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ECR development for accelerated radioactive ion beams

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Abstract:

The development of Electron Cyclotron Resonance Ion Sources (ECRIS) for accelerated radioactive ion beams has seen a very fast evolution in the last years. This evolution is discussed in view of mainly three different approaches. The first one considers the production of the radioactive atoms in a target located externally of the ECRIS, the second one places the target inside the source in a region very close to the plasma and the third considers the use of a primary ion source for production of $1+$ ions with subsequent injection in an ECRIS for charge multiplication. The advantages of each mode are discussed and the results of some tests are presented.

1. INTRODUCTION.

The advent of Electron Cyclotron Resonance Ion Sources (ECRIS) in Nuclear Physics and, in general, on Particle Science has placed an important milestone on the history of the development of new Heavy-Ion beams with high energy and high intensity [1]. In the particular case of on-line RIB (Radioactive Ion Beams) production, the first proposition for using an ECRIS in an on-line separator has been made in 1985 in the Accelerated Radioactive Beams Workshop at Parksville, Canada [2]. The interest at that time was mainly for having a good ionisation efficiency for the production of the noble gases Neon and Xenon and the elements Nitrogen, Oxygen and Carbon, since their molecular compounds N_2 , O_2 and CO are very reactive in hot enclosures [3]. For noble gases, in particular, the overall ionisation efficiency of ECRIS can be significantly high, of the order of 80%, therefore allowing high yields for radioactive noble gas beams. Moreover, ECRIS is well suited for production of highly charged ions, which is an important ingredient for producing accelerated beams in a wide range of energy.

The first accelerated radioactive ion beam produced after a thick target has been obtained at CRC-UCL, Louvain-La-Neuve, Belgium [4]. The radioactive beam of ^{13}N has been obtained from the reaction $^{13}C(p,n)^{13}N$ impinging protons of 30MeV from the CYCLONE-30 Cyclotron on a powder ^{13}C target. The radioactive ^{13}N was transferred into an ECRIS through a long transfer tube. The atoms were ionised, extracted and injected in the cyclotron CYCLONE. The first results obtained by the Louvain-La-Neuve group quoted 10^6 pps of radioactive ^{13}N after acceleration. At the present time, this number has been significantly enhanced ($\sim 10^9$ pps) [5] and other ion beams are delivered to experiments at Louvain-La-Neuve.

There exist in the world a total of 5 laboratories where intense use of ECR Ion Sources for production of RIB is being made or is in progress. These laboratories are: TISOL - TRIUMF (Vancouver Canada) [6], CRC-UCL (Louvain-La-Neuve, Belgium) [7], INS (Tokyo, Japan) [8], PIAFE - ISN (Grenoble, France) [9] and SPIRAL - GANIL (Caen, France) [10,11].

The aim of this paper is to discuss and to present some results of mainly three different operation modes of ECR Ion Sources for On-Line radioactive ion beam production. These three modes are: i) External Target Mode ii) Internal Target Mode, and iii) Stripping Mode. In principle, each mode described here is well adapted for the production of some radioactive elements, depending upon their chemical properties, i.e. vapour point and adsorption enthalpy. Nowadays there is no universal mode for the production of all the periodic table of elements using ECRIS or even other kind of ion sources.

It should be noted that a few different modes can be used for the on-line production, as for instance, the internal catcher mode, where the radioactive elements are produced externally of the ECRIS and implanted in a catcher which is placed inside the ion source[12]. By the way, these other modes will not be discussed in this paper.

A special chapter is dedicated to a discussion on the use of a separator with ECR ion sources. This point is substantially important due to the known high emittances of

ECRIS. It is shown that the use of a cyclotron accelerator as a separator can give a substantial mass resolution power while accelerating the ion beam. This will be used as main mass selection system in the SPIRAL project at GANIL, France, using the new cyclotron CIME [13].

2. ECRIS CHARACTERISTICS.

An ECRIS with high performance can be conceived respecting the known recommendations given by R. Geller [1]: 1) The better the confinement, the higher will be the ionisation efficiency and the production of higher charge states. In order to achieve a better confinement, radial magnetic mirrors, in addition to axial mirrors should be built in the ECRIS. This concept is called "minimum B structure", having a minimum magnetic field in the centre of the cavity (see figure 1). 2) The mirror ratio should be of the order of $B_{\max}/B_{\min} \approx 2$. 3) In addition, a ratio of $B_{\max}/B_{\text{ECR}} > 1.5$ is recommended. 4) A weaker mirror near the extraction will increase ion leaks there with respect to the injection side, therefore enhancing the performances of the ECRIS.

In complement one can add that the radial magnetic field can be hexapolar, octupolar or even dodecapolar. ECRIS with such radial magnetic confinements works properly. The quadrupole configuration is not likely due to its very narrow radial extension.

The higher the plasma density, the higher will be the mean charge of the plasma, therefore allowing higher charge states for the extracted beams. One possibility to achieve this higher density is to enhance the magnetic field and/or the Microwave Frequency injected in the ECRIS. Examples of magnetic fields and frequencies for high performance ECRIS are given in table 1.

In order to deliver high beam currents, the ECRIS needs high magnetised plasma volume, which implies in large volume chambers. Considering the production of radioactive ion beams, high beam currents are in principle not necessary, therefore very compact systems can be built. In particular, one can build compact systems which requires a minimum of power in the production cave, like full permanent magnet ion sources [18].

2.1. The emittance of the ECRIS.

It is well known that ECR ion sources have relatively high emittances, when compared with other sources used in on-line separators. This is an intrinsic characteristic of ECRIS due to three main factors: The wide energy dispersion of the ions when leaving the plasma (around 5eV), the necessary large plasma diaphragm at the extraction of the source and the high magnetic field at the acceleration gap. These three factors together with the fact that the extraction potential is usually made between 10-40 kV, yield to a high emittance between say, 30-150 π mm mrad at 15kV. These emittances are confirmed by J. Mandin and L. Maunoury [19] at GANIL for ECR-4M [16] (CAPRICE-type) and the full permanent magnet NANOGAN-II [17].

The extraction geometry plays a certain role for the emittance. At GANIL, we developed a multi-electrode [20] extraction system with two accelerating gaps in

order to correct for eventual distortion of the electric field in the extraction zone and to compensate the space charge force during acceleration. This multi-electrode has been installed in the extraction of the ECR-4M ion source. The emittance of ^{15}N beam at 14kV of extraction voltage is shown as a function of the charge state in figure 2. The comparison between the multi-electrode and the "standard" conical-type electrode shows an improvement of the emittance for low charge states. For higher charges the improvement is not significant. A decreasing behaviour of the emittance is observed as a function of the charge state. For the NANOGAN-II ion source the decreasing effect, as a function of the charge state, is less evident; by the way a mass effect is observed when one compares the emittance of ^{16}O , ^{40}Ar and ^{84}Kr (figure 3). All the GANIL data has been obtained with a transport efficiency better than 90% between the ion source and the Faraday cup installed after the analysing magnet. This was easily verified by the ratio between the current of the full ion source spectra and the current delivered by the extraction power supply. It is important to note that different results can be found in the literature, for instance from the work of K.A. Harrison and T.A. Antaya [21], where a "bell shape" curve is observed for the emittance as a function of the charge state. Nevertheless, the order of magnitude of the emittance is unchanged.

Finally, the emittance of ECRIS can be certainly a problem if one would use "standard" separators. On the other hand, one can show that if the accelerator after the ECRIS is a cyclotron, the emittance of the source would neither deteriorate the mass resolution of the full system (section 4), nor diminish the transport efficiency.

2.2. The ionisation efficiency of the ECRIS.

The ionisation efficiency of ECRIS is well known to be optimum for gases in general. This efficiency can be interpreted as a product between an ionisation efficiency and a delay function, regarding the time which an atoms spends inside the ion source before the first ionisation. Being in principle a cold source, the efficiency for condensable elements depends basically on the plasma density, i.e. the probability for an atom to be captured during a single travel across the plasma. It is evident, therefore, that an atom which is not condensable will have better efficiency.

Direct measurements of the ionisation efficiency for stable noble gases and condensable elements has been done for several ion sources (see for example [2,22]). Their results are quite similar and depend a little on the tuning and the particular overall performances of each ECRIS. One can define a common value for the overall ionisation efficiency for noble gases (or non reactive gases in general) of the order of 80% for all ECRIS. For a particular charge state, the performance of the ion source NANOGAN-II (GANIL) or SHyPIE (GANIL, to be described in the following section) is of the order of 20% for the most probable charge. This value is verified using a calibrated leak of the requested gas in the injection of the source and analysing the charge state spectrum after a separator, as shown in figure 4. This efficiency is observed for gases up to $Z=18$. For higher atomic numbers, the efficiency for a given charge state decreases due to the wider charge distribution obtained.

Concerning condensable elements, tests using ^{50}Cr has indicated that this efficiency is strongly dependent on the evaporation geometry of the oven placed inside the

ECRIS. For the best case, an oven placed at the maximum $B_{\text{injection}}$ and with a geometry which is optimised in order to focus the evaporated element at the extraction diaphragm can give an efficiency between 7% and 15%. For the most probable charge state the efficiency turns around the standard value of 20% (of the extracted beam). The product gives the overall efficiency between 1.5% and 3%.

Radioactive atoms should not influence too much the ionisation efficiency if the life time is longer than the confinement time, which is of the order of milliseconds. The charge state distribution of the radioactive ^{33}Ar ($T_{1/2}=174\text{ms}$) is compared with the stable ^{40}Ar in the figure 5. No effect is observed. It is important to note however, that this result has been obtained for a configuration where the production target is placed outside the ion source. In the internal target mode the performance of the ECRIS can be modified, as we will see in the section 3.

2.3. Radiation damage of the permanent magnets.

When one discuss about on-line systems it is important to conceive a source which is compact, reliable and radiation resistant. If one wants a compact system, permanent magnet ion sources are a good solution. More than that, the power consumption of permanent magnet ECRIS is reduced to the Microwave power, which is obviously a reasonable advantage inside the production cave. The question which one could ask is about the radiation damage effect on permanent magnets.

There exists data about radiation damage on Fe-Nd-B and Sm-Co magnets [23-25]. The Sm-Co magnets are more resistant to the radiation effects in general. Considering light particles, the radiation effect is very destructive. A dose of some tens of kGy can completely destroy the permanent magnets. This means that the ion source should be absolutely well protected against light particle radiation. Considering gammas, the resistance is largely enhanced. Measurements show that a dose of 0.4 MGy had reduced the remanence of only 1.5% for Fe-Nd-B and of 0.5% for Sm-Co magnets.

The final consideration is about neutrons. It is shown that losses of 10% in remanence can be observed for a radiation dose of 0.2×10^{17} to 2×10^{17} n/cm². One important consideration is the fact that the ECRIS at TISOL-TRIUMF works since 7 years and the sextupole structure (Sm-Co) has only suffered a loss of 5% in remanence.

Nevertheless, one very important point which should be also considered is not only the loss of remanence but the loss of coercivity of the permanent magnets. The magnetic structure needed for building the magnetic multi-mirror structure is such that some magnets are forced to work in a very singular functioning points. This means that the magnets are immersed in a very strong field inverted to its own magnetisation. The radiation can act in this case diminishing the coercive force of the magnet, giving as result the inversion of the magnetisation of the permanent magnet after some time of irradiation. This particular phenomena has been observed at GANIL in the irradiation of Fe-Nb-B magnets of a very compact ECRIS. We observed that the very fast neutrons (30-100 MeV) emitted at forward angles in the nuclear reaction between $^{20}\text{Ne} + \text{C}$ were largely more destructive than backward neutrons of

about 5MeV. This can be understood by the fact that reactions of the type $B(n,np)$, $B(n,n\alpha)$, etc. have threshold energies around 15MeV.

For SPIRAL, care on the design of the Target-ECRIS has placed the target in a position where the ECRIS is not irradiated by forward neutrons. The life time of the ECRIS inside the cave has been estimated of about 1400 hours of non-stop ^{12}C beam at maximum intensity (2×10^{13} pps).

3. USING ECRIS IN ON-LINE PRODUCTION SYSTEMS.

3.1. External Target mode.

In this mode the production beam bombards a production target which is placed outside the ECR ion source. The radioactive atoms produced by nuclear reactions are released from the target, which is heated at high temperature (~ 2300 K), and pass through a transfer tube into the ECRIS. The radioactive atoms are then ionised, extracted and selected by its ratio q/m . A typical set-up (TISOL) is shown in figure 6.

This mode is currently used at TISOL-TRIUMF, CRC-UCL and are being tested at INS (Tokyo) and at the test bench SIRa of the SPIRAL-GANIL project. Good production yields have been obtained for a number of elements which can be found as gaseous substances - He, C, N, O, Ne, Ar, Kr and Xe - see [6,7,11] for details and table 2 for yields.

The system designed to the SPIRAL project at GANIL is very compact and allows to the complete remotely removal of the target-ion-source ensemble from the production cave (figure 7). This is of fundamental importance to give reliability to the system and allows the easy changing of the characteristics of the ion source depending on the ions one would like to produce. It is clear that, for example, a lower performance ion source is required for the production of $\text{Ne}(3+)$ beams than for the $\text{Ne}(5+)$. The most expensive part of the ion source are the permanent magnets, which can be sensibly reduced in the case of production of $\text{Ne}(3+)$ ions. For doing this, a frequency variable Microwave emitter (8-18 GHz) will be used in the SPIRAL ECRIS. The NANOGAN-II ion source is considered as a medium performance ECRIS (equivalent to ECR-3 [26]) and useful for production with good performances of ions up to, for example $\text{Ne}(6+)$, $\text{Ar}(9+)$, $\text{Kr}(14+)$ and $\text{Xe}(25+)$.

It is important to note that in principle other elements, even condensable ones, could be produced using this technique. One could imagine that the heating at high temperature of the transfer tube could allow for the production of less volatile elements, like alkali, for example. By the way, specially for alkali elements, the introduction of a hot surface before the ECRIS can ionise the atoms before the ECR plasma. This ionisation has a catastrophic effect in the performance of the ECRIS. A positive ion at thermal energies cannot be captured by the ECR plasma because the plasma potential in ECRIS is also positive of the order of several tens of volts. Therefore, the ion with thermal energies is simply repulsed by this potential. This effect has been observed at ISN (Grenoble) and at GANIL. In the subsection 3 of this chapter a possible solution to this problem is suggested.

Finally, tests performed at GANIL showed that the introduction of a hot intruder inside the ECRIS is not a trivial task. This subject is discussed in the following subsection.

3.2. Internal Target Mode.

In this mode the production beam impinges a target which is placed inside the ion source as close as possible of the plasma itself. This mode is, in principle, optimum for production of very reactive condensable elements, which can stick to the walls of a transfer tube (which does not exist in this configuration). The radioactive elements which diffuses from the target are in close contact with the plasma of the ECRIS, allowing a very fast ionisation. It should be noted that the maximum ionisation efficiency which we would expect for this mode for a condensable element should be, in the better case, of the order of the off-line efficiency for condensable elements given in the section 2.2.

For gases, the ionisation efficiency should be equivalent to the external target mode. The gain in this case will be the transit time between target-ECRIS. Therefore, very short living isotopes can be produced.

The configuration of the target-ECRIS system used in tests at GANIL - the SHyPIE (Hybrid Source for Exotic Ion Production) - is shown in figure 8 (see Nathalie Lecesne [27]). The beam entered into the ECRIS through its extraction electrode and hit a 15mm long and 8mm wide target placed in the injection side of the source at 5mm inside the octupolar radial confinement magnetic field. The target was a piece of Carbon with good diffusion properties -grain size 4 μ m and open porosity of 8% furnished by Le Carbone Lorraine. As discussed in the section 2.3 the magnetic structure of the ECRIS was well protected from high energy neutrons by construction, since the permanent magnets were only present at angles larger than 90°. SHyPIE is an hybrid source because its magnetic field is produced by a mixture of coils and permanent magnets. The ions extracted from the ECRIS were driven to the SIRa separator through an electrostatic deflector. An on-line test has been performed using the 75.A MeV ^{36}S primary beam at 0.125pA of intensity. Ions of $^{35,41}\text{Ar}$, $^{34,38,38m,39}\text{Cl}$, $^{35,37}\text{S}$, $^{29,30,34,35}\text{P}$, $^{28,29}\text{Al}$, $^{22,27,29}\text{Mg}$, $^{21,25,26}\text{Na}$, $^{18,23,25,26}\text{Ne}$, $^{21,22}\text{F}$ and $^{21,22}\text{O}$ with reasonable intensities and multiple charge states have been detected at the end of the separator. The calculated overall efficiency for $^{25}\text{Ne}(4+)$ ($T_{1/2}=602\text{ms}$) was 1.9%. The beam intensity at the end of the separator for the radioactive ^{35}S beam was 2×10^7 pps. The data obtained in this experiment is under analysis.

The presence of a hot target inside an ECRIS can significantly modify the performance of the ion source, i.e. the charge state distribution. The intensity of the contaminant $^{40}\text{Ar}(5+)$ beam - which was present during the whole experiment - was suppressed by a factor of 2 during the on-line run. Preliminary results show that the overall performance of the system is 10 times lower than the expected one. This efficiency should be understood.

Another singular effect observed was the relatively weak production of alkali elements. This effect is related to the already discussed phenomena of "pre-

ionisation" of alkali elements before reaching the ECRIS plasma. This pre-ionisation can occur because the ions leave a very hot target and consequently can be thermo-ionised. The plasma potential acts in this case as a repulsive wall for positive ions, reducing drastically the capture efficiency. It has been confirmed by the fact that the 1+ extracted ^{25}Na current was increased by a factor of approximately 10 when the Microwave emitter of the ECRIS was turned off.

Although the problems observed in this first tests, the possibility of having a target inside an ECRIS should not be discarded. Reasonable yields of several elements could be observed. In principle, this method could give the best results for short living and very reactive condensable elements in on-line production. More R&D is fundamental in order to improve the technique.

3.3. Stripping Mode.

The stripping mode is a solution for on-line production of multi-charged ions which allows the separation between the highly radioactive area and the ECRIS. The idea is to use the ECRIS as a very low energy stripping source. In order to do that, the production system placed at the production cave, can have a target with an ion source for 1+ charge production. After ionisation and extraction the ion beam is decelerated and injected into the ECRIS - which can be placed far away from the radioactive area. The first advantage is to keep the ECRIS far from the activated region. The second and the most important, is the possibility to make use of the at least 30 years of knowledge on on-line production target-ion-sources for 1+ production [28]. This technique is being developed at ISN-Grenoble, France and more recently in a collaboration between ISN-Grenoble and GANIL. The PhD thesis of Claire Tamburella is an important reference on the subject [12].

Tests of the stripping mode with a stable Rb (1+) beam have been performed at ISN using the set-up of the figure 9. The 1+ thermo-ionic ion source and the Minimafios [29] ECRIS were placed at slightly different potentials, given an independent ΔV power supply. The intensity of the ion beam which was injected into the ECRIS was measured by a Faraday cup placed just before the injection side of Minimafios. The analysed multi-charged beam was measured just after the first dipole of the beam analysis line. The beam intensity of the Rb(9+) extracted is plotted as a function of the ΔV voltage in figure 10. We can see that the beam intensity has a "resonant" pronounced peak placed at $\Delta V=15\text{V}$ with a width of the order of 5V. This very pronounced peak is the signature of the plasma potential, which in this case should be of the order of 15V. In order to be captured by the plasma the ion should first overcome the plasma potential; this explains the threshold of the phenomena around 13V. On the other hand, the residual energy of the ions should not be too high in order to be captured by the plasma. If the ions have too high energies - bigger than 20V in this case - they will not be captured and will be lost in the walls of the ECRIS chamber. The width of this capturing window is function of the plasma density and the mean charge state. The position of the window is related with the value of the plasma potential. C. Tamburella observed, for instance, that ΔV varies as a function of the Microwave power. The measured overall efficiency of the capture, i.e. the ratio between the analysed Rb (9+) particle current and the injected Rb (1+) current was of

the order of 2%. It should be noted here that an evaluation of the transport efficiency of the system has not been done up to now.

One important point is to note that the width of the acceptance window is very narrow, which means that the energy dispersion of the 1+ ion source should also be narrow. This fact puts an "a priori" important constraint on the choice of the ion source for 1+ production.

The results obtained for noble gases using an ECR ion source as 1+ ioniser are surprising. One could imagine that the efficiency of the stripping would be very weak due to the wide energy dispersion of this kind of ion source. The inverse was observed. The efficiency for the stripping of Kr (1+ to 9+) was 6.5% and of Xe (1+ to 14+) was 4%. This is understood due to the fact that noble gases do not stick in the walls of the plasma chamber and, therefore, are recycled by the ECRIS. A very wide acceptance window of several hundreds of volts confirmed this interpretation.

The efficiencies observed in these experiments are very competitive. For noble gases they are only a factor of two or three smaller than the observed in the external target mode. For the particular case of alkali elements, good performances have been obtained. More R&D is necessary in order to improve the method and to expand the range of chemical elements which could be produced with this technique.

4. USING A CYCLOTRON AS MASS SEPARATOR.

The large emittance of ECRIS is a limitation to the practical resolution power of the separator associated. Medium resolution separators ($R \approx 2,000$) can be built for emittances of ECRIS, like the Large Acceptance Mass Separator LAMS proposed by B. Bru, A. Chabert and Ch. Ricaud [30]. However, high resolution separators ($R \approx 20,000$) need low ion source emittance, like the EXCYT separator proposed by H. Wollnik [31]. The high resolution and high acceptance can be achieved if one uses a cyclotron as mass separator while accelerating the radioactive ion beam. This method gives excellent results and even was used to measure the mass of the double magic ^{100}Sn [32].

The cyclotron CIME for the SPIRAL project is designed to accept an ion beam with emittance up to 80π mm mrad, which is compatible with ECR ion sources. The separation of masses was simulated by L. Boy [33] and is shown in figure 11. In the case 1, the cyclotron is tuned in order to keep the selected beam isochronous (in this case ^{35}Ar). The contaminant ^{35}Cl arrives at the extraction radius of the cyclotron together with the selected beam. In the case 2, the cyclotron is tuned in such a way that the contaminant is eliminated during the acceleration. This isochronism fault can be achieved by detuning the field correction coils of the cyclotron [34]. With such a tuning a mass resolution power of $R \approx 6,000$ can be obtained with reduced extraction efficiency due to a larger energy dispersion of the beam of a few per cent. If one looks again carefully to the case 1, we can see also that the two extracted beams are separated at the end of the accelerator by a phase shift of approximately 35° , which corresponds in this case to a time delay of approximately 10 ns. If one uses the electronic signal of the cyclotron Radio Frequency (RF) for tagging our events in an hypothetical experiment, one could separate off-line the events coming from the first

and the second beam, simply because they arrive at different times in the target. A maximum separation power of $R \approx 50,000$ -depending on the harmonics and number of turns inside the cyclotron- can be achieved with this technique.

5. CONCLUDING REMARKS.

The characteristics of ECR ion sources relevant to on-line production of radioactive multi-charged beams has been given. Three different modes for using ECRIS in such separators have been presented. One could remark that the three modes yield for advantages and disadvantages depending on the chemical nature of the radioactive atom, the reliability of the system and the radiation level in the production cave. The proved external target mode presents the advantages of the simplicity and reliability. The disadvantages are contradicting: It is a disadvantage to have the ECRIS close to the target from the radiation point of view. It is also a disadvantage to have the ECRIS far from the target (linked by a transfer tube) from the production point of view.

The internal target mode has as disadvantage the proximity of the ECRIS to the target, from the radiation point of view. Good results could be expected for very short living and most of condensable elements.

The stripping mode combines the safety of the ECRIS - now placed outside of the production cave - with the fast transfer of the radioactive beam, which can be produced very close to the target by a $1+$ ion source. The disadvantage is that a two stage system is required. Therefore, the efficiency of the full system will be the product of the two independent ionisation efficiencies times the injection efficiency into the ECRIS.

The latter two modes require important R&D in order to improve the present results and to gain in reliability.

It is important to remember that the ion source for RIB production is linked to a target. Therefore, the full target-ion source system should be optimized simultaneously. In this particular case, new techniques [35,36] can be used in order to understand and quantify the different efficiencies of each particular process in ISOL.

Finally, a discussion about the use of cyclotrons as mass separators has been presented. It has been shown that an "equivalent mass separation" power of $R \approx 50,000$ can be achieved if one uses cyclotrons as mass separators, while accelerating the radioactive ion beam. This mass separation does not really eliminate the contaminant but separate it on time from the selected one. This technique can certainly be used in several RIB experiments.

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FIGURE CAPTIONS.

- (1) Multi-mirror ECRIS B structure [1]. The multi-mirror are obtained by a superposition of double axial mirror and a hexapolar field.
- (2) ^{15}N emittance at 14 kV of ECR4M as a function of q/A for standard conical extraction electrode and multi-electrode [19].
- (3) Emittance of NANOGAN-II ion source as a function of q/A at 15kV of extraction voltage for different elements [19].
- (4) Beam intensities of SHyPIE ion source running off-line and tuned in order to optimise the beam of ^{50}Cr (6+). The beam current of ^{40}Ar and ^{50}Cr as a function of the q/A are plotted.
- (5) Normalised beam intensities of ^{33}Ar ($T_{1/2}=174\text{ms}$) and ^{40}Ar beams as a function of the charge state q .
- (6) The TISOL-TRIUMF [6] ECR on-line ion source.
- (7) Project of the SPIRAL cave. 1- The target-ECRIS system. 2- The high energy front-end. 3- The low energy front end. All parts can be remotely removed from the cave.
- (8) The SHyPIE system for the Internal Target mode [27].
- (9) The ISN-Grenoble $1+ - n+$ system [12]. The Rb ($1+$) beam is produced by the thermoionic ion source, extracted, decelerated and injected into the MinimaFios ECRIS. After extraction, the $n+$ beam is analysed in the Faraday cup $n+$.
- (10) Ratio between the detected Rb($9+$) beam intensity to the Rb($1+$) measured before injection as a function of the voltage difference between the two ion sources [12].
- (11) Simulation of the acceleration inside the CIME cyclotron. The case 1 of the text corresponds to the correct isochronous trajectory. The case 2 corresponds to the "S" trajectory. Observe that in the case 1 the two beams arrive at the extraction radius with 10ns of time difference. In the case 2 the ^{35}Cl contaminant is eliminated [33].

TABLE CAPTIONS.

- (1) The maximum magnetic field in the injection, the minimum in the valley and the second maximum at the extraction zone are given for some ECRIS, as well as their working frequencies. SCECR-MSU [14], AECS - LBL [15], ECR4-GANIL [16] and NANOGAN-II of GANIL [17].
- (2) Published intensities of RIB produced in the TISOL-TRIUMF, CRC-UCL and SIRa-GANIL facilities. It should be noted that the primary beams are completely different for each case and that the yield given for CRC-UCL corresponds to the accelerated RIB (after the cyclotron CYCLONE).

Ion Source	Binj. (T)	Bmin. (T)	Bextrac. (T)	Freq. (GHz)
SCECR-MSU	1.25	0.15	0.65	6.4
AECR - LBL	1.05	0.40	0.65	14.5
ECR4-GANIL	1.05	0.35	0.90	14.5
Nanogan-II	0.90	0.35	0.80	14.5

Table 1.

RIB	TISOL [6]	CRC-UCL [7]	SIRa- GANIL [11]
^6He		1.2×10^6	6.0×10^7
^8He	3.7×10^5		2.1×10^5
^{10}C	1.2×10^7		
^{11}C		1.0×10^7	
^{15}C	5.6×10^4		
^{13}N		4.0×10^8	
^{16}N	3.4×10^6		
^{17}N	2.5×10^5		
^{18}N	7.2×10^2		
^{18}F		1.0×10^6	
^{17}Ne			3.1×10^4
^{18}Ne	3.3×10^6	4.2×10^5	3.1×10^6
^{19}Ne	3.3×10^8	1.9×10^9	5.0×10^7
^{23}Ne	2.2×10^7		
^{24}Ne	2.4×10^6		
^{25}Ne	4.3×10^3		
^{32}Ar			1.0×10^2
^{33}Ar			1.8×10^4
^{34}Ar	4.6×10^4		1.4×10^6
^{35}Ar	1.1×10^6	1.0×10^5	6.2×10^7
^{72}Kr			2.6×10^2
^{73}Kr			2.5×10^3
^{74}Kr			7.0×10^4
^{75}Kr			1.8×10^5
^{76}Kr			3.6×10^6
^{77}Kr			6.1×10^6

Table 2.

figure 1.

figure 2

figure 3

figure 4

figure 5

figure 6.

figure 7

figure 8

figure 9

figure 10

Villari fig. 11