ECR Ion sources for radioactive ion beam production

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Abstract. ECRIS's dedicated to radioactive ion production must be as efficient as those used for production of stable elements, but in addition they are subject to more specific constraints such as radiation hardness, short atom-to-ion transformation time, beam purity and low cost. Up to now, different target/ion-source systems (TISSs) have been designed, using singly-charged ECRISs, multi-charged ion sources or an association of singly-to-multi-charged ECRISs. The main goals, constraints and advantages of different existing ECR setups will be compared before a more detailed description is given of the one designed for the SPIRAL II project and its future improvements.

Key words: Electron cyclotron resonance, Ion source, Electromagnetic isotope separator, Radioactive nuclear beams, Charge breeding

1 Introduction

The production of radioactive ions by the ISOL (Isotope Separator On Line) method has stimulated the development of numerous target/ion-source systems [1] (TISSs), owing to the variety of chemical and physical features of the isotopes sought.

For stable gases, the most common ion sources are the ECRISs (Electron Cyclotron Resonance Ion Sources) due to their historical performance, their reliability and their capacity to deliver multi-charged ions needed by the accelerator for the production of high energy ion beams. They are good candidates for the ionization of radioactive gases but additional constraints must be taken into account during their design [2, 3].

In radioactive ion beam (RIB) facilities, the major part of the radioactivity consists in the activation of equipment and production of other unwanted radioactive atoms, contributing to the high dose rate in the vicinity of the production target. The cost of a RIB project is directly related to this amount of undesirable activity, via several technical constraints such as remote handling and recycling systems for the TISS, the volume, type and treatment process for the waste, operation rules (e.g. access in case of breakdown, etc.) and more generally through the management of all problems related to the safety rules.

The present operation scheme plans to use each production system during 3 months without failures, and without access to it. In contrast to the standard criteria for such sources, the ECRIS dedicated to the RIB production must then be radiation-hard and as small, simple and reliable as possible

In the case of stable beams, intensities currently reach some hundreds of micro-amps. The maximum intensities of RIBs are generally smaller, i.e. some nano-amps in the easiest cases. Behind the mass spectrometer, which is situated at the exit of the ECRIS, it can be difficult to observe the peak of the specific ion of interest within the mass spectrum. The target is strongly heated to accelerate the diffusion of the radioactive elements out of the material, which also leads to release much out-gassing which can give rise to undesirable ion peaks in the mass-to-charge spectra. This out-gassing can also degrade the source itself (by deposition of a thin layer on the RF window, for example), and which can change the working point of the ion source, depending on its capacity to absorb this additional gas flow.

If the peak of interest can not be directly observed during the tuning of the beam line, a stable beam with a close mass-to-charge ratio and a higher intensity can be used. The contaminants can then be separated from the RIB by means of a better mass spectrometer such as a cyclotron. Nevertheless, to eliminate the contaminants, the best method consists of selecting the element of interest as soon as possible, *i.e.* in the TISS

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itself. For the ionization of gases, the ECRIS is a good solution since the ionization efficiency of gases is currently an order of magnitude higher than for condensable elements.

In case of ECRISs dedicated to the production of stable elements, the atom-to-ion transformation time is not of first importance, and most ECRIS users ignore it. Nevertheless, the efficiency ε_{ai} is a direct consequence of the competition between the probability per unit time λ_i for the atoms to be ionized and the probability per unit of time λ_{eff} for the atoms to find the exit hole [4]. In the case of radioactive atoms, one has also to consider the competition with the radioactive decay probability λ, especially in case of short-lived nuclei which are the most interesting in term of exoticism. The efficiency is then given by:

$$\varepsilon_{ai} = \frac{\lambda_i}{\lambda_i + \lambda_{eff} + \lambda} \quad (1)$$

In the case of stable elements, high ionization efficiency ECRISs can be slow, provided that $\lambda_i >> \lambda_{eff}$. In case of radioactive elements, high ionization efficiency ECRIS must be faster than the radioactive decay. To optimize an ECRIS for RIB production, we must then add "relative short response time" to the previous constraints, i.e. radiation-hardness, small size, simplicity and reliability.

On the basis of these considerations, two RIB production methods are presented and commented upon.

2 Atom-to-Ion Transformation by Direct Injection in A Multi-charged ECRIS

One solution to obtain multi-charged radioactive ions at the exit of a TISS consists of associating a production target to a multi-charged ECRIS, as at GANIL in the design of the TISS of SPIRAL I [5] (Système de Production d'Ions Radioactifs Accélérés en Ligne version I) (Fig. 1). The carbon target is coupled to a multi-charged ECRIS NANOGAN III through a cold tube, which limits the transfer of the atoms to the gaseous atoms or molecules. Their proximity leads to a global atom-to-ion transformation time for Ar close to 160 ms, which is mainly governed by the effusion of the atoms in the vacuum chamber. The influence of the source tuning on the time response is very small. Beyond an RF power of 30 W, the ionization efficiency is close to 100%, but the charge-state distribution, peaked on low charge-states at low power, is shifted towards higher charge-states at higher RF power. This spreads the atoms over different charge-states and reduces the relative abundance of the ions in the charge-state of interest, what can be considered as a loss of efficiency compared to a singly-charged ion source.

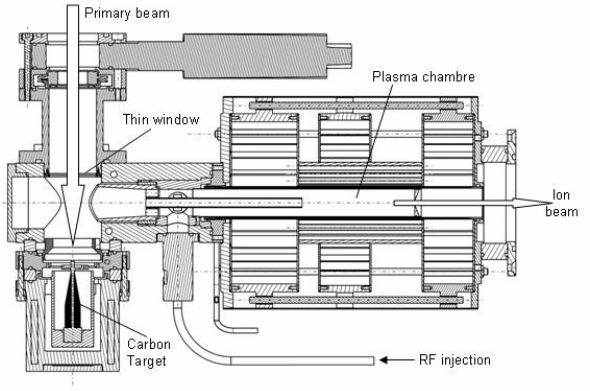

Fig. 1. Drawing of the TISS of SPIRAL I.

The NANOGAN III source is realized with permanent magnets. An earlier experiment [6] has confirmed that similar magnets are too sensitive to neutrons to be used in RIB facilities as SPIRAL II , for which the power of the primary beam will be one hundred times higher (200 kW of deuterons at 40 MeV) and for a longer period, even if the irradiation conditions are not similar. At present, no multi-charged radiation-hard ECRIS exists. One has thus either to build one or to find another solution to produce the multi-charged ions of radioactive elements.

3 The 1+/n+ Method or Mharge Breeding

A cheap ion source placed close to the target seems to be the best solution. Since no existing multi-charged ion source can be installed close to the target, the use of a singly-charged ECRIS can be considered owing to its simplicity and possible magnet-free construction. Such an ECRIS, named MONOBOB II (see Fig. 2), has been developed at GANIL, after a first version [7] developed to test the magnetic principle.

The magnetic structure has been realized using coils made with radiation-hard materials only, i.e. copper and glass fibres, inserted in an iron yoke. The magnetic field permits the injection of a 2.45 GHz RF wave using a coaxial antenna to avoid the pollution of a large RF window (~4 cm × 8 cm at 2.45 GHz). Owing to the "weak" plasma, the ionization efficiency of ^{40}Ar reaches 60% with N_2 as support gas and 84% with He.

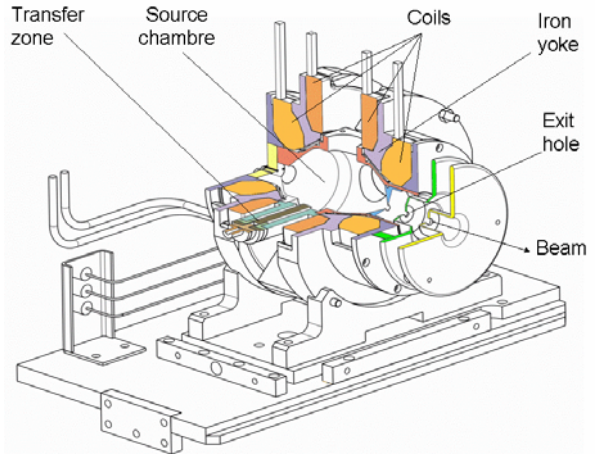

Fig. 2. Drawing of the MONOBOB II ECRIS designed to produce the singly-charged ions from radioactive gases in the SPIRAL II project.

To obtain the multi-charged ions, the 1+ ion beam is injected in a multi-charge ECRIS via a mass spectrometer, both placed out of the irradiation area. This method, named 1+/N+ conversion[8], presents several important advantages: i) The multi-charge IS is out of the "hot zone"; ii) the 1+ beam is purified before being introduced into the N+ source, which limits the pollution of the N+ mass-to-charge spectra and the radioactive pollution of the N+ source; iii) the 1+ source can be replaced without changing the N+ source, and it is thus possible to chose the 1+ source most suited to the element sought.

Nevertheless, this method presents some difficulties. The 1+ ions are decelerated at the entrance of the N+ source to optimized their capture by the plasma. In addition to the standard 1+ beam tuning, a slight potential difference, which depends on the element to ionize, is introduced between the 1+ and N+ sources to balance the effect of the energy of the ions at the exit of the 1+ source and the plasma potential of the N+ source. Modifying the high voltage of the N+ source makes it necessary to retune the 1+/N+ beam line if the beam line is not on a floating platform. To conserve the maximum conversion efficiency, the current injected into the N+ source must typically be of the order of 100 nAe, which is very low if any pollutant accompanies the 1+ ion of interest. The emittance of the 1+ beam must be lower than the admittance of the N+ source, limited to #30 π.mm.mrad at 20 kV.

One other problem can appear in the case of short-lived elements. In the N+ source, the 1+ ions can be converted in to N+ ions by two main process: direct 1+/N+ conversion, and indirectly via 1+→0+→N+. i)- If an ion is directly captured by the plasma, the conversion is very fast (some tens of milliseconds), as in the case of condensable element spread in an ECRIS plasma by laser ablation [9, 10]. If the ions are not captured during their first pass through the plasma, they stick on the wall of the source chamber and are neutralized. If condensables, they are lost, but if they are gases, they leave the wall and can pass as atoms through the plasma several times, to be re-ionized and captured. The conversion time in the N+ source depends on the 0+/1+ conversion time and on the 1+/N+ charge breeding time as in a usual ECRIS, which can be of the order of several hundreds of millisecond [11]. It is governed by the competition between the ionization and effusion probabilities, as given by the expression (1). Regarding the general performances of an ECRIS like Phoenix [12], developed at LPSC Grenoble, the ionization probability is high enough to lead to an ionization efficiency of the gas close to 100%, but the measured values with stable elements are close to 30%. This can be explained by the large aperture required to inject the 1+ beam which favors the effusion probability λ_{eff} with respect to the ionization probability λ_i, and by the backward ion beam. In the case of radioactive elements, the ionization and effusion process will have to compete with the radioactive decay, what will reduce the previous 1+/N+ conversion efficiency. Moreover, if the ions are not directly captured by the N+ plasma, the 0/1+ conversion time is counted twice, once in the 1+ ion source and once in the N+ source.

5 Next Step: The Radiation Hard Multi-Charged TISS

The results obtained with the development of the MONOBOB ECRIS have demonstrated the possibility of building a radiation-hard ECRIS for which the ionization efficiencies for Kr and Xe should be higher than for Ar, i.e. 60% or more. This first source suggests a possible design of a multi-charge ion source based on the same magnetic principle, but with a much stronger magnetic field. It could be placed on the axis of the 1+ ion source, and coupled via a selective filter of some centimetres, approximately as described for the production of multi-charged alkalis [13]. A schematic view is given Fig. 3. According to the chemical specie of the ion sought, the design of the TISS could be different.

Production of ions from radioactive gas: A 1+ ECRIS is not necessary. The selective filter consists of a simple cold transfer tube placed between the target and the N+ ECRIS, as for the SPIRAL I TISS. The selectivity will probably be lower for lower than with the charge breeding method, since the out-gassing will pollute the N+ source, but such a TISS would present a lot of advantages when compared with the 1+/N+

chare breeding method: there is no 1+ beam and thus no emittance limitation on the 1+ beam and no limitation on the injected intensity as observed with the SPIRAL I TISS for which the maximum gas flow can be much higher than some hundreds of p.nA. There are no losses due to the backward beam extraction and to the effusion through the injection hole. Moreover, the atom-to-ion transformation time between the instant of production in the target and the instant of exit out of the source will be shorter. The final efficiency will thus probably be higher for all gases, and especially for short lived isotopes.

Production of ions from condensable elements: The 1+ ion are produced by a surface ionisation source or by laser ionisation source, close coupled with the target. The beam of the 1+ ion source is injected in the N+ ECRIS through a short 1+ beam line equipped with a pumping system in order to avoid pollution of the N+ ECRIS and the perturbation caused by the out-gassing flow. The total selectivity results from the pumping system and from the selectivity of the 1+ ion source, which is very important is the case of laser ion source and surface ion source. Limiting the out-gassing flow permits the injection into the ECRIS of the support gas most suitable for the ion specie sought.

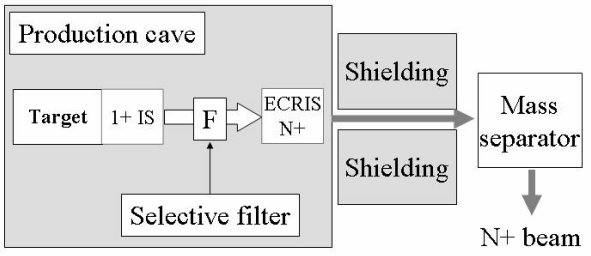

Fig. 3 : Schematic view of the radiation hard multi-charged TISS.

This radiation hard multi-charged TISS presents some other advantages:

- In the case of surface ionization and laser ion source, the emittance of the beam is typically of the order of 10 π.mm.mrad, which is significantly lower than the emittance required for the injection into the charge breeder.
- If the cold transfer tube of the version dedicated to the production of ions from gas is heated, the condensable elements will reach the N+ ECRIS and will be ionized with an efficiency of some percent, as in the case of stable elements with a multi-charged ECRIS. The total efficiency of the TISS will then mainly depend on this ionization efficiency and on transfer time of the atom from the target to the source. Compared to a non-selective FEBIAD type ion source, this solution allows ionizing a larger variety of elements and producing of multi-charged ions.
- The magnetic structure permits the installation of the RF injection between the coils, which opens up the injection zone at the rear of the source
- Owing to the material of the magnetic structure, the source can be heated up to some hundreds of degrees, what can accelerate the out-gassing of the source and improve the recycling of condensable elements
- the system can be installed on the same platform, making the tuning of the 1+ beam injection easier and making it independent on the tuning of the HV platform.
- in this case, the system installed in the cave is slightly larger but the total system is much smaller, requiring correspondingly less room.

In terms of safety, design, operation and cost, the consequences on a RIB project of this solution alternative to the charge breeding are obviously very important.

1 U. Koester and the ISOLDE Collaboration. Radiochemica acta, 2001, **89**: 1
2 Availablefrom : http://saferib.web.cern.ch/saferib/program.html
3 R. Leroy, Y. Huguet, P. Jardin, C. Marry, J.Y. Pacquet, A.C.C. Villari. Rev. Sci. Instrum. 1998, **69**: 758
4 P. Jardin et al. Nucl. Instr. Meth. Phys. Res., 2003, **B 204**: 377
5 Antonio C.C. Villari, the SPIRAL group. Nucl. Instr. Meth. Phys. Res., 2003, **B 204**: 31
6 N. Lecesne, PhD thesis, University of CAEN, France, 1997, p. 110
7 C. Huet-Equilbec, P. Jardin, P. Gorel, J-Y. Pacquet, G. Gaubert, J. Cornell, M. Dubois, N. Lecesne, R. Leroy. Nucl. Instr. Meth. Phys. Res., 2005, **B 240**: 752
8 C. Tamburella, J.L. Belmont, G. Bizouard, J.F. Bruandet, R. Geller, G. Gimond, B. Vignon. Rev. Sci. Instr., 1997, **68**: 2319
9 V. Mironov, S. Runkel, K.E. Stiebing, O. Hohn, G. Shirkov, H. Schmidt-Böcking, A. Schempp. Rev. Sci. Intrum., 2001, **72**: 2271
10 R.C. Pardo, R. Harkewicz and P.J. Billquist. Rev. Sci. Instrum., 1996, **67:** 1602
11 F. Ames, R. Baartman, P. Bricault, K. Jayamanna, M. McDonald, M. Olivo, P. Schmor, and D.H.L. Yuan. Rev. Sci. Instrum., 2006, **77**, 03B103
12 P. Sortais, J.F. Bruandet, J.L. Bouly, N. Chauvin, J.C. Curdy, R. Geller, T. Lamy, P. Sole, and J.L. Vieux-Rochaz. Rev. Sci. Instrum., 2000, **71**: 617
13 C. Eleon, O. Tuske, G. Gaubert, J.Y. Pacquet, M. Dubois, M.G. Saint Laurent, P. Jardin, J. Cornell, R. Leroy. Rev. Sci. Instr., 2006, **77**, 03A704