CURRENT PLANS FOR BEAM COOLING AT FAIR

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Abstract

The accelerators of the international FAIR project are designed to provide stable heavy ion beams, rare isotope beams and antiprotons with high intensity and high beam quality. Beam cooling is indispensable to improve the beam quality of secondary beams produced by bombardment of thick targets. The goals of the project as well as the methods to achieve high intensity and high quality secondary beams will be described. Due to budget constraints the project realization is planned in a staged scenario. The main accelerator systems in the first project stage to provide cooled beams will be the Collector Ring for pre-cooling of secondary beams and the High Energy Storage Ring for experiments with stored cooled antiprotons.

INTRODUCTION

The international FAIR project will provide heavy ion and proton primary beams over a large range of energies [1]. These beams serve four basic physics programs, research with high energy antiprotons, studies of compressed baryonic matter, nuclear structure and related astrophysics, and atomic and plasma physics and their applications. The use of beam cooling is foreseen for highly charged primary heavy ion beams, for rare isotope beams from the new large acceptance separator SuperFRS and for antiproton beams produced in a dedicated antiproton source with a target and a separator section. A number of storage rings was conceived for various purposes, such as pre-cooling of the hot secondary beams immediately after the production target, for accumulation of the pre-cooled secondary beams and finally storage rings equipped with powerful cooling systems which allow the use of high quality cooled beams in high precision and high luminosity experiments with internal targets [2]. Another option will be the deceleration of cooled secondary beams for experiments at low energy and even after further deceleration in linear decelerators, nearly to rest, for which beam cooling is indispensable. For these purposes mainly four storage rings were designed, the Collector Ring (CR) for the pre-cooling of antiprotons and rare isotopes, the accumulator ring RESR for the accumulation of high intensity antiproton beams by a dedicated stochastic cooling system, the New Experimental Storage Ring (NESR) as a storage ring for internal experiments with heavy ions and rare isotopes and deceleration of cooled beams of ions and antiprotons, and the High Energy Storage Ring (HESR) for experiments with cooled antiprotons using internal hydrogen targets. These storage rings together with the other new accelerator facilities of the FAIR project were documented in technical design reports [3].

After a revision of the project cost, it was decided that the project will be constructed in a staged manner. The first stage of the project, called Modularized Start Version (MSV), is conceived such that it can serve all four basic pillars of the physics program of FAIR. Due to the limited money available for the first part of the FAIR project, however, the accumulator ring RESR and the ion storage ring NESR had to be postponed to a later stage of the FAIR project and will not be constructed in the frame of the MSV. As a compensation of the lack of stored ion beams in the MSV of FAIR it was decided that the operation of the existing ESR storage ring will be continued.

FAIR ACCELERATORS OF THE MODULARIZED START VERSION

The MSV is based on the existing linear accelerator UNILAC for heavy ions serving as injector into the existing heavy ion synchrotron SIS18. An extended upgrade program is under way to improve the performance of these injector machines and towards increased intensities and acceleration with higher ramp rate. The MSV now comprises the following new accelerator facilities. A new 70 MeV proton linac as injector in front of the synchrotron SIS18 will provide the high intensity proton beam required for the production of antiprotons, it can fill SIS18 up to the space charge limit. The new synchrotron SIS100 uses the SIS18 as injector for high intensity proton and heavy ion beams. The maximum magnetic rigidity of 100 Tm allows either acceleration to higher energy or the acceleration of low charge states, which provides higher beam intensity as no additional stripping stage in front of SIS18 is needed, thus avoiding the reduction of intensity associated with the use of the stripper foil. The SIS100 design is based on superferric magnets allowing fast 4 T/s ramping of the magnetic field which is needed to provide high average beam intensities [4]. The 1080 m circumference ring tunnel of SIS100 will be prepared for the later installation of an additional 300 Tm superconducting synchrotron for the acceleration of heavy ions to correspondingly higher energy or for use as a stretcher ring for slow extraction of 100 Tm beams accelerated in SIS100.

After SIS100 two stations for the production of secondary beams will be constructed. The SuperFRS has a target for the production of rare isotope beams by projectile fragmentation followed by a large acceptance superconducting magnetic separator [5]. The fragment beams can be used either for fixed target experiments or for injection into the CR storage ring [6] where phase space reduction by fast stochastic pre-cooling allows the transfer to a subsequent storage ring for internal experiments or deceleration to lower energy. Therefore SIS100 will provide both a slow and a fast extraction mode for heavy ions. The second target station is designed for the production of antiprotons from an intense 50 ns short bunch of 29 GeV protons. A nickel target followed by a magnetic horn and a magnetic separator provides 3 GeV antiprotons for the injection into the CR storage ring. Fast bunch rotation and debunching and subsequent stochastic cooling in the CR prepare the antiprotons for further use.

In the MSV the only user of the pre-cooled secondary beams will be the HESR [7]. The HESR is a storage ring of 50 Tm maximum magnetic rigidity. The 3 GeV antiprotons from the CR will be accumulated at 3 GeV by a combination of an rf system for compression of the circulating beam into a fraction of the storage ring and stochastic cooling. The feasibility of the proposed stacking scheme in the HESR was recently investigated in a proof-of principle experiment at the ESR [8]. This experiment demonstrated the feasibility of the proposed accumulation scheme and confirmed the predictive power of computer simulations which are used to study and optimize the antiproton accumulation in the HESR [9].

COLLECTOR RING CR

The Collector Ring CR was from the very beginning of the FAIR project designed as a pre-cooling ring for secondary beams. Both types of secondary beams, antiprotons and rare isotopes are produced in a thick solid target by bombardment with a high intensity primary beam. Consequently, the production of the secondary beam is associated with angular scattering and energy straggling in the target. The secondary beam has large transverse emittance and longitudinal momentum spread. Therefore the main design issue for the storage ring was a large acceptance, transversely and longitudinally. The use of large aperture magnets and a lattice design which considers the higher order components affecting particles with large betatron amplitudes were major design aspects. These aspects did not change in the frame of the MSV. The same is true for the use of fast bunch rotation and adiabatic debunching of the incoming short bunch of secondary particles which requires a dedicated rf system.

In the original full FAIR project the pre-cooled secondary beams from the CR were transfered to another storage ring for accumulation of intense secondary beams, for antiprotons the accumulation was foreseen in the dedicated accumulator ring RESR, for rare isotopes accumulation in the NESR should precede the preparation of the rare isotope beam for the experiment.

After postponing both rings to a phase after the construction of the MSV, the CR design had to be modified for the transfer of the antiproton beam directly to the HESR. The direct connection to the HESR requires the extraction of the beam on the Western side of the ring, compared to the previous location of the extraction point on the Eastern straight section. The basic magnetic structure remained unchanged, but various components had to be rearranged, in addition various technical aspects required an increase of the ring circumference by about 10 m. All this resulted in the latest version of the CR, called CR version 68. The most recent design parameters can be found in Table 1.

Table 1: Parameters of the CR storage ring version 68.

circumference	221.45 m	
maximum bending power	13 Tm	
beam species	ions	antiprotons
energy	740 MeV/u	3 GeV
revolution frequency	1.124 MHz	1.315 MHz
betatron tune Q_x, Q_y	3.19,3.71	4.27,4.84
transition energy γ_t	2.82	3.85
momentum slip factor η	0.186	-0.011
horizontal acceptance	240 μm	240 μm
vertical acceptance	200 μm	200 μm
momentum acceptance	± 3.0 %	± 1.5 %

The main subsystem of the CR is still after all modifications the stochastic cooling system. It is designed for cooling of both antiprotons and rare isotopes. As both secondary beam species are injected at the maximum magnetic rigidity of the CR of 13 Tm the system must be able to cool particles at different velocities, the relativistic velocity β of rare isotopes of 740 MeV/u kinetic energy is 0.83, for antiprotons of 3 GeV β is 0.97. These two velocities govern the design of all components of the stochastic cooling system, particularly the design of the electrodes used as pickups and kickers of the stochastic cooling system, but also parts of the low level rf components like signal combination and delay lines.

For the ring design the two velocities have resulted in two ion optical modes with different transition energy γ_t and consequently different momentum slip factor η. The momentum slip factor should have a small absolute value, for antiprotons η is -0.011, for rare isotopes it is 0.186. This uses the flexibility of the focussing structure of the CR with 11 independently controlled families of quadrupole magnets. Moreover, 6 families of sextupole magnets are adjusted to achieve maximum acceptance for the large emittance secondary beams. For both secondary beam species the ring will be operated near the maximum magnetic rigidity, which results in small variations of field quality with field level. However, the different ion optical settings for ions and antiprotons and the different polarity will require special care when operating the CR with the two species.

Injection and extraction of antiprotons and ions will be performed along the same beamlines. Nevertheless, the requirements for injection components are different and as some kicker modules are used for both injection and extraction a bipolar kicker system is required. For the latest version of the ring lattice the main change is caused by the change of the extraction point from one straight section to the other one. A special new requirement comes from the small momentum acceptance of the HESR storage ring which will accumulate the antiprotons. The bunch transfered from CR to HESR should be as long as possible in order to minimize the momentum spread. The bunch length is limited by the rise and fall time of the kicker pulse. As an economic trade off rise and fall times of 200 ns are specified for the large aperture kicker magnets.

A system which was only minutely affected by the recent lattice changes is the bunch rotation rf system. It is located in one of the two dispersion free straight sections of the CR and will provide up to 200 kV rf voltage at the revolution frequency of the particles (1.32 MHz for antiprotons, 1.12 MHz for rare isotopes). Five rf cavities filled with magnetic alloy material have to provide the large rf amplitude over less than 1 ms in order to transform the incoming 50 ns short bunch into a nearly coasting beam by fast change of the bunch phase by 90 degrees. An optimized scenario for the combination of bunch rotation and adiabatic debunching of the incoming antiproton bunch will reduce the momentum spread from $\pm 3.0\%$ to $\pm 0.7\%$. This will result in a minimum cooling time of the stochastic cooling system which is applied after the rf manipulations. For rare isotopes the bunch will be of similar length and the rf manipulation will reduce the momentum spread from $\pm 1.5\%$ to less than $\pm 0.4\%$.

On this nearly coasting beam with reduced momentum spread the stochastic cooling system will act. The stochastic cooling system for the CR has been developed over several years. Changes of the ring design did not influence the major hardware specifications which are determined by the necessity to use the same system for antiprotons and ions. The frequency band of the basic cooling system is 1 - 2 GHz with an option to add cooling systems in the band 2 - 4 GHz. The necessity to cool the different velocities of antiprotons and ions strongly affected the choice of the electrodes and the low level rf system. Due to the low signal to noise ratio of the antiprotons the electrodes are designed for cooling them to 20 K. The electrode structures of slotline type have been designed and studied with model electrodes. Measurements of the properties of these electrodes have been performed and their design was optimized [10]. At present the main task is the manufacturing of the electrodes in an ultrahigh vacuum compatible technology. They should be produced from alumina with UHV compatible metalization. First prototypes are in production and their electromagnetic properties will be measured and optimized.

Further improvement of the electrode sensitivity is achieved by movement of the pick-up electrodes. Special mechanisms have been designed and tested which allow a controlled movement of the electrodes matched to the progress of the transverse cooling process. A prototype vacuum chamber with movable electrode mechanisms based on fast moving linear motors has been manufactured. The control of the motors was optimized for fast (cycle times of about 1 s are required for the cooling of rare isotopes) and shock-free motion.

Low level rf in the band 1 - 2 GHz is designed which allows fast changes of delays for the necessary changes between antiproton and ion operation. Many other parameters of the rf components need to be controlled in the course of the cooling process or due to the different beam species.

The use of the three orthogonal cooling systems is presently studied in computer simulations [11]. One aspect is the necessity to specify the parameters of the various stochastic cooling system, another aspect is the definition of an optimum strategy to operate and move the different electrode arrays in order to achieve the required phase space reduction within a minimum cooling time. The results of the simulations will provide the information for the optimum specification and later operation of the different cooling systems. An extension of the longitudinal cooling system to the band 2 - 4 GHz will be studied in the simulations as this is a promising option to both increase the cooling speed and to reduce the momentum spread for better acceptance of the pre-cooled beam by the HESR. Space for the installation of the additional cooling system in the CR straight sections is reserved.

HIGH ENERGY STORAGE RING HESR

The High Energy Storage Ring HESR has a circumference of 574 m and can be operated up to a magnetic rigidity of 50 Tm. The antiprotons will be injected at an energy of 3 GeV. In the scenario of the MSV the antiprotons will come from the CR and will be accumulated in the HESR, in a later stage the accumulation will be performed in the RESR. After accumulation of a high intensity antiproton beam, the antiprotons are either decelerated or accelerated in the HESR to an energy in the range 0.8 to 14.1 GeV according to the requirements of the internal experiment. The main HESR experiment is focussing on the PANDA detector which is a large 4π detector system installed around the interaction point with an internal hydrogen target [12].

Beam cooling in the HESR in the frame of the MSV has two main goals, accumulation of a high intensity antiproton stack and the preparation of best beam quality for experiments with the internal hydrogen target. The operation of the HESR with beam cooling is described in a separate contribution to these proceedings [13]. The stochastic cooling system, which will be available in the MSV, mainly covers the energy range from the injection energy 3 GeV up to the maximum energy of 14.1 GeV, an option to use time of flight cooling instead of filter cooling for lower energies is under investigation [14]. The same system will also be used to provide cooling for the preparation of a stack of up to 1×10^{10} antiprotons. Pre-cooled antiprotons from the CR are accumulated in combination with an rf system which allows compression of the stack into a fraction of the ring circumference. The rf system will generate barrier buckets which allow a flexible control of the fraction of the ring which is filled by the stack and the fraction which is available for injection of new particles. The barrier bucket system of the HESR was foreseen from the beginning for the compensation of the energy loss during operation of the HESR with an internal target. The optimum strategy for the accumulation in the HESR was studied in computer simulations [15]. It is expected that accumulation of up to 1×10^{10} antiprotons can be performed with an efficiency close to 100 %. In the full version of the FAIR project the stochastic cooling system will support the operation with high intensity stacks, after accumulation in the RESR storage ring, of up to 1×10^{11} antiprotons in a high luminosity mode.

For better beam quality in a high quality mode an electron cooling system was proposed which should at least cover the energy range up to 8 GeV and after an upgrade the full energy range of HESR operation [16]. The high energy electron cooling system, however, is out of the scope of the FAIR project and is an option for a future upgrade. An option for electron cooling in the HESR is still in reach. The 2 MeV electron cooling system for COSY could, after decommissioning of COSY, be transfered to the HESR [17]. It can then cover the lower energy range, approximately the energy range below the injection energy (0.8 to 3 GeV), and provide high quality antiproton beams for internal experiments. Electron cooling in this energy range is expected to be more powerful than the proposed stochastic cooling by the time of flight method.

EXTENSIONS OF THE MODULARIZED START VERSION

The accelerator sections which were part of the full FAIR project, but are not contained in the Modularized Start Version are planned to be realized as extensions depending on the availability of funding. The largest additional accelerator subproject is the SIS300, a superconducting synchrotron for the acceleration of heavy ions up to a maximum magnetic rigidity of 300 Tm. SIS300 will be installed in the ring tunnel of SIS100 where sufficient space is reserved in the tunnel design of the MSV. Therefore this addition does not require money for the construction of an additional building. Some additional investment will have to go into high energy beamlines and the extension of experimental areas. The main goal is an increase of the energy for heavy ion beams either for low charge states and highest beam intensities or for high charge states and maximum beam energy.

Two extension are directed towards the improvement of possibilities with cooled beams. These are the construction of the two storage rings RESR and NESR which will provide improved beam quality or higher beam intensities by application of cooling, in particular for the accumulation of secondary beams.

RESR

The main mission of the RESR storage ring is the accumulation of high intensity antiproton beams [18]. The RESR has the same magnetic rigidity of 13 Tm as the CR, the beams will be transfered to the RESR with the energy which is used for pre-cooling in the CR. The basic ion optical structure of the RESR is fixed, but the ring circumference had to be increased in order to be able to install the RESR in a common tunnel with the CR. The change of the extraction point of the CR also resulted in a corresponding change of the injection point of the RESR. As extraction from the RESR is required in both straight sections of the RESR, in order to serve both HESR and NESR from RESR, the design of the extraction systems remained unchanged.

The ion optical lattice of the RESR offers a large momentum acceptance as required for the proposed accumulation scheme which will follow the procedure formerly used at the AA ring at CERN [19]. It will provide large flexibility to adjust the momentum slip factor which is regarded a key parameter to optimize the stochastic accumulation system. The accumulation procedure has been studied in simulations and the required performance for sufficiently fast accumulation was confirmed [20].

As the RESR is located in a common tunnel with the CR no additional building needs to be constructed. All technical infrastructure and space for the technical subsystems of the RESR is already planned and will be provided in the frame of the MSV. Therefore additional funding is only required for the RESR ring and its technical supply systems.

NESR

The NESR storage ring has different modes of operation [21]. The standard injection into the NESR will be performed at the maximum magnetic rigidity of 13 Tm, either antiprotons or ions. The pre-cooled secondary beams will come from the CR via the RESR, stable ions will come from either SIS18 or SIS100 via a separate direct beamline. An electron cooling sysem is foreseen which covers the energy range from the maximum injection energy for ions (740 MeV/u) down to the minimum energy after deceleration (4 MeV/u). Electron cooling will also be crucial for the deceleration of antiprotons from 3 GeV to 30 MeV for experiments with slow antiprotons in the FLAIR facility after the NESR [22].

Electron cooling in the NESR will provide powerful cooling for all experiments with stored ions over a large energy range. The most challenging aspect involving cooling, the accumulation of low intensity rare isotopes has been prepared by experiments in the existing ESR storage ring at GSI [23]. These experiments demonstrated the feasibility of longitudinal accumulation by combination of an rf system which compresses the stack into a fraction of the ring circumference with electron cooling. This scheme is identical with the foreseen accumulation of antiprotons in the HESR, except that electron cooling will be applied instead of stochastic cooling in the HESR. The experiments were performed with different rf manipulations, fixed barriers, moving barriers and injection onto the unstable fixed point of an harmonic rf operating at harmonic number $h = 1$. From the comparison with simulations it can be concluded that the simulation tools have sufficient predictive power to base the design of the NESR systems on the simulations. Another conclusion was that the quality of the technical systems will be crucial for the efficiency of beam accumulation. Particularly the quality of the pulse generated to provide the injection kick for the incoming bunch is of outstanding importance. Short rise and fall times have to match the relatively short revolution time of the beam in the NESR and any ringing of the kicker system after the pulse will unavoidably heat the circulating beam transversely resulting in extended cooling time and additional inefficiency of the accumulation method. The same is true for the control of the rf waveform used to compress the beam and the synchronization of the the incoming bunch with the rf voltage and the kicker pulse. These are very demanding requirements for the control and performance of these accelerator subsystems.

The funding of the NESR is a more critical issue than for the RESR since funding is not only required for the accelerator, but also for additional buildings for the NESR ring, the technical systems and the low energy experimental area after the NESR.

STATUS AND OUTLOOK

The contracts for the foundation of the FAIR company were signed and the new FAIR company was founded end of 2010. The first partner countries started to transfer their financial contributions. Germany, as the main partner country started to assign funding which is presently used to start the ordering of the most time critical accelerator components. The completion of all documents for the civil construction work for FAIR is a prerequisite for first construction activities. After the building permit by German authorities, the first construction work for FAIR is still expected to start in the fourth quarter of 2011. In parallel the activities to start production of accelerator components will be intensified. A large fraction of the production of components will be supervised by GSI, either as German in-kind contributions to the FAIR project or as orders by the FAIR company based on international cash contributions. The stochastic cooling system of the CR is planned as a major German in-kind contribution provided by GSI. Similarly, most parts of the HESR storage ring, and its beam cooling systems in particular, will be a German in-kind contribution provided by Forschungszentrum Jülich. A general time schedule for the FAIR project based on the present information on the expected resources, financial and man power, is in work. Specifications for all required components are worked out as a basis for the hardware contributions to the FAIR project regarding the general standards of the project.

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