matter (CBM), nuclear structure and related astrophysics, and atomic and plasma physics and applications. Already in the MSV, all the various types of experiments expect unprecedented possibilities for their research field. The programs with secondary beams are largely based on beam cooling which will be used for phase space reduction of antiprotons, rare isotope beams and highly charged ions.

The MSV of the FAIR project comprises various existing, but even more new accelerator systems. The program with heavy ion beams requires the existing UNILAC linear accelerator and the heavy ion synchrotron SIS18 as injector chain. By the addition of the synchrotron SIS100 [2] the heavy ion beam energy can be increased according to the higher rigidity of 100 Tm, alternatively lower charge states can be accelerated gaining in beam intensity by abandoning intermediate stripping with associated intensity reduction. With a new 70 MeV proton linac a source of intense proton beams is under construction which serves as injector into the chain with SIS18 and SIS100 which will result in 29 GeV protons for the production of antiprotons.

The high energy, high intensity beams after SIS100 will produce either highly charged ions, rare isotope beams by projectile fragmentation, or antiprotons from a primary proton beam. The antiprotons exit from a nickel production target where antiprotons at 3 GeV are selected in a magnetic separator for injection into the new Collector Ring (CR) [3]. For Rare Isotope Beams (RIBs) the new large acceptance superconducting fragment separator SuperFRS [4] will conduce to the production of high intensity secondary beams which can be used for fixed target experiments or for injection into the CR in order to apply phase space compression.

With respect to beam cooling the CR will be the key accelerator to improve the quality of secondary beams, both antiprotons and RIBs. For both species the primary beams in SIS100 will be compressed into a short single bunch with a length of 50 ns. The secondary particles after production in the target basically retain this time structure, however, with an increased momentum spread. Immediately after injection of the short bunch a bunch rotation system reduces the momentum spread and subsequent stochastic cooling will allow a fast reduction of the momentum spread providing a high quality secondary beam for transport to a subsequent storage ring where it is stored and prepared for the experiment. In the MSV the High Energy Storage Ring (HESR) [5] will be the exclusive user of pre-cooled CR beams. It is mainly designed for the storage of antiprotons and experiments using the PANDA set-up. Recently plans for the operation of the HESR with ion and rare isotope beams were discussed and are being worked out in detail.

As a continuation of ongoing GSI activities and in view of the delay of the RESR and NESR storage rings which are postponed within the FAIR project, the operation of the existing ESR storage ring [6] will be continued. Since it is equipped with a stochastic and an electron cooling system, it can be used as a test bed for FAIR developments. The option to decelerate heavy ions to 4 MeV/u opens already now the field of low energy beams foreseen in the FAIR project. Further deceleration with the HITRAP [7] decelerator and the plan to install the CRYRING [8], which is a contribution to the FAIR program with low energy antiprotons and ions, will allow accelerator and experimental developments for a low energy physics program at FAIR.

PRE-COOLING IN THE COLLECTOR RING CR

The Collector Ring CR is a large acceptance storage ring for the storage of secondary particles. The production of the secondary beams in a thick solid target results in a large emittance increase, both transversely and longitudinally. The large transverse acceptance of the CR allows efficient use in the capturing of secondary beams emerging from the target. Different optical modes will be used for antiprotons and ions. This is a consequence of the requirements of stochastic cooling for proper mixing

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conditions of the particles. The increase of the longitudinal momentum spread in the target is minimized by forming a short bunch of the primary beam which is directed to the production target. The bunch length is virtually unchanged in the target and mainly the momentum spread is increased. To be matched with the incoming bunch the CR has large momentum acceptance. However, the cooling time of the beam with the stochastic cooling system in the CR can be reduced by reducing the momentum spread. A dedicated rf system is designed to provide a reduction of the momentum spread by bunch rotation and adiabatic debunching of the incoming bunch. This results in a nearly coasting beam with reduced momentum spread for the subsequent application of stochastic cooling. The main goal is the production of good beam quality in shortest time. For antiprotons the cooling time limits the average production rate, whereas for RIBs the access to short-lived isotopes is determined by the time needed to prepare the beam parameters to values which are useful for the experiment.

The cooling time depends on the ring parameters and the choice of the cooling system. For longitudinal cooling the momentum slip factor of the CR has been optimized. The different velocities of antiprotons and ions (ß = 0.97 and 0.83, respectively) are matched by the optical setting of the ring magnets with optimized momentum slip factor, both locally and averaged over the ring. In addition, the ring lattice has to be designed for proper phase advance between the pick-ups and kickers of the two transverse cooling systems and for their installation in dispersion-free sections. All these aspects, which are relevant for stochastic cooling, were considered in the ring lattice and combined with the requirements for large acceptance which is further optimized by a dedicated sextupole correction scheme [9]. Another more recent consideration came from the necessity to transfer beam directly from the CR to the HESR resulting in a new extraction point.

The actual stochastic cooling system for the coasting beam after bunch rotation was designed on the basis of analytical estimates and numerical simulations. Design issues were the choice of the system bandwidth 1-2 GHz, both for the longitudinal and the transverse cooling systems and the decision for notch filter cooling [10]. For RIBs the notch filter cooling needs additional pre-cooling with a Palmer cooling system which has to be added due to band overlap in the injected hot secondary beam and the relatively large momentum slip factor of the lattice for RIB operation.

The ring installations of the stochastic cooling system consists of horizontal and vertical pick-up and kicker tanks, all four located in the dispersion-free straight sections with proper phase advance between respective pick-ups and kickers. The signals of both transverse systems are also used in a sum mode for the longitudinal notch filter cooling and the correction signals are sent to the kicker electrodes. Each tank accommodates two times eight electrode arrays of the slot line type on both sides of the beam. The slot line electrodes are well suited for operation in the velocity range which is defined by the velocity of ions (ß = 0.83) and antiprotons (ß = 0.97). The low signal to noise ratio for antiprotons and the necessity of fast cooling have resulted in two additional features. The pick-up electrodes can be cooled during operation to 20 K in order to reduce thermal noise and can be moved synchronously with the reduction of the beam size in order to provide optimum pick-up signals.

The electric parameters of the electrodes have been measured on the test bench and their design has been optimized [11]. The measurements also provide the input for the design of the electric circuit and for computer simulations of the cooling process. A new optical notch filter was developed for application in the cooling circuit. After extensive measurements in the laboratory, the expected performance was demonstrated with beam in the ESR. The present funding of the stochastic cooling system foresees installation of a total rf power of 8 kW, an upgrade to higher power with corresponding increase of the cooling rate is an option, if additional funding is available.

Table 1: Main Parameters for the stochastic cooling of antiprotons in the CR.

ring circumference C	221.45 m
revolution frequency	1.315 MHz
slip factor ring total η/ pickup-kicker η_{pk}	-0.011/ -0.033
distance pickup-kicker / C	0.378
antiproton number	1×10^8
initial rms emittance	45 mm mrad
initial rms momentum spread	3.5×10^{-3}
system bandwidth	1 – 2 GHz
pick-up/kicker impedance	11.25 / 45 Ω
number of longitudinal pick-ups/kickers	128 / 128
number of transverse pick-ups/kickers	64 / 64
total installed power at kickers	8 kW

The feasibility of the required fast cooling was studied in computer simulations. The most important parameter is the momentum spread after cooling. It determines the requirements for the efficiency of the transfer to the HESR, due to the limited momentum acceptance of the HESR. The simulations were performed with an existing CERN code which was adopted and optimized for the CR calculations. It calculates the rms momentum spread as the second moment of the distribution function applying the Fokker-Planck equation to the longitudinal degree of freedom and solving it numerically. In the first calculations the cooling of antiprotons was studied. Many parameters of the storage ring and cooling system were taken into account in great detail as listed in Table 1. The simulations were performed not only for notch filter cooling, but also for Time-Of–Flight (TOF) cooling [12]. TOF cooling offers larger momentum acceptance, but no noise suppression [13]. Notch filter cooling is more powerful with a reduced momentum acceptance which is determined by the shape of the notches. According to the

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simulations, notch filter cooling is able to reduce the initial momentum spread of 3.5×10^{-3} (rms) with the planned rf power in less than 10 s to a momentum spread below 5×10^{-4} (Fig. 1). This complies with the requirements of efficient antiproton production and transfer to the HESR. A further increase of the cooling rate can be expected by an increase of the installed rf power, which would allow an increase of the antiproton production rate.

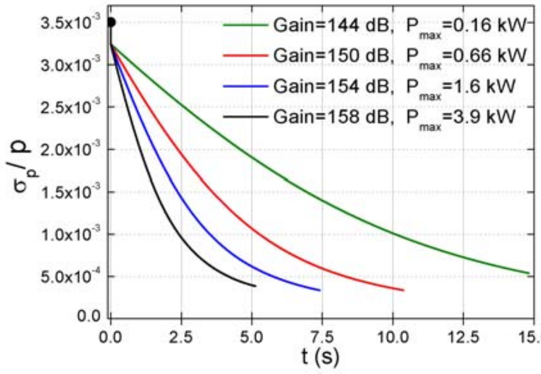

Figure 1: Simulation of the reduction of the momentum spread of a beam of 10^8 antiprotons after bunch rotation in the CR for different gains of the stochastic cooling system.

Similar simulations are needed for the cooling of RIBs from the SuperFRS, where much shorter total cooling times (below 1.5 s) are expected due to the higher charge of the ions. The simulations are crucial for the design of the various subsystems which will be installed in the frame of the MSV and are presently prepared.

HIGH ENERGY STORAGE RING HESR

Storage of antiprotons for experiments with an internal hydrogen target as part of the PANDA physics program was the main motivation for the construction of the high energy storage ring HESR. A magnetic bending power of 50 Tm allows a maximum antiproton energy of 14.1 GeV. Two 132 m long straight sections in the circumference of 575 m provide comfortable space for experimental installations and beam cooling systems. The injection system is designed for antiprotons of 3 GeV energy as provided from the CR, or in a later stage after accumulation in the RESR. After injection the antiprotons can be either accelerated to any energy between 3 and 14.1 GeV or decelerated to a minimum energy of 0.8 GeV. The ramping rate is limited to 0.025 T/s due to available rf voltage and the ramp rate of the main power converters of the ring magnets.

In the MSV the accumulator ring for antiprotons RESR is missing. Therefore an alternative scheme for the accumulation of antiprotons in the HESR by a combination of barrier buckets and cooling was proposed. For antiprotons the stochastic cooling system appears more promising than the planned electron cooling system.

The lack of stored ions and RIBs in the new storage rings constructed within the MSV of the FAIR project triggered a feasibility study of ion beam storage in the HESR [14]. The injection scheme can follow the concept of the injection of antiprotons from the CR. The magnetic rigidity should be 13 Tm as for antiprotons using the same magnetic components with reversed polarity. Changing the polarity is not a severe issue, as the time scale for switching between antiproton and ion operation will be weeks to months. As for antiprotons, accumulation of ions with barrier buckets and cooling is an option, if beam intensities higher than available in a single transfer from the CR will be requested. The available intensities will vary over a large range depending on the ion species. Energies in the range 0.2 to 5 GeV/u, depending on the ion species, can be achieved by acceleration or deceleration in the HESR.

The main cooling system of the HESR considered from the very beginning is stochastic cooling [15]. The cooling system operates in the frequency band 2 – 4 GHz. Special slot coupler rings were designed as electrodes which provide signals for all three phase space planes. The pick-up tanks are designed for cryogenic cooling to 20 K by cold heads. The expected performance of the slot coupler structure could be demonstrated with beam in COSY [16]. Similar to the CR, also in the HESR longitudinal cooling by the TOF-method and by notch filter cooling will be available. The low level rf system components including optical delay lines as well as the power amplifiers are studied and designed for integration into the cooling system. Originally designed for antiprotons above 3 GeV, studies have shown that stochastic cooling can also be used at energies below 3 GeV, which is particularly valuable for the plans to operate the HESR with ions [17]. The system will be able to compensate the heating by the internal hydrogen target, but depending on the target thickness an additional rf system will be needed to compensate the energy loss in the target.

A proposed high energy electron cooling system for the HESR which could cool antiprotons up to 8 GeV, and after an optional upgrade up to the full antiproton energy of 14.1 GeV, was shifted to a later stage of the project. Nevertheless, a detailed design study was preformed for this high energy electron cooler [18]. As a less expensive alternative an electron cooling system is now under construction at the Budker Institute, Novosibirsk, which, for antiprotons, can cover the energy range below the injection energy of 3 GeV [19]. In this energy regime electron cooling is still powerful and can provide high quality beams and can efficiently compensate the heating by the internal target. The electron cooling system presently passes the final commissioning with electron beam at the Budker Institute, where it also was designed and manufactured.

After successful commissioning at the Budker Institute, the electron cooling system will be shipped to Jülich for installation in the COSY storage ring. In the

COSY the performance can be studied with a proton beam and optimized over the full energy range which will be relevant for cooling in the HESR, both at the antiproton injection energy and nearly the full range of ion energies. Thus this electron cooling system will be of high importance in the operation of the HESR with stored ions. It can be used for accumulation but more importantly for the preservation of good beam quality during operation of an internal target. This situation was studied in simulations with the BETACOOL code [20]. Assuming realistic parameters of the electron cooling system even with a hydrogen target in the range 10^{14}-10^{16} hydrogen atoms/cm^2 electron cooling provides emittances below 1 mm mrad and a momentum spread in the low 10^{-4} range (Fig. 2).

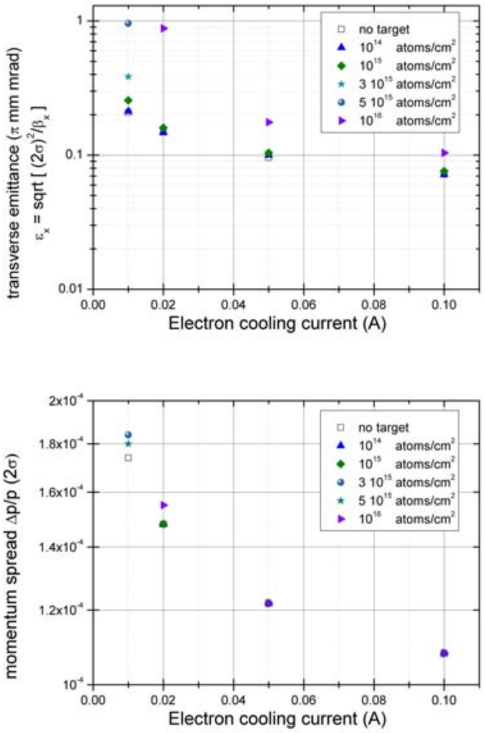

Figure 2: Transverse emittance and longitudinal momentum spread of a cooled beam of 1×10^8 stored U^{92+} ions at 740 MeV/u for various densities of the internal hydrogen target as a function of the electron current.

The ion beams for the HESR will be provided along the same line as the antiprotons. They will be injected from the CR with a magnetic rigidity around 13 Tm. The primary ion beams will be accelerated in the synchrotron SIS18 and, if necessary, in the synchrotron SIS100. They can be stripped to a high charge state or sent to the target of the SuperFRS for the production of rare isotopes. Similar to the production scenario for antiprotons, a short bunch from SIS100 is needed, The CR bunch rotation and debunching rf system is also applicable to ions reducing the momentum spread of the short bunch for subsequent stochastic cooling.

Stable beams of primary highly charged ions can be transported without stochastic cooling in the CR. In case that cooling is required, it has been checked that for up to 1×10^8 ions the cooling time does not exceed 1.5 s, for larger particle numbers the cooling time increases with the particle number. The emittance and momentum spread after cooling should be sufficiently small for injection into the HESR.

The experiments with ions in the HESR will focus on an internal target. Simulations have confirmed that the lifetime even in the unbaked HESR vacuum system with an average pressure in the low 10^{-9} range will be much longer than the lifetime due to the dense internal target which is expected to be in the order of minutes [14]. The ion optical properties are well suited for the detection of projectile-like particles which are used as signature of the interaction of circulating ions with target atoms. The high beam energy could even allow the interaction with a very thin fibre target with efficient use of the stored beam. Another option is the use of lasers for experiments with the stored beam, the long straight sections of the HESR provide long overlap regions between ion and laser beam.

ESR OPERATION FOR ACCELERATOR DEVELOPMENT

The existing ESR storage ring [6] was operated at GSI over more than two decades allowing both accelerator development and physics experiments. In the full version of the FAIR project it was planned to stop ESR operation and use various ESR components in the Recuperated Experimental Storage Ring (RESR). In the full version of the FAIR project the main ring for physics experiments with stored ions was the New Experimental Storage Ring (NESR). Both new rings, RESR and NESR, are not included in the MSV. Therefore it was decided to continue ESR operation. With the large experience in ESR operation, the various operation modes and the advanced diagnostics techniques, the ESR is an ideal test bed for beam physics experiments and the exploration of new concepts and techniques required in the FAIR project.

One of the important concepts in the FAIR project is beam accumulation supported by beam cooling. Originally proposed for the accumulation of RIBs in the NESR, the combination of barrier buckets and cooling is now the proposed method for antiproton accumulation in the HESR. In the NESR electron cooling was proposed, for the HESR stochastic cooling is preferred. The accumulation by barrier buckets and cooling first was studied in the ESR with electron cooling [21], as required for the NESR, and later also with stochastic cooling [22] as needed with antiprotons in the HESR. The successful experiments confirmed the predicted benefits of the accumulation methods and allowed benchmarking of the simulation tools which are applied to predict the performance in the new FAIR storage rings [23][24].

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Very recently the stochastic cooling system of the ESR was modified to test the optical notch filter which is under development for the CR. The signals of the Palmer cooling pick-ups are used in sum mode, sent through the notch filter and after amplification applied to the beam. The cooling by the notch filter method was studied with a 400 MeV/u Ar^{18+} ion beam. The performance of the standard Palmer cooling was compared to filter cooling and TOF cooling which was realized by opening the delay line of the notch filter. The comparison proved that notch filter cooling is more powerful resulting in shorter cooling time, but TOF cooling can capture particles with a larger momentum spread at the cost of longer cooling time (Fig. 3). A combination of pre-cooling by the TOF-method and notch filter cooling might offer optimized cooling of hot secondary beams with large momentum spread.

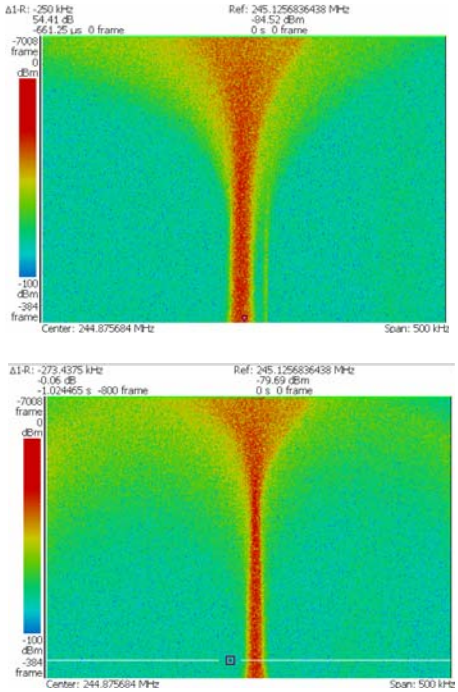

Figure 3: Longitudinal Schottky signal measured during stochastic cooling of a 400 MeV/u Ar^{18+} beam. TOF cooling (upper picture) evidences a larger capture range in longitudinal momentum, whereas notch filter cooling (lower picture) cools the beam in shorter time with a reduced capture range and smaller final momentum spread.

Another important feature of the ESR is the deceleration of highly charged ions. In the FAIR project deceleration of antiprotons in the NESR was proposed. The original CRYRING [8], formerly operated at the University of Stockholm, was proposed as a second stage for the deceleration of antiprotons. As the CRYRING is available already now, but the NESR will not be constructed in the MSV, a scenario was worked out to install the CRYRING behind the ESR and use it with decelerated highly charged ions and RIBs from the existing GSI facility. Electron cooling will be applied both in the ESR and in CRYRING to prepare beams of small phase space volume and to improve the efficiency of deceleration and will again be crucial for optimum performance of the deceleration cycle. The combination of the two rings allows the study of some aspects of the decelerator chain in preparation of future FAIR operation.

The CRYRING with a dedicated injector chain, similar to the one used in Stockholm, will be operated as a small scale test facility for the FAIR accelerators and various aspects of new diagnostics and the new control system can be developed. This will bridge a gap in the operation of the GSI accelerators caused by the inevitable modification of the existing accelerators for FAIR.

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