EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/INTC 2001-023
INTC/P-143
20 August 2001

Proposal to the INTC Committee

Charge Breeding of Radioactive Ions in an Electron Cyclotron Resonance Ion Source(ECRIS) at ISOLDE

F. Ames[1], M. Cavenago[6], K. Connell[3], G. Nyman[7], D. Habs[1], G. Huber[4], B. Jonson[7], O. Kester[1], T. Lamy[2], M. Lindroos[8], K. Reisinger[1], T. Sieber[1], P. Sortais[2], L. Tecchio[6], A. Villari[5], D. Warner[3], F. Wenander[8], B. Wolf[4]

[1] *LMU München,* [2] *ISN Grenoble,* [3] *CLRC Daresbury,*
[4] *ISOLDE and Universität Mainz,* [5] *GANIL,* [6] *INFN LNL,* [7] *Chalmers Göteborg,* [8] *CERN*
and the EU charge breeding collaboration

Spokesperson: D. Habs
Contact person: O. Kester

Summary

The development of an efficient charge breeding scheme for the next generation of RIB facilities will have a strong impact on the post-accelerator for several Radioactive Ion Beam (RIB) projects at European large scale facilities. At ISOLDE/CERN there will be the unique possibility to carry out experiments with the two possible charge breeding set-ups with a large variety of radioactive isotopes using identical injection conditions. One charge breeding set-up is the Penning trap/EBIS combination which feeds the REX-ISOLDE linear accelerator and which is in commissioning now. The second charge breeder is a new ECRIS PHOENIX developed at the ISN ion source laboratory at Grenoble. This ECRIS is now under investigation with a 14 GHz amplifier to characterize its performance. The experiments are accompanied by theoretical studies in computer simulations in order to optimize the capture of the ions in the ECRIS plasma.

A second identical PHOENIX ECRIS which is under investigation at the Daresbury Laboratory is available for experiments with radioactive ions at ISOLDE in order to compare the breeding efficiency with the Penning trap/EBIS breeder with the same isotopes. The goal of the breeding experiments proposed are the investigation of the injection of ions into the ECRIS plasma and the loss mechanism, the maximum breeding efficiency and the breeding times. A comparison with REX-EBIS results will allow a more objective evaluation of both schemes. Especially the breeding efficiency for very weak currents will be of interest.

A total of 15 shifts of beam time with an UC_2 target combined to various ion sources are requested to study charge breeding of radioactive isotopes like fission fragments. Later the ECRIS test stand will be available for experiments in astrophysics and deep implantation for solid state physics.

1 Introduction

For the presently built and the planned second generation RIB facilities several concepts of post-acceleration are discussed or are already in use [1]. For the energy range of interest between 5 and 10 MeV/u a LINAC or a cyclotron can be used. Both types of ion accelerators can be run in cw-mode, the LINAC can be pulsed as well. The size of the post-accelerator needed to bring the unstable nuclei to the energies required to study nuclear reactions depends on the charge state of the radioactive ions. The capability to raise the charge state from 1+ to n+, where n may correspond to a charge-to-mass ratio of 1/ 6.5 or higher, will therefore produce an enormous reduction in cost as well as the possibility to accelerate heavier masses with increasing efficiency. The charge breeder has in addition the advantage that the radioactive ion beams can be cooled and bunched within the charge breeding system. Hence the duty cycle of a LINAC and therefore the RF-power consumption can be reduced significantly and there is no pre-stripping LINAC required which accelerates the ions to stripping velocities. The objective of the EU-RTD network HPRI-CT-1999-50003 is the development of the technique of an efficient charge transformation of exotic ions for RIB-facilities by charge breeding devices [2]. This charge breeding study will also be part of a scientific and technological collaboration between ISOLDE, LMU Munich and CLRC to develop the new radioactive beam facilities REX-ISOLDE, MAFF and SIRIUS [3]. It furthermore will supply essential information for the EURISOL EU-RTD network HPRI-CT-1999-50001 [4], which prepares the design and layout of a large European ISOL facility.

2 Current Status of Charge State Breeding

Several schemes of charge breeding have been considered in Ref. [5] using two types of ion sources capable of reaching the required charge states [6]. These sources are the Electron Beam Ion Source (EBIS) [7] and the Electron Cyclotron Resonance Ion Source (ECRIS) [8].

Schematically the setup of an EBIS is shown in fig. 1. A dense mono-energetic electron beam from an electron gun is used to further ionize the injected radioactive ions. The electron beam is focused and compressed by a strong magnetic field created by a surrounding solenoid. Ions injected into the EBIS are confined radially by the electrostatic forces from the space charge of the electron beam and the magnetic field, and longitudinally by potential barriers, established by cylindrical electrodes surrounding the beam. Inside the trapping region the high-energy electrons collide with the ions, which are stepwise ionized, until they are finally extracted by lowering the extraction barrier.

The main features of an EBIS are: the fast breeding (some tens of milliseconds), the high breeding efficiency, the good beam properties (transverse and longitudinal emittance) and the low contamination of the extracted beam (capable of handling down to a few ions per pulse). The disadvantage of the Penning trap/EBIS compared to the ECRIS is the maximum throughput of only 10^8 ions/s which may be improved by shorter breeding time (e.g. by larger electron beam compression), continuous injection and higher breeding capacities. This

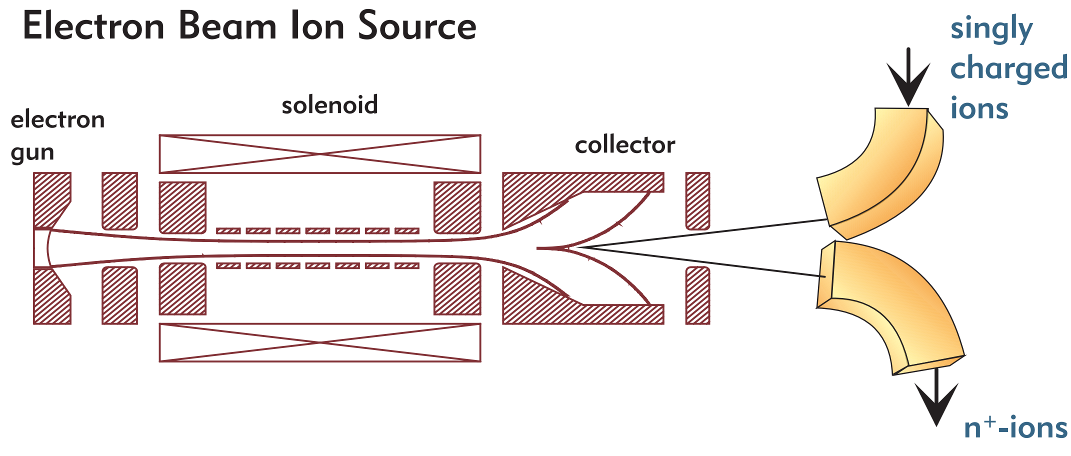

Figure 1: *Schematic setup of an EBIS.*

is no principal limitation of the EBIS concept, where 10^{11} ions per pulse and repetition rates of 100 Hz appear feasible, but of the preceding Penning trap where the Brillouin limit for the ion density and the cooling and centering times limit the throughput. Here the gas-filled continuously working RFQ-cooler, planned for ISOLDE, may significantly improve the situation. The ion cooler can match higher beam intensities to the small transverse acceptance of the EBIS in the accu-mode [9].

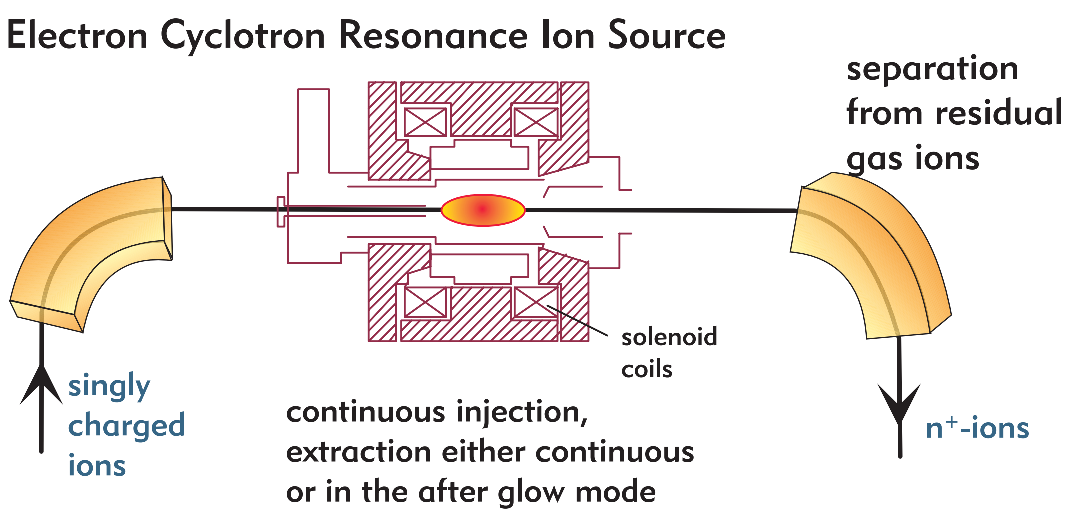

Figure 2: *Schematic setup of an ECRIS.*

The second approach to achieve high charge states is to use the stripping mode ($1^+ \rightarrow n^+$) for the ECRIS, which has been developed at ISN-Grenoble for the PIAFE project [10] and for the SPIRAL project [11, 12] at GANIL. Fig. 2 shows schematically the injection and extraction for an ECRIS. An ECRIS can be considered to be composed of three entities: a magnetic field, a microwave RF-field and a low-pressure ionized gas. The chamber is situated inside a magnetic field created by a set of solenoids and by permanent magnets which create a multi polar field. RF is coupled into the source and a plasma is ignited by microwave ionization, thereafter maintained and developed by electron impact ionization.

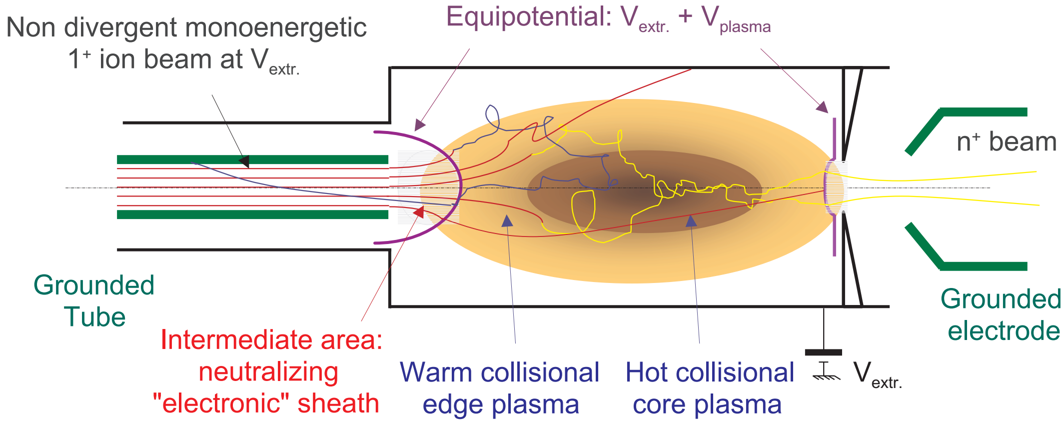

Figure 3: *Ion motion inside an ECRIS.*

With Fig. 3 we want to explain the principal operation of the ECRIS in charge breeding. Electrons heated by the RF in the electron cyclotron resonance zone contribute to the successive ionization. Inside an ECRIS the plasma usually has a positive potential with respect to the walls. Since the electrons in an ECRIS have a higher mobility and leave the plasma faster than the ions, the plasma potential assumes a positive value in order to accelerate ions and to retard the electrons. In the core of the plasma inside an ECRIS a small negative potential dip $\Delta\phi$ occurs, which retains the ions in the central hot plasma and traps the hot electrons. Singly charged, non divergent, monoenergetic ions are injected over the small barrier $\Delta\phi$, then they thermalize inside the plasma and become highly charged. The highly charged ions move to the axis of the source, from where they are extracted with a special electrode system. If the microwave feeding is abruptly turned off, the steady-state operation is replaced by the so-called afterglow-mode. This mode is suitable for a bunched operation with a high peak intensity and short pulses.

We want to compare both high charge state ion sources, in order to define the favours of both sources. These main properties are compiled in Table 1.

The EBIS can reach much shorter breeding times (5 - 20 ms instead of 20 - 100 ms for the ECRIS), shorter extraction pulses (15 - 30 μs instead of 2 - 10 ms for the ECRIS) and higher efficiencies in one charge state in the pulsed mode (30% instead of 2.2% for the ECRIS). The emittances of the beams from the EBIS or the ECRIS are comparable and show values between 10 - 20 π mm mrad at 20 keV beam energy. For an EBIS an achromatic mass separator is required due to the energy spread of the ions. In case of the ECRIS a pure magnetic separator is sufficient. Furthermore the ECRIS is (as a charge breeder) operated at a pressure of $\approx 10^{-7}$ mbar, while the EBIS is operated under UHV conditions with 10^{-11} mbar. The lower rest gas pressure in the EBIS simplifies the separation of low intensity radioactive beams from the residual gas ions. The separation of very low intensities of radioactive ions from residual gas ions extracted from an ECRIS is a challenge, due to the high background level in the mass spectrum which results from charge exchange of the extracted ions. The rather different operation conditions of EBIS and ECRIS and the multidimensional parameter space require individual optimizations before one can decide which is the more appropriate scheme. To clarify this situation, both breeders are setup

EBIS	ECRIS
higher charge states ($q/A_{max} > 0.3$), short breeding times, high repetition rate	high charge states ($q/A_{max} \approx 0.2$), higher breeding times, lower repetition rate
low beam intensities ($\approx 10^9/s$), electron beam = confinement	high beam intensities ($\approx 10^{12}/s$), plasma volume = confinement
emittance at 20 keV: $\approx$ 10 - 20 π mm mrad	emittance at 20 keV: $\approx$ 10 - 20 π mm mrad
narrow charge state distribution	broader charge state distribution
requires UHV conditions (10^{-11} mbar)	usually high vacuum (10^{-7} mbar)
pulsed injection, pulsed ion extraction	continuous injection, pulsed extraction in afterglow mode (ECRIT)
efficiency for one charge state: fast injection N^{7+} 30%, Ar^{14+} 9.4% accu mode N^{7+} 0.1%	efficiency for one charge state: continuous In^{20+} 10%, pulsed Rb^{15+} 2.2%

Table 1: Comparison of the Properties of the EBIS and ECRIS.

at ISOLDE using identical injection conditions. Nevertheless the aim is to produce intense radioactive beams, which exceed by far the capacity of the present Penning trap/EBIS system of 10^9 ions/s and where only the ECRIS is able to serve as a charge breeder.

In the following two paragraphs we compile the recent achievements for both breeding schemes.

2.1 The Penning Trap/EBIS Combination at REX-ISOLDE

The charge breeding of an EBIS has been demonstrated already before REX-ISOLDE got started [13, 14, 15, 16]. The measurements with N and Ar beams have shown efficiencies of N^{7+} and Ar^{14+} of 30% [14] and 9.4% [13] respectively.

Fig. 4 shows the two storey setup of REX-TRAP and REX-EBIS. In order to prepare beams from the production target of the ISOLDE facility for a pulsed LINAC with low duty cycle, the Penning trap REX-TRAP is used for accumulation, emittance cooling and bunching of the beams with an EBIS following. Both components, the Penning trap REX-TRAP [17] and the REX-EBIS [18, 19, 20], have been operated successfully as separate units. The combined operation will be tested in the next few weeks. With REX-TRAP an capture efficiency of 45% has been measured, but we are hopeful that finally 100% can be reached. The emittance from REX-TRAP was determined to be about 10 - 12 π mm mrad at 30 keV, which should be completely accepted by the EBIS.

The REX-EBIS has so far been operated with an electron current of 250 mA and 4 keV and beams of rest-gas ions have been extracted. The transfer from REX-TRAP to REX-EBIS failed, however, in first tests for several reasons:

- The low electron beam current in the REX-EBIS due to the damaged cathode reduced the acceptance.

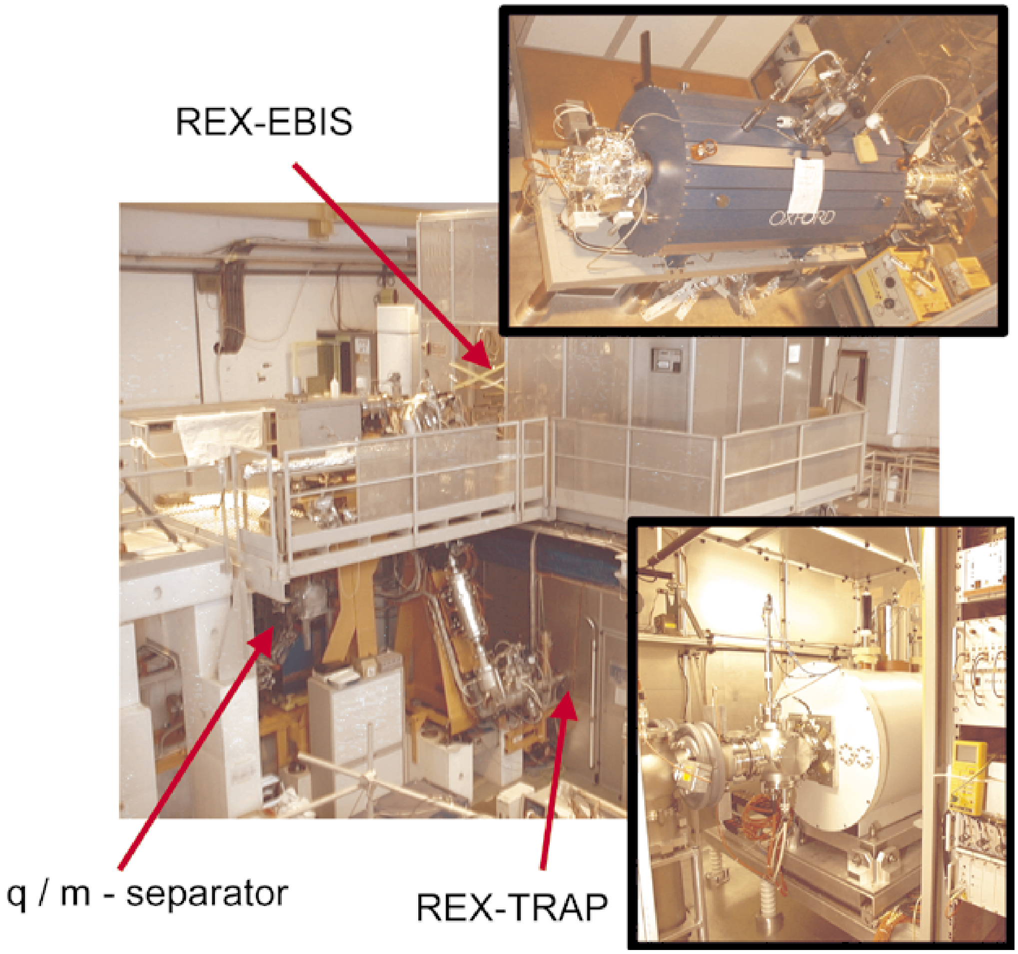

Figure 4: *Picture of REXTRAP and REXEBIS and the q/m-separator at ISOLDE. Inserts show the superconducting magnets of the Penning trap and the EBIS.*

- The relatively high level of rest-gas background inside the trapping region of REX-EBIS made the identification of injected ions from rest gas ions a difficult task.
- Misalignments of the inner structure and of the magnetic axis with respect to the optical axis of REX-EBIS complicated ion injection.
- The diagnostics at the entrance of the EBIS was not sufficient to properly align the injected ion beam.

These defects recently have been corrected and we now are optimistic that in the next few weeks the interface between the buncher/cooler and the breeder will be established, resulting in a high performance unit, producing multiply charged ions with high efficiency.

2.2 The PHOENIX ECRIS

The charge breeding mode of the ECRIS was first examined in detail in Ref. [21, 22] with the MINIMAFIOS source. The ion injection into the ECRIS is always continuous so that no preceding accumulation is required. The peak efficiency $1^+ \rightarrow n^+$ for the MINIMAFIOS in the continuous charge breeding mode was about 10% for Ar^{8+}, Kr^{12+} and Xe^{14+} and about

5% for alkaline ions [23] while the breeding efficiency for all charge states was about 53% for noble gases and 35% for alkalis.

The second mode is of interest for a pulsed low duty cycle LINAC and is called the trapping or ECRIT mode (Electron Cyclotron Resonance Ion Trap). In the ECRIT mode the ions are extracted in the so called afterglow mode, where the RF is switched off and the ions are expelled in a short pulse when the plasma confinement breaks down. In both modes the ECRIS can deliver 10^{12} highly charged ions without saturation effects. Due to the large plasma volume, the ECRIS is able to accept the full transverse emittance of nearly any 1^+-ion source. There is no restriction from the trapping capacity concerning beam intensities of 10^{12} ions/s. The 1^+-ions are decelerated inside the ECRIS by the retarding potential. The kinetic energy of the ions is adjusted so that they can cross the plasma potential and thermalize by ion-ion collisions in the plasma. However, a single pass RFQ buffer gas cooler would be also very advantageous for the ECRIS, because a rather small energy spread of the injected ion beam, required for an efficient trapping, could be reached independent of the properties of the primary ion source.

The confinement time of the ions in the plasma could be determined in the ECRIT mode and is longer than 300 ms. Depending on the species and charge state to be reached the required breeding time is about 30-50 ms. Thus in case of short lived isotopes losses in the breeding cycle can occur due to nuclear decay. In addition the FWHM of the extraction pulse is about 10 ms. This will cause problems with the LINAC duty factor, because a long RF-on period of more than 10 ms is required. One should note, however, that the MINIMAFIOS was a low performance source not dedicated for the charge breeding purpose.

Recently the new $1^+ \rightarrow n^+$ ECRIS charge breeder called PHOENIX at ISN Grenoble has produced impressive results concerning the breeding efficiency and the breeding time. Fig. 5 shows a photograph of this new ECRIS source, which has rather small dimensions when compared to the REX-EBIS/REX-TRAP system. The breeding efficiency for all charge states of the ECRIS PHOENIX has reached the same level of 70% for metallic as well as for gaseous ions. The most abundant charge state reaches 10 to 15% depending on the mass. The breeding time has been reduced significantly reaching e.g. 25 ms for Ag^{19+} [24, 25, 26, 27]. Fig. 6 shows as an example the charge state distribution of In-ions after injecting 1300 nAe of In^+ into the ECRIS PHOENIX operating with 14 GHz. After about 20 ms breeding time 3000 nAe of In^{20+} are extracted corresponding to 11.5% efficiency in the optimum charge state. The global efficiency, integrating over all charge states, is 65% for In.

3 The Proposed Experiment

We want to install the ECRIS PHOENIX, which is being tested at Daresbury Laboratory, during the winter shutdown in the ISOLDE hall as shown in Fig. 7. In a first experiment we plan to measure with PHOENIX the yields of highly charged fission fragments, which will be produced in an UC_2 production target at ISOLDE. Since at the same time REX-ISOLDE is operational, we want to study in a parasitic mode for the same ions the yields of highly

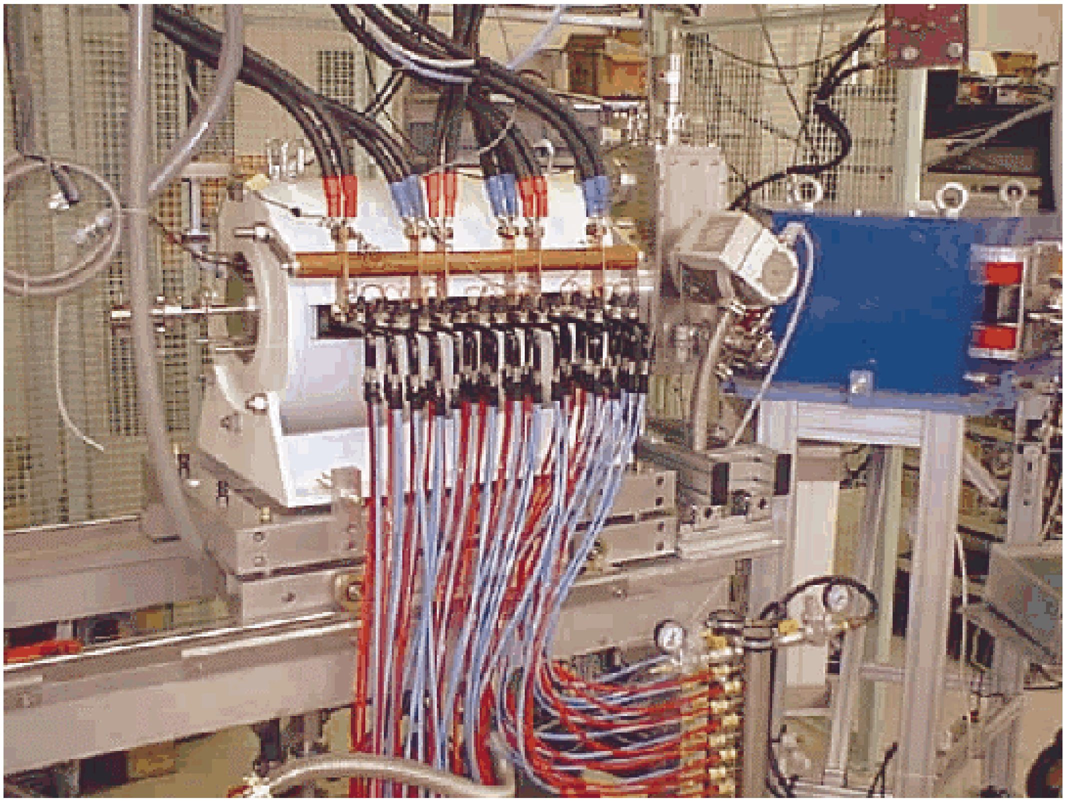

Figure 5: *Picture of ECRIS PHOENIX at ISN Grenoble.*

charged fission fragments there. During the set-up and commissioning phase we want to test the system with stable beams.

A central issue to the INTC-committee is the question, why radioactive isotopes and not just stable beams are necessary for running the ECRIS PHOENIX at ISOLDE. In general the physics involved in an ECRIS is rather complex (and moreover not fully understood) covering atomic physics, plasma physics, charged particle motion, wave-plasma interactions etc. Therefore we think that a real measurement of breeding efficiencies and breeding times under realistic conditions is essential for the planning of second generation RIB facilities like MAFF, SIRIUS, SUPER-ISOLDE and EURISOL. Here basic data for realistic planning are delivered.

Significant losses may occur to the chamber walls. The yields of specific reference nuclei like ^{132}Sn should be determined under realistic background conditions. Are there yield changes due to the behaviour of different chemical elements in the ECRIS ? Noble gases are recovered more easily when they hit the chamber walls. It will be interesting to study the additional purification from other isobars by selecting the proper charge state. E.g. ^{132}Cs can be ionized to higher charge states than ^{132}Sn, thus allowing for a suppression of ^{132}Cs. It will be interesting to inject ^{98}Sr -^{102}Sr into the ECRIS and to store them for more than the nuclear halflife of 200 ms in the ECRIS, so that most of the Sr has decayed to Yb. How big are the losses of these highly charged ions from the plasma by the nuclear recoil? In this way refractory daughter elements could be obtained for acceleration, while easily produced mother-isotopes are injected into the ECRIS. For radioactive isotopes even very weak intensities can be identified, because we can measure their radioactive decay in a tape station after extraction and separation.

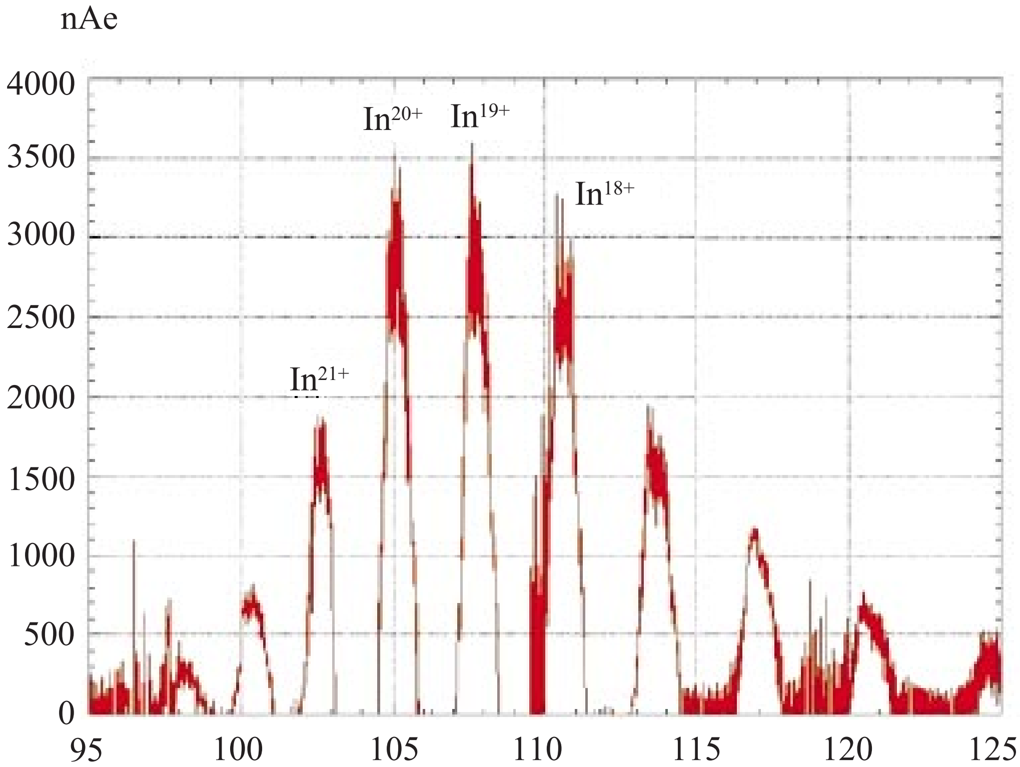

Figure 6: *Charge state distribution of PHOENIX for In-ions.*

This study of isotopes with small yields requires radioactive beams. For the studies with the ECRIS we want to cover most of the NUPECC elements in addition, which are: Be, Na, Ar, Ni, Kr, Ga, Sn, Fr. For Be, Ni and Sn-isotopes the laser ion source is required. For Ar, Kr and Ga isotopes the cold plasma source will be used and for Fr isotopes the W-surface ionizer is foreseen. In the first beam time with the REX-ISOLDE charge breeder experiments with Na isotopes are planned. In order to compare breeding efficiencies we plan to breed Na isotopes with the PHOENIX as well. In addition we want to investigate the differences in wall losses of metallic ions and noble gas ions. Therefore we choose Kr and Sn isotopes.

In a more short term perspective an ECRIS charge breeder at ISOLDE could be used as a compact ion source, delivering ions with n-times the energy of the present ISOLDE production ion source, which is of interest for low energy astrophysics experiments and deep implantation for solid state physics. Once the possibility of the ECRIS charge breeder is realized at ISOLDE we expect a further request for beam time later for dedicated experiments in astrophysics and deep implantation solid state physics. In astrophysics the most challenging experiments using low energy light ion reactions with Be and Li isotopes have to be selected.

4 Experimental Requirements

The planned setup of the ECRIS PHOENIX including the beamline and the analyzing system is shown in Fig. 7. The test beam line at ISOLDE consists of an injection beam line (lens, steerer, diagnostics) for the ECRIS and an extraction and separation beam line after the ECRIS. Behind the ECRIS we want to install the separator, which already has been tested with PHOENIX. This can be the ISN separator as well as the Daresbury one. In Fig. 7 the Daresbury system is included. The efficiency measurement for radioactive ions uses the spectroscopic tape station from GANIL. We want to install these systems during the winter shut-down. The magnets require a cooling power of 300 kW in the hall, which is available.

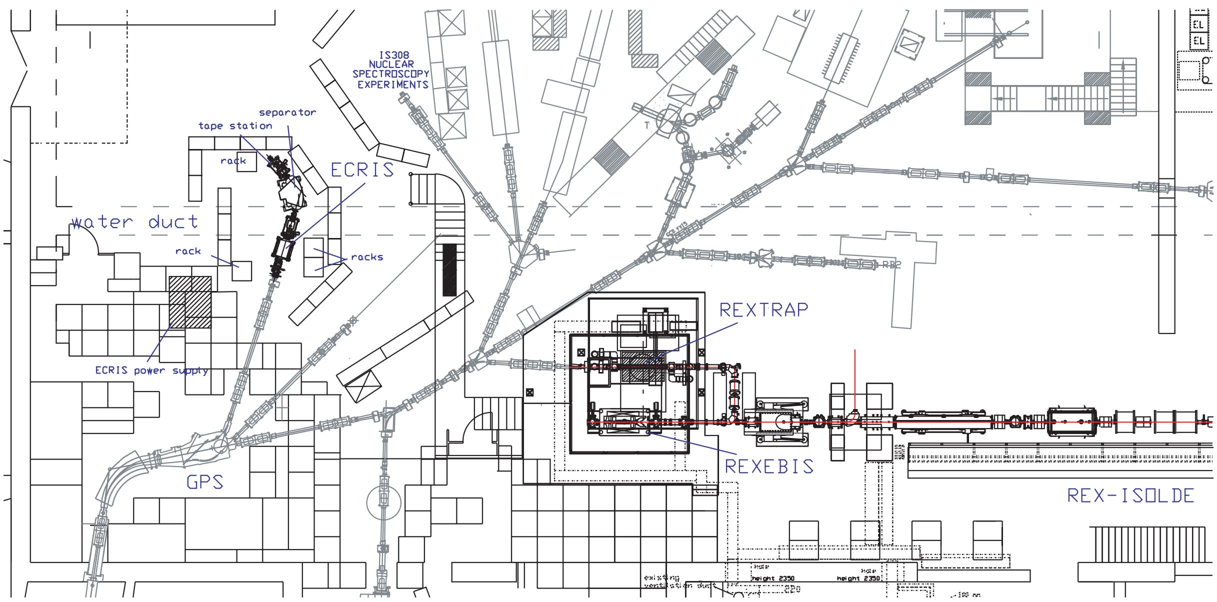

Figure 7: *Layout of the ECRIS PHOENIX setup in the ISOLDE-hall.*

The system requires different cooling circuits with different pressures. The cooling of the coils requires 60 l/min at 15 bar pressure. In addition 70 l/min for the power supplies at 2 bar and 15 l/min for the magnets at 3 - 5 bar are required. Since the main water line of the ISOLDE cooling circuit is close to the experimental setup no problems are foreseen. The power amplifier and the big Bruker power supply could be put on top of the GPS concrete shield which is in close neighborhood to the ECRIS beam line [28]. Commissioning with a test ion source is not foreseen. For that purpose stable beams from an ISOLDE ion source are required to adjust the breeder to typical ISOLDE beam emittances.

A special problem to be solved is the fine adjustment between the high voltage platform of the ISOLDE production target and PHOENIX. Due to the small potential dip of typically only 0.5 V in the center of the ECRIS plasma a fine adjustment of 1-2 V accuracy is required to stop the injected ions in the plasma and not to loose them at the chamber walls. Since the ISOLDE platform is put to ground level during injection of the proton beam a special filtering circuit is required, which accurately aligns the two high voltages when ions are injected into the ECRIS. Here some new developments have to be tested.

For unpacking of the delivered items from the different institutes for the charge breeding beam line and for the off line assembly, installation and test of various items floor space of about 20 m^2 is required. In addition to that electricity supply and tension distribution are required as well.

5 Beam time Request

For a variety of fission fragments and NuPECC elements charge distributions, breeding efficiencies and breeding times will be determined. This will be done in a variety of runs and not in an single experiment. All breeding experiments will sum up to total of 15 shifts with the UC_2 target combined with various ion sources and in a frequent access to stable beam in a parasitic use for commissioning which will sum up to 15 shifts as well.

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