OPERATION OF THE HESR STORAGE RING OF THE FAIR PROJECT WITH IONS AND RARE ISOTOPES

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Abstract

The High Energy Storage Ring (HESR) of the Facility for Antiproton and Ion Research (FAIR) was originally designed for experiments with stored antiprotons. As it is fed through the chain of FAIR accelerators which can provide heavy ions and rare isotope beams, it will be straightforward to transfer these beams to the HESR as well. No major modifications of the HESR concept and no additional installations except from the dedicated experimental set-ups are required. Therefore the use of the HESR with heavy ions is a cost efficient addition to the experimental program at FAIR. The available ion beams and their parameters are discussed. The conditions for ion beams in the HESR with respect to beam lifetime and beam quality and the possibility of in-ring experiments with ions will be described.

INTRODUCTION

The original exclusive use of the High Energy Storage Ring (HESR) of the FAIR project was the performance of experiments with stored antiprotons interacting with an internal target. The HESR has a maximum magnetic rigidity of 50 Tm and a circumference of 575 m with two 132 m long straight sections [1]. The antiprotons are produced with a primary proton beam accelerated in the synchrotron SIS100 to an energy of 29 GeV which is directed onto a production target. A subsequent magnetic separator and a Collector Ring (CR) are used to select antiprotons at an energy of 3 GeV and to prepare them by means of stochastic cooling, then the antiprotons are transferred to the HESR.

Until recently all experiment proposals for the HESR were based on the storage of antiprotons. Due to the lack of other storage ring facilities for experiments in the first stage of the FAIR project, the Modularized Start Version, proposals are now in preparation to use the HESR also with stored ion beams, either stable ions or unstable isotopes. Corresponding to the operating range of antiprotons which covers magnetic rigidities between 5 and 50 Tm, the HESR can store highly charged ions in the energy range 200 MeV/u up to 5 GeV/u. Particularly, the higher energies are not available in any other storage ring facility worldwide. Planned experiments with ions in the HESR will employ an internal target as well as an electron cooling system as a target of free electrons. Not only gaseous internal targets, but also very thin solid targets, e.g. fiber targets, are considered. It is foreseen to provide intense laser beams, e.g. in the long straight sections of the HESR, either for laser cooling or for precision spectroscopy experiments.

PARAMETERS OF IONS IN THE HESR

The scenario for the operation of the HESR with ions will be analogous to the operation with antiprotons. Since the only injection beam line to the HESR is coming from the Collector Ring CR, the ions will be injected after storage in the CR. The same rigidity of 13 Tm as for antiprotons will be used for storage and transfer of ions to the HESR. The ions will be accelerated in the synchrotron SIS18 and, if necessary, in the synchrotron SIS100. Stable ions will come directly from the synchrotron with the option either to keep the charge state which was accelerated or to produce a required higher charge state in a stripping foil in between SIS100 and CR. The primary heavy ion beam could also be used for the production of rare isotopes in the new fragment separator SuperFRS. The fragment beam from the SuperFRS will be injected into the CR at a magnetic rigidity around 13 Tm.

For isotope production the SIS100 beam will be compressed into a 50 ns short single bunch. In the CR bunch rotation and debunching will decompress the bunch and prepare a coasting beam with reduced momentum spread for stochastic cooling. Total cooling times of less than 1.5 s in the CR are matched to the period of the fastest acceleration cycle of SIS100 [2]. For primary ion beams most of these procedures are dispensable. The reduced momentum spread of the heavy ion beam after acceleration and the lack of need to produce short bunches should allow transfer of stable ions to the HESR without stochastic cooling in the CR. However, if the beam quality requires, stochastic cooling in the CR could improve the beam quality for injection into the HESR. 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. Transverse emittances of $\varepsilon_{x,y}$= 0.5 mm mrad and a momentum spread of $\delta p/p = 5\times10^{-4}$ (2σ-values) can be provided after stochastic cooling in the CR.

OPERATION OF THE HESR WITH IONS

The main difference to the antiproton operation is the change of polarity of all magnetic elements. As the HESR is designed for ramped operation and as the commissioning of the HESR with protons is foreseen, no major difficulty for the polarity change is expected. The energy range from 200 MeV/u to 5 GeV/u for ions corresponds to the same rigidity range as for antiprotons. Due to the lower velocity of the ions the revolution frequency is correspondingly lower. This can be compensated by operating the rf system at a higher harmonic. It can be easily achieved since the HESR rf system covers the frequency range 400 kHz – 5 MHz.

The experiments with stored ions in the HESR will greatly benefit from the availability of beam cooling in the HESR. A stochastic cooling system in the frequency range 2 - 4 GHz was designed for cooling of antiprotons at energies above 3 GeV [3]. An electron cooling system is presently in preparation which will be first tested in the existing COSY storage ring and will later be installed in the HESR [4]. This system allows electron energies up to 2 MeV corresponding to stored ions from the minimum energy of 200 MeV/u up to about 3.5 GeV/u. The electron cooling covers most of the energy range which is possible with ions and the stochastic cooling will complement it for the high energy range. The heating of the stored beam by the internal target will be compensated by cooling. If the energy loss in the target is too large, a barrier bucket rf system could be used which is also foreseen for antiproton accumulation and beam manipulations [5].

ADDITIONAL INSTALLATIONS FOR EXPERIMENTS WITH IONS

Many ion experiments will use an internal target. As the accessibility of the antiproton experimental area around the PANDA target is rather limited, the installation of an additional gas target in the first part of the arc is planned. In the free space which is available due to the missing dipole concept of the HESR such a target can be installed. Many of the ion experiments are based on the detection of ions which change charge due to the interaction with the target. This requires space for the installation of detectors in the dispersive arc section after the target. Ion optical calculations have confirmed that with the standard ion optical mode of the HESR this requirement can be fulfilled.

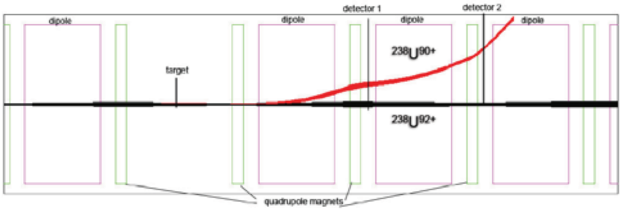

Figure 1: Separation of charge states in the arc section after the proposed location for the internal target planned for experiments with stored ion beams in the HESR.

The separation of the charge states is sufficient to insert a detector for down- and/or up-charged ions without intercepting the stored ion beam. Ions can be detected after the first dipole behind the target for larger reduction of the momentum or the charge. If the charge change is smaller or higher resolution is required, e.g. for ions which have lost longitudinal momentum due to the interaction with the target, the detection will be done after the second dipole (Figure 1).

The particle detectors will be installed between dipole and quadrupole magnets. Due to the high projectile energy these detectors can be mounted in pockets with thin stainless steel entrance windows which separate the detector from the ring vacuum. This allows easy exchange of detectors without breaking the ultrahigh vacuum.

ION BEAM LIFETIME

Since the HESR was designed as a storage ring for antiprotons in the GeV energy range and for experiments with a rather thick internal hydrogen target, the lifetime of the beam was not expected to be limited by the residual gas pressure. The basic HESR concept does not foresee a general bakeout of the vacuum system, but preparations are taken to allow for a bakeout, if the vacuum pressure is unacceptable. In the energy range of the HESR operation the lifetime of highly charged ions is predominantly determined by Radiative Electron Capture (REC), while Non-Radiative Electron Capture is weaker. REC scales with the fifth power of the atomic number of the projectile Z_p^5. Therefore, even for the energy range of ions which can be stored in the HESR the beam lifetime due to the interaction with the residual gas needs more careful consideration.

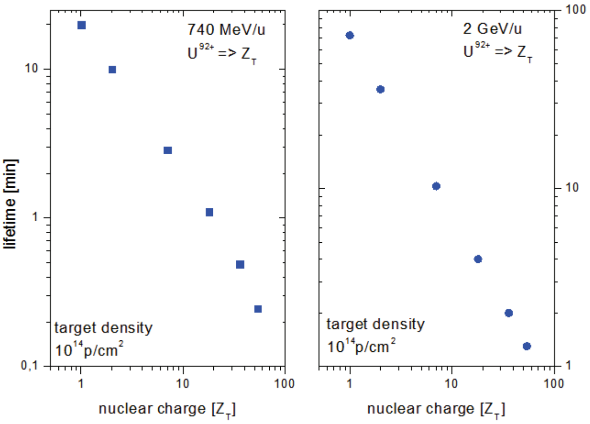

Figure 2: Lifetime of bare uranium ions at two energies (740 MeV/u and 2 GeV/u) as a function of the target atomic number with an internal target of 10^{14} atoms/cm^2.

For bare uranium beam and two beam energies (740 MeV/u and 2 GeV/u) the lifetime of the beam was calculated for an internal target of density 10^{14} p/cm^2 as a function of the target atomic number (Figure 2). Even for the heaviest target nuclei the beam lifetime is some ten seconds, increasing to the range of minutes for lighter target nuclei. As expected for REC the capture cross section increases linearly with the atomic number of the target. For energies below the injection energy the target density might be reduced as the expected interaction and event rates increase towards lower energies. With an internal hydrogen target, the lifetime increases from about

10 min at the injection energy to more than 100 min at the highest energy accessible in the HESR.

COOLING OF IONS IN THE HESR

The HESR is equipped with stochastic cooling and electron cooling. Both can be employed in experiments with stored ions. The performance of stochastic cooling for ion beams is described in a separate contribution [6]. Stochastic cooling will be most powerful for energies above 2 GeV/u. where notch filter cooling can be applied. By switching to TOF cooling, the band overlap problem of notch filter cooling at lower energies can be avoided and ions can be cooled with reduced cooling power.

The achievable cooling times and equilibrium beam parameters with the 2 MeV electron cooling system [3] were studied with the BETACOOL program [7]. It was assumed that the ions are pre-cooled in the CR at an energy of 740 MeV/u by stochastic cooling resulting in transverse emittances of $\varepsilon_{x,y}$= 0.5 mm mrad and a momentum spread of $\delta p/p = 5\times10^{-4}$ as initial beam parameters. With an electron current of 0.5 A the time for cooling a bare uranium beam with an energy of 740 MeV/u to equilibrium is 6 s, for a lighter ion like the radioactive $^{132}Sn^{50+}$ the cooling time increases to 11 s, due to the lower charge. This is much shorter than the typical beam lifetime and therefore would be suitable for experiments. Application of electron cooling at higher energies takes much longer, e.g. for an energy of 3 GeV/u the cooling time increases by roughly a factor of 35. Cooling times of 180 s and 360 s for the two species and the same electron current were calculated, even if the adiabatic shrinking of the phase space volume was taken into account. Consequently, for fast cooling at higher energies stochastic cooling is preferable.

When the beam is cooled down and the internal target is switched on, the electron current can be reduced to a value which is just sufficient to compensate the heating by the internal target. The equilibrium beam parameters according to BETACOOL-simulations for an experiment with a hydrogen internal target are shown in Figure 3 as a function of the electron current.

The availability of a barrier bucket rf system in the HESR [5] offers additional options for the operation with ions. Firstly, the energy loss in a dense internal target can be compensated, if the power of the cooling system is inadequate. Secondly, low intensity rare isotope beams can be accumulated using the same scheme foreseen for antiprotons. The pre-cooled ions from the CR can be injected into a gap in the stored HESR beam created by the barrier bucket system and by simultaneous cooling the process can be repeated as long as the accumulation rate exceeds the loss rate which might be related to charge changing processes or to the finite lifetime of unstable isotopes. As this procedure has to be performed at an ion energy of 740 MeV/u, the energy for pre-cooling in the CR, electron cooling would be preferable due to the low cooling power of the HESR stochastic cooling system at this energy.

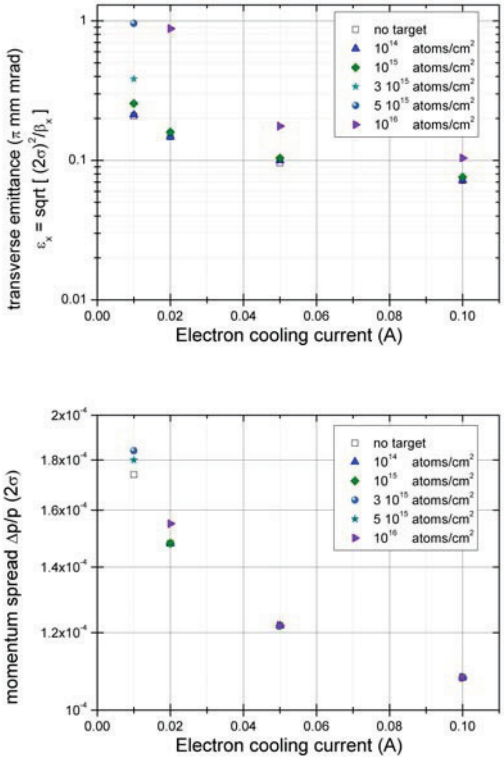

Figure 3: Transverse emittance and longitudinal momentum spread of a cooled beam of 1×10^8 stored U^{92+} ions at 740 MeV/u for various densities of the internal hydrogen target as a function of the electron current.

FURTHER OPTIONS

The high beam energy in the HESR might even allow experiments with thick internal targets, either heavy gases or a thin fiber target, still having a reasonable beam lifetime. A dedicated electron target can be added to study the interaction of ions and electrons at adjustable relative velocity. The long straight sections of the HESR can be used for studies of the interaction with a collinear laser beam for precision spectroscopy or laser cooling. The availability of pre-cooled rare isotope beams offers another field of nuclear physics experiments which can be explored after successful commissioning of the FAIR facility with rare isotope beams.

REFERENCES

[1] R. Maier et al., PAC'11, New York, March 2011, THOCN2, p. 2104 (2011); http://www.JACoW.org.
[2] M. Steck et al., COOL'11, Alushta, Ukraine, September 2011, MOIO05, p.10 (2011); http://www.JACoW.org.
[3] R. Stassen et al., COOL'11, Alushta, Ukraine, September 2011, TUPS15, p.129 (2011); http://www.JACoW.org.
[4] J. Dietrich et al., COOL'11, Alushta, Ukraine, September 2011, MOIO05, p.15 (2011); http://www.JACoW.org.
[5] R. Stassen et al., IPAC'12, New Orleans, May 2012, MOPPD008; http://www.JACoW.org.
[6] H, Stockhorst et al., IPAC'12, New Orleans, May 2012, MOPPD009; http://www.JACoW.org.
[7] A.O. Sidorin et al., Nucl. Instr, Meth. A558 (2006) 325.