FEASIBILITY STUDIES FOR A RADIOACTIVE-ION STORAGE RING

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Abstract

The low intensities of beams of unstable isotopes make it vital to use them efficiently. Their collection in a storage ring would open up a number of possibilities: higher beam intensities, enabling better suppression of background and more accurate measurement of isotopic and ionic properties; higher luminosities, by the use of beam cooling and internal targets; acceleration to higher energies; quasi-simultaneous operation with fixed-target experiments; and colliding- or merging-beam experiments with protons, electrons, muons, etc. The most crucial design aims are rapid accumulation of the beam and avoidance of beam spoilage and loss through interactions with strippers, residual gas and targets. This has led us to study injection by foil stripping and storage of the whole range of charge states produced, in the context of the ISAC radioactive beam facility at TRIUMF.

INTRODUCTION

In line with a recommendation in the Canadian Subatomic Physics Five Year Plan (2001), studies have begun of the scientific potential and technical feasibility of a storage ring for the radioactive ions from ISAC. Such a ring (the ESR) has been successfully built and used at GSI Darmstadt, and others are being built, proposed or considered at IMP Lanzhou, RIKEN, TU Munich, GSI, and CERN (ISOLDE). Some of the attractive possibilities which a storage ring would open up are:

- measurement of otherwise inaccessible interactions;
- cooling of the beam, significantly improving position, time and energy resolution, and allowing the use of internal gas targets and the achievement of higher luminosities than with solid targets in the ISAC-II beam;
- acceleration to higher energies;
- direct measurement of nuclear and ionic properties (mass, lifetime, magnetic moment, ...);
- quasi-simultaneous operation with ISAC-II experiments using the same ions;
- fast extraction of high-intensity pulsed beams for studying interactions with very low cross sections;
- radioactive muonic atom production by merger with a muon beam;
- electron-ion collisions (with the help of an electron storage ring).

ISAC beams

The ISAC-I RFQ and drift-tube linacs currently accelerate light radioactive ions ($A \leq 30$) to 1.5 MeV/u. ISAC-II, now under construction, will add a charge-state booster and further accelerating cavities, extending the mass range to $A \leq 150$) and raising the maximum energy/nucleon E/A to 8 MeV/u for the heaviest ions and 20 MeV/u for the lightest. The superconducting cavities downstream of the second stripper S2 are capable of accelerating several neighbouring charge states in a good quality beam[1]. For ^{132}Sn, for instance, five states q = 29-33, comprising 80% of the beam, can be transmitted within a transverse emittance of 1.5π mmmrad and a longitudinal emittance of 9.6π keV-ns. Figure 1 shows the expected dependence on atomic number Z of various properties of the beam leaving ISAC-II, including $A/\bar{q}$ (where $\bar{q}$ is the average charge), and $n_e = Z - \bar{q}$, the average number of electrons remaining.

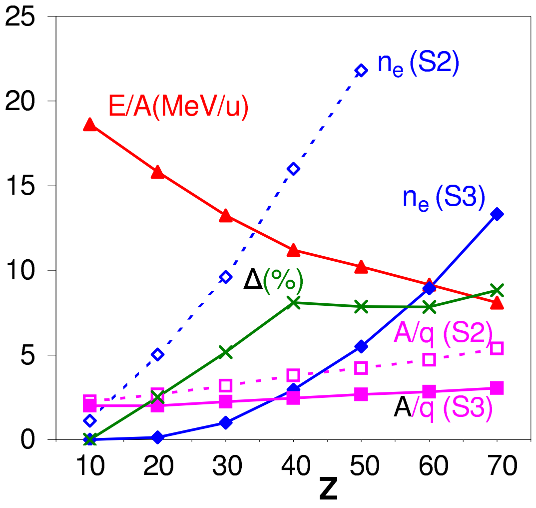

Figure 1: ISAC-II beam properties versus atomic number Z, before (S2) and after (S3) stripping at final energy E/A.

Possible ring scenarios

Three general scenarios might be considered, in order of increasing complexity and cost:

Mini: An accumulator ring, with no provision for cooling or further acceleration (similar in purpose to the 5 MeV/u “Recycler” proposed for the Munich Accelerator for Fission Fragments at the high-flux reactor FRM-II).

Midi: A storage ring with cooling and modest acceleration - say to four times greater energies - 35 MeV/u for the heaviest ions and 80 MeV/u for the lightest.

Maxi: A cooler storage ring capable of handling (say) 100 MeV/u beams delivered by a further ISAC accelerator (linac or cyclotron).

Stable versus radioactive ions

An example of a storage ring for stable ions in a similar energy range is the TSR at MPI Heidelberg, which has a bending power of 1.5 T-m and diameter ≃15 m; ions have been successfully stored over a wide mass range, those that are highly stripped exhibiting lifetimes of many minutes[2]. With a charge (or momentum) acceptance of $\pm 4\%$ it has also demonstrated that multiple charge states can be stored if the dispersion is kept low and the apertures are sufficiently large. Injection into the TSR proceeds by conventional mulititurn betatron and momentum stacking - a relatively complicated process in which batches of tens of turns are successively injected and cooled. The latter process takes almost a second but nevertheless tens of thousands of turns can be accumulated over about 10 minutes. The use of momentum stacking requires finite dispersion at the injection point and so is only compatible with the injection of single charge states.

For radioactive ions the time spent in accumulation is crucial, as is the collection of maximum beam intensity. Focusing on the problems peculiar to storing unstable ions, we have studied the feasibility of injecting by stripping, and of storing the whole range of charge states produced.

Injection by stripping

Advantages: Injecting by stripping in a foil S3 would:
- be simpler and quicker, enabling collection of as many turns in a single batch as can be obtained by stacking many batches with intermediate cooling delays;
- increase the average ionic charge $\bar{q}$, reducing the bending power $B\rho$ and diameter D required for the storage ring;
- reduce the fractional width of the charge-state distribution (CSD), enabling a greater fraction of the beam to be contained;
- make possible capture of the multiple charge states which ISAC-II is capable of accelerating simultaneously.

The significant reductions that can be effected in both n_e and $A/\bar{q}$ by stripping the beam leaving ISAC-II are shown in Fig. 1. Also shown (as a percentage measure of the CSD width) is the parameter $\Delta = (q_+ - q_-)/2\bar{q}$, where q_+ and q_- are the charge states enclosing ≥99% of the CSD. These parameters have been calculated following the prescriptions of Shima *et al*[3]. Apparently an acceptance of ±9% would be sufficient to contain 99% of the beam.

Hazards: The basic drawback to injection by stripping is that the stored beam may make further passes through the foil, leading to loss of beam quality and possibly of the ions themselves. The major factors to consider are multiple scattering, energy straggling, energy loss and electron transfer. The estimates below assume a 260 μg/cm^2 carbon foil, sufficiently thick to give an equilibrium CSD.

Multiple scattering, which varies as $Z\sqrt{1+(Z/6)^{2/3}}$, is most serious for heavier ions. For $Z = 65$, though, Meyer's formula[4] predicts an rms angle of only 1.3 mrad, one-third of the maximum acceptable divergence (see below), so losses should be <1%.

Energy straggling is also relatively unimportant. Data from GANIL[5] indicate a HWHM value around 10 keV/u, with very low Z-dependence. The energy loss, however, is important. Although the amounts, 20 keV/u, 150 keV/u and 340 keV/u for Z = 6, 36 and 65 respectively, correspond to only 0.06%, 0.6% and 2.0% momentum offsets, well within the momentum acceptance, it will probably be impossible to provide an rf bucket large enough to contain the decelerated heavy ions. Assuming use of ISAC superconducting cavities at 141 MHz, the minimum voltages required would be 9 kV, 1.2 MV and 13 MV respectively, while the space available would permit only about 5 MV.

Electron transfer is an even more serious threat: on each passage the CSD will re-equilibrate and the empty charge states outside the ring's acceptance will be repopulated. Thus if a certain fraction of the CSD lies outside the charge acceptance, that same fraction will be lost on each pass through the foil. It is clearly vital to maximize the charge acceptance and minimize the number of foil interceptions. The latter can be significantly reduced by painting the incoming beam over the acceptance, as discussed below.

Painting

If the ring's acceptance $A \gg \epsilon$, the incoming beam emittance, and the equilibrium orbit is gradually moved away from the stripping foil, stored ions will only intercept the foil for a short period. Imagining the acceptance to be composed of concentric annuli $i = 1, 2, ..., I$ each as wide as the beam spot, the fraction of interceptions as each is filled is given[6] by a geometrical factor F_i (Fig. 2).

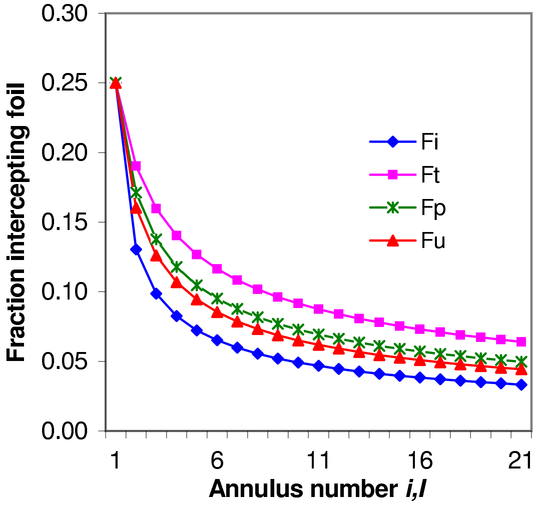

Figure 2: Fraction of foil traversals versus number of annuli.

The figure also shows how the average fraction over the whole acceptance depends on the time spent on each annulus - F_t for equal times, F_p for equal passes through the foil, and F_u for uniform phase space density. In the latter case, $I = 16$ reduces the average foil traversals to 1 in every 20 turns. If this is done in both planes, the average drops to 1 in 400 turns. Assuming the incoming beam can be focused to half its natural width, $I = 16$ implies a ring acceptance of $16^2 \times 1.5\pi = 384\pi$ mmmrad.

High charge acceptance

The ability to store a wide range of charge states would:
- enable almost the entire beam leaving the stripping foil to be captured rather than just the most populous charge-state;
- strongly reduce the beam loss due to leakage into the tails of the CSD by charge-exchange (as discussed above).

It would also strongly affect the ring design:
- high charge/momentum acceptance requires a low dispersion lattice, large aperture magnets, and careful control of higher-order effects;
- storage of multiple charge states requires zero dispersion at the stripping foil, ruling out momentum painting.

RING PARAMETERS AND LATTICE

The following table shows approximate values for the major ring parameters for each of the scenarios mentioned above, with the TSR for comparison. Injection by stripping, which reduces the A/q for heavier ions from 5 to 3, clearly has a major impact on the bending power $B\rho$ required, and hence on the ring diameter.

Table: Storage Ring Parameters

Ring	Stripping Injn.	Z	A/q	Energy (MeV/u)	$B\rho$ (T-m)
TSR	No		2	30	1.5
Mini	No	6	2	20	1.3
	No	65	5	8	2.0
	Yes	6	2	20	1.3
	Yes	65	3	8	1.2
Midi	No	6	2	80	2.6
	No	65	5	35	4.2
	Yes	6	2	80	2.6
	Yes	65	3	35	2.6
Maxi			2	100	2.9

Lattice design

Initial lattice studies have focused on the Midi ring, which is conceived as being four-sided, with the long straights assigned to injection, cooling, acceleration and experiment. As all these functions require zero dispersion, a natural choice for the arcs has been a double-bend achromat (DBA). The lattice chosen, of the form 0FD0B0F0B0DF0 (Fig.3), restricts the dispersion to a narrow region with a low peak value of 1.24 m and also low β_x - crucial features for realizing a high charge acceptance. The circumference is 57.8 m, the tunes 2.57(x) and 1.84(y), and the transition energy 7.08. Initial tracking studies have shown good behaviour for charge or momentum excursions up to ±4%. These studies will be extended to include families of sextupoles and octapoles to see how wide an acceptance can be achieved.

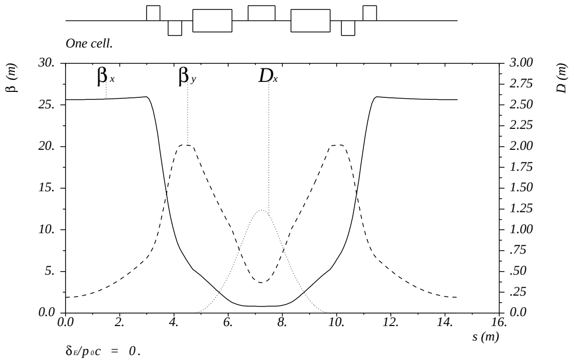

Figure 3: Twiss functions for the lattice under study.

For a beam filling the acceptance $A = 384\pi$ mmmrad specified above, the x envelope has maxima of 10.0 cm in the end F quadrupoles, while the y envelope has maxima of 8.8 cm in their D partners. At the injection point the maximum divergence is 3.8 mrad in x and 10 mrad in y. At the dispersion maximum each charge-state beamlet has a width of 2.4 cm, while a full ±9% CSD will spread across ±11.2 cm. Magnet apertures consistent with such beams will be required.

CONCLUSIONS

We have attempted to show that foil stripping can not only provide the rapid injection process essential for radioactive ions, but that ion losses can be kept to the λ = 1% level for each traversal if the ring has a high enough charge acceptance, and if Z is not so high that the energy loss is unacceptable. Painting the beam in the x and y planes can reduce the average foil traversal rate per turn F_xF_y to 1/400. If charge Q is injected on each turn, then the stored charge will exponentially approach $Q/\lambda F_xF_y = 40,000Q$, though a more practical aim would be to stop after 40,000 turns (≃40 ms) with ≃25,000Q. Even if the loss rate were 10 times higher, 2,500Q would be a sizeable improvement over present beam intensities.

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