SEPARATION OF REACTION OR DECAY PRODUCTS FROM COOLED ION BEAMS STORED IN THE ESR

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Abstract

The Experimental Storage Ring ESR, presently under construction at GSI Darmstadt, will be used for atomic and nuclear physics experiments with cooled beams of heavy ions [1]. Interaction between beam particles and internal target atoms or free electrons, e. g., in the electron cooler beam, will be studied. Numerous atomic or nuclear processes cause moderate jumps of the charge-to-mass ratio of projectile recoils. This paper discusses the selective extraction of these special recoils out of the storage ring, where detection or additional analysis of kinematic parameters may be carried out. On the other hand, especially for heavy ion storage rings, the described method seems to be a valuable alternative to conventional resonant beam extraction techniques.

1. Characteristics of the ESR

In the ESR all kinds of ions with magnetic rigidity from 0.5 to 10 Tm can be stored. The heavy ion synchrotron SIS [2], a 18 Tm-ring, will deliver beams of fully stripped ions up to uranium. The beams are stored, in general, at maximum energies between 550 MeV/u (uranium) and 830 MeV/u ($Z/A = 0.5$), cooled, and either extracted for external experiments or used for in-ring experiments. Special capabilities of the ring are: variation of beam energy from maximum values down to 3 MeV/u, stochastic pre-cooling, electron cooling at different energies, and an internal gas jet target with variable thickness. Beam storage at energies of about 10 MeV/u, without major beam loss within a few minutes, will be possible due to an ultra-high vacuum of 10^{-11} mbar.

Primary goals of the ESR design are:

- *Experimental instrument:*
  Many experiments investigating the interaction between circulating ions and internal target atoms, electrons or electro-magnetic radiation (LASER) are in preparation. The maximum luminosity is expected to be about 10^{30} cm^{-2}s^{-1}.

- *Accumulator of secondary beams:*
  Energetic heavy ion beams allow the production of secondary beams of radio-active projectile fragments. Rather high intensity and quality for these exotic beams will be achieved by stochastic pre-cooling [3], rf-stacking and final electron cooling [4].

- *Cooler and stretcher for SIS:*
  The improvement of the quality of the synchrotron beam is desirable for the majority of the proposed external target experiments.

- *Re-injector for SIS:*
  After stripping, intermediate storage and cooling in the ESR, the beam can be re-injected to the SIS. Post-acceleration - the energy of uranium is increased from 1 GeV/u to 1.35 GeV/u - or deceleration down to energies near the Coulomb barrier is feasible.

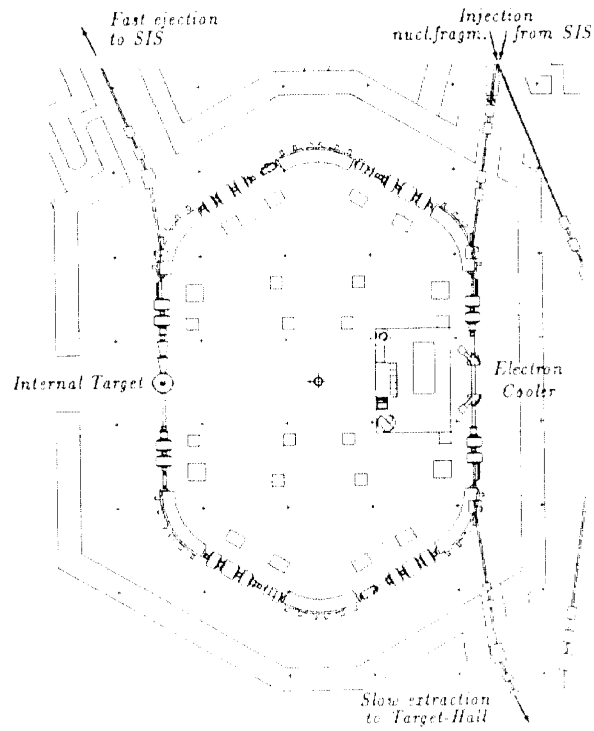

Figure 1: The Experimental Storage Ring ESR.
The computer plot shows the ring within radiation shielding walls. Pillars and transoms for the concrete ceiling are marked by rectangles and dotted lines, respectively.

2. Ion optical aspects

Optimal beam adaption to the different tasks of the ESR had to be ensured by a rather flexible, but also reasonably simple, structure of the magnet lattice. Beam injection, slow and fast beam extraction had to be provided as well as beam matching to stochastic pre-cooling, to electron cooling and to a large variety of in-ring experiments. Even dynamical transitions, i. e. changes of ion optics while the beam is stored, turned out to be desirable.

Four triplets and four doublets of quadrupole magnets are the focusing elements within the twofold mirror symmetric arrangement of six bending magnets of the ESR (see Fig. 1). The ion optical flexibility is obtained mainly by supplying 10 pairs of quadrupoles independently of each other. By this way, 10 parameters of the lattice functions ($Q_{h,v}$, $\beta_{h,v}$, $\beta'_{h,v}$, α_p, and α'_p) can be varied at several important locations of the orbit (internal target, electron cooler etc.). Beam envelope functions $\sqrt{\epsilon_{h,v}\beta_{h,v}}$ and the horizontal dispersion $\alpha_p \Delta p/p_o$ for one special mode are plotted in Fig. 2. over one half of the ring circumference, i. e. one of two identically structured focusing periods. An important attribute of the shown focusing mode is that both α_p and its first derivative α'_p disappear on the long straight sections. This achromatic beam optics avoids coupling of momentum loss and straggling in the internal target into the horizontal phase space. Jumps of ion rigidity within the (momentum) acceptance will not cause necessarily the loss of respective particles. For instance, according to the momentum acceptance of ±2 % in this achromatic mode, charge states from +89 to +92 of uranium can circulate simultaneously.

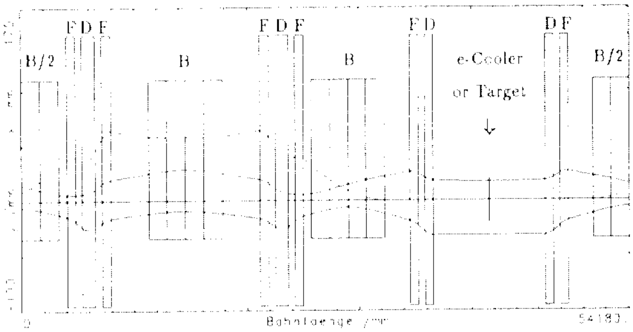

Figure 2: Achromatic mode of the ESR-lattice.
Horizontal (upper solid curve) and vertical (lower solid curve) beam envelope functions and horizontal closed orbit for a momentum deviation $\Delta p/p = +1$ % (dashed curve) over a superperiod, i.e. one half of the ESR. Transverse beam emittances are $\epsilon_h = 20\ \pi$ mm mrad and $\epsilon_v = 20\ \pi$ mm mrad, betatron tunes are $Q_h = 2.2$ and $Q_v = 2.4$. F and D denote horizontally focusing and defocusing quadrupoles, respectively, B are 60°-bending magnets. Within given scales the boxes illustrate effective lengths and useful apertures of magnet elements. Characteristics and application of this mode are described in the text.

3. Charge or mass jumps of stored ions

Several atomic and nuclear reactions between circulating heavy ions and internal target atoms or free electrons can cause change of the charge or the mass of projectile recoils by one unit, but do not have major influence on the trajectories of projectiles. Momentum loss, momentum straggling and slight growth of transverse emittances due to small angle scattering in the internal target can be compensated if electron cooling is active at the same time. By this way, the beam life time is expected to be essentially stretched. On the other side, one could think about extraction of the particles immediately after one of the reactions listed below.

a) Atomic collisions:

Radiative capture [5] of a free electron (REC) in the cooler takes place with rates increasing $\propto q^2/v_{rel}$, where q is the atomic charge state and v_{rel} the velocity difference between ion (X) and electron.

$$X^{+q} + e^- \rightarrow X^{+(q-1)} + \hbar\omega(\Delta E)$$

where $\hbar\omega$ is a photon of energy ΔE according to the sum of the kinetic energy of the electron in the system of the moving ion before capture and its binding engergy after capture: $\Delta E = m_e v_{rel}^2/2 + E_b$.

Di-electronic recombination (DER) in the electron cooler is a resonant capture of an electron by a partially stripped ion which is initially in atomic ground state (X_0). In this primarily non-radiative process ΔE is used for the excitation of another bound electron ($X_{\Delta E}$).

$$X_0^{+q} + e^- \rightarrow X_{\Delta E}^{+(q-1)}$$

The excited state of the ion may decay by auto-ionization, Auger-cascade or/and emission of radition. If the velocity spread in the ion beam is large and that of free electrons is small, this process acts selectively only on a very narrow sub-band of the velocity distribution [6].

Electron capture or loss induced in collisions with target atoms:

$$X^{+q} + Y \rightarrow X^{+(q\pm 1)} + Y^{+n} + (n \pm 1)e^-$$

Both the projectile and the target recoil ion are, in general, excited and will decay to ground state by emission of radiation or electrons.

b) Nuclear processes:

Loss of protons or neutrons without major energy loss or scattering from the initial trajectory takes place in peripherical collision of heavy projectile nuclei with light target nuclei. Moderate rigidity jumps are possible also by *electro-magnetic dissociation* or *fragmentation*.

β-decay into bound states is a possible dacay process of some special fully stripped nuclei which are stable in neutral state [7]. Of cosmological interest is, for example, the decay

$$^{163}_{66}\mathrm{Dy}^{+66} \rightarrow ^{163}_{67}\mathrm{Ho}^{+66}$$

which leaves the rigidity of the daughter particle unchanged. at first: the nuclear charge is increased by one unit, but the escaping electron is bound to the nucleus. The rigidity jump necessary to discriminate the daughter nuclei must be done artificially by stripping the electron in the internal jet target.

4. Extraction of secondary particles

a) Resonant extraction

The utilization of a 3rd-integer betatron resonance for slow beam extraction is a well-known method. The extraction speed - here the number of turns necessary to transport a particle from the border of the stable area in the xx'-phase plane (separatrix) across the septum of the first eflecting element - is determined by the strength of the sextupole harmonic exciting the resonance. The typical shape of the separatrix near the sextupole resonance $Q_h = 7/3$ at the position of the electrostatic ESR-septum for slow beam extraction is plotted in Fig. 3. It illustrates the situation during normal slow extraction of a primary beam supplying external experiments.

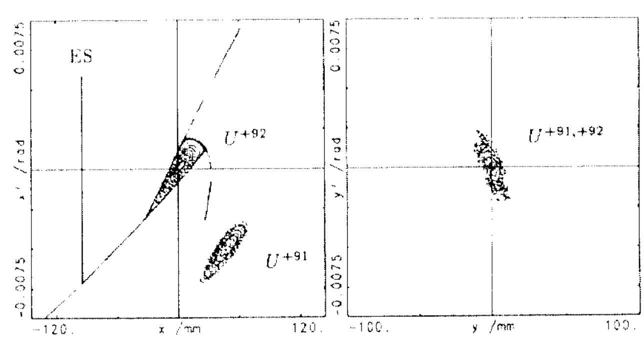

Figure 3: Separatrix near the sextupole resonance Q_h=7/3.
The primary U^{+91}-beam is obviously not influenced by the resonance whereas the secondary U^{+92}-particles outside the stable triangle are pushed towards the septum. Particles outside the septum (ES) are deflected by about 5 mrad for final eflection out of the ESR. On the right: vertical emittance of both beams.

For resonant extraction of reaction products one has to choose the horizontal tune Q_h and chromaticity $\xi_h = d\ln Q_h/d\ln p$ in a way that the recoil particles are exactly in the resonance whereas the primary beam particles are too far away from it to be influenced. For example, extraction of U^{+91}-ions at 3rd-integer resonance $Q_h = 7/3$ after a capture of an electron could be realized by the choice $Q_h = 2.37$ for the primary U^{+92}-beam and $\xi_h = -1.5$.

Handicaps using resonant extraction for the separation of secondary beam particles are:

- Trajectories of the resonantly extracted particles do reflect neither the phase space volume of the primary beam nor - desirable in some cases - the kinematics of the investigated reaction.

- Resonant extraction in parallel to the necessary two-beam operation would need a large fraction of the horizontal aperture. In the ESR, the extraction of secondary charge states would be restricted to ions heavier than xenon, for which the relative rigidity jump is smaller than about ±2 %.

• Some short living nuclear reaction recoils may not survive the extraction process, because many turns are necessary before particles leave the ring.

b) Non-resonant extraction

For non-resonant, fast extraction of particles after rigidity jumps the closed orbit of these particles is lead through the gap field of the first eflecting septum which might be electro-static or magnetic. The extraction mechanism is illustrated in Fig. 4. Trajectories for a primary beam of U^{+91}-ions (central trajectory) and two secondary beams constisting of the more rigid U^{+90}-ions (upper trajectory) and of the less rigid U^{+92}-ions (lower trajectory) are shown. It is assumed that the secondary charge states are produced by electron capture or loss (stripping) in the internal jet target, where $\alpha_p = 0$ and $\alpha'_p = 0$ according to Fig. 2. The distance between secondary and primary beams is nearly 60 mm, i. e. there is rather comfortable space between primary and secondary beams for the insertion of relatively thick septa, shielding the circulating primary beam from deflecting fields. The less rigid secondary beam is easily extracted out of the ESR by using the electro-static septum provided for the standard slow extraction. A kick of 4.5 mrad is sufficient to bend the trajectory into the gap of the septum magnet for final eflection out of the ring. The more rigid U^{+90}-beam needs a kick of practically the same strength in the same direction. It could be done by a small septum magnet which is not designed in detail yet, but does not seem to be a technical or space problem.

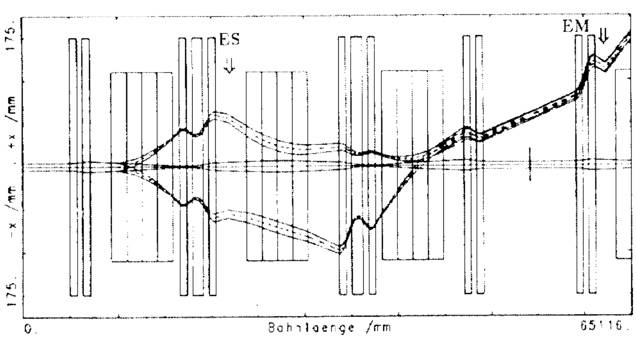

Figure 4: Beam trajectories for non-resonant beam extraction.

The plot starts at the internal target, which is located in the center of a 10 m long straight section, and ends after the final eflection septum magnet for slow extraction. A primary beam of U^{+91}-ions (central beam) is assumed out of which secondary beams are produced in the internal target by electron loss (U^{+92}) or electron capture (U^{+90}). At the location of the electro-static septum (ES) both secondary beams need the same bend of -5 mrad to come nearly coaxially into the gap of the final eflection septum magnet (EM). Elements ES and EM are used also for the standard slow beam extraction.

Benefits of the described non-resonant extraction of secondary beams in comparison with the resonant method are:

• Particles are extracted in the very first turn following to the rigidity jump. Thus, unstable particles with life-times down to a few microseconds can be detected, counted and analyzed outside the ring.

• External dectection and analysis does not influence the ultra-high vacuum of the ring.

• Extraction can be carried out without intrinsic loss of particles because the rigidity change is fixed to a finite value. However, this value must be large enough with respect to the thickness of the first septum element and small enough with respect to the momentum acceptance of the ring.

• The emittance of the extracted beam is practically the same as that of the primary beam as shown in Fig. 5. Effects due to atomic collisions are neglegible, and extracted beams may be used for external on-line emittance measurement for the stored beam.

• Some phase space dilution must be expected after nuclear processes, but this is not necessarily unwanted, because it offers the possibility for external spectrometry of projectile recoils of internal target experiments.

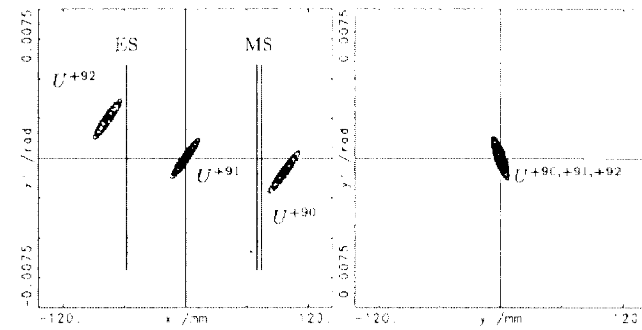

Figure 5: Beam ellipses at first extraction septum.

Position and size of beam emittances in the horizontal phase plane (x,x'-plane) for the primary U^{+91}-beam and two neighbouring charge states. The U^{+92}-beam can be extracted by the field of the electro-static wire septum (ES), for the U^{+90}-beam a short septum magnet (MS) with a bending power $B\ell = 0.05$ Tm is additionally needed.

5. Conclusion

In heavy ion storage rings numerous atomic and nuclear reactions between circulating ions and internal target atoms or free electrons cause jumps of projectile mass or charge. The secondary particles are well separated from the primary beam according to the horizontal dispersion function and can easily be extracted out of the ring. This direct, non-resonant particle extraction might be a valuable addition to the analyzing equipment for internal target experiments as well as an alternative method to supply external experiments with beam. For the latter application, extraction rates can be controlled by the (variable) thickness of the internal gas jet target or, if radiative capture of electrons is is utilized, by the current density of the cooler electron beam. Extraction times from 1 s up to 100 s or even 1000 s might be obtained this way.

References

[1] B. Franzke, H. Eickhoff, B. Franczak, B. Langenbeck: internal GSI-Rep. GSI-SIS-INT/84-5 (1984) and
B. Franzke; Nucl. Instr. and Meth. B24/25 (1987) 18

[2] K. Blasche, D. Böhne, B. Franzke, H. Prange; IEEE NS 32, No.5 (1985) 2657

[3] F. Nolden, G. Berthes, D. Böhne, B. Franzke, A. Schwinn; these proceedings (1988)

[4] N. Angert, H. Beyer, B. Franzke, B. Langenbeck, D. Liesen, F. Nolden, H. Schulte, P. Spädtke, B. Wolf; these proceedings (1988)

[5] D.R. Bates, A.E. Kingston, and R.W.P. McWhirter; Proc. Roy. Soc. 267A (1962) 297 , and
H.F. Beyer, D. Liesen; these proceedings (1988)

[6] P. Mokler, G. Reusch ; GSI Scientific Report 1985, GSI-86-01 (1986) 371

[7] F. Bosch, B. Franzke, W. Henning, P. Kienle, O. Klepper, W. Koenig, R. Mann, E. Roeckl. K. Suemmerer; in GSI-87-7 (1987)