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CHARGE BREEDING TECHNIQUES

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Abstract

The numerous newly built and forthcoming post-accelerators for radioactive ions, produced with the isotope separator on-line (ISOL) technique, all have a need for an efficient method to accelerate the precious primary ions. By increasing the ion charge-to-mass ratio directly after the radioactive ion production stage, a short and compact linear accelerator can be employed. Not only the efficiency, but also the rapidity of such a charge-to-mass increasing process, called charge breeding, is a crucial factor for the often short-lived radioisotopes.

The traditional foil or gas stripping technique was challenged some five to ten years ago by novel schemes for charge breeding. The transformation from 1^+ to n^+ charged ions takes place inside an Electron Beam Ion Source/Trap (EBIS/T) or Electron Cyclotron Resonance Ion Source/Trap (ECRIS/T) by electron-ion collisions. These charge breeders are located in the low-energy part of the machine before the accelerating structures. Because of the capability of these devices to produce highly charged ions, mass-to-charge ratios between 4 and 9 are easily obtained.

In this article the performance and the features of the above listed charge breeding concepts will be compared and discussed. An outlook on charge breeders for the next generation of radioactive ion beam facilities is also given.

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1 Motivation

The world wide construction of radioactive beam facilities [1] clearly reflects the strong scientific interest of physics with such beams. The interest has raised requests for radioactive ions accelerated to and above the Coulomb barrier, i.e. to a few MeV/u. Also lately, with the beta-beam scenario [2] and its GeV radioactive beams appearing on the stage, even more research is performed on the post acceleration of ISOL-produced beams. The post-accelerators, optimised for high quality ISOL-produced beams, provide easy energy variability, high energy precision and small emittances. An efficient transformation of the radioactive beams by so-called charge breeding, or $1^+ \rightarrow n^+$ ion conversion, at an early stage in the accelerator chain has a critical influence on the lay-out of the post accelerator (see Fig. 1) and several advantages [3]. The post accelerator can be compact and relatively simple as the mass-to-charge acceptance of the acceleration structures is limited (A/q typically between 3 and 9). On the other hand, by introducing charge breeding the complexity of the low-energy stage in the machine increases, which has to be weighed against the operation reliability of a long low-charge accelerator. The energy per nucleon is given as $W_{nucleon}$ [MeV/u] = $E_{acceleration}$ [V/m] * q/A [e/u] * L [m], where $E_{acceleration}$ is the mean field gradient (~5 MV/m) and L the effective length of the accelerator. If a 1^+ ion of mass 50 is to be accelerated to 5 MeV/u, the length of the low frequency, large cavity, linear accelerator (LINAC) becomes in the order of 50 m, with a price tag around 25 MUSD (assuming a LINAC cost of 0.5 MUSD per meter acceleration field)[1]. A number of other properties are of importance for the charge breeding processes, such as the efficiency, rapidity, beam properties etc, which all will be addressed below for each method.

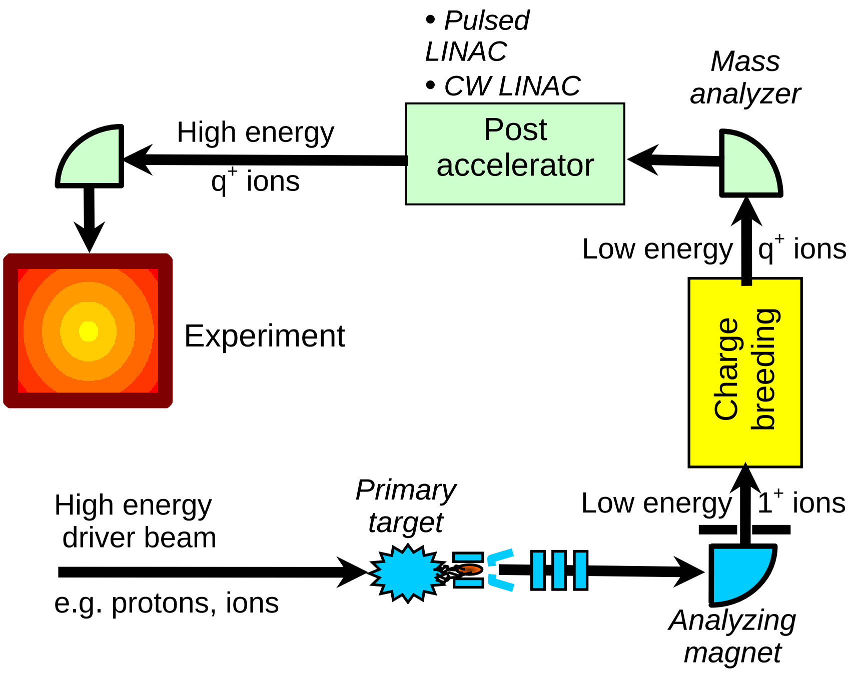

Figure 1. Principal scheme of an ISOL-beam with charge breeder and post accelerator.

The techniques available for charge transformation to higher charges are gas/foil stripping, EBIS and ECRIS charge breeders. Fig. 2 illustrates the principal difference between the methods. The two latter concepts have been available for almost 10 years now, and are sufficiently mature for an evaluation and comparison with the former. The ECRIS charge breeding studies commenced [4] at ISN, Grenoble, in 1993 for the now abandoned PIAFE project. Injection and charge breeding of stable isotopes into an EBIS have been performed since the early 90's, but the first dedicated efficiency tests were carried out at Saclay [5] and at MSL in Stockholm [6] in 1994. Radioactive ions were first charge bred in an EBIS at ISOLDE in 2001.

[1] Price estimation based on an average of LINAC2 (CERN) and the post accelerators EURISOL and REX-ISOLDE.

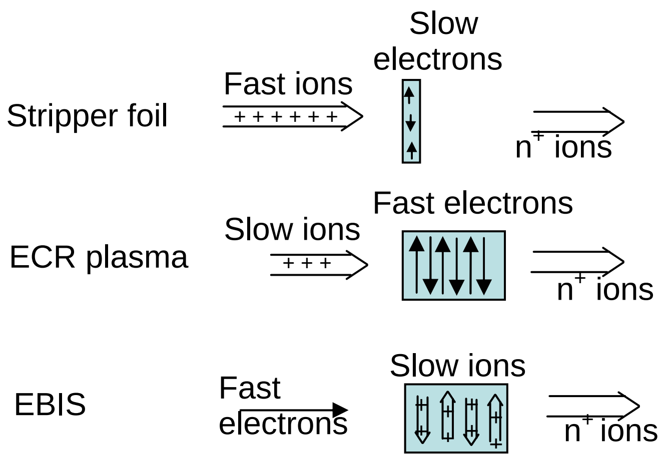

Figure 2. Three different techniques for $1^+ \rightarrow n^+$ ion conversion: stripper, ECR plasma and EBIS. In each case the electron cloud is hot and dense relative to the ions, so successive ionisation is achievable.

2 Classic stripping techniques

A traditional way of creating highly charged ions is to use either foil (for instance carbon or Al/Al_2O_3) or gas (mainly noble gases) stripping. The pre-accelerated singly charged ions are stripped in the dense electron cloud. For gas and foil stripping pre-acceleration of 5 to 25 keV/u and >150 keV/u, respectively, are mandatory. The low-energy gas stripping produces only multi-charged ions of low charge, while foil stripping (one or two stage) at higher energies can deliver fully stripped ions. A bunch rotating rf cavity is mandatory in order to generate a time focus at the stripper to minimise the longitudinal emittance growth due to energy straggling. The stripper features are briefly summarized below.

* *Uncomplicated method relying on passive elements (except for the bunch rotator).*
* *No special prerequisites (emittance or beam structure) for the injected beam.*
* *Outgoing beam properties*
    - *transversal emittance blow-up of incoming beam with several ten percent.*
    - *energy spread of a few per mille.*
* *No beam contamination from the stripping process permits low beam intensities.*
* *Sub-millisecond half-life isotopes are feasible as the delay time is only the flight time through the foil.*
* *Narrow charge state distribution for light ions and high charge states achievable.*
* *Charge state tuning possible by changing the stripping foil or gas density.*
* *Macro bunching capability non existent.*
* *Overall efficiency of a few percent.*
* *Very high beam capacity >100 eμA.*
* *Lifetime limited by the foil breaking[2], ~50 mC/cm^2 for 3.2 MeV Ne^+ at 3-4 μA [7].*
* *High cost of the pre-accelerator.*

As already pointed out, a critical issue for charge breeding of radioactive ions is the efficiency of the process. An example of a post accelerator for radioactive ions using stripping is the SPES design scenario [8]. With a bunching efficiency of 65%, gas stripping efficiency of 40% at 8 keV/u, and a foil stripping efficiency of 20% at 500 keV/u, an overall efficiency of 4% for ^{132}Sn is expected. For heavier ions the total transmission in a machine using strippers drops below 1%. The RIA concept predicts higher efficiencies: ~30% for $^{40}Ar^{9+}$ and ~10% for $^{120}Sn^{22+}$, for single-charge state acceleration.

To increase the efficiency for heavy ion beams, where multiple stripping is foreseen, multi-charge state acceleration is an option, as considered for the RIA project. Instead of selecting a single charge state after the

[2] A gas jet avoids the problem, but complicates and increases the cost of the machine.

stripping stage, a broader band of charges ($\Delta q/q$ ~10%) is accelerated leading to approximately the double particle intensity [9]. The disadvantage is an increased transversal and longitudinal emittance of at least a factor 3 compared with single charge-state acceleration.

3 The EBIS as a charge breeder

3.1 Penning trap - EBIS concept

The charge multiplication in an EBIS is done by electron bombardment by a mono-energetic electron beam with energies typically between 3 and 20 keV, or higher. The ions are trapped in a magneto-electrostatic trap, established by a combination of a solenoidal magnetic field, the electron beam and a longitudinal electrostatic potential created by cylindrical electrodes surrounding the electron beam. Presently, one EBIS working as charge breeder for radioactive ions is operational, the REXEBIS [10] at the REX-ISOLDE [11] post-accelerator at CERN. An exhaustive description of EBIS in general is found in reference [12].

The ISOLDE beam can not be injected into the EBIS with high efficiency without beam preparation. Thus a Penning trap, the REXTRAP [13,14], is installed in front of the EBIS. It accumulates the continuous ISOL-beam, bunches (extraction time ~10 μs) and phase space cools (cooling time ~10-20 ms, transverse emittance >10 π·mm·mrad for 80% at 30 keV) the semi-continuous beam. A considerably higher injection and trapping efficiency into the EBIS is obtained compared with continuous injection, and ISOL emittances up to >30 π·mm·mrad (at 60 kV) can be accepted. The extracted pulse is transferred to the EBIS via a transport line, and because of the buffer gas pressure (~10^{-3} mbar of Ne or Ar), several stages of differential pumping have to be inserted into the transport line to ensure a high vacuum inside the EBIS. All elements with exception for He can be handled by the trap with efficiencies (extracted cooled ions / injected ions) up to 50%. No inherent physics prevents the efficiency of the Penning trap to be increased by a factor of two, to values close to 90%. Space charge effects start occurring for more than 10^5 ions/pulse, with an efficiency decrease and emittance increase as a result [15,16]. That means, presently the Penning trap-EBIS concept has a limited ion throughput of ~10^8 ions/s.

Because of the pulsed beam injection into the EBIS, its potential can be ramped between injection and extraction and thereby the potential of the ISOL production part is decoupled from the injection energy into the LINAC. The price for the REXTRAP and REXEBIS construction was about 1.1 MUSD in total, manpower excluded.

3.2 EBIS performance

3.2.1 Breeding capacity

If the current limitation of the Penning trap is disregarded, the maximum capacity is given by the space charge of the electron-beam trap inside the EBIS. The REXEBIS has a theoretical capacity of ~$5\cdot10^{10}$ charges/pulse, and so far $2.3\cdot10^{10}$ charges of residual gas beam have been extracted. Assuming only radioactive ions in the beam gives that $3\cdot10^9$ Na^+ can be charge bred into Na^{8+} per pulse. This is one order of magnitude larger than the number of ions that can be accumulated in the Penning trap. Nevertheless, poorly cooled beams of Na^+ larger than 100 pA have indeed been injected into the EBIS and charge bred, but with a worse efficiency compared with low intensity beams. Even though the efficiency decreases to some percent for high current beams, the overall ion throughput is still increased.

3.2.2 Breeding efficiency

The charge breeding inside an EBIS is element independent, apart from the breeding time, as the ions do not interact with any surfaces. A number of stable and radioactive ions have already been charge bred and injected into the LINAC for physics experiments, see Table 1. Although, helium isotopes can not be cooled with the sideband cooling in the Penning trap due to charge exchange phenomenon with the buffer gas, all other elements can.

Stable	*Radioactive*
$^{7}Li^{2+}$	$^{9}Li^{2+}$
$^{23}Na^{7+}$	$^{24-29}Na^{7+}$
$^{27}Al^{8+}$	
$^{24}Mg^{8+}$	$^{30}Mg^{8+}$
$^{39}K^{10+}$	
	$^{74,76}Zn^{18+}$
$^{84}Kr^{20+}$	$^{88}Kr^{21+}$
$^{133}Cs^{32+}$	
$^{138}Ba^{26+}$	
	$^{153}Sm^{28+}$
	$^{156}Eu^{28+}$

Table 1. Elements that have been cooled and charge bred in the REX-ISOLDE buncher and breeder.

The extracted charge-bred ions have a charge state distribution, with approximately 25% of the ions in the main charge state (more for light elements and if the electron-beam energy is close to the ionisation potential of a closed shell in the electron configuration). Only one specific charge state is selected so the inherent efficiency is typically <30%. The best attained efficiency result for the REXEBIS (including beam transport from trap to EBIS, EBIS injection-breeding-extraction, and a mass separator efficiency of 80%) is >10% for potassium breeding. The average efficiency over the whole range Li to Cs is between 5 and 10% [17], and for higher intensities the efficiency can drop to as low as 2%. To this value the trap efficiency of ~40% should be included.

3.2.3 Breeding time

The mean charge state is easily selected by simply varying the breeding time. For longer confinement times, up to 1 s or similar, almost fully stripped uranium can be achieved in high performance EBIS [18]. In the REXEBIS one reaches a mass-to-charge ratio of 3 to 4 for A<50 within less than 20 ms. For heavier elements, for instance ^{132}Cs, a mean charge state of 32^{+} was reached within 150 ms with the source's present performance. The breeding time is inversely proportional to the electron-beam current-density j_e, which presently is between 100 and 150 A/cm^2 in the REXEBIS. That means a higher electron current not only increases the space-charge capacity of the EBIS but also decreases the breeding time. Higher electron beam densities have been achieved in other sources. For the total cycle time of the buncher-charge breeder, the cooling time of the Penning trap (typically shorter than 20 ms) should be added.

3.2.4 Beam properties

The injection efficiency is significantly higher for a bunched beam (injection time <50 μs) than for cw injection. An energy spread of the order of 50 eV can be accepted. The extracted beam can either be cw or bunched. In the REXEBIS a t_{FWHM} of ~20-30 μs with an estimated energy spread of a few ten eV times q is achieved, but faster (down to <10 μs) and slower (ms) extraction is in principle feasible, resulting in higher and lower energy spread, respectively. The extracted ion beam has appropriate beam properties (time structure and emittance) from a linear accelerator point of view. Furthermore the bunching improves the signal-to-noise ratio for low-intensity beams.

The acceptance of an EBIS is limited, approximately 10 π·mm·mrad (95% at 60 kV) [10], which in many cases is smaller than the emittance of a primary radioactive ion source. The geometrical emittance of the REXEBIS has been measured as ~10 π·mm·mrad (95% at 20 kV) [19], but the value is strongly dependent on the ion neutralisation of the electron beam. For longer confinement times, i.e. increased compensation level due to higher charge state and more residual gas ionisation, the emittance amounts to 70 π·mm·mrad or similar.

3.2.5 Beam contamination

The purity of the extracted beam is of high importance for most experiments. The REX-ISOLDE achromatic mass separator [20] has a limited A/q-resolution of 100-150, which is not always sufficient to resolve a radioactive peak from a close stable ion peak originating from residual gas ionisation. Then, if possible, a different A/q value has to be selected. As the EBIS is an ultra high vacuum device operating in the low 10^{-11} mbar region, it is capable of handling fA beams. The noise level beside any A/q-peak is not measurable, that means smaller than 100 fA. In spite of the good vacuum, the residual gas peaks can be an order of magnitude larger than the radioactive ions, as shown in Fig. 3.

A ^{9}Li run [21] at REX demonstrates the difficulty with overlapping A/q-peaks for lighter elements. $^{9}Li^{3+}$ was not viable as it was overlapped by a strong C^{4+}, but also $^{9}Li^{2+}$ was overlapped by the residual gas isotope $^{18}O^{4+}$. In this particular experiment the oxygen rate at the target was $3 \cdot 10^{4}$ ions/s, to be compared with the $1 \cdot 10^{5}$ ions/s of ^{9}Li. However, the release time profile of lithium from the target unit peaked at 80 ms after the proton-impact, and by using gating, a 15 times higher yield of Li than O at the experiment was achieved.

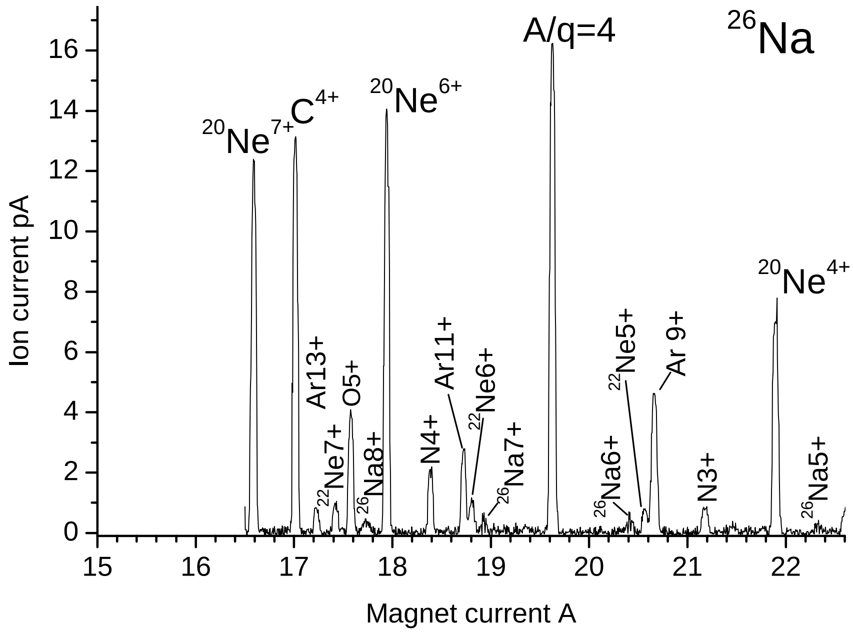

Figure 3. An extracted mass spectrum from the REXEBIS illustrating the ability to resolve sub-pA radioactive beams from the background noise and nearby residual gas peaks with considerably higher intensity. (The Na yield is low due to non-optimised setup.)

3.2.6 EBIS drawbacks as a charge breeder

The Penning trap-EBIS is a fairly complicated setup that involves beam cooling, injection into traps, beam transport and delicate technical issues such as super conductivity, pulsed traps, ultra high vacuum etc. The complexity is a major drawback for this concept. The limited lifetime of the electron gun cathode is a second subject, although this can be technically improved.

4 The ECRIS as a charge breeder

4.1 The ECRIS principle

In an ECRIS charge breeder the singly charged ions are slowly injected into a plasma with hot electrons. The electron ensemble has a broad energy distribution, with a mean energy of some keV. The electron density inside the plasma is about 10^{11} to 10^{12} electrons/cm^{3}. The plasma is confined in a magnetic structure, a so-called minimum B-field configuration, with field strength of ~0.5 T. An rf power of several 100 W is injected to heat the free electrons that successively strip the ions from their electrons. The ionic confinement varies between some 10 and several 100 ms. The ECRIS concept is thoroughly described in references [22,23], and the breeder aspects are covered in references [24,25,26].

The ECRIS as a charge breeder is not as complex as the EBIS. Another technical advantage of the ECRIS is the possibility to put only the plasma chamber on high voltage while maintaining the power consuming items (coils, rf generator etc) on ground potential. The operation time is long as the ECRIS has no cathode limitations. The disadvantage with the cw beam injection is the need for either variable extraction energy from the primary radioactive ion source to carry out the energy matching to the LINAC, or a variable energy RFQ after the ECRIS.

4.2 ECRIS performance

4.2.1 Beam properties

The ECRIS accumulates a continuous beam and there is no need for a bunching trap within the scheme, although, an RFQ cooler would improve the injection efficiency by reducing the energy spread. As the ions have to be stopped by collisions within the plasma, the injection energy has to be within 1 eV, otherwise the ions may be lost at the chamber walls. The extracted beam has an energy spread of some eV times the ion charge, and can be cw or pulsed. The pulsed extraction is generated by the so-called afterglow method. The ECRIS then works as a trap and buncher [24,27], and when the rf power is switched off a short pulse of ions is released. For the PHOENIX source [28] the afterglow length is around 2 to 4 ms, and to some extent tuneable.

The acceptance of an ECRIS is large compared to the EBIS. An acceptance of 55 π·mm·mrad (90% at 12 kV) for a 2 μA Ar^+ has been measured [29], and similar values are claimed for metallic ions. The emittance for the Ar charge bred into 6^+ was 45 π·mm·mrad (90% at 12 kV, 1.2 μA). A smaller emittance than acceptance is due to the centering of the highly charged ions in the plasma.

4.2.2 Breeding capacity

The ECRIS has a very high current capability as charge breeder. Several μA can be injected with high efficiency, for instance 8 μA of Ar^+ was charge bred into 8^+ with a 10% efficiency. The space charge capacity is mainly determined by the microwave frequency and the source volume. From the PHOENIX booster operating at 18 GHz, $2 \cdot 10^{12}$ charges of charge bred ions have been extracted per pulse when operated in afterglow mode [30].

4.2.3 Breeding efficiency

In a charge breeding ECRIS the ions can leave the plasma in both directions, towards the injection side and downstream. This means that the global efficiency (the summation of all extracted charge states) can at most become ~50%. An optimized ECRIS charge breeder has a performance close to this, so the particle loss inside is small. Thus the activation of the machine is also low. The charge state distribution is broader than for an EBIS due to the continuous injection, with approximately 20% of the extracted particles in the maximum charge state. The ECRIS works as breeder for any element, and any 1^+ ion source. Noble gases (can be recuperated after wall collisions) and heavier elements (easily stopped in the plasma) show the highest efficiency.

The daily production of A/q~7 for a number of elements was demonstrated by a collaboration between TRIUMF Vancouver and LPSC Grenoble. For example, ^{115}In, ^{109}Ag, ^{64}Zn, ^{120}Sn, ^{88}Sr, ^{69}Ga, ^{90}Y, ^{39}K, ^{85}Rb and ^{59}Co were all charge bred within about 10 days with an efficiency of at least 3%. In general, an efficiency of at least 3% for A>40 is easily attained (within an hour for relatively large, >100 nA, stable ion beams), and with some tuning it can be augmented to >6%. The efficiency is sustained when the injected current is decreased. For afterglow extraction, a lower efficiency of ~2% [27] has been demonstrated with the old MINIMAFIOS source, but higher values could be expected from the PHOENIX. An extracted charge-state spectrum is shown in Fig. 4.

4.2.4 Breeding time

The extracted charge state is determined by the confinement conditions of the ions inside the plasma. The confinement is intricately dependent on the tuning parameters of the source, such as the rf power, the magnetic field and the support gas pressure. The better the confinement, the higher the charge state. The PHOENIX produces ions with a typical mass-to-charge ratio <6 within 50 ms for A<50. This source type also reduced the confinement time by a factor 3 to 10 compared with the older MINIMAFIOS as a result of its better tuning range. The breeding times have been measured in the PHOENIX at 10 GHz for a number of elements, for instance for Ar^+ to 9^+ ~25 ms, Kr^+ to 14^+ 60 ms, Ag^+ to 19^+ 25 ms. For the higher frequency of 14 GHz, Sr^+ was bred to 14^+ in 50 ms and Sn^+ to 19^+ in 20 ms.

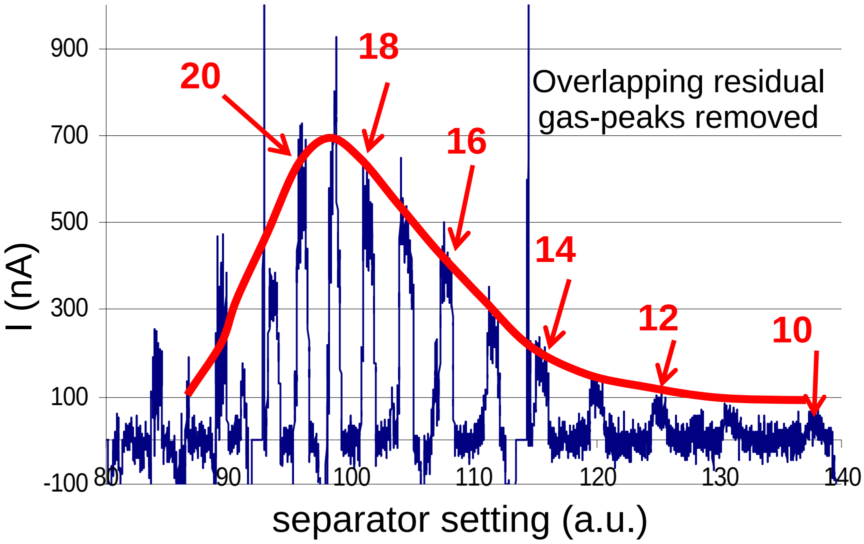

Figure 4. A typical charge-state spectrum for extracted beam from a PHOENIX charge breeder. A 520 nA In^+ beam was injected with 20 keV. The rf power was 340 W at 14 GHz, and the total extracted current measured 1.1 mA. The conversion efficiency from 1^+ to 18^+ was 6%, with a global efficiency of 45%.

4.2.5 Beam contamination

In contrast to the EBIS, the ECRIS is not a ultra high vacuum device, but has a working pressure of around 10^{-6} mbar. This also means the residual gas peaks are larger and more numerous in the mass spectrum, and in some cases orders of magnitude larger than the radioactive ion peaks. The total extracted current from the source is around 1-2 mA. Low intensity In^+ beams down to 10 nA have successfully been charge bred with maintained efficiency [30]. Although, for the KEK-JAIRE charge breeder a current noise level of several tens of nA was measured over the range $6<A/q<7$ [31]. The residual gas problem is being addressed, NEG pumping is being tested and ultra high vacuum devices are at the design stage. Clean, mono-isotopic buffer gas can be used, as well as Wien filters for the mass separation. A certain buffer gas pressure has to be preserved to keep the plasma ignited and to stop the incoming 1^+ ions.

4.2.6 ECRIS drawbacks as a charge breeder

The tuning of an ECRIS can be challenging due to the many parameters (RF power and tuning, magnetic field, buffer gas pressure etc) and care has to be taken at high power levels, but it is in general a technically simpler device than an EBIS. The main disadvantages are the high extracted current of stable ions from the residual gas and the large emittance.

5 Future development

5.1 EBIS

As different ideas of how to increase the performance of the trap-EBIS charge breeding system are discussed in ref. [32], only the latest advancements are presented here.

At Brookhaven a successful development of a highly performing EBIS, the RHIC Test EBIS [33,34], has been carried out. A 10 A pulsed electron beam at 20 keV has an electron density larger than 400 A/cm^2. In each pulse, injected Au^+ ions are transformed to $1.5\cdot10^9$ Au^{33+} within 40 ms (with 8 A and 0.7 m long trap) and the charge capacity of the trap exceeds $3\cdot10^{11}$ charges. The injection efficiency has not been measured, but the acceptance should be large because of the large electron beam. The drawbacks of such a large electron beam are a high energy spread and a large transverse emittance. The high electron density enables a short breeding time, which means higher efficiency for short-lived species, and a larger ion turnover.

A novel cooling scheme for the Penning trap, the so-called rotating wall compression, could possibly increase the number of stored ions per bunch by some orders of magnitude. Tests are on-going and $5\cdot10^8$ ions per bunch have been cooled, but the results are not final [35]. The EBIS ionisation efficiency (as defined above) was approximately 5%.

5.2 ECRIS

The hope is that modular sources, such as Advanced PHOENIX (A-PHOENIX) [36], can further decrease the afterglow pulse length and reduce the confinement time.

By raising the microwave frequency, the electron density of the plasma increases, following the scaling rule $n_e \propto \omega_{RF}^2$. A higher density means a more effective thermalisation, i.e. better capture and efficiency, higher charge states and larger charge capacity. The negative aspect is the need for higher B-field, as $B_{resonance} \sim \omega_{RF}$, often involving superconducting coils. The next generation ECRIS (GyroSERSE [37], A-PHOENIX, VENUS [38]) will operate with 28-40 GHz, creating plasma densities of 10^{13} cm^{-3} or more. Optically coupled, pulsed, UHF devices are also foreseen [39].

An improved residual gas suppression is of high priority for the ECRIS. Thus ultra high vacuum and bakeable devices are under consideration. Alternative pumping methods (for instance NEG) are being tried out, together with mono-isotopic buffer gas.

Presently (autumn 2003) another two PHOENIX Booster charge breeders for radioactive ions are under installation: one at the ISAC facility at TRIUMF, and the second at ISOLDE. A third breeder is under commissioning at KEK-JAIRE. It should deliver A/q<7 at an operation frequency of 18 GHz with normal conducting coils. A breeding efficiency of 6.5% for Xe^+ to Xe^{20+} has been reported [30].

5.3 Other advanced concepts

An idea proposed by E. A. Lamzin [40], and recently also investigated by A. Villari, GANIL, addresses the limited efficiency for charge breeding within an ECRIS. Instead of losing all unwanted charge states in a post-source spectrometer, the ions are re-injected into the breeder until the correct charge state is attained. The recycling is done by an electrostatic ring, connected to the injection and extraction side of the ECRIS. The 1^+ ions, and the desired n^+ ions, are injected and selected, respectively, in a large magnetic merger/selector (see Fig. 5). Due to the symmetry of an ECRIS, the ions go in both directions through the electrostatic ring, and the inherent ~50% extraction loss from an ordinary ECRIS can therefore also be avoided with this concept. Nevertheless, the method increases the hold-up time and the success is heavily dependent on the rapidity and efficiency of the individual stages. So far no experimental proofs have been obtained.

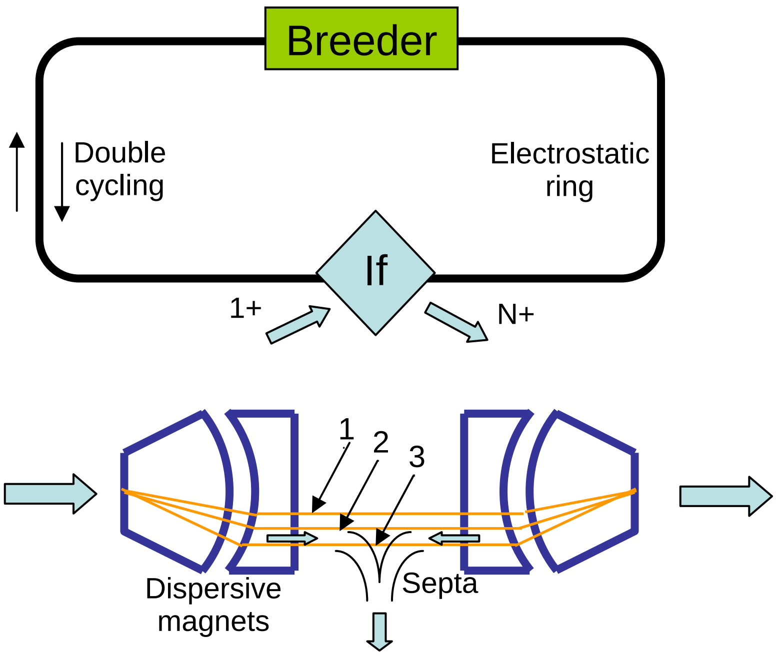

Figure 5. Top: the double directed electrostatic ring connected to the ECRIS charge breeder and the If-condition gate. Below: the If-gate in the form of a large dispersive magnetic separator/merger. Singly charged ions are injected on the 1^+ track, and desired n^+ ions extracted and merged by two septa.

Within the EU 5th Framework RTD a Charge Breeding Network has been active for 4 years [41]. A future Advanced Charge Breeding project is expected to be launched within the EURISOL network in the near future, with the aim to address advanced concepts for boosting the efficiency, rapidity and low/high beam capability of the EBIS and ECRIS.

6 Conclusions

The feasibility of charge breeders has been proven with the REX-ISOLDE Penning trap – EBIS concept and the ECRIS studies at LPSC Grenoble. The systems can handle ion life-times down to some 10 ms, with a charge breeding efficiency of around 5%. Each machine has its virtues and drawbacks. The clean EBIS is capable of handling low intensity beams, <1 nA, but the Penning trap-EBIS setup is relatively complicated. The ECRIS has a large charge capacity, and is the natural choice for beams larger than 1 nA. However, the beam contamination is significantly higher. Neither of the two charge breeders can so far manage very short-lived isotopes. Then the technically simpler stripper technique has to be used. Its efficiency is comparable, and very clean high or low current beams can be dealt with. The price tag for the pre-accelerator is the main drawback. An attractive solution for higher energies is to combine an ECRIS charge breeder with a stripper foil to further enhance the moderate charge state out of the ECRIS.

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