# ACCELERATION OF HEAVY IONS GENERATED BY ECR AND EBIS

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*Abstract*

ECR and EBIS have become well-known ion sources for most heavy ion accelerator projects. The basic difference arises from the method, how energy is provided to create dense energetic electrons: An ECR uses microwave heating of a magnetically confined plasma, while in an EBIS the energy comes from a power supply to accelerate an electron beam and focus it to high density in a strong solenoidal magnetic field. Basically ECR sources are dc sources of heavy ions but the afterglow extraction also provides intense mA pulses in ms. In contrast to this EBIS sources provide an intense ion pulse in 1÷100 μs and therefore find application in feeding synchrotrons. This determines most of the accelerator applications: ECR sources have very successfully extended the range (and life) of cyclotrons, while EBIS has found application at high energy facilities. For radioactive beam facilities, both kind of sources are in use. ECR sources in the trapping mode (ECRIT) perform the ionization (charge breeding) of high intensity primary beams, while EBIS can reach higher charge states at lower emittance, which provides an improved signal to noise ratio for rare isotopes.

## INTRODUCTION

In the beginning of EBIS (1967) and ECR (1971) development both sources have been important to improve the charge to mass ratio over that available from Penning sources, which so far had been used exclusively for cyclotrons and linacs. Today both sources (including the electron beam ion trap, EBIT) are seen as charge breeding devices, which can put the burden for the production of delicate singly charged ions to specialized ion sources. This also includes accelerators for rare isotope production using the ISOL or the fragmentation method with subsequent gas stopping [1].

The production of highly charged ions is governed in both sources by the same physical collision processes: sequential ionization by successive electron impact, heating of ions by small angle Coulomb collisions, cooling of ions by ion-ion-collisions, and internal loss of highly charged ions by charge exchange and radiative recombination as well as losses to the wall of the ionisation chamber. Both sources differ very much from each other in construction and in the mix of collision and loss processes, which makes it worth to have a closer look on common and differing features. EBIS as well as ECR ion sources may be purchased from companies today, nevertheless for sophisticated applications in cutting edge research, ECRIS and EBIS devices are still being developed. In particular for heavy ion accelerators, high performance devices are in construction. In case of ECRIS, those devices use super-conducting (SC-) magnets and operate with 28 GHz Microwave frequency [2]. In case of EBIS/T, high performance devices use multi ampere electron beams, strong magnetic fields from SC- magnets and high electron beam current densities [3].

## BASICS OF ION PRODUCTION IN EBIS/T AND ECRIS

The sequential ionization needs – depending on the charge state to be reached and the density of ionizing electrons – a certain time to evolve. Therefore the ions require a confinement. In EBIS/T the trapping is electrostatic by the negative space charge of the electron beam, which cannot be exceeded by the ionic space charge. This limits the yield of extracted ions but simple laws then allow to design an EBIS with a required ion yield straightforward (BNL [4]). In ECR sources the trapping mechanism is not so clear. Some people in the past have favoured a magnetic trapping, but also an electrostatic trapping is possible by the ECR-zones, where electrons are heated up and have similar density as nearby but a higher energy. These ECR-zones therefore are regions with more ionic than electronic space charge, causing the electrostatic potential to form a barrier for ions. This has been well proven by trapping measurements with an ECRIT, although another explanation has been given by the authors at that time. Accepting the electrostatic barrier then immediately explains the after-glow operation by opening this barrier after switch-off of the rf and the action of the biased disk by using the space charge of an axially oscillating electron beam to lower the barrier in the reflection zone of these electrons. It also explains the cooling of trapped ions by collisions with ions from the mixing gas, as explained later.

The ionizing collisions of electrons, however, are at the same time Coulomb collisions. In spite of the fact that the electron mass is negligible with respect to the mass of heavy ions, many Coulomb collisions transfer energy from the electrons to the ions. Therefore the ions are heated considerably, in particular the highly charged ones, which are bombarded during the whole confinement time. By setting the ionization time equal to the heating time, an unique relation is obtained for the ionic energy in dependence of the ionic mass A, the cross sections for stepwise ionization $\sigma_{i-1\to i}$, and the electron energy $E_e$:

$$E_i \approx \frac{10^{-18}}{AE_e}\sum_i^q \frac{i^2}{\sigma_{i-1\to i}} \qquad (1)$$

For energies much higher than the ionization energy cross sections in Eq. (1) are falling with $1/E_e$ and electron heating of ions becomes independent of electron energy. The dependence on the ionic mass is consistent with the "isotope effect" found by Drentje [5]. The result of Eq. (1) for 3 keV electrons and for noble and residual gases is shown in Fig. 1. For higher charge states than $Ne^{9+}$, $Ar^{16+}$, $Kr^{27+}$, and $Xe^{35+}$ the ion energy by electron heating exceeds 10 eV which will correspond to a transverse energy of extracted ions of the same order.

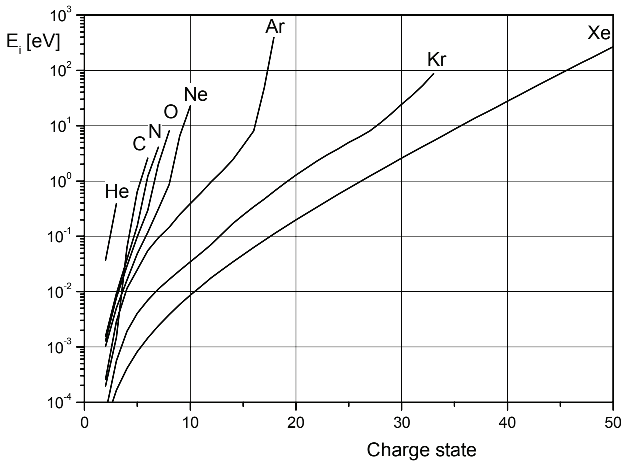


Figure 1: Ion energies by Coulomb collisions with 3 keV electrons during stepwise ionization.

While EBIS/T traps are deep enough to confine much hotter ions, this becomes a problem for the shallow trap of an ECR. In any case, this transverse energy will require attention for ion beam extraction and transport, which will be explained later. While charge exchange can be suppressed strongly in EBIS/Ts, which are essentially UHV-devices, it cannot be avoided in ECRs, due to the required high support gas pressure in the range of $10^{-8}$-$10^{-7}$ mbar for the generation of the plasma. Charge exchange with neutrals has two distinct effects on the resulting charge distribution. The charge spectrum is wider and becomes limited to higher charge states.

This is well demonstrated in Fig. 2 for a charge breeding simulation of lead without and in Fig. 3 including charge exchange at a residual gas pressure of $10^{-8}$ mbar. The simulation in Fig. 2 shows an interesting feature when mono-energetic electrons are used for ionization, which is not possible for ECRs. The ionization energy of $Pb^{54+}$ is at 5026 eV. Providing only 5025 eV inhibits the ionization of $Pb^{54+}$ resulting in a maximum abundance of this ion. This shell effect is most pronounced at closed subshells of the ions, like for $Pb^{54+}$, which is alike nickel.

Including charge exchange shows in Fig. 3 that at a given instant, say $j*\tau=100$, the charge state distribution contains 12 instead of 7 different charge states at the same time. Also the highest charge state is less than $Pb^{54+}$. These results become even more important, when considering the classical procedure in ECRs and EBIS/T, to cool the heated ions by ion-ion collisions.

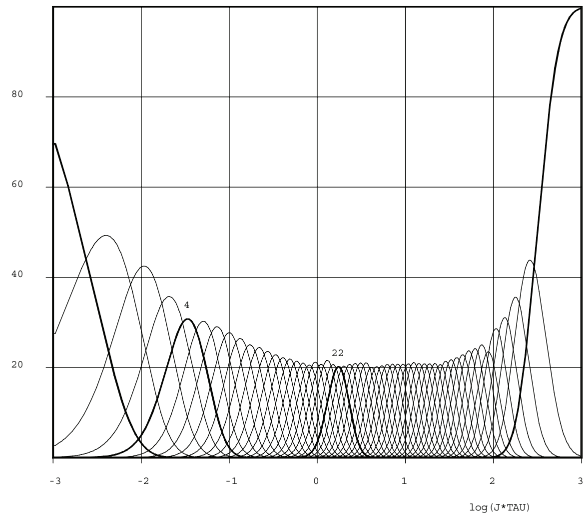


Figure 2: Charge breeding of lead at 5025 eV electron energy, without radiative recombination and without charge exchange.

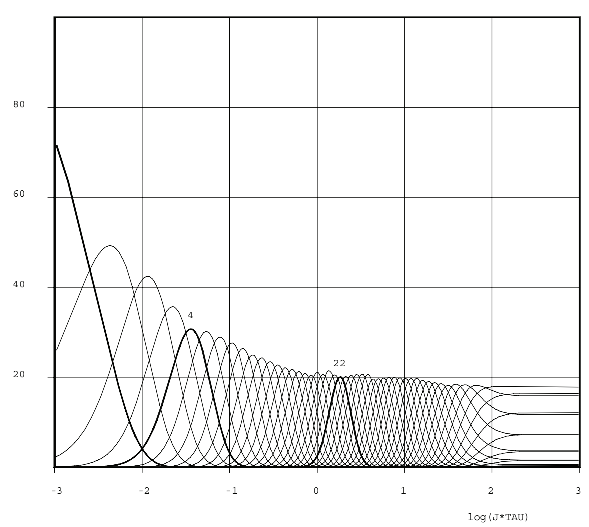


Figure 3: Charge breeding of lead at 5025 eV electron energy including charge exchange at a pressure of $10^{-8}$ mbar.

In order to create cold ions inside the source, an additional gas species must be fed in (gas mixing). The ions from this gas are absorbing energy by Coulomb collisions from the wanted ions. Then the competition starts, which kind of ion can survive in the potential trap and which one will be evaporated out. It is therefore important that the cooler ions cannot be ionized to the same high charge state as the wanted ones. Only then the trapping potential is less for the cooler ions than for the wanted ones. In literature this is quite often confused by referring to the ion mass. This is not wrong, because the ion mass is also an indicator for the highest possible charge state, but it is hiding the underlying physical effect.

## MAGNETIC EMITTANCE

Busch's theorem in electron (and ion) optics reflects the conservation of the angular momentum of a charged particle, when moving through solenoidal magnetic fields. This has noticeable effects for ions generated in high magnetic fields and extracted to almost vanishing fields. By the conservation of the angular momentum each ion will have a skew trajectory, increasing the 2D subsections of the transverse emittances. The following formulation of the "magnetic" (caused) emittance has been given [6], which can well dominate the emittances caused by thermal effects and by aberrations

$$\varepsilon = \frac{\pi}{4}\sqrt{\frac{2eq}{M}}\frac{B_z r^2}{\sqrt{U_0}} \quad [m] \tag{2}$$

Here $B_z$ is the magnetic field at the birth place of the ion, $q$ and $M$ are the charge and mass, and $U_0$ is the extraction voltage of the ion. For ECRs and EBIS the magnetic fields are now in the region of a few T, even higher for EBITs. The extraction voltage is also quite the same – a few 10 kV. Therefore the main parameter influencing the magnetic emittance is r, the radius of the ion at $B_z$, which is typically 5 x $10^{-3}$ m for ECRs and $10^{-5} \div 10^{-4}$ m for EBIS. This is the reason, why ECRs have a much larger magnetic emittance than EBIS devices. In ECRs the magnetic emittance usually dominates, while in EBIS the emittance by transverse velocities and by aberrations is the dominating part. Ion-ion cooling has led to an interesting effect in ECRs which is similar to the effect observed in EBIS/T devices: highly charged ions concentrate near the axis and therefore have a reduced magnetic emittance to lower charged ones in contradiction to Eq. 2. This has been proved by emittance measurements done at ECRIS [7].

## BEAM TRANSPORT AND INJECTION INTO THE HEAVY ION ACCELERATOR

The transport and charge state separation of extracted ions in particular for ECRIS devices is a matter of ongoing discussions, although some solutions have been found, which seem to be satisfactory [8,9,10]. One has to distinguish between high current sources for beam production at high performance driver linacs and sources used for charge state boosting of ions prior to their acceleration. In the latter case the purification especially of weak secondary beam or rare isotopes from residual gas contamination is an issue. In case of intense beams of highly charged ions for injector and driver linacs, the space charge of the extracted beams leads to a significant beam spreading.

### *Transport of Beams of Charge Bred Ions*

Usually an achromatic mass and charge state separator is used downstream an EBIS/T to select the required charge state and isotope prior to the injection into the subsequent accelerator [11]. The principle of such a Nier-type achromatic separator is shown in Fig. 4. Typical for this application, a mass resolving power of R~100 for beams of emittances of as high as 0.6 mm-mrad normalized is adequate for most beams of interest. Emphasis is given to obtain achromatic mass separation since the electron impact processes in EBIT type breeders tend to create beams of non-negligible energy spreads [12]. Usually the intensity of charge bred exotic ions is several orders of magnitude lower than the intensity of the rest gas contaminants, even in the EBIS/T case. Hence the maximum overlap with a residual gas peak should not exceed 0.01% of the ion in the corresponding charge state. Therefore the achromatic system compensates the energy dependence of the magnets resolving power and is a velocity filter that purifies the spectrum from ions which did undergo charge exchange and have therefore the wrong kinetic energy.

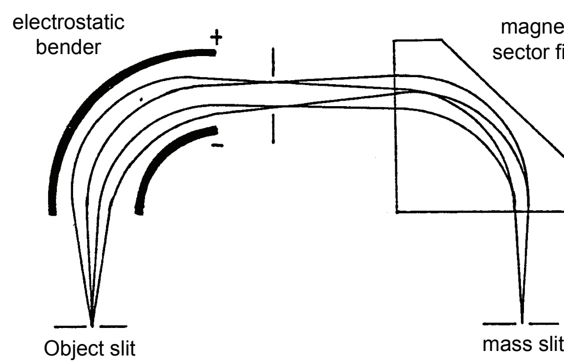


Figure 4: Principle of an achromatic Q/A-separator or a separated function velocity filter.

Even in case of an ECR charge state breeder, the extracted beam intensity is several mA and therefore the beams are space charge dominated, because a certain plasma density is required, which can only be delivered by the support gas. The intensity of typical secondary beams is much lower and does not contribute significantly to the space charge of the extracted ion beams. Here the usual approach is a triode extraction system to allow for space charge compensation, a short drift through a pumping station and a subsequent double focusing magnet for charge state and mass selection [13,14]. In case of ECRs used as charge state breeder, the intensities of the rare isotopes are even lower then the constant background of ions produced by charge exchange in the extraction region. The intensity of this background can be several nanoamperes [15]. Therefore the use of a combination as shown in Fig. 4 used as velocity filter reveals a significant cleaning of the spectrum from scattered and charge-exchanged ions as shown in ref. [16].

The time structure of the extracted beams is another important topic, which determines the duty cycle of the following post accelerator and is of relevance for the experiments served. EBIS/T devices allow for a huge variation of the pulse length of several orders of magnitude, ranging from a few microseconds to several ten milliseconds by pushing the ions slowly over the collector barrier. However, while ions are extracted from an EBIS/T, ions cannot be injected into the device. Hence macro pulses cannot be avoided. ECRs allow continuous injection of singly charged ions and extraction of highly charged ions at the same time. In case of the ECRIT mode of operation, a pulsed extraction using the after glow mode is applied. The length of the extracted ion bunches is usually a few milliseconds.

The longitudinal matching of the highly charged ions to the subsequent accelerator can be done with a multi harmonic buncher [17] or a Radio Frequency Quadrupol (RFQ) accelerator with shaper and adiabatic buncher section [18]. Both schemes, sketched in Fig. 5, are used in present radioactive ion beam facilities and have certain benefits.

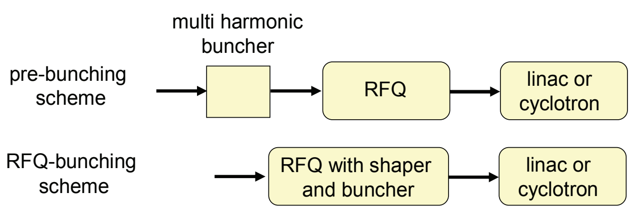


Figure 5: Schemes of micro bunching of the ion beams extracted from EBIS/T and ECRIS devices using an external buncher-RFQ combination or an RFQ with shaper and buncher section.

Pre-bunching of the ion beams with a multi harmonic buncher (up to three harmonics or a double drift buncher) reduces the longitudinal emittance significantly (up to a factor of five) compared to the bunching in an RFQ. The number of cells and therefore the length of the RFQ can be reduced as well, which is mandatory for linacs operating at lower frequency (<50 MHz) and large A/q acceptance (up to 50) like the ISAC RFQ at TRIUMF. The matching with a three harmonic buncher system has an efficiency of about 80%. Using just an RFQ without a separate pre-buncher instead allows for highest transmission close to 100%, as demonstrated with the REX-ISOLDE linac.

### *Transport of intense Beams of highly charged Ions*

For the transport of intense beam of highly charged ions in the order of several milliampere usually solenoid lenses are used for beam focusing. Theses magnetic lenses have the advantage of keeping space charge compensation of the beam and axial symmetry. However, these lenses couple the phase space in both lateral directions and the focusing strength depends on the charge state of the ion species.

The most common approach of a LEBT in case of ECRs is a solenoid lens in front of the separator magnet and one lens downstream the separator magnet. In case of the injection of ions from RHIC EBIS into the RFQ a solenoid lens is used too [19], because pulses from RHIC EBIS can reach several mA of peak current. No separation is done, as in RHIC EBIS the background pressure is so low, that any contamination of the beam can be neglected and different charge states of the required ion species are singled out in the linac and prior to injection into the AGS booster.

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