RARE ISOTOPE ACCUMULATION AND DECELERATION IN THE NESR STORAGE RING OF THE FAIR PROJECT *

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Abstract

Production of rare isotope beams is one of the most important tasks of the accelerators of the FAIR project. The rare isotope beams can be stored in the NESR storage ring where powerful electron allows high precision experiments. Various modes for experiments are foreseen, interaction with internal targets, collisions with counter-propagating electrons or antiprotons, deceleration of the ions from the injection energy of 740 MeV/u to a minimum energy of 4 MeV/u and mass measurements by Schottky noise detection. If the intensity of single shots of rare isotopes is too low, a longitudinal accumulation scheme in combination with electron cooling allows accumulation of intense rare isotope beams.

INTRODUCTION

The New Experimental Storage Ring (NESR) is core part of the proposed Facility for Antiproton and Ion Research (FAIR) at GSI [1], [2]. Due to the availability of a large variety of particle species, it will be operated with stable heavy ion beams and with secondary beams. The secondary beams can be either antiprotons which are produced by the bombardment of an iridium target with 29 GeV protons or rare isotope beams (RIBs) which are produced by bombardment of a light target material with heavy ion beams of up to 1.5 GeV/u. The secondary beams are selected by a magnetic separator in the beam line after the production target. For RIBs a new Superconducting Fragment Separator (SuperFRS) [3] will allow selection of certain species by magnetic separation, also in combination with energy loss separation. Subsequently the secondary beams are transferred in a large acceptance beam transport system to the storage ring complex.

The primary beams are accelerated in the chain of the existing UNILAC linear accelerator, which will be complemented by a new 70 MeV proton linac, the present synchrotron SIS18 and the new synchrotron SIS100 of the FAIR project [4]. Highest primary heavy ion beam intensities will be achieved by acceleration of low charge states without intermediate stripping.

The hot secondary beams after the production target will be injected as a short bunch of about 50 ns length, which is produced at the end of the acceleration in SIS100, into the Collector Ring (CR). The CR is equipped with rf cavities for fast bunch rotation and debunching and a stochastic cooling system in order to prepare secondary beams occupying a reduced phase space volume [5]. The stochastic pre-cooling system in the CR is designed for the two energies of antiprotons and RIBs, respectively. Good conditions for transfer of the pre-cooled beams to the NESR and final electron cooling in the NESR are provided.

Before injection into the NESR the pre-cooled secondary beams have to pass through the new RESR storage ring [6]. For antiprotons the RESR is operated as an accumulator ring, a dedicated stochastic cooling system is used in the RESR, too. For RIBs the RESR allows deceleration from the injection energy of 740 MeV/u to a minimum energy of 100 MeV/u, which is beneficial when highest stability of all components in the NESR is required, particularly when the NESR is operated as a collider ring.

As an additional option, direct injection of primary heavy ions or RIBs from the SuperFRS into the NESR via a dedicated beam line bypassing CR and RESR is foreseen, which allows operation of the NESR independent of the CR/RESR complex. Therefore the NESR can be used for experiments with ion beams in parallel to antiproton operation in the other storage rings.

RING PARAMETERS OF THE NESR

The NESR is a 222 m circumference ring designed for a maximum rigidity of 13 Tm. The basic ion optical parameters have been defined [7]. A fourfold symmetry lattice with doublet focussing provides four long straight sections for experiments. Fully stripped ions will be injected independent of their mass at an energy of 740 MeV/u as a single bunch from the CR/RESR complex. Further cooling in the NESR employs an electron cooling system with large flexibility in the choice of the electron beam parameters [8]. Various experimental installations are foreseen in the NESR. The four straight sections of 18 m length will accommodate the electron cooling system, an internal gas target, an electron target and a section which allows to collide the ions with counter-propagating electrons or antiprotons.

BEAM PARAMETERS IN THE NESR

The RIBs have to be prepared in the NESR according to the requirements of the experiments. Electron cooling is the standard method to achieve good beam quality. The electron cooling system is designed to compensate the heating caused by the interaction of the ion beam with any of the experimental installations. A maximum electron energy

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of 450 keV is adequate to cool the RIBs at injection energy and to apply electron cooling to antiprotons after deceleration to 800 MeV. A magnetic guiding field of up to 0.2 T in the cooling section and electron currents up to 2 A together with transverse magnetic expansion or compression of the electron beam provide highest flexibility for the optimization of the electron beam parameters for best cooling conditions.

Fast cooling is mandatory for short-lived isotopes which must be cooled down faster than they decay. For the various in-ring experiments high cooling rate is also needed to counteract the various heating sources deteriorating the quality of the ion beam. The main heating source for high phase space density ion beams is intrabeam scattering. For thick internal targets also the scattering in the internal target is significant, scattering in the residual gas is expected to be much lower, as the NESR is designed for ultra high vacuum conditions with a basic pressure of 1×10^{-11} mbar.

Short cooling times for secondary beams by electron cooling are only achieved after stochastic pre-cooling. For antiprotons due to the single charge electron cooling at an intermediate energy of 800 MeV will provide a cooling time on the order of minutes, even after stochastic pre-cooling in CR [9]. This intermediate cooling will support the deceleration from the injection energy 3 GeV to a minimum energy of 30 MeV. For RIBs the situation is much more favorable because of their higher charge. With the expected emittance $\epsilon_x, \epsilon_y = 1$ mm mrad and a momentum spread of 5×10^{-4} (2σ-values) after stochastic pre-cooling the cooling time is less than 1.5 s. Thus full profit can be taken from the minimum cycle time of the synchrotron SIS100, which provides the primary heavy ion beam, and the stochastic cooling time in the CR, both time periods are expected to be 1.5 s.

A typical case was previously studied for a $^{132}\mathrm{Sn}^{50+}$ beam injected at 740 MeV/u after stochastic pre-cooling in the CR. From a simulation with the BETACOOL program [10] a total cooling time of 0.2 s was found [9]. For other highly charged ions the cooling time at this energy can be scaled with A/q^2, with the mass number A and the charge number q of the ion. This fast cooling time with electron cooling, however, is based on the stochastic pre-cooling. The situation is less favorable, if RIBs are directly injected from the fragment separator SuperFRS without stochastic pre-cooling in the CR. If beams are injected with momentum spreads of up to ± 1.5 % and emittances up to 100 mm mrad, as can be provided by the SuperFRS, the cooling time increases with the third power of the corresponding velocity spread (Fig. 1). Particularly, large transverse emittance results in extended cooling time. For the largest velocity spreads accepted by the NESR the cooling time will increase by nearly five orders of magnitude. As this is not acceptable for most experiments with RIBs, particularly if their nuclear lifetime is much shorter than the cooling time, the emittance of the injected beam must be limited. Injection of pre-cooled beams from the CR will be the preferred mode with RIBs.

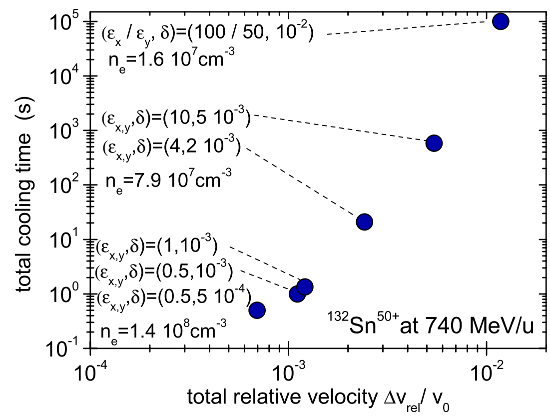

Figure 1: Dependence of the cooling time on the total relative velocity due to the ion beam emittance and momentum spread calculated with the BETACOOL code. The calculation was performed for $^{132}\mathrm{Sn}^{50+}$ at an energy of 740 MeV/u cooled by an electron beam whose parameters are optimized for best overlap. Beam emittance ϵ (in mm mrad) momentum spread δ and optimized electron density n_e are given in the legend.

DECELERATION

For the efficient production of RIBs by fragmentation of the primary beam, energies around 1 GeV/u are most favorable. This determines the energy of the secondary beams of several hundred MeV/u. Stochastic cooling which is needed to prepare the secondary beams does not allow a large variation of the beam energy. Therefore, if energies different from the production energy are needed, the beam has to be either accelerated or decelerated. As many experiments benefit from reduced particle velocity, deceleration of the beam is provided to improve the conditions for high precision measurements. In order to cope with the short lifetime of some species the power converters of the ring magnets and the high voltage system of the electron cooler are designed for a fast ramp rate of 1 T/s corresponding to a deceleration time of 1.6 s to the lowest energy. The minimum energy of 4 MeV/u after deceleration of ions requires a change of the magnetic fields of the ring magnets by a factor of 25. The same range of field strength corresponds to a deceleration of antiprotons from 3 GeV to 30 MeV. As the beams are cooled in the NESR, a moderate rf voltage of 20 kV is sufficient for deceleration of the small momentum spread beam. The rf frequency swing ranges from 1.1 to 2.8 MHz. For the full energy range operation at three harmonics ($h = 2, 4, 8$) is needed. This rf system also allows adiabatic debunching of a single bunch after injection from the RESR or from SIS100.

PRECISION MASS MEASUREMENTS

The method of precision mass measurements by the detection of Schottky noise was developed at the existing ESR storage ring [11]. At the NESR it can be extended to nuclides further off stability due to three main advantages. The primary beam intensities of SIS100, which are more than two orders of magnitude higher, will result in the production of useful amounts of RIBs even with correspondingly smaller production rates. The large acceptances of SuperFRS and the storage rings result in higher secondary beam intensity. Finally, the fast stochastic pre-cooling in CR and the optimized electron cooling time in NESR will give access to nuclides with lifetimes down to about 1 s.

The Schottky mass measurement method is based on a precise determination of the revolution frequency, which must be stabilized to 10^{-7} or better. The main components which determine the revolution frequency are the bending field in the ring dipole magnets and the energy of the electrons which cool the ions to a certain velocity. Consequently the power converters for dipole magnets and the accelerating voltage of the electron beam must be highly stabilized. From the transition energy $\gamma_t = 5.4$ a required bending field stability of 3×10^{-6} or better can be deduced. For the electron accelerating voltage stability a value in the 10^{-6} range is needed, both with respect to ripple and long term stability. The value of the required voltage stability depends on the applied cooling rate. For most other components stringent requirements on stability apply as well. The detection of single ions, which was also demonstrated at the ESR, will require a high sensitivity Schottky pick-up optimized for the injection energy and the cooled fragment beam.

BEAM ACCUMULATION

For the accumulation of high intensity RIBs a longitudinal stacking scheme supported by electron cooling is foreseen. Two options are under investigation, both by beam dynamics simulations and by experiments in the ESR (Fig. 2). The first option uses a barrier bucket rf system to compress the beam stack into a fraction of the ring circumference and to inject a new bunch into the empty part by a full aperture fast kicker system. Single sine waves can be used as barriers. The second option is based on a harmonic system operating at harmonic $h = 1$ to create a single stored bunch, a new beam bunch is injected onto the unstable fixed point of the rf. In both schemes electron cooling will compensate the heating of the stack due to the rf manipulation and cool the newly injected beam merging it with the stack. The same procedure can be repeated until an equilibrium between beam loss and injection rate is achieved. The small momentum spread of the cooled stack of 10^{-4} or better requires only moderate rf voltage for the longitudinal phase space compression preceding the next beam injection. The final equilibrium intensity can be limited by various quantities, e.g. the beam lifetime (nuclear or atomic), the momentum spread of the stack, transverse instabilities or space charge tune shift. Comparisons of the experimental results with available simulation tools confirm the expected accumulation rates in the NESR.

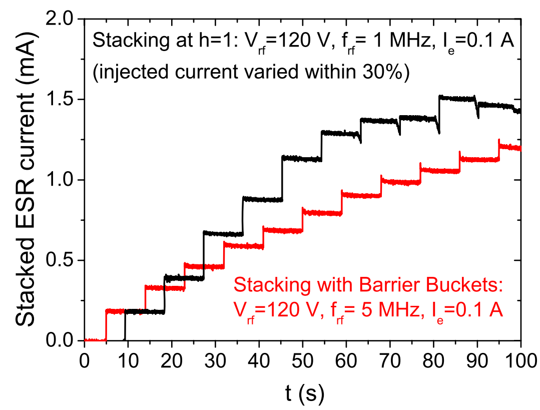

Figure 2: Experimental demonstration of the two proposed accumulation methods (barrier buckets and injection at the unstable fixed point) with an $^{40}Ar^{18+}$ beam at 65 MeV/u in the ESR. Similar accumulation rates could be achieved with both rf techniques and electron cooling. Variations of the injected current are caused by source current variations.

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REFERENCES

[1] An International Accelerator Facility for Beams of Ions and Antiprotons, Conceptual Design Report, GSI, 2001.

[2] FAIR Baseline Technical Report, GSI, 2006, http://www.gsi.de/fair/reports/btr.html.

[3] H. Geissel et al., Nucl. Instr. Meth. B 204 (2003) 71.

[4] P. Spiller, contribution to this conference.

[5] F. Nolden, K. Beckert, P. Beller, U. Blell, C. Dimopoulou, A. Dolinskii, U. Laier, G. Moritz, C. Mühle, I. Nesmiyan, C. Peschke, M. Steck, Proc. of EPAC 2006, Edinburgh, Scotland, (2006) 208-210.

[6] P. Beller, K. Beckert, C. Dimopoulou, A. Dolinskii, F. Nolden, M. Steck, J. Yang, Proc. of EPAC 2006, Edinburgh, Scotland, (2006) 199-201.

[7] M. Steck, K. Beckert, P. Beller, C. Dimopoulou, A. Dolinskii, F. Nolden, J. Yang, Proc. of EPAC 2006, Edinburgh, Scotland, (2006) 217-219.

[8] V.V. Parkhomchuk et al., GSI-Acc-Report-2005-04-001.

[9] C. Dimopoulou, K. Beckert, P. Beller, A. Dolinskii, U. Laier, F. Nolden, G. Schreiber, M. Steck, J. Yang, PRST-AB 10 (020101) 2007.

[10] A.O. Sidorin, I.N. Meshkov, I.A. Seleznev, E.M. Syresin, G.V. Trubnikov, Nucl. Instr. Meth A 558 (2006) 325.

[11] B. Franzke, K. Beckert, H. Eichkoff, F. Nolden, H. Reich, A. Schwinn, M. Steck, T. Winkler, Proc. of the 6^{th} Europ. Part. Acc. Conf., Stockholm, 1998, 256-258.

