# EFFICIENT COLLECTION AND COOLING OF RADIOACTIVE ION BEAMS IN A COLLECTOR RING (CR)

B. Franzke, K. Beckert, F. Nolden, P. Beller, M. Steck, J. Struckmeier, GSI Darmstadt, Germany,
A. Dolinskii, INR, Kiev, Ukraine

## *Abstract*

This contribution discusses the conceptual design of a large acceptance collector ring CR provided for the efficient collection and cooling of secondary beams of radioactive nuclides (i.e. radioactive ion beams, RIB) at a specific kinetic energy of 740 MeV/u. Cooling time constants of about 0.1 s are envisaged in order to attain experimental access to correspondingly short-lived exotic nuclides far from the valley of stability. Similar to the conception for the former Antiproton Collector AC [1] at CERN, bunch rotation and active de-bunching shall be combined with subsequent stochastic cooling in all phase planes. The pre-cooled beams shall be transferred without any additional intensity loss to an experimental ring like the existing ESR [2].

## 1 INTRODUCTION

At GSI radioactive ion beams (RIB) are produced by fragmentation or fission of accelerated primary heavy nuclei (e.g. uranium) at specific kinetic energies close to 1 GeV/u. There is a strong demand for higher primary beam intensities which is being partly fulfilled by means of the recently commissioned high current injector HSI of the UNILAC. It shall provide beams with sufficiently high currents to fill the synchrotron SIS up to the space charge limit, e.g. up to $4\times10^{10}$ $U^{73+}$-ions per 3 s-cycle [3].

An additional upgrade of the RIB intensities by a factor of 100 is necessary for the next generation of experiments with stored and cooled RIBs. Major objectives are measurements of masses, lifetimes and decay modes applying Schottky [4] or TOF [5] mass spectrometry, of nuclear reactions using internal targets, and of nuclear charge distributions by scattering experiments with 100-500 MeV electrons. Experimental access to nuclei with a half-life of about 1 s, i.e. to nuclei as far as possible away from stability, is considered to be essential for the understanding of nuclear structure near the stability limits and of astrophysical processes. With $1\times10^8$ stored exotic nuclei luminosities of up to $1\times10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for internal target experiments and $1\times10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for electron scattering experiments are envisaged.

Besides increased primary beam intensities, there is considerable potential for additional upgrades of the RIB intensity by improving the whole concept of their production, collection, cooling and accumulation. Necessary conditions are described in the following section.

## 2 RIB PRODUCTION AND FORMATION

High energy of primary ions: A specific kinetic energy of 1 GeV/u of primary nuclei turned out to be close to the optimum for RIB production. The high energy allows for

- relatively thick production targets of a few g/cm$^2$ with corresponding mean energy loss of about 25 %,
- making use of the “kinematic focusing” effect delivering secondary beams with not too large full momentum spread $\delta p/p$ and transverse emittances $\varepsilon_{x,y}$,
- a yield of more than 60% fully stripped heavy fragments (e.g. for Francium isotopes), and
- still reasonably small mean magnetic rigidity of RIBs (e.g. 13 Tm at 740 MeV/u).

Small beam size at the production target: A beam diameter of less than 1 mm for $\varepsilon_{x,y} = 20\,\pi$ mm mrad (typical for fast beam ejection at the SIS) and vanishing dispersion functions ($D$ and $D'$) minimise the growth of transverse beam emittances. Compared to the present position of the target near the beam extraction channel of the SIS, an additional space of about 20 m would be necessary for the improved beam optics.

A new large acceptance magnetic separator: An acceptance of $A_{x,y} \approx 50\,\pi$ mm mrad and $\Delta p/p$=5 % would enable to accept up to 100% of the produced secondary nuclei, i.e. over a factor of 10 more than the existing separator FRS [6] ($A_{x,y} \approx 20\,\pi$ mm mrad and $\Delta p/p$=2 %).

Optimal longitudinal optics: For minimum longitudinal emittance growth the primary beam bunches at the production target have to be as short as possible. A bunch length of ≤ 50 ns at full relative momentum spread $\delta p/p$ of 1 %, as foreseen by the SIS bunch compression project [7], would be adequate for the application of a fast reduction of $\delta p/p$ in the RIB bunches by bunch rotation in a collector ring. The conditions for fast stochastic cooling (SC) of the beam could be improved essentially this way (see below).

## 3 CR LATTICE DESIGN

The preliminary layout of a collector ring CR for RIB (see fig. 1) aims at the same acceptance as that of the new fragment separator mentioned above. The initial $\delta p/p$ of 5 % in the injected RIB bunches corresponds to a velocity spread $\delta\beta/\beta = \gamma^2\delta p/p$ of nearly 1.6 % (full width), which is much too large for starting the SC-process. Therefore, immediately after injection, $\delta p/p$ shall be reduced to less than 1 % by means of fast bunch rotation and subsequent adiabatic debunching like in the former AC-ring at CERN

[1]. However, there is still a rather large velocity spread of 0.31 % in the coasting beam and with a normal lattice layout the Schottky bands would start with overlapping already at harmonic numbers of about 600 (0.9 GHz). Therefore, the application of a reasonable bandwidth (1-2 GHz) for SC requires a lattice design with small frequency dispersion ($\gamma_t$ close to $\gamma$, i.e. nearly isochronous) in the bending section between pick-ups (A ,C in Fig. 1) and kickers (B ,D).

On the other hand, the bending section between kickers and pick-ups should be designed for strong Schottky band overlap in order to attain optimal mixing conditions for fast cooling. The applicability of this "split ring" concept [8, 9] with different local $\gamma_t$ for both 180$^0$-bending sections is being investigated for the CR. It might be advantageous for SC as well as with respect to cost optimisation (large apertures only where necessary).

Table 1: Preliminary ring and RIB parameters.

| | |
|---|---|
| central orbit circumference | 170 m |
| maximum $B\rho$ | 13 Tm |
| particle species | isotopes of Ne to U |
| specific ion energy | 740 MeV/u ($\gamma \approx 1.8$) |
| charge states $Z$ | 92 |
| maximum $A/Z$ | 2.7 ($A$ mass number) |
| mean ion velocity | 0.83 c |
| injector | SIS, prod. target, FRS [7] or new 200 Tm-ring, new FRS |
| number of ions p. inj. | $1\times10^4$ to $1\times10^9$ |
| bunch length | 50 ns |
| inject./eject. method | full aperture kickers<br>1 or more bunches |
| init. transv. emittances | 50 $\pi$ mm mrad |
| init. momentum spread | 5 % (full width) |
| frequency of rf-cavities | 6 or 8 MHz (h=4 or h=5) |
| rf voltage | ≈1 - 1.5 MV, bunch rotation<br>≈5 kV (de/rebunching) |
| momentum spread (coast.) | ≈1 % (full width) |
| stochastic cooling | all phase planes, $\tau_{SC} \approx 0.1$ s |
| final transv. emittances | ≤5 $\pi$ mm mrad |
| final momentum spread | ≤ 0.05 % (full width) |

Preliminary ring and RIB parameters are listed in table 1. The layout of the CR lattice has to take into account also the optional use of the CR for the collection and cooling of 3 GeV antiprotons with initial bunched beam parameters $\varepsilon_{x,y} \approx 240\,\pi\,$mm mrad, $\delta p/p = 6\,\%$. As may be deduced from the envelope plots of figs. 2a and 2b, the width of vertical apertures in bending magnets (±65 mm) are determined by the latter option. The rather large useful horizontal apertures of ±160 mm in 8 of the 24 bending magnets and ±170 mm in 11 of 48 quadrupole magnets are required because of necessarily large dispersion function amplitudes in the arc between SC pick-ups and kickers (arc 1, table 2) for RIB as well as for antiproton beams.

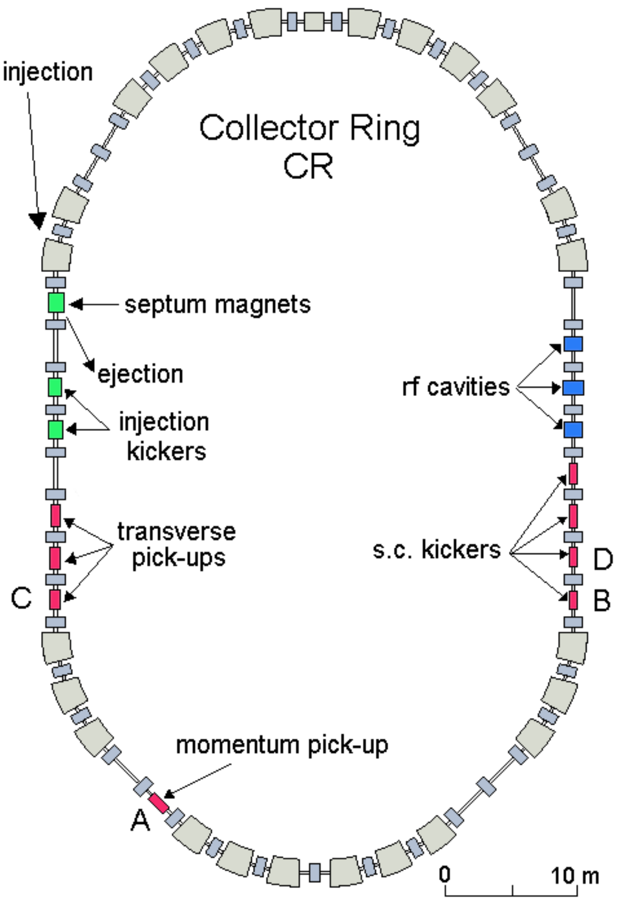

Figure 1: Preliminary layout of the Collector Ring CR. Local transition points are: $\gamma_t(\mathbf{A}\to\mathbf{B}) \approx 2.5$ for momentum cooling and $\gamma_t(\mathbf{C}\to\mathbf{D}) \approx 2.8$ for betatron cooling.

The "split ring" concept mentioned above seems to be advantageous not only for fast SC, it would allow also to tune the 180$^0$-arc between SC-kickers and pick-ups (arc 2, table 2) to high local $\gamma_t$ with identical quadrupole settings for both the RIB and the antiproton beam. The correspondingly reduced dispersion amplitude would allow to reduce the horizontal apertures to ±100 mm for both the bending and the quadrupole magnets (see fig.3). In addition, because of identical betatron phase advance between septum magnets and kickers, the concept for injection and ejection for both types of beams is more or less the same.

Table 2: Preliminary lattice parameters (for half CR).

| Quantity | | arc 1/RIB [fig.2(a)] | arc 1/pbar [fig.2(b)] | arc2 /both [fig.3] |
|---|---|---|---|---|
| betatron tunes | $Q_x$ | 1.67 | 1.74 | 2.85 |
| | $Q_y$ | 1.56 | 1.23 | 1.925 |
| beta-functions | $<\beta_x>$ | 13.8 m | 9.4 m | 6.7 m |
| | $<\beta_y>$ | 14.1 m | 12.5 m | 7.5 m |
| chromaticity | $\xi_x$ | ≈0 | -2.1 | -5.7 |
| | $\xi_y$ | ≈0 | -2.3 | -6.4 |
| dispersion (max). | $D_x$ | 5.4 m | 4.5 m | 3 m |
| transition half ring | $\gamma_t$ | 3.5 | 4.5 | 8.1 |
| transition full ring | $\gamma_t$ | 4.35 | 5.6 | --- |

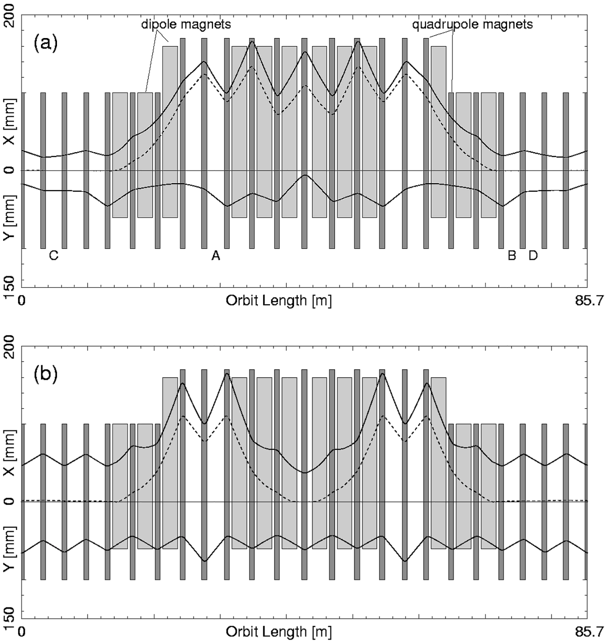

Figure 2: Plot of horizontal (x) and vertical (y) beam envelopes (solid curves) over a half of the CR circumference (arc 1 in table 2) for RIB (a) and antiproton beams (b) corresponding to initial bunched beam parameters. Dashed curves show closed orbits for momentum offsets of +2.5% (a) and +3% (b). Because of the higher energy of the antiproton beam $\gamma_t$ for case (b) has to be higher.

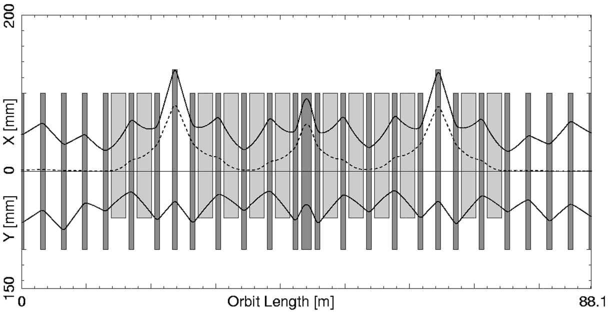

Figure 3: Same plot as in fig. 2, but for the other half of the ring (arc 2 in table 2).

## 4 STOCHASTIC COOLING CONCEPT

The concept of fast stochastic cooling is based on the good experience at the ESR with momentum cooling applying the Palmer method, where a cooling time of 0.4 s was recently achieved for a $U^{92+}$-beam at 391 MeV/u. The installed rf-power in the band 0.9-1.6 GHz was approximately 500 W at 5 modules consisting of four 50 Ω-super-electrode couplers each [10].

With an optimised ring lattice, sufficient space for the installation of a larger number of pick-up and kicker electrodes – maybe with higher impedance of up to 100 Ω –, and finally with increased band-width (1.4 GHz instead of 0.7 GHz) we hope to attain a SC cooling time of about 100 ms. The final beam parameters have to be matched in a way that the overall time between beam injection to the CR and experiments with the electron cooled beam in an experimental ring – similar to the existing ESR – is minimised.

Before starting with the technical design of the SC system, several technical details have to be investigated carefully. Examples are feasibility of sensitive but mechanically simple planar SC electrode systems, feasibility of 75 Ω or 100 Ω electrodes, or necessity of cryogenic techniques at pick-up resistors. Though the high charge states $Z$ of ions lowers the noise-to-signal ratio $U$ proportional to $Z^{-2}$, the inherently small yield of short-lived nuclei requires to make $U$ as small as possible, maybe also by means of reducing the pick-up apertures during the SC process [1].

## 5 SUMMARY

Compared to the existing FRS-ESR the efficiency of a new RIB facility could be raised by approximately two orders of magnitude. The new facility should consist of a new FRS with larger acceptance, a dedicated large acceptance ring CR for collection and fast stochastic cooling, and an experimental ring similar to the existing ESR with electron cooler and internal target experiments. Beams of exotic nuclei with life times as low as a few 100 ms could be made available for experiments.

The new facility may be considered as part of a future upgrade project at GSI. One objective among others is the further increase of the primary beam flux for uranium ions from a few times $10^{10}$ $s^{-1}$ to about $1\times10^{12}$ $s^{-1}$. However, the envisaged high beam intensity requires careful investigation of technical problems, e.g. fast heating of the production target and activation of accelerators.

## REFERENCES

[1] E.J.N. Wilson ed., ACOL design study, CERN 83-10 and H. Koziol, S. Maury, CERN 95-15 (AR/BD)
[2] B. Franzke, Nucl. Instr. and Meth. in Phys. Res. B24/25, 18 (1987)
[3] N. Angert, Proc. of the 6th Europ. Part. Acc Conf., Stockholm 1998, 125 (1998)
[4] B. Franzke et al., Physica Scripta T59, 176 (1995)
[5] M. Hausmann et al., Nucl. Instr. and Meth A446, 569 (2000)
[6] H. Geissel et al., Nucl. Instr. and Meth. B70, 286 (1992), and private communication May 2000
[7] K. Blasche et al., Proc. of the 6th Europ. Part. Acc. Conf., Stockholm, 1998, 1347 (1998)
[8] D. Möhl, CERN Accel. School, 5th Adv. Accel. Phys. Course, Rhodes/GR 1993, CERN 95-06, p. 587-671
[9] R. Giannini, P. Lefevre, D. Möhl; SuperLEAR Conceptual Machine Design LEAP'92, Courmayeur/I 1992, CERN/PS 93-02
[10] F. Nolden et al., Nucl. Instr. and Meth. A441, 219 (2000) and contribution to this conference