9 REX-ISOLDE low-energy stage

Fredrik Wenander

9.1 Introduction

The REX-ISOLDE low-energy stage prepares the radioactive ions produced at ISOLDE for acceleration in a compact LINAC to energies up to 3 MeV per nucleon [1]. It consists of a Penning trap (REXTRAP), a charge breeder (REXEBIS), and an achromatic A/q separator of the Nier spectrometer type. The charge breeding efficiency depends critically on the quality of the injected beam, i.e., its longitudinal and radial emittances. The purpose of the trap is to collect and cool the radioactive ions delivered by ISOLDE before they are sent in bunches into the EBIS. Within the trapping area the ion motions are damped by the combined effect of collisions with a buffer gas (He, Ne or Ar) and a transverse RF excitation at the ion cyclotron frequency. In the EBIS, the ions are charge-bred into charge states fulfilling the requirements of the subsequent injection into the LINAC, i.e., $3 \leq A/q \leq 4.5$. Thereafter the mass separator selects the charge state of interest. The typical cycle time is made up of 20 ms trapping followed by 20 ms charge breeding. For ions heavier than mass 40 longer breeding times can be needed. Until now, the longest breeding time with radioactive ions was 198 ms for ^{142}Xe. Routinely, an overall efficiency for the REX-ISOLDE low-energy stage between some per cent and 10% is obtained. A detailed description of the beam preparation can be found in the CERN Report describing the REX-ISOLDE facility [2].

9.2 Motivation for breeder upgrade

Several factors can limit the efficiency of the beam preparation, for instance high beam intensities and breeding of heavy elements. These are also the two main reasons for an upgrade of the low-energy stage as described below.

9.2.1 Charge breeding of heavier ions with maintained short breeding time

With an upgrade of the LINAC energy the Coulomb barrier can be reached, and transfer reactions carried out, for heavier elements. Because of the unfavourable Z/A ratio and the higher number of shells that has to be depleted from electrons for heavier elements, the charge-breeding time becomes longer. The present breeder is designed for $A < 50$. To reach the required A/q for $A > 100$, breeding times longer than 100 ms are required. Long breeding times have several negative aspects, for example:

- Decay losses inside trap and EBIS, particularly for short-lived elements.
- Dead-time losses in the experimental detectors when the breeding repetition rate is low.
- Space charge saturation in the Penning trap as the trap has to collect 1^+ charged ions during the long breeding time.

The way to maintain a short breeding time is to increase the electron beam current density inside the EBIS. As the attained charge state is proportional to the breeding time multiplied by the electron current density, we conclude that the electron beam density has to be increased from a present measured value of ~100 A/cm^2 to at least 500 A/cm^2, a value that is feasible in an EBIS. In addition, losses occur in the breeder for heavier elements since the electron beam potential of the modest electron beam current in the REXEBIS is not sufficient to keep the highly charged ions confined when they become heated by electron–ion collision. To counteract this, an increased electron beam current is required.

9.2.2 *Increased radioactive beam intensities*

With HIE-ISOLDE the proton intensity on the primary target will be increased as well as the radioactive yield production. Then, for high yield isotopes the space charge limitation inside the Penning trap (and eventually the EBIS) may become a limitation. The present Penning trap–EBIS arrangement is limited to approximately $1.3{\cdot}10^8$ ions/pulse by the space charge limitation in the Penning trap; at 50 Hz that corresponds to 1 nA. However, even at some ten pA from ISOLDE, space charge effects can prevent a proper cooling of the ion cloud inside REXTRAP. The injection efficiency into the EBIS then suffers from a lower beam quality. If the current is even larger (>100 pA), the space charge can also inhibit the trapping fields and losses might occur in the trap. In conclusion, an increased space charge capacity of the low energy stage is called for.

9.2.3 *Upgrading the existing REXEBIS*

The quickest and most cost effective approach would be to upgrade the electron beam of the existing REXEBIS. In fact, there is already an ongoing programme investigating the possibilities (see further down), but even if fully successful it would only partly resolve the issues mentioned above. For instance, the relatively low solenoidal magnetic field (2 T instead of 5–6 T for high performing EBIS devices) makes the launching and compression of a high-current electron beam difficult due to the Brillouin limit. Secondly, the REXTRAP would still be necessary for bunching and cooling of the ISOLDE beam, thus still limiting high-current beams. Finally, the inherent fragility and lack of modularity of the REXEBIS would remain.

9.3 RHIC EBIS or PHOENIX ECRIS

It is important to stress that the buncher–breeder part in the REX-ISOLDE post-accelerator scheme should not become ‘an experiment in the experiment’. It can lead to long set-up times and low reliability, which reduces the useful beam time to the users, and in addition calls for extensive manpower for the operation. We therefore advocate relatively straightforward, and well-proven, machine concepts and avoid a number of suggestions as to how, for example, the efficiency and the charge state distribution of the breeder can be improved by special and ion-beam case-specific manipulations. Which of the two solutions presented below will be preferred will be decided upon after the evaluation period.

9.3.1 *RHIC EBIS solution*

An attractive solution would be to replace the REXEBIS with a charge breeder similar to the RHIC EBIS [3]. This has a high electron beam current density and very high current so both the charge state/breeding time and intensity problems could be addressed. It could be installed at the same position as the REXEBIS and connect to the beam transfer line from the trap and to the mass separator. Thus, the modifications of the existing systems would be minimal. The idea would be to copy the RHIC EBIS to a very large extent and benefit from the thorough R&D that has gone into this device. Most of the performances of the RHIC EBIS have already been proven with the TestEBIS [4], see Fig. 9.1, which is a shorter version and serves as a test stand.

The TestEBIS runs with an electron beam current of 10 A, to be compared with a normal operation current of 200–300 mA for the REXEBIS. The electron energy is 20 keV, which is sufficient for ionizing all elements to $A/q < 4$. With a trap length of 0.7 m, more than $1.5{\cdot}10^9$ Au^{32+} ions have been extracted from one pulse. The current density in full field is > 500 A/cm^2, which produces Au^{32+} ions within 35 ms (experimental value). To breed the extreme case of uranium to 55^+ takes 200 ms, while Xe^{31+} is reached in only 50 ms (theoretical values). The RHIC EBIS, which is going to have double the trap length and electron beam current, will have an even more impressive breeding performance.

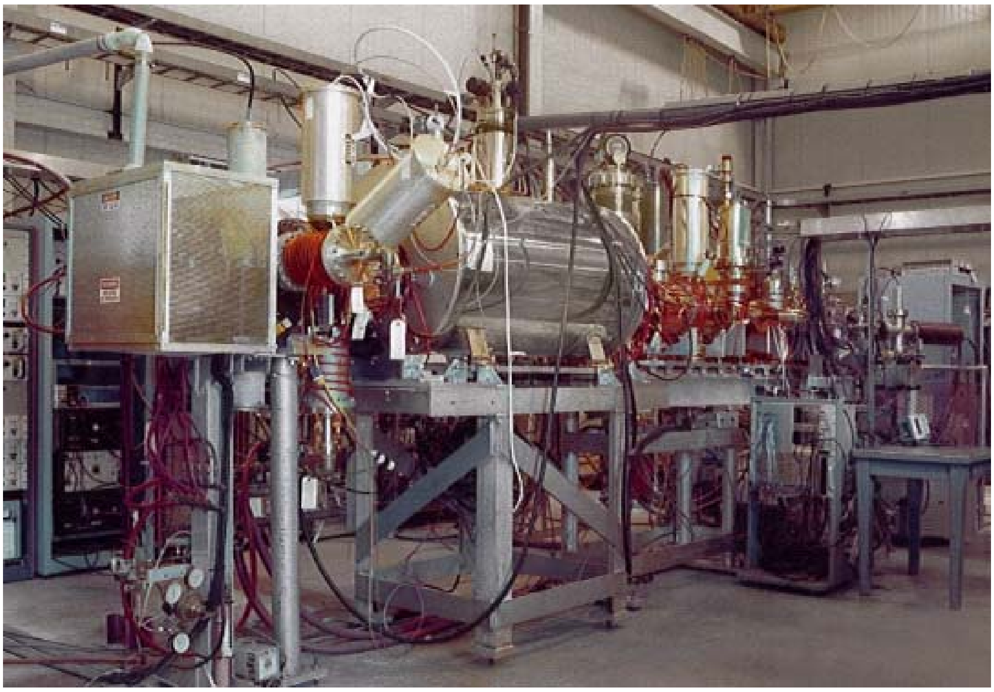


Fig. 9.1: The RHIC TestEBIS setup at BNL

To make full use of the large breeding capacity of a RHIC-type EBIS the current-limiting Penning trap has to be bypassed. With the bunching and trapping switched off and the trap on ground potential, and in the absence of buffer gas but with magnetic field present, it should be possible to transport close to 100% of the beam through the REXTRAP[1]. The necessary improvement of the transverse phase space could be carried out in the RFQ cooler [5] to be installed after the HRS magnets. The cooler can work in continuous mode and should be capable of handling 10 nA beams. The injection into the EBIS then has to be continuous, which could lead to a reduced efficiency. Nevertheless, an efficiency of 4% in one charge state for continuous injection has already been shown in the REXEBIS, and with the large current and current density in a RHIC EBIS higher values should be attainable. For lower beam intensities (<100 pA) the Penning trap and RHIC EBIS are used in series with bunched operation as at present.

The striking features of the RHIC EBIS as charge breeder are its fast breeding and large space-charge capacity. In addition, it is modular with the gun, trapping and collector regions vacuum-separated. Electron gun interventions can therefore be carried out separately and this should increase the reliability and up-time. A different, larger cathode than for the REXEBIS is used with longer lifetime. The larger electron beam current should also lead to an enlarged ion-injection acceptance.

A few remarks and questions have to be posed. For example, the higher ion beam acceptance of the device also means that the ion beam emittance will be larger than for the REXEBIS, typically 30 π·mm·mrad at 20 kV. This emittance can be accepted by the RFQ cavity, but one still has to verify the transmission through the separator with beam simulations. Moreover, the energy spread of the extracted beam is large, around 1.5 keV $\cdot q$ for self-extraction (~50 μs), so a slow extraction (ms) might have to be used in order to control the energy spread. The high electron beam current could also lead to higher residual gas peaks unless the vacuum is kept under control. Finally, the continuous injection mode should be further experimentally verified for this system, as it inherently has a lower efficiency than for the pulsed injection. In connection with this, the efficiency, emittance and current limitation of the RFQ cooler should be verified.

---

[1] In fact, 75% transmission was obtained with the trap at a voltage similar to that of the ion source.

9.3.2 ECRIS as charge breeder injector for the REX LINAC

At ISOLDE, there exists a second charge breeding device, the PHOENIX ECRIS charge booster [6]. The ECRIS works at 14 GHz radiofrequency, with permanent magnets and normal coils, and is designed to allow ion injection. Currently it is installed in the experimental hall at the GHM beam line, Fig. 9.2.

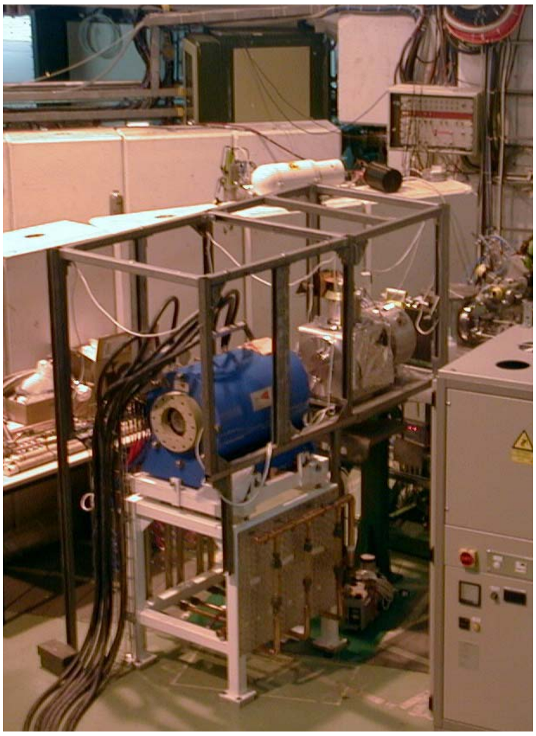


Fig. 9.2: Phoenix ECRIS ion source installed at the GHM beam line at ISOLDE

The main advantage of an ECRIS charge breeder is its large space-charge capacity and its operation without a preparatory buncher/cooler, which would allow for a high current throughput. In continuous wave mode the ECRIS can support injected beams of several μA. In pulsed mode 2×10^{12} charges per pulse have been demonstrated. Its ability to operate in continuous wave mode would also make full use of a superconducting LINAC and reduce the event pile-up in the experimental detectors associated with pulsed beams. Finally, its operation is simpler than for the combined trap–EBIS system.

The PHOENIX ECRIS, currently being evaluated as charge breeder at a dedicated setup in the ISOLDE hall, could be installed at the side of the REXTRAP/REXEBIS system for injection in parallel into the REX LINAC. For low ion intensities and high purity beam requests, the EBIS would be used, while for high intensities the ECRIS would feed the LINAC. The ECRIS should be installed at the present position of the solid-state experiment ASPIC and be connected to the REX LINAC via a magnetic and electrostatic spectrometer (already available, but not installed) similar to the REX mass separator. Using such a separator, mass and energy selections can be performed and the high residual-gas contamination be suppressed to a large extent. A movable bender directs the beam into the REX beam line. The emittance of the extracted beam from the ECRIS is smaller than the acceptance of the RFQ. Using afterglow, an extraction time of ~5 ms can be achieved. With a confinement time of 70–200 ms, the duty cycle for the LINAC falls within the present specifications (<10%). However, with a mass-to-charge ratio between 4 and 8 after breeding, the REX LINAC needs to be modified as it is designed for $A/q < 4.5$. The proposal would be to introduce a stripper foil for the heavier masses (typically $A > 80$) at the 1.2 MeV/u energy, that is after the IH structure, with a 10–20% transmission for the selected charge state.

The high A/q inside the RFQ and IH structure calls for modification of these accelerating structures. Exchange of the drift tube structures and increased cooling due to a higher acceleration voltage and higher RF power are required. A design similar to the injector for UNILAC at GSI could be used, limiting the effort to production of the structures. The RF frequency can be maintained, but the RFQ, buncher, and IH amplifiers have to be upgraded for the higher power level. Also the lenses of the matching section and the inner tank triplet inside the IH structure have to be upgraded as they are not specified for such a high A/q value. After the IH structure a box containing a stripper foil unit has to be added. As such an upgrade may entail a shift in axial position of certain LINAC elements as the stripper box is added for example, the upgrade should occur at the same time as the major upgrade of the LINAC.

Apart from the moderate A/q produced in an ECRIS, a number of other issues remain to be clarified. For instance, until now the recorded breeding efficiency for afterglow operation is only a couple of per cent. The breeder also exhibits difficulties in breeding elements lighter than $A = 40$. The large extracted stable beam originating from the residual gases amounts to several nanoamperes over the complete mass spectrum and often swamps the radioactive peaks. Finally, the confinement time for the ions in the plasma can in many cases exceed 100 ms which can lead to decay losses for short-lived ions. Several of these issues are under investigation in the programme Advanced charge breeding of radioactive isotopes within EURONS [7] and in Beam Preparation within EURISOL [8].

9.4 Development projects on the existing setup

Apart from the two upgrade scenarios suggested above, several less resource intensive development projects are being pursued on the present setup. Some have already started. The different R&D projects can be grouped into three categories: efficiency improvements of the different elements; electron gun development; and beam purity and beam optics enhancements. In addition, we are examining alternative uses for the ECRIS charge breeder. A summary of the status and needs of the different projects follows.

9.4.1 Improving the overall efficiency of REX-ISOLDE

9.4.1.1 Improving the trap efficiency

During the design study of REXTRAP, simulations of the ion injection, trapping and cooling processes were undertaken. A trapping efficiency close to 100% was expected. Experimentally 50–60% has been obtained for beams of intensity smaller than 10 pA, even less for higher intensities. Two possible reasons for the limited efficiency have been pointed out. Firstly, the magnetic mirror effect makes the injection from ISOLDE quite difficult, and on the injection side the ions may already be reflected before they enter the trapping region. Secondly, the ion-cooling method may not be strong enough to compress the ion cloud so it can exit the trap through the last collimator without a fraction being lost. A careful re-analysis of the beam injection conditions and a modification of the internal structure could improve the situation. By varying the beam focus and the diameter of the entrance and exit diaphragms, the losses could perhaps be reduced.

9.4.1.2 Narrowing the charge state distribution in the EBIS

Within the EURONS and EURISOL studies, two different means of narrowing the charge state distribution in the EBIS, and thereby increasing the number of particles in the peak charge state, will be investigated. Currently, a maximum of 25–30% can be obtained in the peak charge state. The first makes use of the large gap in ionization energy at the shell closure of atomic ions. By adjusting the electron beam energy accurately just below the ionization potential of a shell closure electron, a large fraction of the ions can end up in a single charge state. This is a specific case, and a suitable A/q value cannot always be found. The second method utilizes the dielectronic recombination resonance. The electron beam energy is adjusted to energies which enhance the dielectronic resonance cross-section for the dedicated ion species. In this way the recombination rate counteracts the ionization rate and stops the ionization at a certain charge state. This latter should be first tested at Heidelberg MPI-K before being possibly implemented at REX-ISOLDE. Both methods require an electron beam with an adjustable and in many cases low energy, which makes it cumbersome for the REX-ISOLDE, as the space-charge capacity will be low due to the perveance limit.

9.4.2 Electron gun development

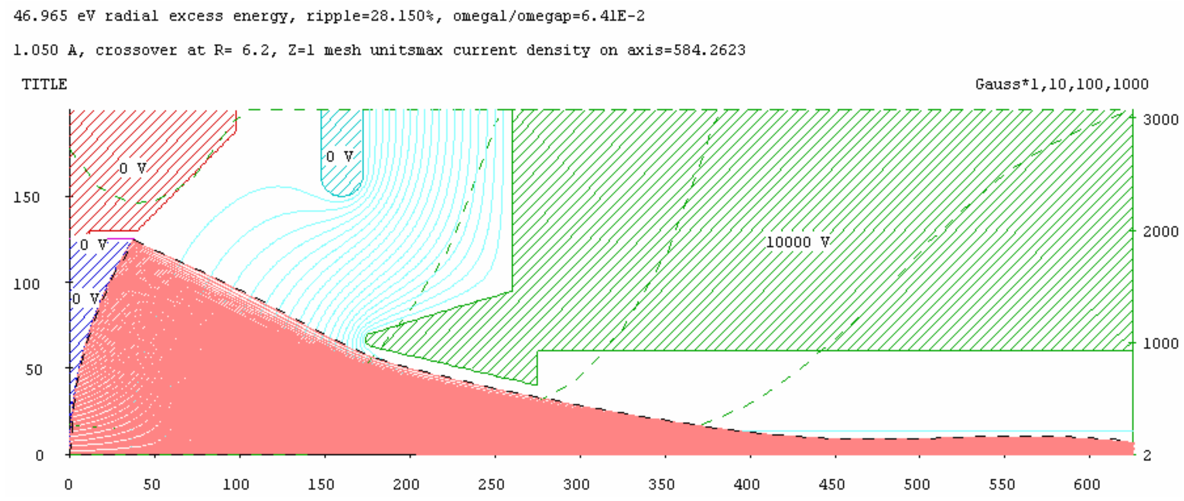
The performance of an EBIS charge breeding system relies mainly on its electron optical system and thus on the electron source used. With two different approaches, the post anode gun and the high compression gun, the electron beam performance issue is addressed [9].

9.4.2.1 Post anode gun

The post anode gun, which should improve the beam quality and reduce the losses of electrons on electrodes, is a modification of the present gun. If successful it will yield a ~5 keV 0.5 A ripple-free beam. The beam scalloping present in the actual gun might be responsible for the beam losses limiting the operation to below 350 mA. Additionally, the beam radius minima might act as local ion traps, which reduce the ion extraction efficiency. A common way to reduce this ripple without major changes in other beam parameters is resonance focusing using a post anode at a high positive voltage. This has been implemented mechanically, but the commissioning and the optimization remain.

9.4.2.2 New high-compression gun

The design of a completely new gun making use of electrostatic and magnetic compression has begun. The gun should reach a current density of 400 A/cm^2, more than three times the current density in the present system, and has a density compression of 300. To reach this value it is no longer possible to make use only of the magnetic compression with the present 2 T solenoid because of the Brillouin limitation. That means additional electrostatic compression is required. With a larger emitting surface and lower emission current density the cathode heating can be kept low, leading to an increased lifetime. Another goal is to store and charge-breed more ions in one cycle. For this reason the converging gun was designed to deliver a higher electron current of 1 A. This increases the trap capability by at least a factor 1.6 even at the higher beam energy of 10 keV. A beam simulation of a preliminary design is presented in Fig. 9.3. It turns out to be mechanically difficult to shape the magnetic field so it fulfils proper launching conditions for the electron beam from the gun, so further investigations are needed. The success of the project is uncertain.



```
46.965 eV radial excess energy, ripple=28.150%, omegal/omegap=6.41E-2
1.050 A, crossover at R= 6.2, Z=1 mesh unitsmax current density on axis=584.2623
```

Fig. 9.3: Beam simulation of a preliminary design for the high-compression gun

9.4.3 *Beam purity and higher beam quality*

The purity of the accelerated beam is often a critical issue. After the beam preparation at the trap and EBIS, two types of contaminants may be present. The first one is isobaric isotopes coming from ISOLDE, not separated out in the ISOLDE mass separator. The second one is the multicharged ions of similar A/q ratio originating from the residual gas inside the EBIS. The resolving power of the separator, $(A/q)/\Delta(A/q) \approx 150$, usually gives the possibility of choosing a charge state of interest not superimposed on a residual gas peak in the mass spectrum and thus a pure beam is delivered to the experiment. Nevertheless, in some cases a completely contamination-free beam is not attainable, particularly on a sub 0.1 pA level. In worst cases the beam is composed mainly of unwanted species.

9.4.3.1 Suppressing the isobaric contaminants from ISOLDE

From its intrinsic features the trap can be used as a high resolving mass separator. For example, the ISOLTRAP experiment has demonstrated that a resolving power of about 10^5 could be achieved in the preparatory trap. In 2005 we started a project to evaluate whether a similar resolving power can be attained in the REXTRAP and thereby the isobaric contaminations from ISOLDE could be reduced. However, certain limitations inherent to this separation method need to be studied in detail. Apart from possible space-charge effects, the required time of the RF excitation used for the separation is proportional to the resolving power. This becomes a limitation for short-lived nuclides. Secondly, a high resolving power requires a low buffer gas pressure. This may be a limitation for the trap efficiency. A modification of the internal trap structure and an improvement of the differential pumping scheme are most likely required. Preliminary results reveal that a mass resolution of 10^4 is attainable, see Fig. 9.4.

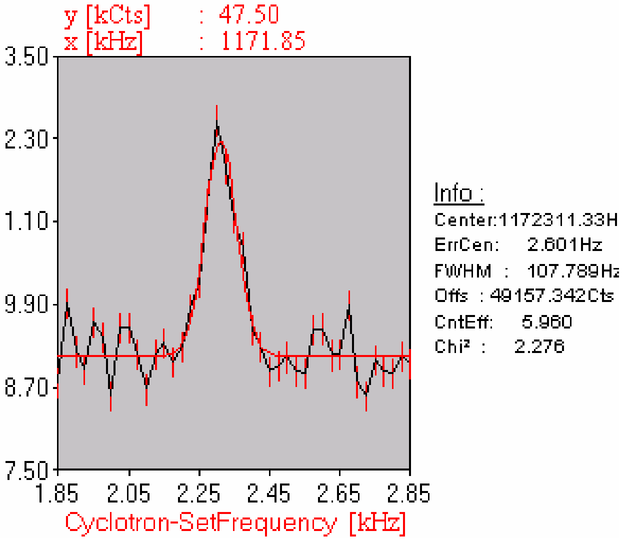


Fig. 9.4: A cyclotron resonance curve with a mass resolution of ~10 000 for $^{39}K^+$ ions at low buffer gas pressure and RF excitation amplitude

9.4.3.2 Molecular beams

To suppress known contaminations from the ISOLDE target-ion source unit, it is in certain cases possible to inject into REXTRAP molecules rather than atomic ions. According to their chemical properties, the radioactive elements produced by the proton bombardment can combine with different impurities present in the target-ion source system to a molecule. The radioactive ion of interest is then moved away in the mass spectrum from the contamination. This method, the so-called molecular sideband extraction, has recently been used with $^{70}SeCO^+$ molecules for the Coulomb excitation of Se nuclides with REX-ISOLDE [10]. In this way it was possible to suppress the contamination of $^{70}Ge^+$ ions.

Within REXTRAP, according to the voltages applied on the electrodes, the molecules could either be dissociated or kept intact. Figure 9.5 shows different time-of-flight spectra corresponding to these two schemes. If the molecule is kept intact inside the trap, the breaking occurs inside the EBIS. Systematic testing and efficiency measurements are needed to verify this method for different molecules, as the optimum trap settings are dependent on the electronegativity of the ion, for example. The optimization of this method would benefit from radioactive beam identification after the trap (see below).

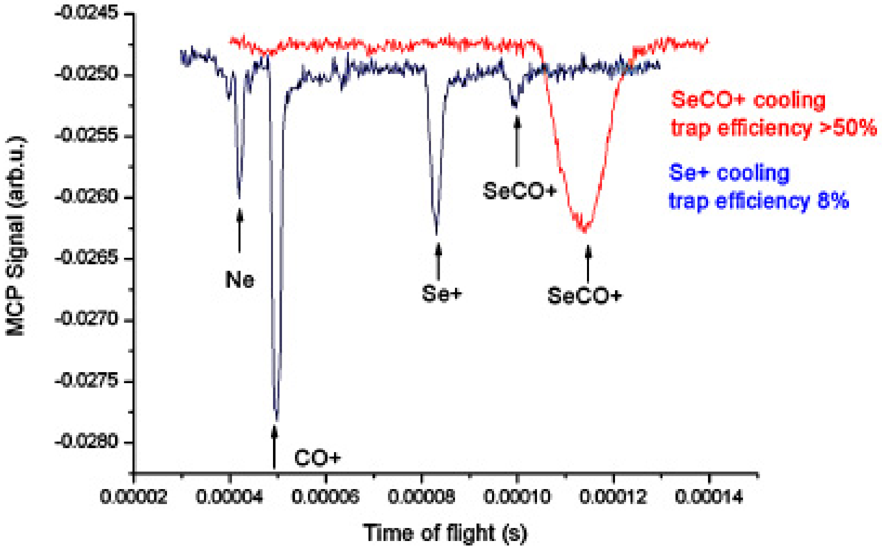


Fig. 9.5: Time-of-flight spectra of the beam ejected from the trap after injection and cooling of $SeCO^+$ molecules

9.4.3.3 Improvement of the vacuum system

The beam purity at the experimental station after acceleration through REX-ISOLDE is in most cases of utmost importance. An uncontrolled stable beam contamination distorts the results from Coulomb excitation and neutron transfer. Therefore, the suppression of residual gas contamination in the EBIS beam is important, and can be increased by coating the interior of the drift tubes and the electron collector with non-evaporable getter material. The major source of the stable impurities (C, N, and O) is the poor vacuum in the mass separator which has to be addressed. An improved vacuum in this section also reduces the electron recombination; this means the transmission efficiency for heavy, highly charged ions is increased. Further improvements involve a complete isolation of the roughing vacuum system for the trap from the rest of the low-energy stage beam lines, as it has been observed that the buffer gas of the trap can be transmitted to the EBIS backwards via the roughing pumping circuit.

9.4.4 Cooling techniques in charge breeders

Different ion–ion cooling methods are to be studied in the EURONS and EURISOL frameworks. They aim to improve the transverse emittance of the extracted beam from the different charge breeders. In the simplest form some cooling can be achieved by introducing a cooling gas into the EBIS. A more advanced scheme entails injection of the radioactive ions into a trapping region already partially filled with pre-injected buffer ions and different injection–trapping–extraction schemes [11]. Although the implementation of such techniques is not straightforward, with the current REXEBIS setup it is a future open possibility. A new electrode structure would have to be designed, and a 1^+ injection source and line added.

9.4.5 Comparison between Penning trap and RFQ cooler

An RFQ cooler buncher with high capacity will be in use at ISOLDE in the near future. Its beam cooling performance should then be compared to that of the Penning trap REXTRAP. The space-charge limitation, the time needed for beam cooling, and the emittance reduction are of primary interest.

9.4.6 Tape station for beam identification

Apart from suppression of unwanted beam contaminations, the identification of the charge bred beam is of utmost importance. Different beam diagnostics tools such as Faraday cups, beam profile and time-of-flight devices are installed at the trap and EBIS. After REXTRAP it is already possible to measure time-of-flight spectra of the cold extracted beam on a multichannel plate, and the beam composition can be determined to a certain extent. However, the present beam diagnostics system does not allow for a distinction between stable and radioactive beams. The identification can only be performed after acceleration at the experimental station. Thus, it would be beneficial to install a tape station with a complete detection system after the REX mass separator. In this way, the beam composition can be established before being injected into the LINAC and the functioning of the low-energy part can be assured. An electrostatic bender arrangement installed after the mass slit and before the RFQ quadrupoles would be necessary to deflect the beam 90° from the beam line onto the tape station.

9.5 Charge breeding ECRIS for beam purification and ion energy boosting

In case the charge breeding ECRIS is not used as an alternative breeder for the REX-ISOLDE LINAC, it could be used for boosting the ion beam energy for solid-state and nuclear astrophysics experiments. The ECRIS can also be used for improvement of the purity of beams. The charge states will develop differently for different elements. By injecting a radioactive mixture of originally the same A/q ratio into the ECRIS, it is then possible to minimize the A/q ratios overlap of the different elements. A subsequent separation of the charge-bred beam significantly improves the beam purity. This has already been proved with neutron-rich argon beams separated from a radioactive krypton contamination [12].

For many applications, particularly in solid-state or nuclear astrophysics, the beams available directly from the ISOLDE separators are too low in energy and the beams from REX-ISOLDE too high. The lowest beam energy from REX is 300 keV/u and the ISOLDE beam energy is between 20 and 60 keV for 1^+ ions. A way to reach the intermediate energy could be to connect the charge breeding ECRIS to a high-voltage platform [13]. With a high-voltage platform, operating at a voltage around –300 kV, installed after the ECRIS, total ion energies of $360 \cdot q$ keV are reachable. The high space charge capability of the ECRIS makes this particularly suitable for high-intensity, solid-state implantations. The PHOENIX is mainly efficient for slightly heavier elements, that is $A > 25$, and the reachable A/q limits the energy to ~50 keV/u. The existing HV platform could be moved to a position after the GHM and ECRIS, and be located 3 m above the floor to allow for an energy analyser after the separator magnet. This option presents very few complications, as space at the necessary position is available with little relocation effort. Apart from the general work on the ECRIS already mentioned, a beam line with focusing possibilities to the platform has to be produced.

Whether the DARESBURY/ISOLDE's PHOENIX ECRIS is used for REX injection or HV platform feeding, a few common upgrades are needed. For instance, the vacuum has to be consolidated and standardized, and the control system upgraded. The magnetic separator has to be combined with an energy analyser to suppress the high level of beam contaminations. Such a separator has already been purchased, but the installation remains. Moreover, a complete radioactive beam diagnostics system including a tape station and multichannel analyser is desirable. Miscellaneous borrowed power supplies should also be complemented. A local ion source in front of the ECRIS would facilitate the injection tests as one would not then be dependent solely on an ion beam delivered from ISOLDE. Finally, the commissioning tests have to be finished and stable working points established.

References

[1] D. Habs *et al.*, Nucl. Instrum. Meth. **B139** (1998) 128–135.

[2] The REX-ISOLDE Facility: Design and Commissioning Report, F. Ames *et al.*, CERN-2005-009.

[3] Electron beam ion source pre-injector project (EBIS) conceptual design report, J. Alessi *et al.*, BNL-73700-2005-IR.

[4] E. Beebe, J. Phys.: Conference Series, 2004, vol. 1, pp. 167–76.

[5] Chapter 8 of this report.

[6] P. Delahaye *et al.*, Rev. Sci. Instrum. **77** 03B105 (2006).

[7] http://www.ha.physik.uni-muenchen.de/jra03cb/

[8] http://www.eurisol.org/site01/index.php

[9] K. Allinger, Electron gun design for improved electron optics at the REXEBIS charge breeder, Diploma thesis, LMU Munich (2006).

[10] P. Delahaye *et al.*, Euro. Phys. J. A, **25** (2005) 739–741.

[11] R. Becker and O. Kester, J. Phys. Conf. Ser. 2 (2004) 20–27.

[12] L. Weissman *et al.*, Nucl. Instrum. Meth. **A556** (2006) 31–37.

[13] H. Haas, CERN-AB-Note-2004-034.