Preliminary report on the charge-breeding techniques study

Task 9: Beam preparation

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Goal of the study

In the framework of the EURISOL-DS, the study and development of charge breeding techniques is of primary interest for the post-acceleration of intense beams from a second generation ISOL facility. Extracted as singly charged ions from the target-ion source units, the radioactive isotopes have to be bred to an n+ charge state prior to their post-acceleration, for an optimized efficiency and compactness of the post-accelerator [1]. This so called “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^{12} ions/s). Some additional constraints arise from the post-accelerator specifications, such as the mass-over-charge ratio acceptance, and/or the final energy that can be reached.

Choice of the criteria

Because of the constraints given above, the charge breeding technique has to be efficient, rapid and versatile to allow a post-acceleration of the 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.

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 can be experienced for heavy ions. This method, although the most rapid method, might be not the best choice for EURISOL, as it brings additional cost to the facility because of a required pre-acceleration stage to reach the minimum energy required by the stripping process [2]. In order to cover a wide mass range such pre-stripper section requires low frequency rf-structures for extreme A/q range like the GSI UNILAC injector. 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], [6] and [7].

During the past 4 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 ^{156}Eu with very different half-life, chemical properties (alkali, metallic, noble gas ions) including fragments of molecular beams coming from ISOLDE. Recently, tests were performed with ^{181}Ta and ^{238}U for the preparation of future experiments with heavy ions. Second, a Phoenix ECR charge breeder, purchased by the CCLRC Daresbury laboratory, is currently installed on a parasitic beam line of the General Purpose Separator GPS, for charge breeding tests. The primary aim of having such a test bench is the comparison of the performances of this booster with the preparation stage of REX-ISOLDE. Secondary objectives such as the use of multiply charged ions for nuclear physics experiments are in addition actively studied [8]. During the past 2 years, the efficiencies of the Phoenix booster were characterized with a variety of stable beams and a few radioactive beams. Both the "native" 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 will report on the implications of using these techniques for a future EURISOL-like facility. Some input from test benches and solutions used in other ISOL facilities, such as GANIL and TRIUMF, are also taken into account.

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:

$$(1)\ Q = 3.32\cdot 10^{11}\cdot L\cdot I_e\cdot E^{-1/2}$$

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 [9].

A detailed description of REXEBIS can be found in [9]. 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 [10]. 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 [12] 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 $\delta(A/q)/(A/q)$~150.

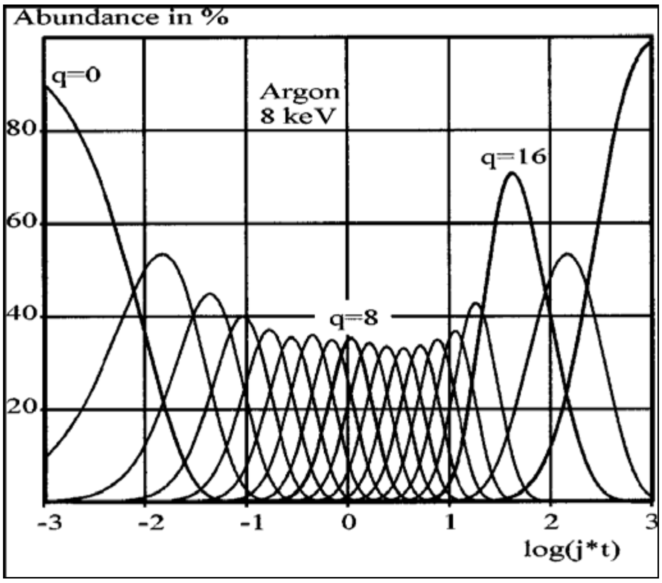

Fig. 1: Charge state distribution of Ar ions as a function of the j*τ factor. Taken from [5].

B-Field	2T
Electron beam	Cathode LaB6 $j_{cathode}$<20A/cm^2 $j_{trap}/j_{cathode}$~10; $j_e=j_{trap}$<200A/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 [9]
Emittance out	15-20 mm·mrad (95% geometrical) for 20·q keV – measured [10]
Max. energy dispersion	50*q eV - estimated [9]
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*).

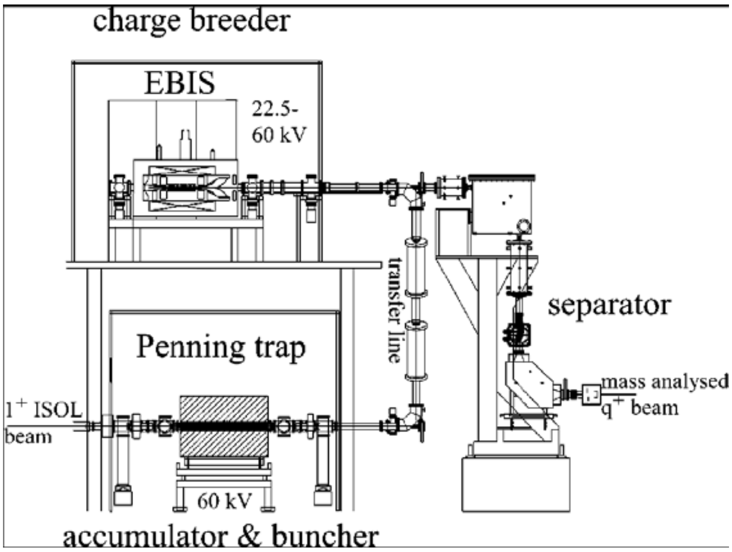

Fig. 2: Low energy stage of REX-ISOLDE: REXTRAP, REXEBIS and the A/q and E separator. Taken from [13].

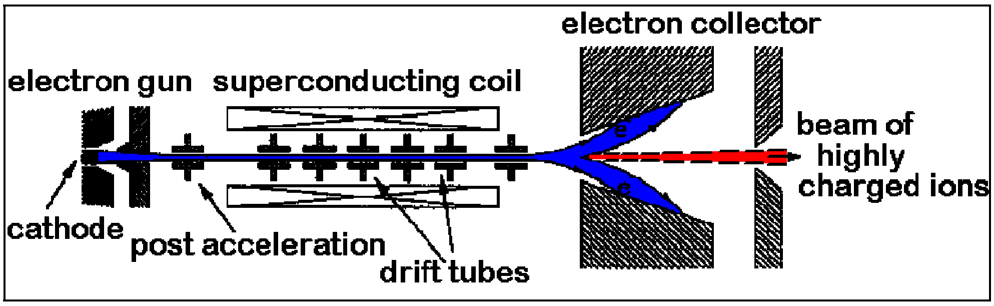

Fig. 3: Simplified cross-section view of an EBIS.

B-field	6T
Electron beam	Cathode IrCe j_{trap}>575A/cm^2 I_e=10A E=20keV
Trap	L=1.5m Theoretical capacity $1.1\cdot10^{12}$ positive charges Capacity $3.4\cdot10^{11}$ positive charges (experimental value with TestEBIS I_e=8A L=0.7m)
Acceptance	20 mm·mrad (RMS) at 11keV- estimate from [15] ~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].

Key parameters for the ECR charge breeder

The reader can refer to [6],[7],[16],[17] 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 [16]. 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 [16],[17],[18],[19]. 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 should 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%) [20]
Emittance out	10 mm·mrad at 19.5*q keV (90%) [17]
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 $5\cdot10^{-5}$mbar.l/s

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

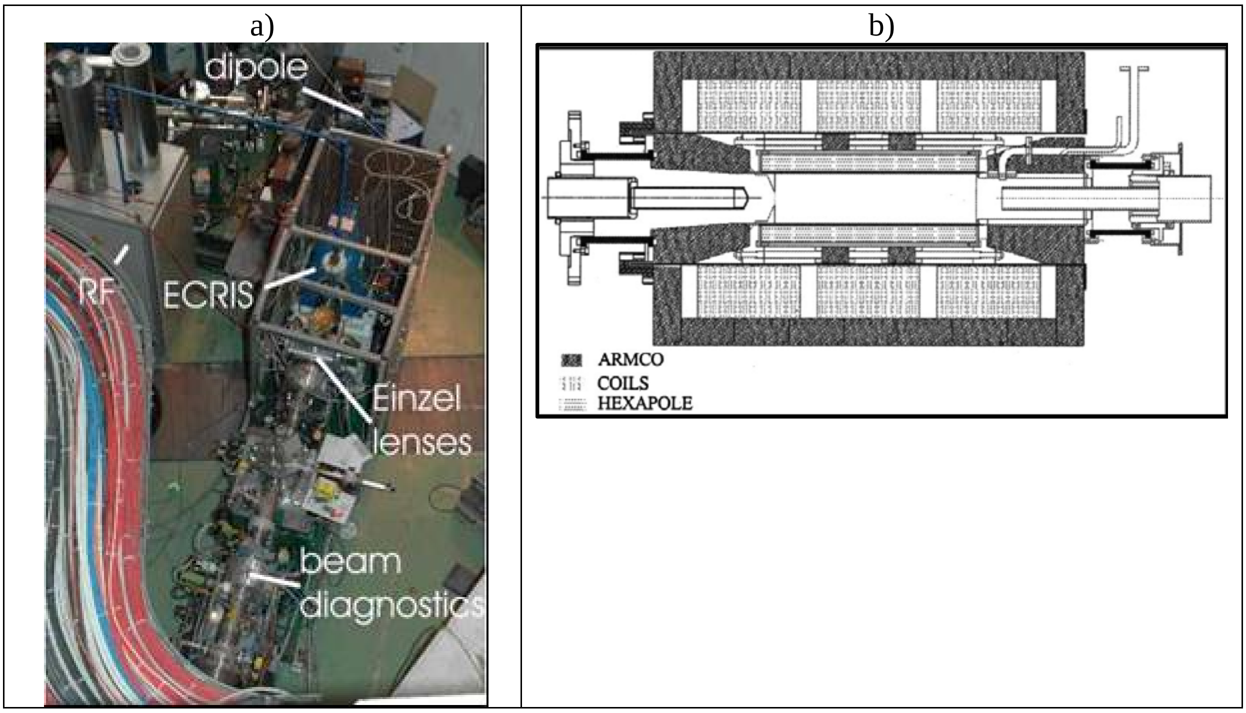

Fig. 4 a) The ECR Phoenix booster test bench at ISOLDE. b) A cross-section view of the Phoenix ECR charge breeder taken from ref [21].

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 [17]. In pulsed mode up to 400nA of Rb^{1+} was injected in MINIMAFIOS [16],[19], 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 [17]. 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 [22], VENUS [23],[24],[25], MS-ECRIS [26] and A-PHOENIX [27]. 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.

REXTRAP/REXEBIS performance

The results obtained with REXEBIS and REXTRAP at REX-ISOLDE until September 2005 have been summarized in ref. [28] (ICIS05 conference). Table 6 regroups the charge state, charge breeding time and efficiencies obtained during 2006 when stable operation conditions where maintained, and a specific result obtained in 2004 with ^{70}Se [29]. The list of isotopes agrees with the table presented in [28]. It has to be noted that the efficiencies given here are including those of the preparation trap REXTRAP, which is routinely performing with an efficiency around 50%. The efficiencies of the REXEBIS alone are therefore about two times higher than quoted in the table, except in the case of Li and Be ions for which the trap efficiency was measured to be around 25% only. For these latter cases the REXEBIS efficiency is about 20-25%. As part of the overall beam preparation, the cooling time has been included in Table 6. For a fair comparison, the ECR charge breeding time shown later in Table 8 has therefore to be compared to the sum of this cooling time plus the EBIS charge breeding time. At this stage, the use of REXTRAP for ion cooling and bunching has been found mandatory in most of the cases to match the limited acceptance of REXEBIS in transverse and longitudinal direction and to match the time structure.

The results 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. The use of molecules has been shown to be a very efficient way for producing pure beams of Al^{7+} (from AlF+, broken up in the trap and charge bred in the EBIS) and Se^{19+} [29] (from $SeCO^+$, cooled as a molecule in the trap, broken up and charge bred in REXEBIS). The 1+ beam was injected as pulses from REXTRAP and extracted as pulses to the separator.

Isotope	Cooling time (ms)	Charge breeding time (ms)	charge	Total efficiency (%)	A/q		Comment
39K10+	20	12	10	15	3.9	Stable	
7Li3+	20	18	3	6	2.333	Stable	
9Li3+	50	15	3	5	3	Radio	Low repetition rate due to LINAC
10Be3+	50	15	3	5	3.333	Radio	Low repetition rate due to LINAC
19F5+	20	7	5	7.8	3.8	Stable	
23Na9+	30	28	9	10	2.555	stable	
27Al7+	20	10	7	16.7	3.857	stable	Injected as AlF molecule
29Mg9+	30	28	9	6	3.222	radio	Very large error bars
71Cu20+	100	98	20	11	3.55	radio	Large error -> overestimated?
65Cu20+	100	68	20	7.8	3.25	stable	Too short breeding time
67Cu19+	100	68	19	12.6	3.526	radio	
65Cu19+	100	68	19	11.1	3.421	stable	
70Se19+	60	58	19	3	3.684	radio	2004 injected as SeCO molecule
68Zn21+	80	78	21	12.4	3.238	stable	
116Cd31+	250	248	31	9.6	3.742	stable	
133Cs33+	200	198	33	10.8	4.03	stable	
136Xe34+	200	198	34	8.7	4	stable	
181Ta40+	200	198	40	2.9	4.525	stable	Tuning not optimum
238U52+	500	498	52	4.3	4.577	stable	

Table 6: Results with REXTRAP and REXEBIS obtained during 2006.

Usually, a 50 Hz repetition rate is used for masses below 40. This year, a slow extraction mode was successfully tested, which permitted enlarging the EBIS pulse from 40 to 300µs without any efficiency loss. Another more exotic mode was tested in 2005, the so-called continuous injection of $^{39}K^{+}$ [28]. The ejection was still pulsed, though. The results of the tests of this so-called “accu” mode are given in the table 7.

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 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

Table 7: “Accu”-mode results.

In principle this mode opens up new possibilities for high intensity beams for which the Penning trap becomes a limiting factor. These latest developments should be described in more details in a forthcoming publication.

14GHz Phoenix Booster performance

The latest results with the Phoenix ECR were presented at the ICIS05 conference [30]. Table 8 regroups the efficiencies obtained in 2005 with stable beams and in 2004 with stable and radioactive beams [31]. The results are for continuous mode operation (continuous injection and extraction).

1+ ion	N+ ion	$\eta(\Delta\eta)$ %	$\tau_{cb}(\Delta\tau cb)$ (ms)	q_{max}	A/q_{max}	Remark
39K+	39K10+	1.7(0.2)	100(50)	10	3.9	[30]
40Ar+	40Ar8+	8.4(-)	-	8	5	[31]
84Kr+	84Kr13+	6.7(-)	-	13	6.46	[31]
96Sr+	96Sr14+	3.5(0.7)	-	14	6.85	[31] $T_{1/2}$=1.07s
116Sn+	116Sn21+	6.3(2.8)	200(50)	21	5.52	[30]
129Xe+	129Xe18+	5.9(-)	-	18	7.17	[31]
132Xe+	132Xe21+	6.2(0.7)	230(30)	>21	<6.29	[30]
133Cs+	133Cs26+	1.7(0.2)	200(50)	26	5.12	[30]
139La+	139La23+	2.4(0.3)	200(50)	>23	<6.04	[30]
139La+	139La23+	2.7(-)	-	>23	<6.04	[31] LaO^+ 2005
208Pb+	208Pb25+	3.4(0.7)	-	25	8.32	[30]
209Bi+	209Bi28+	2.3(0.2)	330(50)	28	7.46	[30]
238U+	238U26+	2(-)	100(30)	26	9.15	[30]

Table 8: Results obtained for cw-mode operation of the Phoenix booster. From [30],[31].

For the elements marked in yellow the efficiencies given were believed to be non-optimized because of occasional problems related to the parasitic beam line operation of GPS. The results of 2004 present lower charge states for comparable masses, and in general shorter breeding times (about 100ms for ^{238}U). These differences can be explained by the use of different magnetic field configurations. 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+ [31]. Some preliminary tests with light molecules CO^+ didn't give any concluding results. No further tests with light ions injection were performed. However, it has to be noted that the light ions injection is known to be rather inefficient for this type of charge breeder. The reason is the difficulty of matching the injected ion velocities with those of the ions of the plasma. In this latter review paper [17] 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.
Some preliminary tests were also performed with pulsed mode using 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. [19] and are presented as for comparison in the same table.

1+ ion	N+ ion	η(Δη) %	$\tau_{cb}(\Delta\tau cb)$ (ms)	q_{max}	A/q_{max}	Ref.
86Kr+	86K13+	1	500(100)	13	6.6	[29]
132Xe+	132Xe18+	2.2	600(100)	18	7.33	[29]
85Rb+	85Rb15+	2.5%	Confinement time 520 ms	15	5.67	[19]

Table 9: Afterglow results from refs. [29] and [19].

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 [32]. An UHV version of the Phoenix booster is studied at LPSC Grenoble.

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 at the present stage of the study. However, the results obtained with the ECR afterglow mode are still not sufficient to provide a good basis for the comparison with the EBIS pulsed-mode operation. For this reason, the continuous mode of the ECR was compared to the pulsed mode of the REXEBIS. A summary can be found in the table 10.

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. Especially short lived heavy isotopes, which will be produced in EURISOL-like facilities with reasonable intensities suited for experiments, can be bred in reasonably short periods of time with an EBIS breeder. 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 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. These are principal 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.

	REXEBIS+REXTRAP Pulsed mode	PHOENIX booster CW mode
Efficiency	15→4%	10→ 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<40
Mode	Pulsed	Continuous or pulsed
Imax	A few nA	> 1 μA
Beam emittance	15-20 mm·mrad (95% geometrical) for 20·q keV – measured [11]	10 mm·mrad at 19.5*q keV (90%) [17]
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

Table 10: Main characteristics of the described charge breeder types.

Considerations from other facilities and setups

At GANIL, the Nanogan ECR source situated just after the target is producing multi-charged ions of He, O, Ne, Kr and Xe isotopes [33],[34]. 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. The pressure of the support gas becomes difficult to keep under control as it depends on the degassing level of the target. In this configuration the production of heavy metallic ion beams in the required charge is not possible. Moreover, as an efficient magnetic confinement is difficult to obtain due to absence of hexapole with permanent magnets which are excluded in this high neutron flux area) high charge states cannot be produced. The resulting overall efficiencies for one charge state and heavy elements are rather low compared to the Phoenix booster.
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 [32]. 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 [35]. 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.

Very recently an EBIT type charge breeder has been build in collaboration between TRIUMF and the Max Planck Institute for Nuclear Physics at Heidelberg. The charge breeder [36] will be used for TITAN [37], 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. The system has been built, successfully passed first off-line tests and is now being brought into operation at TRIUMF. Operated with a 2A electron gun it is expected to provide breeding times close to those of the system discussed in [38]. 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. So far, no injection tests with the TITAN-EBIT have been performed. A similar EBIT-type charge breeder is planned for the MSU re-acceleration facility [39].

At GSI the MAXEBIS, developed at the Institut für Angewandte Physik, Universität Frankfurt, Germany, has been reassembled on a new test bench [40]. This test bench has at present two tasks. It is used as a test injector for the HITRAP low energy section [41], 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.

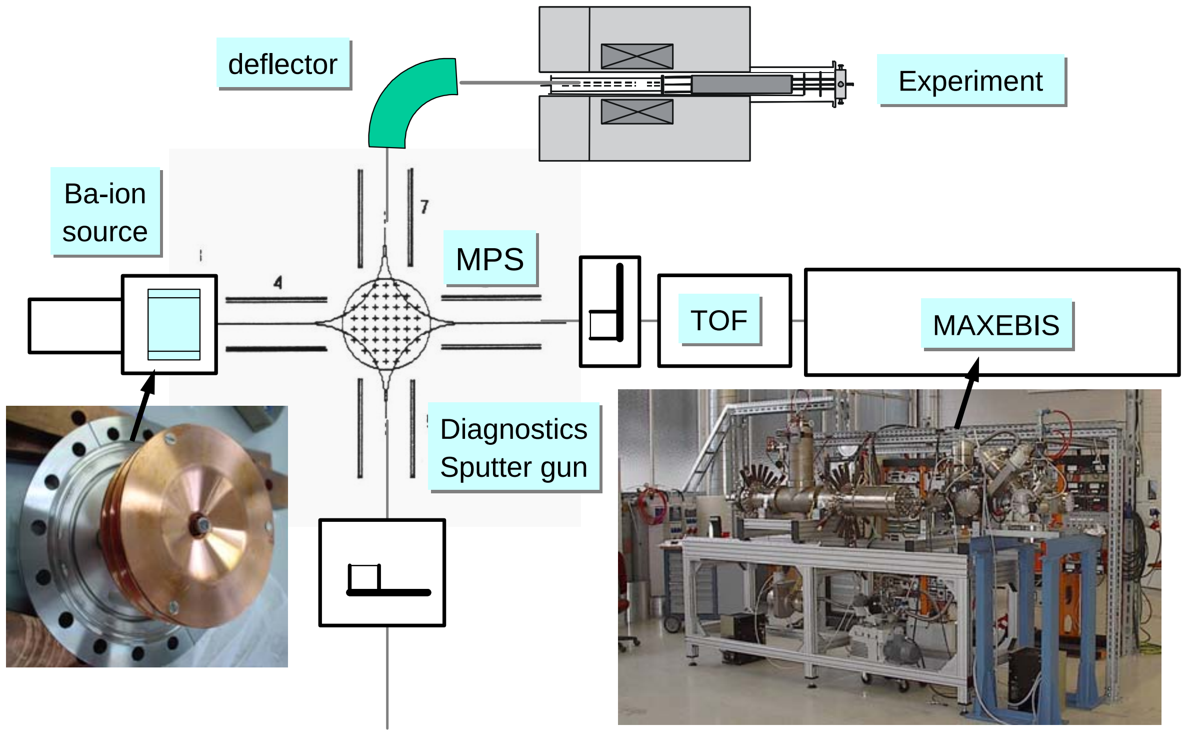

Fig. 5 Setup of the MAXEBIS charge state breeder beam line, TOF= Time of flight.

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.

Preliminary conclusions

The present study has shown, up to now, very good performances for the EBIS type charge breeder, which is particularly adapted to the ISOLDE beams. The high charge states obtained allow for a compact post-accelerator. For any (A, Z) isotope the charge breeding times are far below one second, shorter than the typical diffusion/effusion times from ISOL targets. The overall efficiencies are always above the percent level. The beam purity has usually been satisfying, even for quite exotic beams. The ECR Phoenix charge breeder has been shown to be a powerful machine in terms of intensity capabilities, reliability and simplicity. Having the possibility to operate in cw mode makes it suited for a superconducting LINAC, but the injection energy into the RFQ has to be adjusted with a pre-buncher. In this mode of operation the efficiencies and charge breeding/confinement times for m>40 are in the same order of magnitude as in the REXEBIS case. On the other hand, it presents still a few features that would need to be improved:

- The injection of light masses is quite inefficient.
- The high stable beam background, which is in the order of the nA intensities even far from the ^{12}C, ^{14}N, ^{16}O peaks.
- The longer breeding time and lower A/q in comparison to the EBIS/T.

These issues are being addressed mainly at LPSC Grenoble, while ISOLDE concentrates on the beam purity issue. The use of a more elaborate injection scheme for improving the light ion injection is under investigation [17]. For the reduction of the stable background, an UHV ECR is being designed. In this case the recombination process in the extraction region would be strongly suppressed. At ISOLDE, a two-step separator similar to the one of TRIUMF has been calculated [42]. Its installation after the ISOLDE Phoenix booster or at the Phoenix test bench of LPSC is under investigation.

Concerning the potential upgrades, there is no doubt that a RHICEBIS-like source would provide highly charged beams with very short charge breeding times and higher intensities, mainly because of a higher electron current density. With such a large electron beam current, the charge capacity and the acceptance would be greatly increased. Furthermore, advanced charge state manipulation techniques are being developed for this type of charge breeder in the frame of the EURONS charge breeding JRA03 [43], opening new possibilities for narrowing of the charge state distribution mainly in pulsed operation. In the case of an upgrade of the ECR charge breeder, a RF higher frequency would lead to higher electron densities providing, as in the case of the EBIS upgrade, higher charge states and shorter charge breeding times. The performances of the pulsed mode of the ECR charge breeder would surely be improved by using a stronger magnetic confinement matching the higher RF frequency. At last, the use of UHV components and of a mass and energy separation would permit a much better beam purity.

Related works, references

For the interested reader, former similar studies for the RIA, EURISOL and RHIC projects can be found in [44] and [45].

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