POSSIBILITIES FOR EXPERIMENTS WITH RARE RADIOACTIVE IONS IN A STORAGE RING USING INDIVIDUAL INJECTION

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Abstract

A radioactive ion beam (RIB) produced at a target bombarded with a primary beam has after a fragment separator a relatively large phase volume and small production rate. For instance, typical flux of ^{132}Sn isotope at the exit of fragment-separator is about $5\cdot10^5$ ions/s. Conventionally used scheme of the ion storage in a ring based on multitutrn injection and (or) RF stacking and stochastic cooling application can not provide a high storage rate at so pure intensity especially for short lived isotopes. In this report we discuss an alternative storage scheme which is oriented to the continuous ion beam from fragment separator at production rate of 10^4 ions/s or even less. It is based on the fact, that at low production rate the parameters of each particle can be measured individually with rather high accuracy. The particle trajectory can be individually corrected in a transfer channel from fragment separator to the storage ring using system of fast kickers. A fast kicker in the ring synchronized with a circulating bunch provides continuous injection of the ions. The scheme permits to store the ion number required for precise mass measurements and internal target experiment. A hope to obtain large luminosity of ion-electron collisions is related with a possibility of the ion beam crystallization at small particle number.

INTRODUCTION

Physical program of the RIB investigation using storage rings includes precise mass measurements, investigations of total density distribution of protons and neutrons, spin and isospin properties of nuclei in experiments with internal target, determination of a spatial charge density distribution of nuclei in scattering experiments with RI beams and electron beam at electron-ion collider. Other possible type of experiment - RI - X-ray collisions – was scheduled among others, for instance, at Collider Rings of MUSES (Multi-USe-Experimental-Storage rings) project at RIKEN to determine the mean square nuclear charge radii and the electromagnetic moment by means of isotope shift measurements in the 2S-2P atomic transitions of Li-like RI ions [1]. Results of different types of experiments are complementary one to others and can give complex information about RI nuclear structure.

The precise mass measurements, for instance in isochronous mode of the ring operation, can be performed at $10^3 \div 10^4$ circulating ions. The same level of the beam intensity is necessary for experiments with RI - X-ray collisions.

Required luminosity level of the experiment with internal target estimated in [1] is about 10^{24} cm^{-2}s^{-1}. In the case, when the ion beam radius is less than the target dimensions and the target has a uniform density in the transverse direction the luminosity is given by:

$$L = N_i \rho_T f_0 \qquad (1)$$

where N_i is the ion number stored in the ring, ρ_T is the target density in atoms/cm^2, f_0 is the ion revolution frequency. Gas storage cell can provide the target density value in the range from 10^{14} to 10^{15} atoms/cm^2. Tacking into account a duty factor of the experiment the required number of stored ions can be estimated by the value $10^4 \div 10^5$ ions.

The minimum luminosity to determine density distribution for double magic Tin, which is one of the key isotope for electron-RI collider, depends on detector system design and can be estimated by the value of 10^{26} cm^{-2}s^{-1} [1]. At normal state of the ion beam this level corresponds to about 10^8 stored ions. A possibility to decrease required intensity of the circulating beam is related to ion beam ordering at small ion number. In the ordered state the beam transverse dimensions are decreased by a few orders of magnitude, which, in principle, permits to increase beam-beam parameter in electron ion collisions. Theory upper limit of the beam intensity in the line ordered state corresponds to about $10^5 \div 10^6$ ions, however it never was achieved experimentally before. For investigation of the beam ordering in storage ring $10^3 \div 10^5$ circulating ions are necessary.

Thus, at the nuclei life time of the order of 1 min a storage scheme has to provide storage rate of about $10^3 \div 10^4$ ions/s. Conventionally used scheme of the ion storage in a ring based on multitutrn injection and (or) RF stacking and stochastic cooling application can not provide a high storage rate at pure intensity typical for short lived isotopes.

STORAGE SCHEME

Conventional multi-turn injection can work properly at ion flux $\dot{N}_i$ satisfying the following condition:

$$\dot{N}_i N_{turn} T_{rev} \eta_{inj} >> 1, \qquad (2)$$

where N_{turn} is number of injection turns, T_{rev} is the ion revolution period, η_{inj} is the injection efficiency. In the opposite case averaged number of ions injected during one cycle of injection will be about unit and due to statistical variation of the ion flux intensity a probability to inject at least one ion can be sufficiently less than unit. The injection efficiency at turn number of about 20 can be about 50%. For the ion revolution period of about 1 μs the critical ion flux is

$$\dot{N}_i >> 1 \cdot 10^5 \ s^{-1}. \tag{3}$$

For instance, at continuous operation of cyclotron cascade at RIKEN Radioactive Ion Beam Factory (RIBF) the expected flux of ^{132}Sn ions is about $5 \cdot 10^5$ ions/s only. An application of the multi-turn scheme for injection is not free from technical risk.

An alternative storage scheme is based on the fact, that at low production rate the parameters of each particle can be measured individually with rather high accuracy. Using a system of kickers in the ion transportation channel from the fragment separator to the injection point one can compensate the initial co-ordinate and angle of the ion and realise an “individual particle cooling” in the transfer line. The idea of the “individual cooling” of the low particle flux was proposed in [2] for muons and antiprotons. The initial momentum shift of every ion can be reduced with a profiled energy degrader [3]. The profiled degrader is placed in the achromatic bending section in the region with non-zero dispersion. After the degrader, the momentum spread of the particles is reduced, but due to coupling of the longitudinal and horizontal motion, the particle trajectory is distorted in the horizontal plane. The distortion is compensated by a second system of kickers. The transfer line consisting of quadrupole lenses and bending magnets provides the required transformation of the particle co-ordinates and angles between the elements correcting the emittance and momentum spread. For such a scheme the maximum ion flux is limited by the technically achievable operation repetition frequency of the kickers.

At low ion flux at the entrance of a storage ring one can use for injection a fast kicker which is operated by a signal from analyzing system at the exit of the fragment separator. For fast stacking of the injected ion one can use electron or stochastic cooling system. At ion energy of about 100 - 200 MeV/u an electron cooling system is preferable. Short cooling time is achievable due to small initial phase volume of the beam. To speed up the cooling process an electron beam with gradient of the longitudinal electron velocity along horizontal co-ordinate can be used. In combination with non zero ring dispersion in the cooling section such a system permits to provide maximum cooling rate independently on the ion longitudinal momentum. The efficiency of such a “dispersive” or “gradient” cooling was investigated in experiments at LEAR, AD and TSR [see, for instance, in 4] where the required electron velocity gradient exists due to space charge of the electron beam.

In the general case the discussed storage scheme includes the following elements:

- ion parameter analyzer at the exit of fragment separator,
- transfer line providing require time delay and phase advance between analyzer and correction kickers,
- two systems of correction kickers – one for horizontal plane, other – for vertical,
- profiled energy degrader for momentum spread correction,
- system of correction kickers for compensation of horizontal momentum growth in the degrader,
- septums and fast kicker for the ion injection into the ring,
- modified electron cooling system providing fast stacking independently on the ion longitudinal momentum shift.

All the elements of the storage scheme are described in details in [5]. In this report limitations of the storage rate at individual injection are discussed.

STORAGE RATE AT INDIVIDUAL INJECTION

Knowing the moment of the ion born at the target one can provide an “individual injection” of the ion into the ring. The individual injection scheme presumes that *the stored stack is bunched* at the first harmonic of the ion revolution frequency in the ring. New ion moving from fragment separator is injected by the short pulse of a fast kicker operated by signal from the analyzer. The injection kicker operating in the pulsed mode with the pulse duration much shorter of the ion revolution period T_{rev} brings a new injected particle directly into the stack orbit. To avoid excitation of betatron oscillations of an injected ion the dispersion in the kicker section is to be equal to zero. The kicker operation has to be synchronized with the stack revolution: it can not operate when the stack circulating in the ring passes the kicker, either the stack particles are lost. Thus, the kicker has to be synchronized with the signals from the “analyzer” and with the ring RF system. Injection efficiency is limited by the finite ion bunch length and injection kicker pulse duration. It is equal to:

$$\eta_{inj} = 1 - \frac{l_b + l_{kick} + \tau_{kick}\beta c}{C} \tag{4}$$

where l_b is the bunch length, l_{kick} – the kicker length, τ_{kick} is the kicker pulse duration, βc is the particle velocity, C is the storage ring circumference.

The individual injection scheme is somewhat different for different intensities of the injected ion fluxes. One can distinguish three outmost cases:

$$\dot{N}_i < \tau_{st}^{-1} \text{ - low intensity ion flux,} \tag{5}$$

$$\dot{N}_{i,\max} > \dot{N}_i > \tau_{st}^{-1} \text{ - intermediate intensity ion flux,} \tag{6}$$

$$\dot{N}_i > \dot{N}_{i,\max} \text{ - high intensity ion flux,} \tag{7}$$

where τ_{st} is a stacking duration – period of time required to add new injected ion to the ion bunch, $\dot{N}_{i,\max}$ corresponds to maximum storage rate at continuous injection – this value depends on the stacking time and injection kicker pulse duration and will be determined below.

In the case of low or intermediate ion flux the ring can be operated in the continuous mode, when the ion injection takes a place during stacking process. At high intensity flux the periodic mode of the injection operation is necessary: the stacking procedure can be performed after injection cycle completion only. In this case the injection of new ions during the stacking is impossible.

At low intensity flux the storage rate is equal to

$$R_{stor} = \eta_{inj} \dot{N}_i , \qquad (8)$$

and injection efficiency is closed to 100%.

When the ion flux is larger then the stacking rate the new injection pulses happen during the stacking of the injected ion. Then during the injection the ion circulating in the ring can be lost if it passes inside the kicker when it pulses (the kicker operation is synchronized with the stack revolution only). The probability of the particle loss after single injection pulse can be estimated as a ratio between the kicker pulse duration and the ion revolution period:

$$P_{loss} = \tau_{kick}/T_{rev}. \qquad (9)$$

The injection pulses number during the stacking is equal to $\dot{N}_i \tau_{st}$. The storage rate can be estimated then with the following expression:

$$R_{stor} = \eta_{inj} \left(1 - \frac{\tau_{kick}}{T_{rev}} \right)^{\dot{N}_i \tau_{st}} \cdot \dot{N}_i \cdot \qquad (10)$$

here $\left(1 - \frac{\tau_{kick}}{T_{rev}} \right)$ is the survival probability after one injection pulse. Maximum of the storage rate corresponds to the ion flux determined by the following equation

$$\dot{N}_{i,\max} = -\frac{1}{\tau_{st} \ln\left(1 - \frac{\tau_{kick}}{T_{rev}} \right)} \approx \frac{T_{rev}}{\tau_{st} \tau_{kick}} , \qquad (11)$$

and approximately equal to

$$R_{stor} \approx 0.4 \eta_{inj} \frac{T_{rev}}{\tau_{kick} \tau_{st}} \qquad (12)$$

When the ion flux exceeds the level (11) the storage efficiency fast decreases due to increase of the particle loss probability. In this case it is more optimum is to use periodical injection: the ions are injected into the ring during a time of τ_{inj} after that the injection is stopped for period of time of the order of τ_{st}. In this case during the injection any ion can not be stacked and total ion number outside the stack after completion of the injection is determined only by the number of injection pulses and particle losses during injection pulse. Number of injection pulses is $\dot{N}_i \tau_{inj}$. The ion survival probability is determined by the number of injection pulses that took place after it injection into the ring. Thus the ion number outside the stack after injection completion is equal to:

$$N_{inj} = \sum_{k=0}^{\dot{N}_i \tau_{inj}} \left(1 - \frac{\tau_{kick}}{T_{rev}} \right)^k = \frac{T_{rev}}{\tau_{kick}} \left(1 - \left(1 - \frac{\tau_{kick}}{T_{rev}} \right)^{\dot{N}_i \tau_{inj}} \right). \qquad (13)$$

This number is stacked during the period of time equal to $\tau_{st} + \tau_{inj}$. Thus the storage rate can be estimated as:

$$R_{stor} = \eta_{inj} \frac{T_{rev}}{\tau_{kick} \left(\tau_{inj} + \tau_{st} \right)} \left(1 - \left(1 - \frac{\tau_{kick}}{T_{rev}} \right)^{\dot{N}_i \tau_{inj}} \right). \qquad (14)$$

Limit of the sum (13) at $\dot{N}_i \to \infty$ is simply T_{rev} / τ_{kick} and under the condition $\tau_{st} >> \tau_{inj}$ the maximum storage rate can be estimated by the value:

$$R_{stor,\max} = \eta_{inj} \frac{T_{rev}}{\tau_{kick} \tau_{st}} . \qquad (15)$$

This value does not depend on the ion flux and it is a technical limit of such an injection scheme. Conventional multiturn injection in combination with RF stacking and stochastic cooling at high ion flux provides the storage efficiency of about 10^{-3}. Correspondingly the individual injection application is reasonable at the ion flux up to about 10^7 ions/s. At larger ion flux, even in the case if so high kicker repetition frequency is possible, the individual injection can not provide the storage efficiency comparable with conventional schemes.

To obtain maximum storage rate one needs to provide fast stacking of injected ions. Numerical simulations of the cooling process using BETACOOL program [6] shown, that a conventional electron cooling system can provide the cooling time of about 100 ms. Usage of the “gradient” cooling permits to reduce the cooling time by about 5 times. In this case the storage rate of about $10^3 \div 10^4$ ions/s is achievable.

ACKNOWLEDGEMENTS

This work is supported by RFBR grant #02-02-16911 and INTAS grant #03-54-5584.

REFERENCES

[1] T. Katayama et al., MUSES conceptual design report, RIKEN 2000.

[2] D. Taqqu, Possibilities of cooling the extracted antiproton LEAR beams. in Proc. Third LEAR Workshop, Tignes, 1985, “Phys. with antiprotons at LEAR”, U. Gastaldi et al (eds.) Editions Frontiers, Gif Sur Yvette, France, 1985, p.143.

[3] I.Meshkov, W. Mittig, P. Roussel-Chomaz, et al., Channel for individual trajectory correction of radioactive ions, GANIL R 03 05, 2003.

[4] M.Beutelspacher et al., Dispersive electron cooling experiments at the heavy ion storage ring TSR, NIM A 512 (2003) 459-469.

[5] I. Meshkov, W. Mittig, P. Roussel-Chomaz, A. Sidorin, A. Smirnov and E. Syresin, Individual radioactive ion injection, cooling and storage in a ring, GANIL R 02 04, 2002, Individual rare radioactive ion injection, cooling and storage in a ring, NIM A 523 (2004), 262-270.

[6] I. Meshkov et al., Application of BETACOOL code for dynamic of ions in a storage ring, ECOOL-01, Germany, 2001.