EURISOL Task 9 final report on charge breeding activities

Task 9: beam preparation
Deliverable D7, Final report

"Advance in charge-breeding research and developments"

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1 Introduction

The study and development of charge breeding techniques is of primary interest for optimizing the post-acceleration of intense and exotic beams that will be produced in a facility such as EURISOL [1]. Extracted as singly charged ions from the target-ion source units, the radioactive isotopes have to undergo a charge breeding process to an n+ state to match the acceptance of the post-accelerator. For this latter high charge states and relatively low A/q ratios yield compactness and higher ions final energy. This post-acceleration scheme, also known as "1+ → n+ scenario", presents quite a few technical challenges because of the diversity of the produced isotopes in terms of mass range (spanning the complete nuclear chart) lifetime (short lived > 1ms to stable) and produced intensities (up to 10^{13} ions/s). This report is intended to give guidelines for the future charge breeding techniques to be developed for EURISOL. It is based from results of on-line experiments performed in the frame of the Design Study at ISOLDE and GSI and more generally from experience gained in other charge breeding systems around the world.

2 Charge breeding performances

Because of the few challenges listed above, the charge breeding technique has to be efficient, rapid and versatile and yield high enough charge states to allow the post-acceleration of ISOL-type beams produced by a EURISOL-like facility. Other parameters may additionally influence the choice of the technique, such as its robustness, reliability and flexibility. The first two points will have some importance with respect to the radioprotection issues. The last argument includes various aspects, such as the charge state selection, or the CW and pulsed operation capabilities.

2.1 Charge breeding techniques

Up to now, mainly three charge multiplication-techniques were used for the post-acceleration of radioactive beams. The first one is the use of stripping foils. Whereas it is a very efficient method for the production of bare light ions, a certain drop in efficiency is experienced for heavy ions for which the charge is spread over several states and multiple stripping stages have to be used. It also requires a pre-stripper section with low frequency rf-structures for extreme A/q range like the GSI UNILAC injector that brings the radioactive ions to the minimum energy needed by the stripping process. This method, although the most rapid one, might be not the best choice for EURISOL because of the drawbacks given above and because of the significant additional cost of the pre-stripper [2]. However, it can be used for additional purification of the beam from isobars. This option will not be discussed in this report.

The two other charge breeding techniques make use of either an Electron Beam Ion Source (EBIS) or an Electron Cyclotron Resonance Ion Source (ECRIS) as charge breeders. Some literature describing these two devices can be found in [3],[4],[5], [6] and [7].

During the past 6 years, an appreciable experience was acquired at ISOLDE with both charge breeders. First, the REX-ISOLDE preparation stage consists of a combination of a Penning trap (REXTRAP) for ion cooling and bunching, and of an EBIS (REXEBIS). REX-ISOLDE is routinely providing accelerated beams to users with energies up to 3 MeV/u, mainly for the purpose of nuclear structure experiments. A number of different beams have been accelerated with masses ranging from ^{8}Li to ^{204}Rn with very different half-life, chemical properties (alkali, metallic, noble gas ions) including fragments of molecular beams coming from ISOLDE. Second, a Phoenix ECR charge breeder, purchased by the CCLRC Daresbury laboratory, was tested on a parasitic beam line of the General Purpose Separator GPS. The primary aim of having such a test bench was the comparison of the performances of this booster with the preparation stage of REX-ISOLDE [8]. A secondary objective was the application of the charge breeding technique to nuclear physics experiments. Beam purification for the study of neutron-rich nuclides was successfully demonstrated during two experiments [9],[10]. During the past 4 years, the efficiencies of the Phoenix booster were characterized with a variety of stable beams and a few radioactive beams. Both the natural mode of operation of the booster, the continuous (cw) mode, and the afterglow mode were tested. Rich of this quite unique experience with both charge breeders, this document reports on the possibilities that these techniques would offer to the future EURISOL facility. Some input from test benches and solutions used in other ISOL facilities, such as GSI, GANIL, TRIUMF and TRIAC are also taken into account.

2.2 Key parameters for an EBIS

As review papers, the reader can refer to [3],[4],[5]. The main parameters that will determine the performances of an EBIS are:

- the electron beam characteristics, i.e. total electron current I_e, electron current density j_e and electron beam energy E
- the magnetic field, which compresses the electron-beam to the required current density
- the parameters of the trapping region, especially the trap length L

The charge capacity of the trap can be readily calculated as:

$$(1)\ Q = 3.32\cdot10^{11}\cdot L\cdot I_e\cdot E^{-1/2}$$

where Q is the maximum number of elementary positive charges that can be trapped, L is given in m, I_e in A and E in keV. As the EBIS is essentially a pulsed charge breeder, one usually defines the charge breeding time τ as the time between injection of the 1+ ions and the ejection of the charge bred ions. During this trapping time the ions are step-wise ionized. The charge state distribution will mainly depend on the $j_e.\tau$ product, as illustrated in Fig. 1, so that a higher electron beam density translates to shorter breeding times or higher charge states for the same breeding time. For a non-compensated electron beam, the acceptance of the EBIS will be mainly defined by the electron beam width and intensity [11].

A detailed description of REXEBIS can be found in [11]. The main characteristics are given in table 1. As the REXEBIS is essentially a pulsed device, and as its acceptance is rather small compared to the ISOLDE beam emittances, a bunching and cooling device is required. REXTRAP, a Penning trap filled with Ne gas as buffer, performs these operations [12]. As one bunch is accumulated when the other is charge bred, the total preparation time is at least twice the charge breeding time. A brief summary of the performances of REXTRAP is shown in the table 2. After REXEBIS, a two-steps separator [13] allows a selection in energy and A/q of the beam prior to its post-acceleration in a LINAC, with an achieved resolving power of $\delta(A/q)/(A/q)\sim150$.

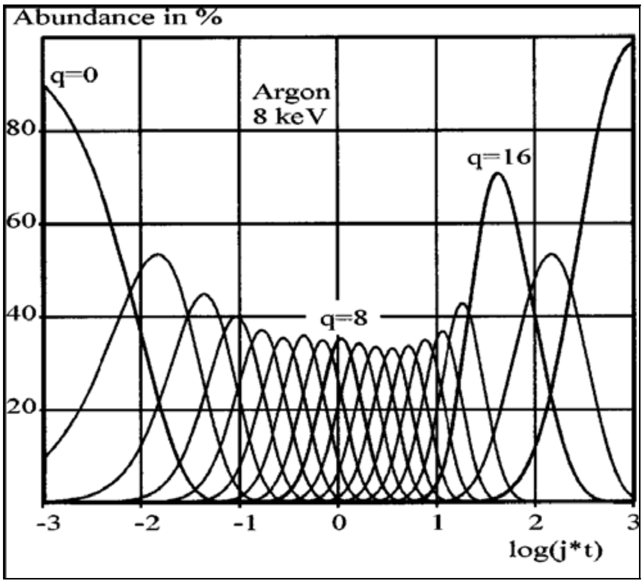


Figure 1: Charge state distribution of Ar ions as a function of the j*τ factor. Taken from [5].

B-Field	2T
Electron beam	Cathode LaB6 $j_{cathode}<20$A/cm^2 $j_{trap}/j_{cathode}\sim10$; $j_e=j_{trap}<200$A/cm^2 I_e=460mA (normal operation 200mA) E=3.5-6keV
Trap	3 drift tubes L=200 to 800 mm Theoretical capacity $5\cdot10^{10}$ positive charges
Acceptance	11 mm·mrad (95% geometrical) for 60 keV– estimated [11]
Emittance out	15-20 mm·mrad (95% geometrical) for 20·q keV – measured [12]
Max. energy dispersion	50*q eV - estimated [11]
Pulse length	FWHM 40μs to 300μs
Vacuum	10^{-10}-10^{-11}mbar

Table 1: REXEBIS main characteristics.

Efficiency	~50% for A>8 ; 15-25% for A<8
Minimum cooling time	10ms
Emittance out	10 mm·mrad at 30keV (80%)
Pulse length	<5μs
Space charge limit	10^8 ions/bunch

Table 2: Summary of REXTRAP performances.

Fig. 2 and 3 present the low energy stage of REX-ISOLDE and a schematic cross-section view of a typical EBIS. Eventually, an upgrade [8] of this kind of charge breeder could result in characteristics similar to the RHICEBIS [14], presented in table 3. In this case, the use of a cooling and bunching device would not necessarily be mandatory, as the transverse beam acceptance is much larger than for the REXEBIS. This high performing source could possibly also be used with a continuous ion injection (see section *REXTRAP/REXEBIS performances*).

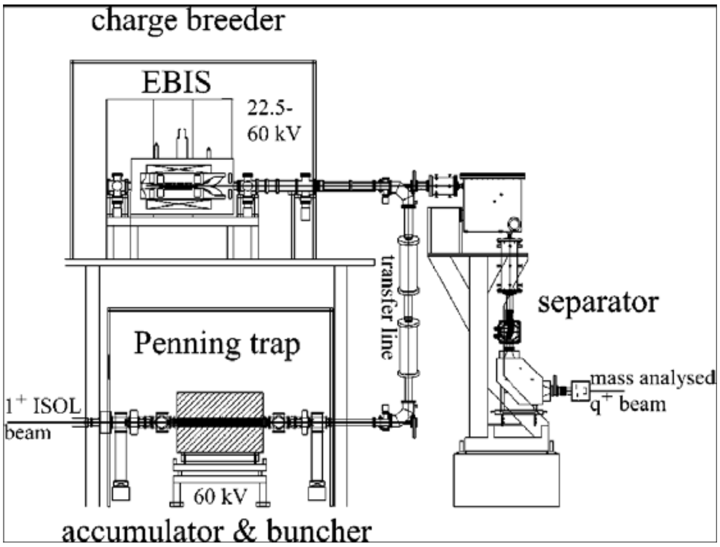


Figure 2: Low energy stage of REX-ISOLDE: REXTRAP, REXEBIS and the A/q and E separator. Taken from [15].

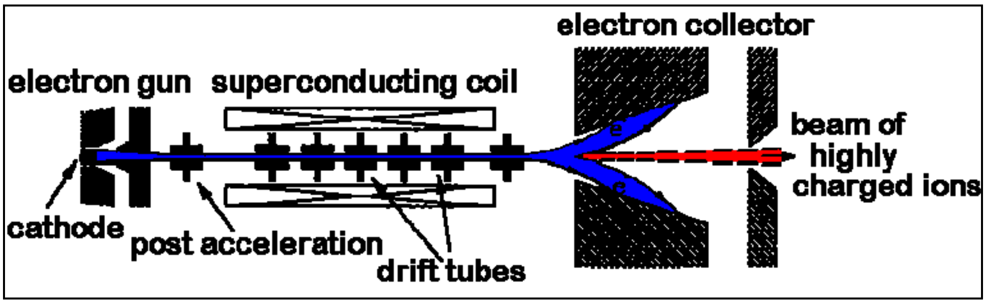


Figure 3: Simplified cross-section view of an EBIS.

B-field	6T
Electron beam	Cathode IrCe j_{trap}>575A/cm^2 I_e=10A E=20keV
Trap	L=1.5m Theoretical capacity 1.1·10^{12} positive charges Capacity 3.4·10^{11} positive charges (experimental value with TestEBIS I_e=8A L=0.7m)
Acceptance	20 mm·mrad (RMS) at 11keV- estimate from [16] ~80 mm·mrad (90%) at 11keV
Beam emittance out	0.35 mm·mrad 90% normalized ~150 mm·mrad 90% in case of 17*q keV, Au^{32+}
Energy dispersion	1.5 *q keV
Pulse length	10-40µs (using fast extraction)
Vaccuum	10^{-9}-10^{-10} mbar

Table 3: Some of the RHICEBIS characteristics, from [14].

2.3 Key parameters for the ECR charge breeder

The reader can refer to [6],[7],[17],[18] for a more complete description of this type of charge breeder. The main parameters of an ECR charge breeder are the following:

- The frequency of the RF wave (f_{RF}). A higher frequency shifts the charge state spectrum to higher charges and permits shorter charge breeding times. When increasing the operation frequency the confining magnetic field of the source has to increase correspondingly in order to maintain a closed resonance surface at a certain distance from the plasma contianer walls. In average the scaling laws [6] show that the electron density n_e is proportional to the square of f_{RF}, at least in the range from 2.45 to 28 GHz. As in the EBIS case, the stepwise ionization process leads to charge states proportional to the product $n_e \cdot \tau_{cb}$, where τ_{cb} is the confinement/charge breeding time of the ions in the plasma before being extracted.
- The magnetic field confinement type and amplitude. A minimum-B structure is usually established to provide MHD stabilization and to create a topologically closed region at which the condition for a resonant excitation of the electron cyclotron motion is fulfilled, i.e. $f_{RF}=eB/m_e$. For this kind of confinement, a magnetic field minimum is created in the middle of the plasma chamber by combining 3 coils in the axial direction with a permanent magnet multipole structure in the radial direction. Depending on the application, simpler structures can be used. In the case of the afterglow mode though, the pulsed operation of the charge breeder, a stronger confinement is required. The trapping time will depend directly on the magnetic mirror ratios at the injection and extraction of the booster.
- The type of support gas (typically oxygen or helium). The power required to sustain or ignite the plasma as well as the charge exchange processes will depend on the nature of the support gas. As it is usually the primary component of the stable background, heavy gases are usually avoided to limit the number of peaks contaminating the A/q spectrum.
- The walls of the plasma chamber. As mentioned before, the confinement should be sufficient in order to prevent plasma leaks to the wall which will induce heating and degassing. In some unprotected devices, it might eventually lead to a demagnetization of some hexapole magnets and thereafter to a hole in the plasma chamber. The material of the plasma chamber can be chosen in order to modify the electron density. For example, the use of aluminium has shown a beneficial influence on the production of high charge states due to the electronic secondary emission. In the case of production of radioactive ions one should be aware of the sticking time of the ions to be produced, and to the impurities contained in the plasma chamber material in order to decrease the unwanted background.

Two charge breeding modes can be used [17]. The meaning of the charge breeding time differs according to the mode of operation. The natural mode of this charge breeder is continuous injection and extraction. In this case, the charge breeding time usually refers to the average time between the injection of a 1+ beam and the extraction of the same multi-ionized one (n+) from the plasma chamber. It includes the charge breeding process and delay due to the confinement of a given charge state. A pulsed mode for the ECR is the so-called afterglow or ECR Ion Trap (ECRIT) mode [17],[18],[19],[20]. For this mode, the amount of extracted ions is suddenly increased by a de-confinement of the plasma induced by a fast RF power switch-off. When the RF wave is suddenly stopped, the electrons of the plasma escape and the plasma confinement is broken, the multi-charged ions are ejected towards the lowest magnetic field area (exit coil). The magnetic field configuration has to allow accumulation, trapping and charge breeding of the ions injected into the plasma between the extraction pulses. The charge breeding process using the afterglow mode of an ECR is similar to the continuous injection mode of an EBIS.

Some of the characteristics of the ECR Phoenix used for these tests are shown in the table 4. The test bench is presented in Fig. 4 with a cross-section view of the Phoenix charge breeder.

RF frequency	14.5 GHz Max power 1kW
Magnetic confinement	B-minimum structure 3 axial coils and a permanent magnet hexapole structure B_{inj}=1.5T, B_{ecr}=0.52T ; B_{min}=0.5T; B_{ext}=1T; B_{rad}=1.35T

	Mirror ratios $B_{inj}/B_{min}=3$; $B_{ext}/B_{min}=2$
Plasma chamber	~1l Stainless steel
Acceptance	>55 mm·mrad at 18 keV (90%) [30]
Emittance out	10 mm·mrad at 19.5*q keV (90%) [18]
Energy dispersion	1-10*q eV
Vacuum	< 10^{-6} mbar in the injection and extraction regions 10^{-7} without plasma.
Support gas	O_2 at $5 \cdot 10^{-5}$mbar.l/s

Table 4: Some characteristics of the Phoenix charge state booster.

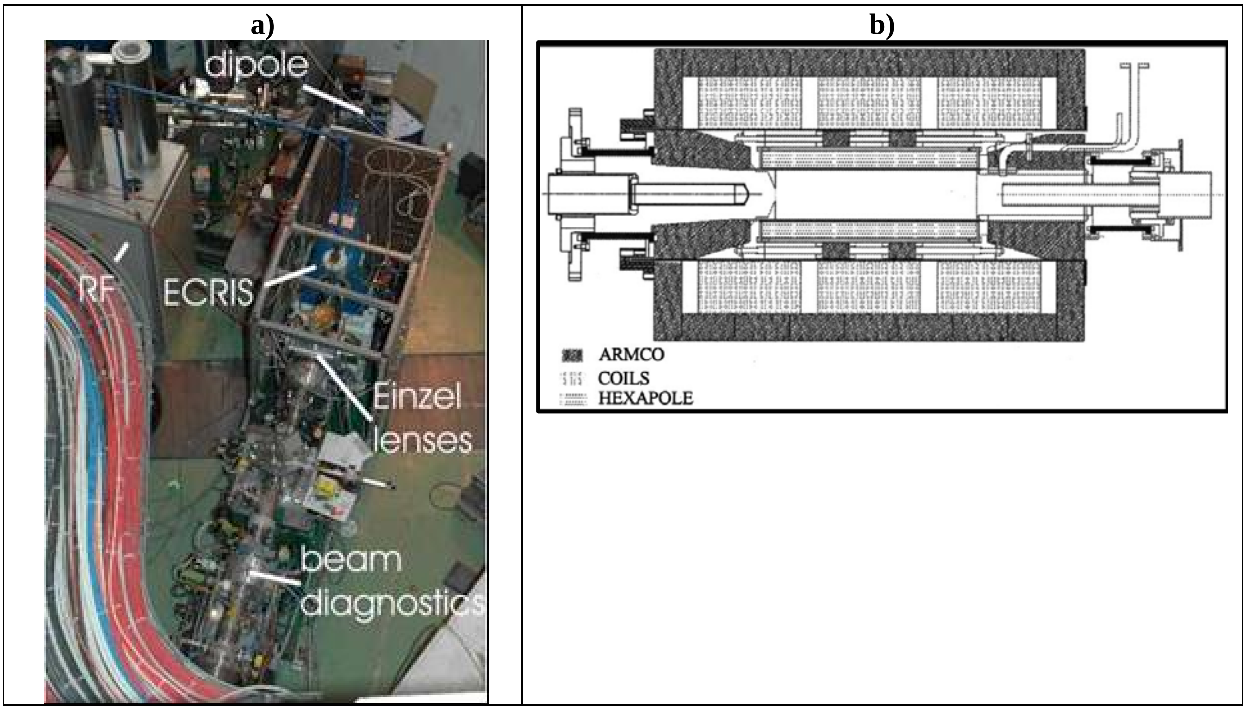


Figure 4: a) The ECR Phoenix booster test bench at ISOLDE. b) A cross-section view of the Phoenix ECR charge breeder taken from ref [22].

As any high performance ECR ion source, the Phoenix charge breeder can handle very intense beams. In continuous mode the injection of beams up to µA has been proven with decent efficiencies [18]. In pulsed mode up to 400nA of Rb^{1+} was injected in MINIMAFIOS [17],[20], a rather modest charge breeder compared to the Phoenix booster. Pulses of a few 10^{10} Rb^{15+} extracted over a length of 20ms could be produced, corresponding to more than 10^{11} Rb ions integrated over the whole charge state spectrum. Because of its sufficient transverse acceptance, ion coolers are not necessary prior to the injection of the 1+ beam. However, a large ion energy spread of the injected ions can spoil the injection efficiency due to the narrow energy acceptance of the ECRIS plasma. An important parameter for the injection of the 1+ beam into the charge breeder is the potential difference ΔV between the acceleration voltage of the primary beam and the high voltage of the booster. Depending on the 1+ ion source and on the nature of the element, the optimum range for this parameter will differ [18]. For alkali and metallic ions, the ΔV acceptance will be in the order of a few volts only, which can eventually limit the efficiency if using 1+ sources with a large energy spread. On the other hand, a rather small energy spread is expected for the n+ beam.

Potentially, almost any kind of ECR ion source can be transformed into a charge breeder system, the main change being the insertion of an axial grounded tube permitting the injection of the 1+ beam. This change could lead to a modification of the RF power injection system, in case it is axial in the original device. The most advanced ECR ion sources in the world are SECRAL [23], VENUS [24],[25],[26], MS-ECRIS [27] and A-PHOENIX [28]. The three first are fully superconducting systems, while the last is a hybrid of HTS superconducting coils and a permanent magnet hexapole. The frequency injected in these ion sources is 28GHz for typical axial and radial B-values of 3-4T and 2T respectively. The SECRAL and VENUS sources are under operation while MS-ECRIS and A-PHOENIX are under construction. Charge breeding developments with such devices is foreseen. Lately, the prototype of Phoenix charge breeder developed by LPSC was further optimized for enabling double frequency operation (14 and 18GHz), producing a more symmetric magnetic field, and injecting the support gas directly into the plasma chamber.

2.4 REXTRAP/REXEBIS performances

A compilation of results for the REX-ISOLDE campaign of 2006 was recently published in [29], former results obtained with REXEBIS and REXTRAP at REX-ISOLDE until September 2005 have been summarized in ref. [30] (ICIS05 conference). Fig. 5 and 6 present an overview of results from 2008 showing trends for the charge breeding times and low energy preparation efficiencies (REXTRAP + REXEBIS). REXTRAP is routinely performing with efficiency around 50-60%. The efficiencies of the REXEBIS alone are therefore about two times higher than presented on Fig. 5. Particularly good efficiencies for K^{9+} and Cu^{19+} can be explained by closed shell effects. A/q values below 4.5 and most generally around 3-4 are routinely used for post-acceleration by REX-ISOLDE. The breeding times were therefore tuned accordingly. As part of the overall beam preparation, the cooling time has to be added to the charge breeding time for a fair comparison with the ECR charge breeding time shown in the next section. As for synchronization purpose, the cooling and bunching time has to be equal to the charge breeding time, the total preparation time amounts to two times the one shown on Figure 6. Usually, a 50 Hz repetition rate is used for masses below 40, as a minimum cooling time of 20ms has to be applied for good injection efficiency into REXEBIS. The results presented in Fig. 5 and 6 were obtained either during the stable beam setup of REX-ISOLDE, or during the actual runs with the radioactive beams. The intensities of the injected beams were always below the space charge limitations of the trap (<<10^8 ions per bunch, see table 2) in the range from 1 to 100 pA. In addition to these beams, the use of molecules has been shown to be a very powerful way for producing isobarically pure beams. A first successful experiment was performed with ^{70}Se [31]: $SeCO^+$ molecules were cooled in the trap, then broken up and charge bred in REXEBIS to Se^{19+}. Two successive mass over charge separations permitted an excellent suppression of the contaminants. The first one was set to select the molecule $SeCO^+$ (mass 98) after the ISOLDE HRS, and the second one was selecting the molecule fragment mass over charge ratio (A/q=70/19) after the EBIS. Since then, several molecular beams were injected and their fragments post-accelerated at REX-ISOLDE, such as ^{10}C from CO, ^{96}Sr from SrF and $^{140\text{-}142}Sr$ from BaF. A detailed report on the use of molecular beams at REX-ISOLDE and with the Phoenix ECR can be found in [32] as part of the EURONS activities.

At this stage, the use of REXTRAP for ion cooling and bunching has been found necessary in most of the cases to match the limited acceptance of REXEBIS in transverse and longitudinal direction and to match the time structure for an optimum charge breeding efficiency. Another mode, the so-called "accu"-mode allowing continuous injection has also been used during beam time because of a temporary failure of REXTRAP. Typical settings and performances of this mode are briefly summarized in Table 6. They are more extensively discussed in [32]. The past years, a slow extraction mode was successfully developed to limit the instantaneous throughput of the accelerator to the MINIBALL experiment and detectors. The EBIS pulse was enlarged from 40 to 400μs without any efficiency loss, and could possibly be further enlarged if it was not limited by the RF pulse of the

LINAC (1ms) [33]. These two modes (“accu”-mode and slow extraction) open up new possibilities for high intensity beams for which the Penning trap becomes a limiting factor.

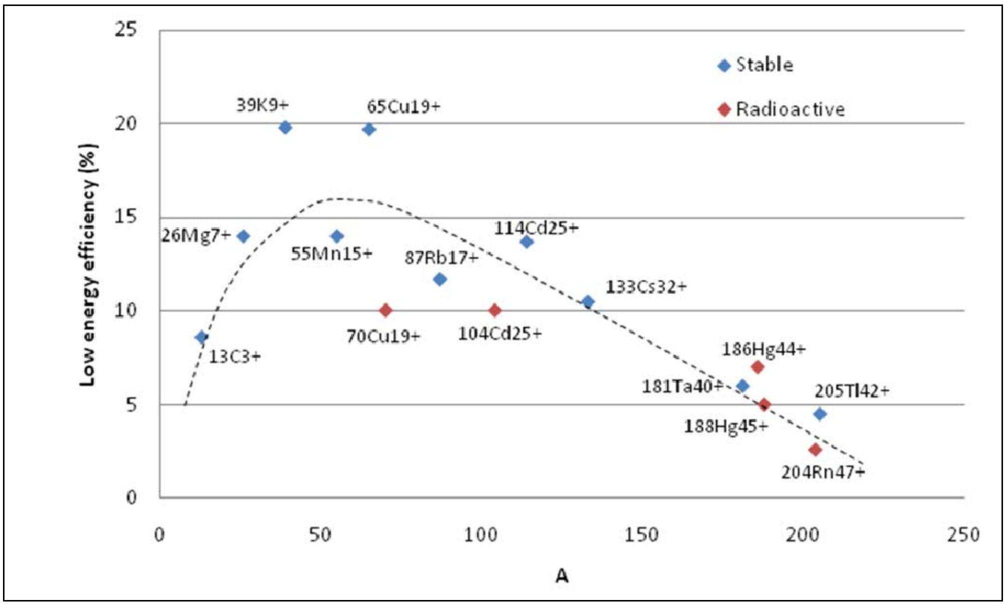


Figure 5: Low energy preparation efficiencies for isotopes charge bred in 2008.

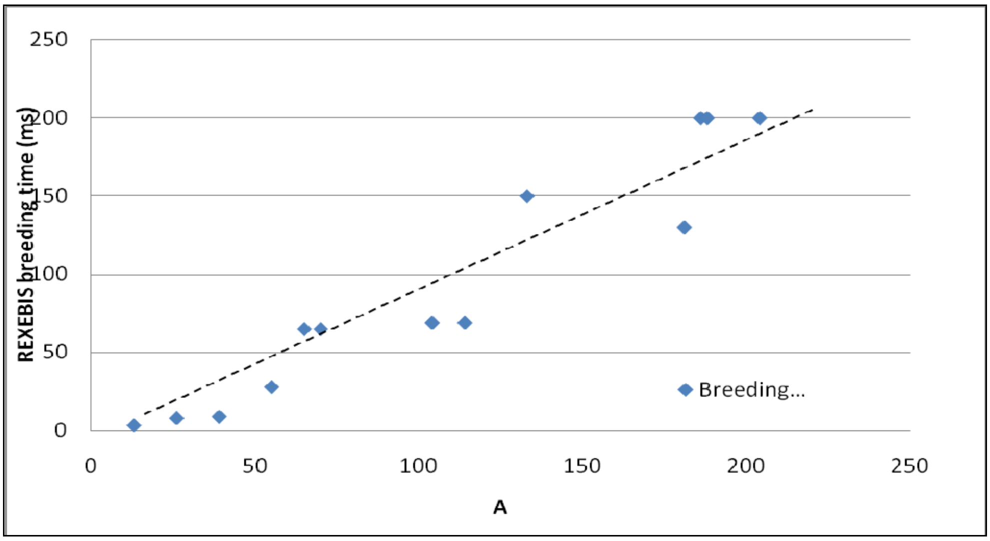


Figure 6: REXEBIS charge breeding time for reaching A/q<4.5 as required by the LINAC for isotopes charge bred in 2008. The cooling and bunching time from REXTRAP - equal to the charge breeding time - has to be accounted for in the complete low energy ion preparation.

Conditions	DC beam from a reference ion source and from ISOLDE with emittances in the order of 10-20 mm·mrad (90%) at 30 kV, and optionally cooled by the RFQ cooler ISCOOL to emittances of about 3π.mm.mrad Shooting through a non-active REXTRAP with 75% efficiency (limited transmission as it was on high voltage potential) Lowered outer barrier for the EBIS trap
Results	4% in $^{39}K^{9+}$ (9.5 ms breeding time) up to 500 pA injected beam

	5% in $^{87}Rn^{17+}$ (29ms breeding time) with cold injected beam from ISCOOL

Table 5: "Accu"-mode results.

2.5 14GHz Phoenix Booster performances

The performances of the Phoenix ECRIS setup at ISOLDE were extensively discussed in [10]. Figure 7 presents ΔV tuning curves extracted from that work. Results of the tests performed in 2005 were also presented at the ICIS05 conference [34] and a summary of the results obtained using the CW mode at ISOLDE together with some results from LPSC was done for EMIS 2007 [35]. It is reminded for discussion in Figure 8.

The ΔV curves shown in Figure 7 were measured during different beam-times for different isotopes. I/Imax is the normalized intensity of the charge state of interest and ΔV is the difference between the ECR charge breeder and the 1+ source potentials. The ΔV acceptance window renders the fact that 1+ ions which are injected with too high energy pass through the ECR plasma without being stopped, and that 1+ ions which are injected with an energy significantly lower than the plasma sheath potential are being reflected. In the stopping process the ions-ions collisions are believed to play a predominant role and to be particularly efficient for similar velocity distributions between plasma ions and injected ions [36]. It is remarkable that the shape of these curves mainly depend on the dichotomy noble gas/condensable elements, and their position on the nature of the 1+ source which is used. In the case of noble gases, the ions injected with energy higher than the ECR plasma will have a non-negligible chance to get recycled from the plasma chamber walls. It is of course not true for condensable species. This explains the plateau that can be at negative ΔV that can be observed for noble gases and that is absent for condensable isotopes for which direct capture is only possible. The difference in position for the different ion sources can be explained by the relative kinetic energy difference of the 1+ beam produced in the respective ion sources. In the case of the surface ionization source, the 1+ ions energy is well defined by the 1+ source high voltage. The ΔV curve is then maximum for a potential of the charge breeder close to the potential of the 1+ source minus the sheath potential of the ECR plasma. In the case of the FEBIAD source ("hot plasma"), the plasma of the 1+ source exhibits a negative potential that increases the absolute value of the ΔV maximum. Although non-mandatory, the knowledge of the 1+ beam energy makes the ΔV tuning much simpler as, for a given ion source, its optimum value is quite reproducible as can be seen in Figure 7.

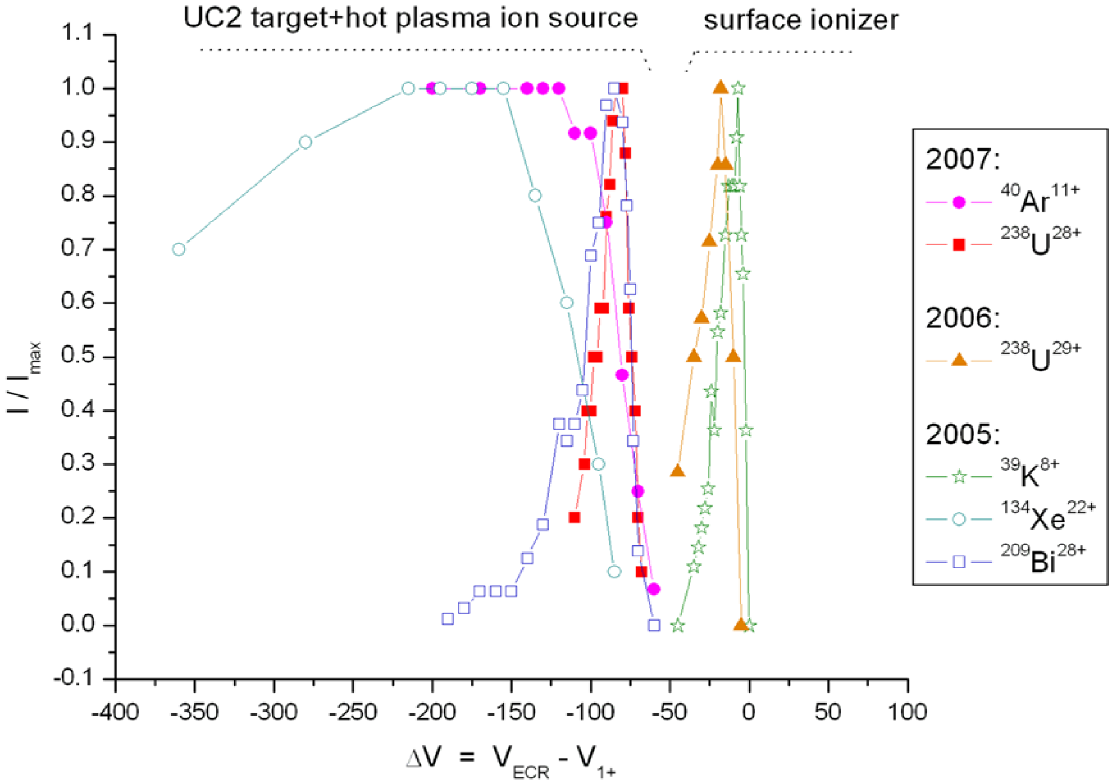


Figure 7: ΔV curves for different stable ions obtained at different beam-times.

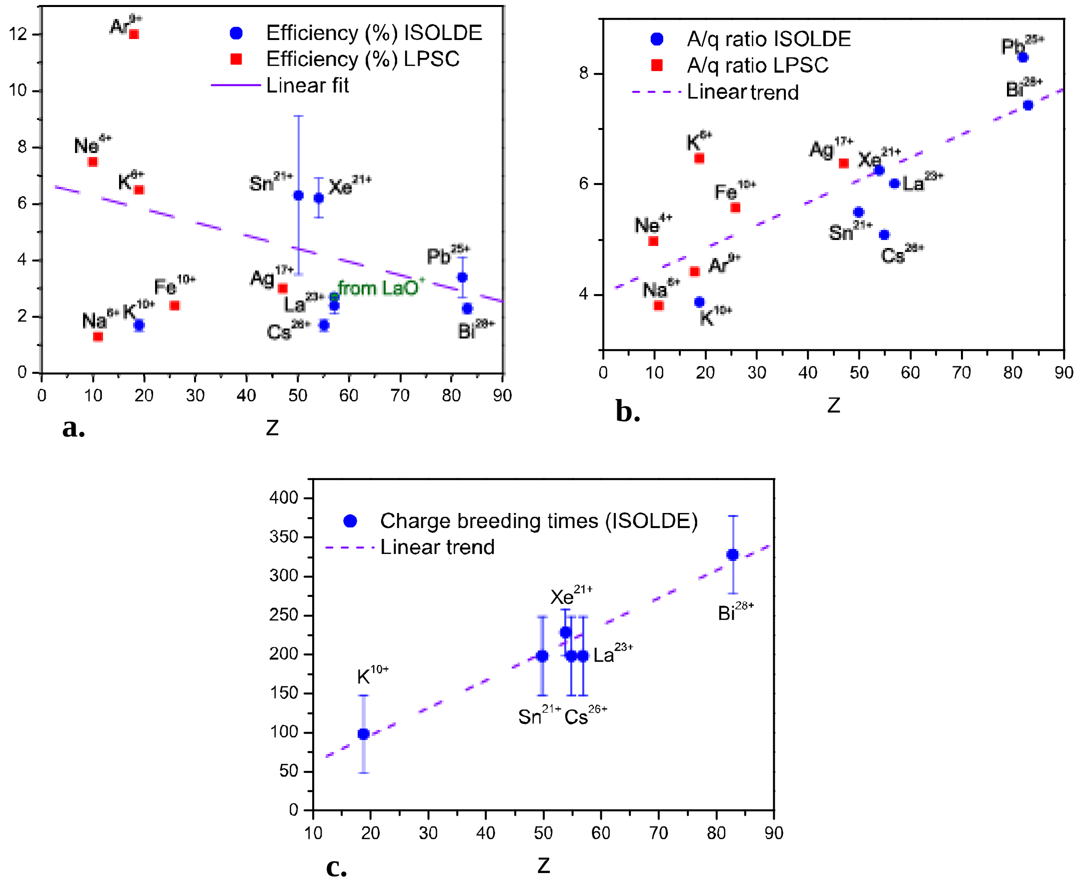


Figure 8: Summary of the performances of the CW mode of the Phoenix booster as measured at ISOLDE and LPSC before its last upgrade [35].

The trend lines on the figures are only meant to guide the eye. Charge breeding efficiencies in one charge state vary between 12 and 2% from Ar to heavy elements (Z>80). Efficiencies for noble gases are higher than those for condensable elements as for these first ones recycling from the plasma chamber walls is possible even at room temperature. Condensable species can only be captured directly into the ECRIS plasma. Injection of light and condensable elements (Z<10) has been shown to be quite inefficient. In this case it is believed that the velocity mismatch between the light ions and the ions of the plasma hinders the capture because of the weakness of the ion – ion collision stopping average force [36][36]. In the review paper [18] the author quote 1.5% efficiency for Na, and gives some preliminary ideas for improving the trapping of these fast ions, such as a tuneable position of the injection tube. The charge breeding times measured there indicate that about 10ms in average is needed for each charge state. As in the EBIS case, the injection of molecules was successfully tested. LaO$^+$ molecules could be injected, broken-up, and the La$^+$ fragment charge bred to a charge state 23+ [35]. A first attempt with light molecules CO$^+$ did not give any concluding results.

Two series of tests were conducted with the pulsing mode of the ECR charge breeder. The first one was performed injecting Kr and Xe beams. Afterglow pulses were produced with a frequency of 10Hz and 10ms duration. The results are presented in the table 9. These are also believed to be slightly under-optimized. Long charge breeding times and rather low efficiencies were obtained for rather low charge states. Some better results with Rb ions were shown for the MINIMAFIOS by Chauvin et al. [20] and are presented as for comparison in the same table.

1+ ion	N+ ion	$\eta(\Delta\eta)$ %	$\tau_{cb}(\Delta\tau cb)$ (ms)	q_{max}	A/q_{max}	Ref.
86Kr+	86Kr13+	1	500(100)	13	6.6	[31]

132Xe+	132Xe18+	2.2	600(100)	18	7.33	[31]
85Rb+	85Rb15+	2.5%	Confinement time 520 ms	15	5.67	[20]

Table 9: Afterglow results from refs. [31] and [20].

A second test was done for the trapping of recoil ions of ^{61}Fe^{13+} coming from the decay of charge bred ^{61}Mn isotopes. This test is extensively described in [10]. A detailed off-line analysis of the recorded data indicated possible traces of recycled Fe.

As for any ECR charge breeder, the high residual pressure in the plasma chamber and extraction region results in a high stable background. After the magnetic separator used in these tests, a few nA of stable beam was visible in the region $3<A/q<7$, even away from the charge states of C, N, and O. The installation of an additional separation stage for energy selection, similar to the REX separator, should significantly decrease the background level [36].

As last remark, an upgraded version of the Phoenix booster including UHV components, double frequency injection system and an optimized magnetic field has been developed at LPSC Grenoble and is presently being tested. Promising results have already been obtained with ^{87}Rb charge bred to charge stated 15+ with record breeding times and efficiencies two times higher than with simple 14GHz operation for 13+ [32].

2.6 Comparison between the methods

Considering the elements listed above, most charge breeding performances of REXEBIS and of the Phoenix ECR charge breeder can be compared. However, it is to be noted that the natural mode of operation of the two charge breeders are significantly different. The results obtained with the ECR afterglow mode are still not sufficient to provide a good basis for the comparison with the natural pulsed-mode operation of the EBIS, and the partial CW modes tested so far with the EBIS – slow extraction and "accu" modes - are still quite far from a true CW mode. For this reason, the performances of the continuous mode of the ECR will be compared to the pulsed mode of the REXEBIS even though their physical meaning can be quite different. A summary can be found in Table 6.

From this table, REXEBIS shows better performances in terms of the final charge state, of rapidity, and of beam purity (several orders of magnitude lower background). Also the universality of the method is quite appreciable since the charge breeding of any element is a priori possible: even for the light ions efficiencies are well above the percent level. The rapidity of the charge breeding is especially important for short lived heavy isotopes, which will be produced in EURISOL-like facilities with reasonable intensities suited for experiments. An EBIT like magnetic configuration allows in addition spectroscopic investigation of isotopes within the breeder. On the other hand, the ECR charge breeder has much higher intensity capabilities, it can be run in CW mode and pulsing mode, and it is robust as a stand-alone machine and requires very little maintenance. The only fragile part is the RF window, which however can be placed rather far away from the plasma chamber itself. There is in principle no need of cooler and buncher prior to the charge breeder. These are important issues as a EURISOL facility should be producing much higher intensities than ISOLDE (several orders of magnitude), the superconducting LINAC foreseen is in essence a CW machine, and the maintenance around the booster may be hindered by a highly radioactive environment.

Rigorously the comparison of the two methods cannot be limited to the REXEBIS and Phoenix cases. The next section briefly presents a few projects of upgrade and of development of new charge breeders which are going on around the world. For both methods, dedicated developments are undertaken. Some have shown already promising results, such as the upgraded version of the Phoenix developed at LPSC for the SPIRAL 2 project with results reported in the previous section.

	REXEBIS+REXTRAP Pulsed mode	PHOENIX booster CW mode
Efficiency	20→4%	12→ 2% - broader charge state distribution
τ	From 13 to 500ms depending on A	100 ms to 300ms
A/q	2 – 4.5	4 – 8
A	No real limitation	Injection difficult A<20
Mode	Pulsed or partially CW	Continuous or pulsed
Imax	A few nA	> 10 µA
Acceptance	11 mm·mrad (95% geometrical) for 60 keV– estimated [11]	>55 mm·mrad at 18 keV (90%) [30]
Beam emittance	15-20 mm·mrad (95% geometrical) for 20·q keV – measured [11]	10 mm·mrad at 19.5*q keV (90%) [18]
Background	Beside residual gas peaks <0.1pA	Usually >2nA
Reliability	Cathode is fragile (cold be solved with different gun design) and overall system complex	Robust and simple (only ΔV tuning, but quite reproducible settings)

Table 6: Comparison of performances of the Phoenix and REXEBIS charge breeders.

2.7 Charge breeding projects from other facilities or projects

At GANIL, the Nanogan ECR source situated just after the target is producing multi-charged ions of He, O, Ne, Kr and Xe isotopes [38],[39]. It is rigorously speaking not a 1+→n+ scenario since in this case the radioactive isotopes are diffusing as gas atoms or molecules towards the ECR zone, before being multi-ionization and trapped in the Nanogan source. This simplified scheme presents some advantages since there are no losses due to beam transport and injection from a 1+ source to the charge breeder. Also the beam tuning is simplified. However, in this case, the high charge state ion source needs to be situated close to the target. This is not without posing problems: the pressure of the support gas becomes difficult to keep under control as it directly depends on the degassing level of the target. Also the harmful neutron flux in the surrounding of the target degrades the magnetic confinement within Nanogan as it is made by permanent magnets only. With such confinement, the resulting overall efficiencies for one charge state and heavy elements are rather low compared to the Phoenix booster. Last but not least, the production of metallic ions/condensable beams is strongly hindered by the use of a cold transfer section and the small open solid angle that the target presents to the ECRIS plasma. Future upgrade plans of the SPIRAL 1 facility rely on a true 1+ n+ scenario for enlarging the number of possible beams post-accelerated by CIME. Sources with hot surfaces such as surface ionization sources and FEBIAD sources similar to the ones used at ISOLDE will be adapted or developed to permit the production of metallic ions and will be complementary to the already existing ECRIS 1+ sources from GANIL. The Phoenix booster that was presented in this report will perform the charge breeding.

For the SPIRAL 2 project [40], LPSC is developing an upgrade of version of Phoenix for which some very recent results were presented in [32].

At TRIUMF, another Phoenix ECR ion source is currently being tested before its future installation prior to the ISAC-II post-accelerator for which charge states corresponding to A/q < 7 are required [36]. This charge breeder will address the acceleration of heavy ions, while the light ions (A<30) are instead being stripped after a first acceleration stage [41]. The test bench is similar to the ones of

LPSC and ISOLDE. As a main difference, an energy separation stage has been added to in front of the mass separation thereby improving substantially the beam purity. A large part of the stable background after a simple A/q selection can be explained by ion recombination occurring in the extraction region of the booster, creating (n-1)+ ions over a wide fraction of the extraction potential. In this respect, the energy selection removes ions with wrong extraction energy (i.e. cuts the energy tails) which results in a reduced level of stable background. With this additional selection stage, less than 100 pA background level has been observed away from the peaks of C, N, O and other stable contaminants, to compare with a few nA with the mass separation alone. For this setup, modified injection optics is being designed, which should use a two step deceleration [42].

Recently, the so-called KEKCB, the charge breeder from the TRIAC facility, has been successfully used for accelerating radioactive ^{92}Kr and ^{126}In [43]. A/q ratios of about 7 were achieved with charge breeding efficiencies around 7% for noble gases and 2% for condensable elements. More impressive, a very low background could be obtained after the exchange of the plasma chamber pieces to aluminium pieces which were first sand-blasted, then polished by highly-pressurized purified water and finally ultrasonically cleaned. Less than 100 pps of background could be measured after the post-accelerator in the A/q operational range ($6 \leq A/Q \leq 7$).

A proposition of Joint Research Activity within the ENSAR I3 bid for purifying intense radioactive beams from ECR charge breeders and ion sources has been lately formulated by several European laboratories (JYFL, GANIL and ISOLDE). The use of an ion cooler for optimized injection efficiency and a simpler ΔV tuning, UHV components for the charge breeder vacuum system and double energy and A/q separation for improving the beam purity were proposed to be tested with the Phoenix ECR charge breeder, as discussed in [35]. ENSAR will be re-submitted to EC at the end of 2009.

An EBIT type charge breeder has been built in collaboration between TRIUMF and the Max Planck Institute for Nuclear Physics at Heidelberg [44] for TITAN [45], an ion-trap project making use of highly charged rare isotope ions produced at ISAC. It is the first high-intensity EBIT system dedicated to charge breeding of externally injected ions. Operated with a 2A electron gun it is expected to provide breeding times close to those of the system discussed in [46]. The TITAN beam line is equipped with a buffer gas filled RFQ cooler-buncher for singly charged radioactive ions. In addition a cooler for highly charged ions using protons stored in a large Penning trap is planned in the second stage of the installation. First highly charged ions were obtained in November 2008, and successful charge breeding tests with the TITAN-EBIT have been very recently performed with radioactive ^{25}Na with very low electron beam intensity (5mA) yielding low charge states (2+ as most populated one).

A similar EBIT-type charge breeder is planned for the MSU re-acceleration facility [47],[48]. Remarkable enough, the authors of the last article foresee as an option to use of two of these EBIT's in push-pull configuration to accommodate a CW operation for the post-accelerating LINAC.

In the frame of HIE-ISOLDE, the upgrade of the present REXISOLDE facility, REXEBIS could be replaced by a similar charge breeding system.

At GSI the MAXEBIS, developed at the Institut für Angewandte Physik, Universität Frankfurt, Germany, has been reassembled on a new test bench [49]. This test bench has at present two tasks. It is used as a test injector for the HITRAP low energy section [50], which is an essential part of the HITRAP project. The second task is dedicated to investigations of advanced charge breeding methods in the framework of EURONS und EURISOL-DS. Here the goal is to apply known ion source techniques in order to improve the critical charge breeding issues, like efficiency, beam quality and purity. This setup is prepared outside GSI at the Heckhalle and is not required to deliver beams for experiments. The test bench is shown in fig. 5. For A/q-analysis a TOF spectrometer and a multi passage spectrometer (MPS) are available. For the external injection of ions into the MAXEBIS a small surface ion source and a sputter gun are used. For profile measurement a YAG crystal serves as fluorescence screen.

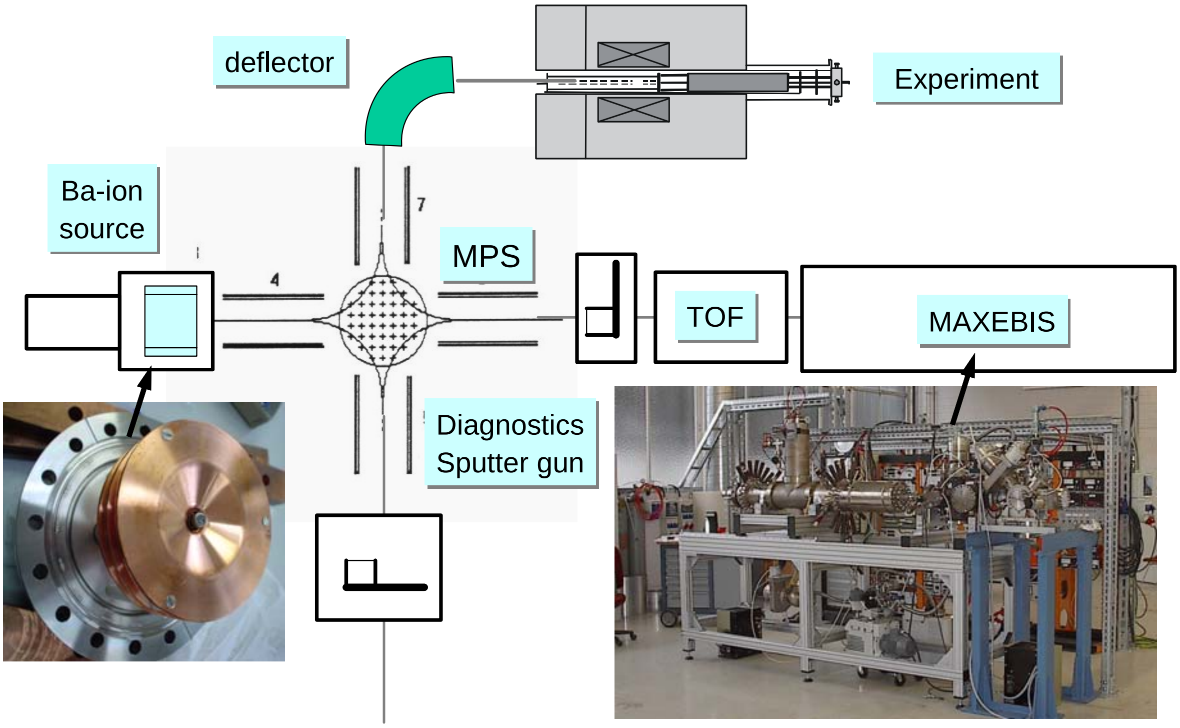


Fig. 5 Setup of the MAXEBIS charge state breeder beam line, TOF= Time of flight.

After first preparation measurements of externally injected Ar-ions from the sputter gun has been performed. Subsequently peaks of highly charge Ar-ions could be detected in the TOF spectra with Ar^{9+} in the maximum. Efficiency measurements could not be performed, because the TOF uses only a fraction of the beam extracted from the EBIS, which is cut out by a fast chopper device.

3 Charge breeding for EURISOL

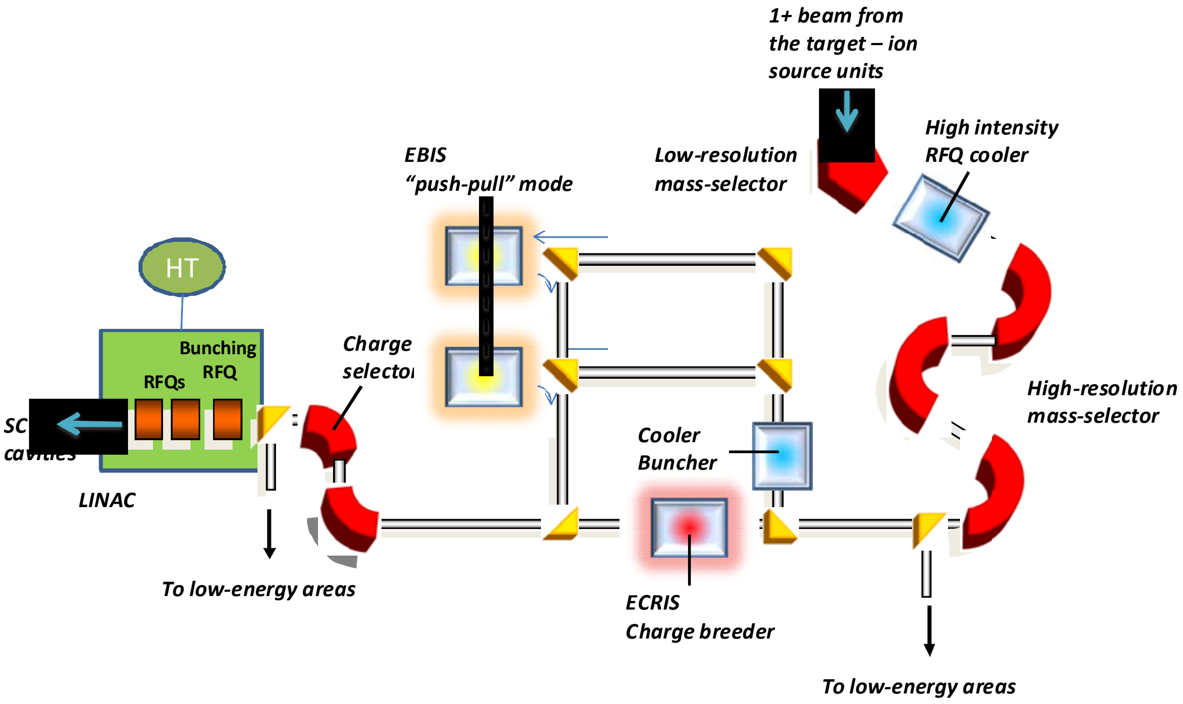
Based on the comparison of Phoenix and REXEBIS performances, and in regards to the first results obtained by the new setups of first upgrades of both devices around the world, a pragmatic solution can be proposed for the system of charge breeding to be used at EURISOL.

3.1 Scope of EURISOL

EURISOL aims at post-accelerating very intense as well as very exotic and low intensity radioactive nuclear beams [51] with a superconducting LINAC up to 100 MeV/A. Such machine is by nature CW. Most intense neutron rich beams such as ^{132}Sn are expected to be produced by a multi-megawatt UCx target, with intensities as high as several 10^{13}/s as 1+ ions. Such beams should be used for producing even more neutron rich nuclides by “cold fragmentation”. Besides these, very exotic neutron rich nuclides such as ^{74}Ni or neutron deficient beams such as ^{62}Ga from 100kW target fragmentation for instance are expected be produced with much lower intensities ($<10^{6}$ particles/s). While in the first case the use of an ECRIS charge breeder seems required, the second case would be much better suited with respect to the beam purity aspect. Higher charge states would also be attainable for short charge breeding times, which could compensate in particular for the unfavourable A/Z ratio of very neutron rich nuclides.

3.2 Proposed solution

Figure 9 presents a possible solution that exploits the complementarities of ECRIS and EBIS charge breeders. They are placed in parallel and one or the other can be used depending on the 1+ beam to charge breed. For a pseudo-CW operation with the EBIS charge breeder, a second EBIS (drawn on Fig. 9) allows for a “push-pull” mode: the ion beam from the buncher is alternatively directed towards one or the other EBIS. While one EBIS is performing the charge breeding, the other one ejects the charge bred ions. Slow extraction could then be used with a release profile as flat as possible.



Detail of the EURISOL Layout

Modified from P. Butler’s presentation, NuPECC meeting June 2007

Figure 9: Detail of the EURISOL layout for accepting both charge breeders. Optionally two EBIS will be run in “push-pull” mode for a pseudo CW operation.

Both ECR and EBIS will be placed on a high voltage platform to stop the 1+ beam within the electron beam or plasma. The 1+ ions energy being fixed to 60keV, the potential of both charge breeders during injection will be of the order of 60kV minus the ΔV for the ECRIS or a few tens of volts for the EBIS charge breeder. Note that in the case of the EBIS charge breeder, the ions are injected and extracted through the same beam pipe as depicted on Figure 9. A kicker can be used for directing the beam to the EBIS during injection and to the LINAC during extraction.

In general there are many advantages to keep the 1+ beam energy fixed. In this case only magnetic elements of the low energy beam lines need to be retuned when the mass or charge state from the charge breeder is changed. In the EURISOL low energy beam lines, only 3 magnetic separators are foreseen: the Low Resolution Separator (LRS), the High Resolution Separator (HRS), and the charge state selector (cf Figure 9). The rest of the beam optics elements are electrostatic (quadrupole doublets or triplets, benders, kickers, switchyards). Moreover, the extraction optics of the 1+ and n+ sources depends strongly on their potentials; even the regime of an ECRIS can be rather different from one biasing tension to another. A 60kV operation guaranties good transport efficiencies within the low energy beam lines and low recombination rate of the charge bred beams in the A/q selector.

Assuming a 60kV operation of the low energy beam lines and of the charge booster, then an energy adaptation of the charge bred beams has to be done for the injection into the RFQ of the post-accelerating LINAC which will accept only mono-kinetic beams of 5 keV/u . For the EBIS charge breeder, the solution is straightforward and already used at REX-ISOLDE: the high voltage is pulsed after injection and before extraction of the charge bred beam. The ions which are trapped and charge bred within the EBIS are not influenced by the quick voltage change. Such scheme can very well be adapted to the “push-pull” mode explained above. For the ECRIS charge breeder, such solution is not possible. Three solutions were then envisaged in the frame of this Design Study, and were summarized in [52]. The first one was consisting in using a fast pulsing RFQ cooler-buncher prior to the charge breeder. The second one consisted in using a pre-buncher cavity prior to the RFQ. The last one proposed to place the RFQ on an HV platform and was formerly proposed for the RIA project [53] . The small energy change could then be well accommodated by the following super-conducting cavities. Latest optics calculations have shown than neither sizeable losses nor significant emittance growth would happen in the transport from the charge breeder to the RFQ if such deceleration would be applied [54]. For this reason and because of its simplicity, this last solution has been found very attractive and is preferred to the first ones, which potentially complicate the beam tuning and induce unwanted losses (~20%).

3.3 Conclusions

The present study within the frame of task 9 has permitted to perform a comprehensive evaluation of present ECRIS and EBIS based charge breeders. Several overviews of the charge breeding activities have been presented at conferences, the last two treating of both EBIS and ECRIS charge breeder together within the EURISOL Design Study [29],[55]. Complementary to EURISOL DS, both techniques have also benefited from the I3 EURONS in the frame of which techniques for regrouping the charge states in EBIS, increasing the charge breeding efficiencies and purification methods for both breeders were developed [10],[32]. Apart from EURISOL, many projects around the world are developing EBIS/T and ECRIS charge breeders as can attest [55]. Among them, SPIRAL 2, SPES and ANL for the CARIBU project and TRIUMF/ISAC will use an ECRIS charge breeder, while MSU is developing their EBIT charge breeder for FRIB on a similar design as the TITAN-EBIT, and MAXEBIS is being commissioned for GSI/HITRAP. In such context the two techniques of charge breeding are expected to rapidly evolve. Second generation ECRIS and EBIS charge breeders are already being built or tested (see section 2.7). This document has presented a compilation of the results obtained in the frame of the Design Study with both charge breeders at ISOLDE, and a brief overview of representative charge breeding projects around the world. Based on this information, a solution has been proposed that should satisfy the needs of a future EURISOL facility as they are defined in previous and present reports. By using both charge breeders in parallel:

- Charge state comprised between A/q=2-3 and A/q=7 can be obtained over the whole chart of nuclides, with lowest A/q for EBIS.
- Efficiencies well above the percent range for any A, Z range can be obtained, with a wide range of isotopes for which efficiencies are around or higher than 5%. ECRIS covers masses above 20 while EBIS covers the whole chart of isotopes.
- Charge breeding times are well below one second (whatever the charge breeder), and are shorter than typical diffusion-effusion times from ISOL targets.
- Intense radioactive beams - up to 10^{13} ions/s - will be charge bred without loss of efficiency by ECRIS charge breeders.
- Clean exotic beams of medium to very low intensity – as low as 10^2-10^3/s – can be charge bred keeping very good beam purity by the EBIS charge breeder.
- CW operation of the superconducting LINAC will be possible using the natural mode of operation of the ECRIS charge breeder, and or two EBIS charge breeders in "push-pull" mode.

In the future, the performances of ECRIS and EBIS may overlap more and more with, for instance, purified beams from ECR charge breeders and true CW operation from EBIS charge breeders. It is not yet clear what will be the frontier of the domain of application between the two methods. The numbers given above are only indicative and will certainly evolve with time. In any case, both techniques are expected to exhibit better and better performances with time as experience is gained along the years and among the numerous projects developing them.

Bibliography

[1] The EURISOL report, http://www.ganil.fr/eurisol/Final_Report.html, and the final report of the RTD-project HPRI-CT-1999-500003, http://www.ha.physik.uni-muenchen.de/jra03cb/

[2] Charge breeding techniques**,** F. Wenander, CERN-AB-2004-035

[3] E. D. Donets, V. I. Ilyushchenko and V. A. Alpert, JINR-P7-4124, 1968

[4] E. D. Donets, Rev. Sci. Instrum. **69**(1998) 614

[5] R. Becker, Rev. Sci. Instrum. **71**(2000) 816

[6] R. Geller, *Electron Cyclotron Resonance Ion Source and ECR plasma*s, IOP, Bristol, UK, 1996.

[7] R. Geller, Annu. Rev. Nucl. Part. Sci. **40**(1990) 15

[8] REX-ISOLDE section of the CERN yellow report CERN-2006-013, *HIE-ISOLDE: the technical options*, editors M. Lindroos and T. Nilsson, CERN , Geneva, 2006

[9] T. Fritioff et al, Nucl. Instrum. and Meth. **A 556**(2006) 31

[10] M. Marie-Jeanne, PhD thesis, *"Investigations of the performances of an ECR charge breeder at ISOLDE: a study of the 1+ n+ scenario for the next generation ISOL facilities"*, Université Joseph Fourier, 2009

[11] REXEBIS – the electron beam ion source for the REX-ISOLDE project, F. Wenander et al. CERN-OPEN-2000-320, and F. Wenander et al., Proc. of the 8th International Symposium on EBIS/T, AIP-Conference-Proceedings, no.572, (2001) p.59-73

[12] F. Ames et al., Nucl. Instrum. Meth. **A 538**(2005) 17

[13] R. Rao et al., Nucl. Instrum. Meth. **A 427**(1999) 170

[14] J. Alessi et al., Brookhaven National Laboratory Internal Report BNL-73700-2005-IR

[15] B. Wolf et al., Rev. Sci. Instrum. **73**(2002) 682

[16] A. Kponou et al, J. Phys.: Conf. Ser. **2**(2004) 165

[17] P. Sortais et al., Rev. Sci. Instrum. **71**(2000) 617

[18] T. Lamy et al., Rev. Sci. Instrum. **77**(2006) 03B101

[19] P. Sortais, Rev. Sci. Instrum. **63**(1992) 2801

[20] N. Chauvin et al., Nucl. Instrum. Meth. **A 419**(1998) 185

[21] T. Lamy et al., Proceedings of the 14th international workshop on ECR ion sources, CERN, Geneva, Switzerland, May 1999

[22] T. Lamy et al., Rev. Sci. Instrum. **73**(2002) 717

[23] L.T. Sun et al., Nucl. Instrum. Meth. **B 235**(2005) 524

[24] D. Leitner and C. M. Lyneis, Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee, USA

[25] D. Leitner et al., Nucl. Instrum. Meth. **B 235**(2005) 486

[26] D. Leitner et al., Rev. Sci. Instrum. **77**(2006) 03A302

[27] G. Ciavola et al., Proceedings of the 17th International Workshop on ECR Ion Sources and Their Applications, Institute of Modern Physics, Lanzhou, china, September 2006

[28] T. Thuillier et al., Rev. Sci. Instrum. **77**(2006) 03A323

[29] F. Wenander, Nucl. Instr. and Meth. in Phys. Res. **B 266**(2008) 4346

[30] F. Wenander et al, Rev. Sci. Instrum. **77**(2006) 03B106

[31] A. M. Hurst et al., submitted

[32] EURONS, charge breeding JRA, http://www.gsi.de/informationen/jofu/EURONS/, and reports on associated deliverables http://www.gsi.de/informationen/jofu/EURONS/Deliverables.html

[33] D. Voulot et al., Nucl. Instr. and Meth. in Phys. Res. **B 266** (2008) 4103

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

[35] P. Delahaye and M. Marie-Jeanne, Nucl. Instrum. and Meth. in Phys. Res. **B 266** (2008) 4429

[36] R. Geller, T. Lamy and P. Sortais, Rev. Sci. Instrum. **77**, 03B107 2006

[37] F. Ames et al, Rev. Sci. Instrum. **77**(2006) 03B103

[38] A. Villari et al, AIP Conf. Proc. **576**(2001) 254

[39] R. Leroy et al, AIP Conf. Proc. **749**(2005) 137

[40] N. Lecesne et al., Rev. Sci. Instrum **79** (2009) 02A907

[41] P. W. Schmor, Proceedings of the 17th international conference on cyclotrons and their applications, 2004, Tokyo, Japan.

[42] F. Ames et al., Rev. Sci. Instrum. **79** (2008) 02A902

[43] N. Imai, Rev. Sci. Instr. **79** (2008) 02A906

[44] G. Sikler et al., Eur. Phys. J. A25 (2005) 63

[45] J. Dilling et al., Int. J. Mass. Spec. 251(2006) 198

[46] R. E. Marrs and R.D. Slaughter, AIP Conf. Proc. **475**(1999) 322

[47] Isotope Science-facility at Michigan State University, MSUCL-1345, November 2006

[48] S. Schwartz et al., Rev. Sci. Instrum., **79** (2008) 02A706

[49] O. Kester et al., Rev. Sci. Instrum. **77**(2006) 03B102

[50] F. Herfurth et al., AIP Conf. Proc. **793**(2005)278

[51] Final report of the EURISOL feasibility study, and its Appendix C *report from the ion source and target task group* http://www.eurisol.org/site02/eurisol.php?ddoc=home#

[52] P. Delahaye A. Jokinen, O. Kester, M. H. Moscatello, T. Stora, *Review of the different options for the velocity matching section issue,* EURISOL DS task note, task 9 “Beam preparation”, http://www.eurisol.org

[53] P. Ostroumov et al., in Proceedings of the 2005 Particle Accelerator Conference, Knoxville, TN, USA, pp. 3360–3362.

[54] G. Normand, *Beam dynamics simulations,* EURISOL DS task note, task 6 “Heavy ion accelerator design”, http://www.eurisol.org

[55] T. Lamy, J. Angot and T. Thuillier, Rev. Sci. Instrum **79** (2008) 02A909