CHARGE STATE BOOSTERS FOR RADIOACTIVE ION ACCELERATION

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Abstract

For the post acceleration of radioactive ions produced at ISOL facilities the increase of the charge state is essential to fulfill the A/q requirements of the accelerators. Many of those existing or proposed facilities are relying on the performance of charge state boosters of EBIS or ECRIS type. Although, in principle both types of sources can be used in pulsed or continuous mode operation an EBIS is better suited for pulsed beams whereas an ECRIS is most efficient in a continuous mode. The first charge state booster of the EBIS type had been installed at CERN/ ISOLDE and is working in a routine way since several years. It has been constantly optimized and reaches efficiencies in the order of 10% for a single charge state. More recently ECRIS type devices with similar efficiencies for noble gas ions are being set up and put into on line operation at KEK and TRIUMF. The paper will discuss the present state of the art with respect to existing data of both sources and potential future developments.

INTRODUCTION

At an ISOL type facility radioactive species are produced by the impact of an energetic beam of protons, heavy ions, electrons or photons on a solid or liquid target. The target is operated at high temperature to allow the products to diffuse out and into an ion source where an ion beam can be extracted. As those conditions, high radiation fields, high outgassing rates, are not very favorable for the operation of sophisticated ion sources normally only singly charged ions are produced. The isotope of interest can be selected by its mass and transported directly to the experiment or to an accelerator to boost its energy. In the later case increasing the charge state of the ions is essential. Transferring singly charged ions into highly charged ones can be achieved via collisions with electrons with total interaction energy higher than the ionization energy for the desired ionization state.

The simplest method to achieve this is accelerating the singly charged ions to a velocity higher than 100 keV/u and directing them through a thin stripper foil. For light ions this can lead to very high efficiency of about 25% in the maximum of the charge state distribution. As this distribution broadens for heavier elements and the cross sections for high charge states decrease the efficiency decreases. Furthermore, at those energies only low or moderate charge states can be reached and a second or third stripping at higher energy will become necessary, thus, reducing the total efficiency even more. Stripping is used at the ISAC I facility after a first acceleration to 150 keV/u. This is achieved with an RFQ accelerator capable of handling ions with a mass to charge ratio of A/q < 30.

So far all other facilities are using or are proposing an active system, where the charge state is increased before acceleration. The ions are injected into an ion source for highly charged ions where they interact with high energy electrons and their charge state is increased before they are extracted again. Two sources are being used for this: an electron beam ion source (or trap) EBIS/T and an electron cyclotron resonance ion source ECRIS. The charge state evolution in both systems can be described by a system of rate equations

$$\frac{dn_i}{dt} = n_e v_e \left[\sigma^{ion}_{i-1\to i} n_{i-1} - \left(\sigma^{ion}_{i\to i+1} + \sigma^{RR}_{i\to i-1}\right) n_i + \sigma^{RR}_{i+1\to i}\right] - n_0 v_i \left[\sigma^{chex}_{i\to i-1} n_i - \sigma^{chex}_{i+1\to i} n_{i+1}\right] - f_i^{coll} \frac{exp\left\{-\frac{ieU_w}{kT_{ion}}\right\}}{-\frac{ieU_w}{kT_{ion}}} n_i$$

with n_i, n_e, n_0 being the density of ions with charge q=i, electron and neutrals, v_i and v_e the velocity of ions and electrons, σ^{ion}, σ^{RR}, σ^{chex}, the cross sections for ionization, radiative recombination and charge exchange, f_i^{coll} the coulomb collision frequency, T_{ion} the ion temperature and U_w the trapping potential. Only charge changes by +/- 1 are considered here. Especially at high electron energies or high charge states this may not be true, but there is only very little knowledge of charge changing cross sections in those cases. In principal the charge state distribution after a limited confinement time or in the equilibrium state can be calculated. As the cross section for ionization strongly depends on the electron energy the electron energy distribution function has to be known.

Charge breeding with both sources will be described in more detail in the following sections.

EBIS

In an EBIS a high intensity electron beam with an energy up to several 10 keV is compressed within a strong magnetic field of usually several T in order to reach current densities of several hundred A/cm^2 or in some modern EBIT devices several 10 kA/cm^2. Ions injected can be confined radially inside the space charge potential of this beam and longitudinally by a superimposed electrostatic potential. They will be ionized to high charge states via collisions with the high energy electrons. The difference between EBIS and EBIT is mainly the length of the trapping region, which is much shorter in case of an EBIT allowing for a higher compression of the electron beam.

For charge state breeding singly charged ions are injected into the source and after some time the electrostatic potential is lowered to extract the ions at the same side; the other side is blocked by the cathode for the electron beam production. This allows only for pulsed beam operation. As the ion beam size has to match the electron beam size for an efficient capturing of the ions its transversal emittance has to be small. This requires bunching and cooling of the injected ion beam. The final charge state depends on the product of confinement time and electron density and on the electron energy.

The only operational system using an EBIS is also the first on line charge state booster for radioactive ions. It has been taken into operation in 2001 at the REX-ISOLDE facility at CERN [1]. It uses a relatively moderate electron beam intensity around 200 mA yielding to a current density of about 200 A/cm^2. Bunching and cooling of the ions is done with a gas filled Penning trap (REXTRAP) [2] in front of it. A broad variety of stable and radioactive ions covering the entire mass range from Li to U has been charge bred. A recent summary of the results can be found in [3]. The total efficiency, including the cooling and bunching, to reach charge states with a mass to charge ratio $A/q < 4.5$ is around 10% with smaller values for the very light and the very heavy elements. The cooling and bunching efficiency is reported to be about 50%. In some selected cases like $^{39}K^{10+}$ where high beam intensity allows for a good optimization of the system the total efficiency can go up to 15%, which is close to the theoretical limit given by the charge state distribution and assuming 100% capture efficiency of the cooled ions. Breeding times vary between a few ms for the low charge state light elements to up to 500 ms for U^{52+}.

As an EBIS is operated at ultra high vacuum, $p < 10^{-8}$ Pa, the background from the ionization of residual gas ions is low. In case of the REXEBIS it is in the order of several 10 pA for the highest peaks in the spectrum. The maximum intensity the system can handle is given by the space charge capacity of both the EBIS and the cooler-buncher. In case of the REX-ISOLDE system the limit is given by the trap at about 10^9 ions per bunch. Working with radioactive ions this is sufficient for most cases but the limit may be reached with strong molecular or stable isobaric contamination in the incoming beam. This will become more severe for future high intensity facilities.

ECRIS

In an ECRIS a plasma is confined in the minimum of a magnetic field structure. In most designs the field is a superposition of a solenoid field in longitudinal direction with a minimum in the centre and a sextupole field for the radial confinement. The plasma is heated by an rf field at a frequency of several GHz and sustained by O_2 or He as support gas. The field strength of the magnet is chosen to allow a resonant energy transfer from the rf field to electrons at their cyclotron frequency on a closed surface around the centre of the source. The maximum of the magnetic field strength is about 2.5 times the field at the resonance. This allows heating and confining electrons up to several 100 keV. The maximum electron density and the maximum in the electron energy distribution mainly depend on the rf frequency. For a state of the art source operating at 14.5 GHz like the PHOENIX booster from Pantechnik [4], the density is about $10^{11}e^-/cm^3$ and the electron energy distribution reaches up to more than 500 keV with most of the intensity below 100 keV. The charge state distribution of the extracted ions depends on the electron density, energy distribution and confinement time. Eventually, equilibrium between the ionization and charge exchange with low charge states and neutral atoms or molecules is reached.

For charge state breeding singly charged ions are injected at one end of the source, captured and confined in the plasma and the highly charged ions extracted from the other side. The method has been developed at LPSC, Grenoble [5,6] and charge state boosters using an ECRIS have been set up at several places including TRIUMF [7], KEK-JAERI [8], ANL [9] and ISOLDE [10]. TRIUMF and ISOLDE are using the 14.5 GHz PHOENIX booster, whereas KEK-JAERI and ANL are using different sources operating at 18 GHz and 10.5 GHz respectively. First operation with radioactive ions has been reported from ISODE and KEK-JAERI. The TRIUMF set-up is expected to produce on line results in the end of 2008. The ISOLDE ECRIS charge breeder has not been used in conjunction with a following accelerator but for beam purification. Typical charge breeding efficiencies reported are 3-5% for condensable elements and more than 10% for noble gases at mass to charge ratios between 4 and 8 [6,7,8]. The efficiency for noble gases is higher because ions leaving the plasma to the wall of the chamber can be reemitted and enter the plasma again. The time necessary for the charge breeding can be measured by pulsing the incoming beam and recording the extracted highly charged ions as function of time after the start of the injection. Reported breeding times vary from some 10 ms up to several 100 ms. Though, in general they increase with charge state the values from different sources don't agree. Their dependence on the source parameters like rf frequency, plasma and neutral density and confinement time and also on the properties of the incoming beam is not well understood and needs some more detailed investigation.

Until now an ECRIS charge breeder is the only system working in true continuous operation mode as injection and extraction of the ions are clearly separated. Pulsed operation is possible if the afterglow mode is used. Here the source is run in a trapping mode with reduced extraction and all ions are extracted in a fast pulse following the switch off of the rf field. Until now only low repetition frequency, around 1 Hz and relatively long pulses, around 1 ms have been demonstrated [6].

A disadvantage of using an ECRIS is the high amount of total current extracted from the source. It mainly consists of ions from the plasma support gas and residual gas. It can be as high as several mA distributed over a broad spectrum of ions from different elements and at different charge states. This makes it difficult to separate the desired highly charged ions and can lead to high contamination of unwanted ions in the beam.

FUTURE DEVELOPMENTS

There are some attempts for the acceleration of multiple charge states (see for example [11]) but common goals for developments for both sources is the increase in efficiency for the desired charge state and the decrease of the necessary breeding time as long delay time in the source reduces the efficiency for short lived radioactive isotopes.

EBIS

A major point for increasing the efficiency of an EBIS system is to increase the acceptance for capturing the incoming ions. This will reduce efforts and also the losses from the beam preparation. It can be achieved by increasing the electron beam current and thus increasing the space charge potential for the ion confinement. At the moment there are several EBIT devices for charge state breeding planned or under construction with total electron beam current of several A and current density of several 10 kA/cm^2 (see for example [12,13]). Additionally, the high electron beam density will shorten the breeding time and allows for higher charge states and intensity.

Adapting the electron beam energy to the binding energy of an atomic shell and utilizing dielectronic recombination ions can be accumulated in a single charge state [14]. Theoretically this can increase the efficiency up to 90% [15].

There are several attempts of operating an EBIS in continuous mode. A semi continuous mode with a continuous injection only interrupted by a short time for extraction has been tested at the REXEBIS [16] with 2% efficiency for the breeding of K^{10+}. A further increase of this value with a precooled beam should be possible.

A new development at JINR, Dubna, [17] is the use of an electron in tubular geometry, with the electrons having undertaken a phase transition into an ordered “string” state yielding to very high current density. Such a tubular electron string ion source, TESIS, would allow a true continuous mode of operation. Both the injection and extraction have to be performed off axis but at different radial location. The proof of formation of electron strings has been done and a source based on the tubular geometry is being set up at the moment.

ECRIS

The capture efficiency in an ECRIS is mainly determined by the plasma density. It can be increased by increasing the rf frequency or by using two different rf frequencies for the plasma heating. Due to the higher electron density this will shorten the breeding time as well.

Several attempts have been made to develop simulation codes for the capturing and further charge state increase in an ECR source (see for example [18]). The results obtained with these simulations will lead to a better understanding of the capturing and charge breeding process in an ECR and can be used for further optimization. Cooling of the incoming ion beam will help in the optimization of effective deceleration optics in front of the source.

In order to reduce the background from residual gas ions future sources will be designed in a UHV compatible way [19] and be operated with ultra pure support gases to sustain the plasma. As the maximum in the charge state distribution is mainly determined by the charge exchange with neutrals this may also lead to higher charge states.

CONCLUSION

Charge state breeding for the post acceleration of radioactive ions at ISOL facilities can be performed with both EBIS and ECRIS. Though, the efficiency reached so far with an EBIS source is higher than with an ECRIS the later can be operated in continuous mode and at higher beam intensities. Until now only the EBIS system at ISOLDE is in routine operation and the ECRIS systems at KEK-JAERI, ANL and TRIUMF are being commissioned at the moment. Beside the common goal of increasing the efficiency future work aims to overcome the limitations of the specific systems, which in case of an EBIS is developing schemes for continuous mode operation and in case of an ECRIS reducing the amount of background ions and shortening the breeding time.

If it comes to choosing a specific system for a facility also operational aspects have to be considered. At the moment the complexity of an EBIS system is much higher as it includes the buncher and cooler for the beam preparations. This increases the set up time for a specific ion beam. ECR ion sources are more commonly used as ion sources for heavy ion accelerators but no extended experience for using them as charge breeders at such a facility exists so far. The complexity of new improved systems will increase as well with the use of superconducting magnets necessary to reach the high magnetic field strengths for higher frequency operation and UHV designs.

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