Proposal to the INTC Committee
Addendum to experiment IS397 INTC-P-143
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Charge Breeding of Radioactive Ions in an Electron Cyclotron Resonance Ion Source(ECRIS) at ISOLDE

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Summary

The capability to raise the charge state of the radioactive ions before injection into an accelerator leads to an enormous reduction of construction and running costs of the accelerator and of the infrastructure. In addition it allows in principle to accelerate ions from all regions of the nuclear chart to the same energy per mass unit. Therefore at ISOLDE the two possible charge breeder devices, which are able to provide high charge states have been installed. One charge breeding set-up uses a PHOENIX Electron Cyclotron Resonance Ion Source (ECRIS) developed at the LPSC ion source laboratory at Grenoble and purchased by Daresbury Laboratory. First breeding experiments have been performed with stable and radioactive metallic isotopes ^{238}U, ^{84}Rb, ^{96}Sr, ^{130}Cs, ^{130}Sr and with isotopes of noble gases like Ar, Kr and Xe. The goals of the IS397 breeding experiments are to investigate and optimize the injection of ions into the ECRIS plasma, the loss mechanism, the maximum breeding efficiency and the breeding times. The experiments could not been completed within the proposed shifts. Especially a comparison with REX-EBIS results could not be done since the ECRIS was used until now in CW mode and thus a more objective evaluation of both schemes is not yet possible. Therefore we propose to perform additional experiments with a total of 20 shifts of beam time with an UC_2 target combined to various ion sources to study the charge breeding of Rb, Sr and Cs isotopes, of abundant Kr and Xe isotopes and eventually of light metallic isotopes like Na and K.

1 Charge breeding of isotopes with the PHOENIX ECRIS

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, does reduce the costs and space requirements and opens the possibility to accelerate isotopes from different mass regions of the nuclear chart [1]. The charge breeder matches the charge state of an isotope to the maximum A/q of the accelerator. An additional advantage of a breeding system is the cooling and bunching of the radioactive ion beams. 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. Within the EU-RTD network "charge breeding" HPRI-CT-1999-50003 [2] the technique of the charge state transformation of exotic ions for RIB-facilities has been examined in detail. The final goals were the installation of both breeder systems at the same radioactive beam facility ISOLDE and to investigate the breeding process systematically for both systems.

One approach to achieve high charge states is to use the stripping mode ($1^+ \rightarrow n^+$) for the ECRIS, which has been originally developed at ISN-Grenoble for the PIAFE project [3] and for the SPIRAL project [4] at GANIL. 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. The principal operation of the ECRIS in this charge breeding mode is shown in Fig. 1. Electrons heated by the RF in the electron cyclotron resonance zone contribute to the successive ionization. Inside an ECRIS the plasma has a positive potential with respect to the walls. In the core of the plasma inside an ECRIS a small negative potential dip $\Delta\phi$ occurs, where the hot electrons are trapped, which retains the ions in the central hot plasma. Singly charged, non divergent, monoenergetic ions are injected over the small plasma potential barrier, 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.

The new $1^+ \rightarrow n^+$ ECRIS charge breeder called PHOENIX from LPSC Grenoble has produced good results concerning the breeding efficiency and the breeding time of stable ions. 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+} [5, 6].

Each step of the injection, capture breeding and extraction action contributes to the breeding efficiency and transmission of the radioactive ions. Thus the influence of the injection emittance and of the beam convergence on the capture and breeding efficiency can be analyzed. In addition the dependence of the breeding efficiency on the rest gas presure, magnetic field adjustment and rf-power can be determined as well. Measurements on the breeding time (to reach the charge state which is required) reveal an optimized source tuning. Therefore a PHOENIX booster test bench has been built by the collaboration as an ISOLDE experiment (IS397), which is schematically shown in fig. 2 and in a photograph in Fig. 3.

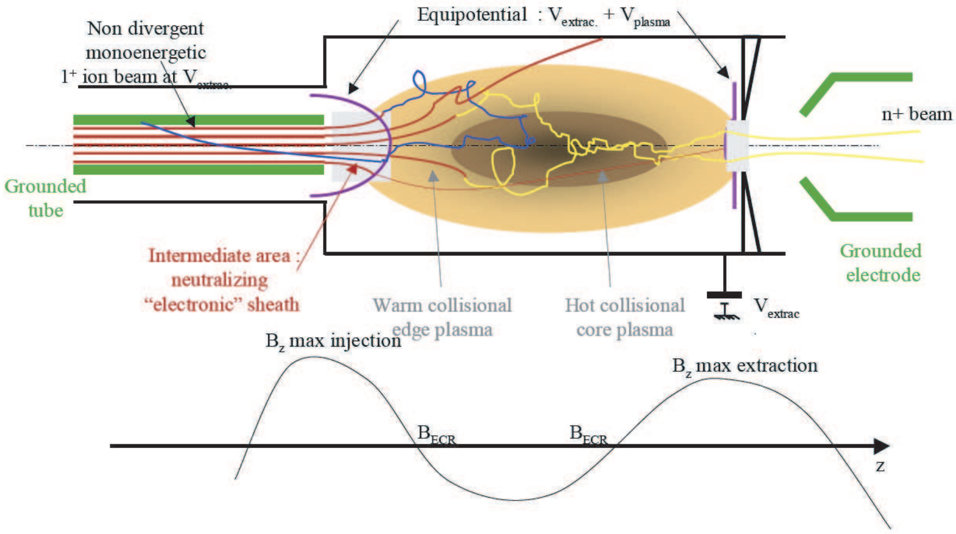

Figure 1: *Ion motion inside an ECRIS.*

2 Status of experiment IS397

Last year some promising results were obtained with stable and radioactive ion charge breeding [7]. Maximal efficiencies in one charge state with A/q≃6.5 close to 10% could be reached for Ar, Kr and Xe stable isotopes, 1.8% was reached for $^{238}U^{26+}$ (see Fig. 4). A measurement of the charge breeding time was made by using a beam gate at the GHM beam line. One example is shown in figure 5 for $^{40}Ar^{7+}$. The beam gate was successively opened and closed during periods of 1s. 200 ms was needed to reach the maximum number of charge breeded ions.

At last the ECR charge breeding technique was used for an astrophysics experiment to suppress the background of same A/q ratio as the relevant n-rich argon beams [8]. During all these tests a CW injection and extraction mode was used.

3 The Proposed Experiment

In the next experiments we want to implement and to test the afterglow method with both stable and radioactive beams, and to extend the charge breeding efficiency measurements to other radioactive isotopes produced mainly in UC_2 targets. Since during the same period REX-ISOLDE is operational, we want to measure and to compare in a parasitic mode for the same ions the yields of highly charged fission fragments. 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, HIE-ISOLDE and EURISOL. Here basic data for realistic planning are delivered.

In addition, some of the goals of the proposed experiment obviously require radioactive beam. The experiment should address the following issues:

1. The measurement of efficiencies of the ECRIS in pulsed mode with the so-called afterglow method. With such a mode, the breeding, confinement and extraction time for different ion source conditions can be accurately measured, and then the measured efficiencies could be

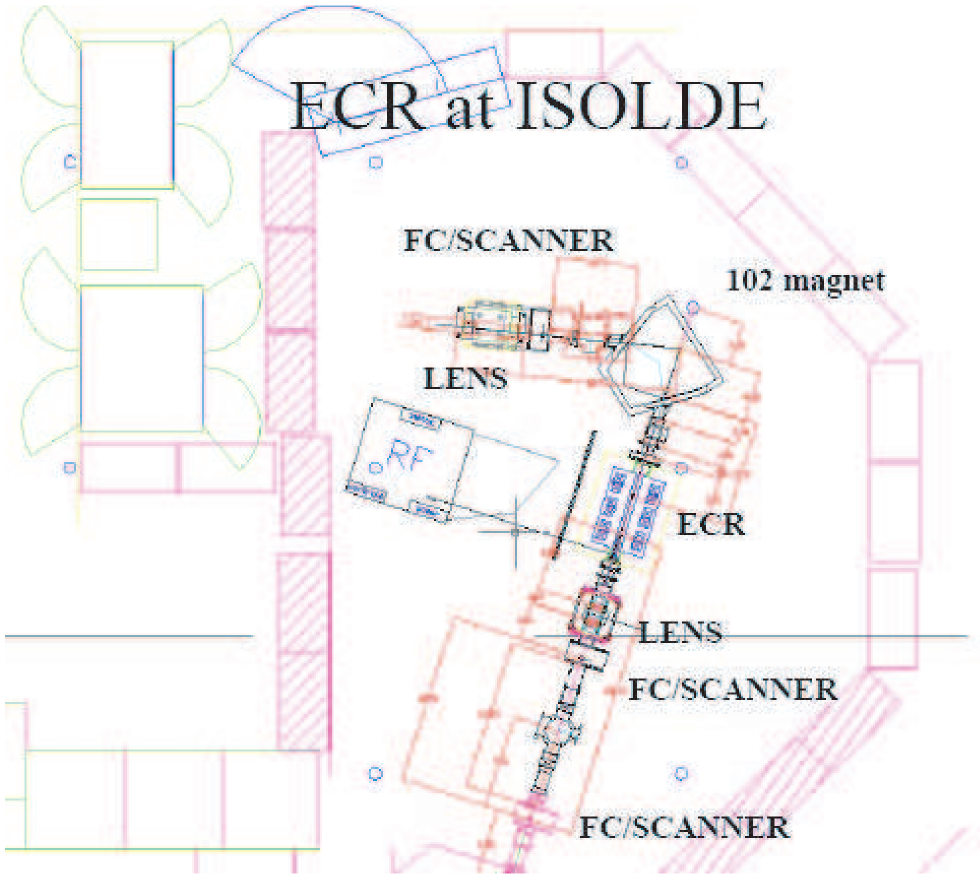

Figure 2: *Schematic setup of the PHOENIX ECRIS booster test bench at ISOLDE.*

directly compared to the REX-ISOLDE ones for proper cycle times. An efficient breeding scheme for short-lived nuclei needs to be demonstrated under realistic conditions, therefore the tests require both stable and radioactive beam. Intense stable and radioactive noble gas beams like Ar,Kr, Xe and stable alkali metals like Rb, Cs would be needed to perform such tests.

2. The charge breeding of different abundant isotopes accelerated at REX-ISOLDE. To make direct comparison of efficiencies of the ECRIS Phoenix with the combination REXTRAP-REXEBIS, we want to study the charge breeding of ^{88}Kr, $^{138-144}$Xe isotopes in pulsed mode.

3. The comparison of the charge breeding efficiencies for different elements. According to the chemical properties of the charge bred element, the adsorption/desorption mechanism on the wall of the chamber may affect considerably the charge breeding efficiency. Significant losses shall occur for reactive elements. In the case of noble gases, hitting the walls helps recovering the ions in the plasma. In order to study this effect, three different isobars are proposed: ^{132}Sn, ^{132}Cs and ^{132}Xe.

4. The possible trapping and breeding of daughter nuclides. Some refractory elements are difficult to produce at ISOLDE, such as Y isotopes. If the Sr mother nuclides are injected into the ECRIS, some of the daughter nuclides might be subsequently trapped in the plasma and charge bred, depending on the recoiling energy . We want therefore to study the charge breeding of ^{98}Sr, which has a half-life of 650 ms, and a low continuous recoil energy spectrum below 220 eV. For this test the tape station and gamma detectors shall be used after the separator because of the weak intensity to detect.

5. The tests relative to molecular sidebands. Last year it has been demonstrated at REX-ISOLDE with SeCO molecules that molecular sidebands could be used for an efficient sup-

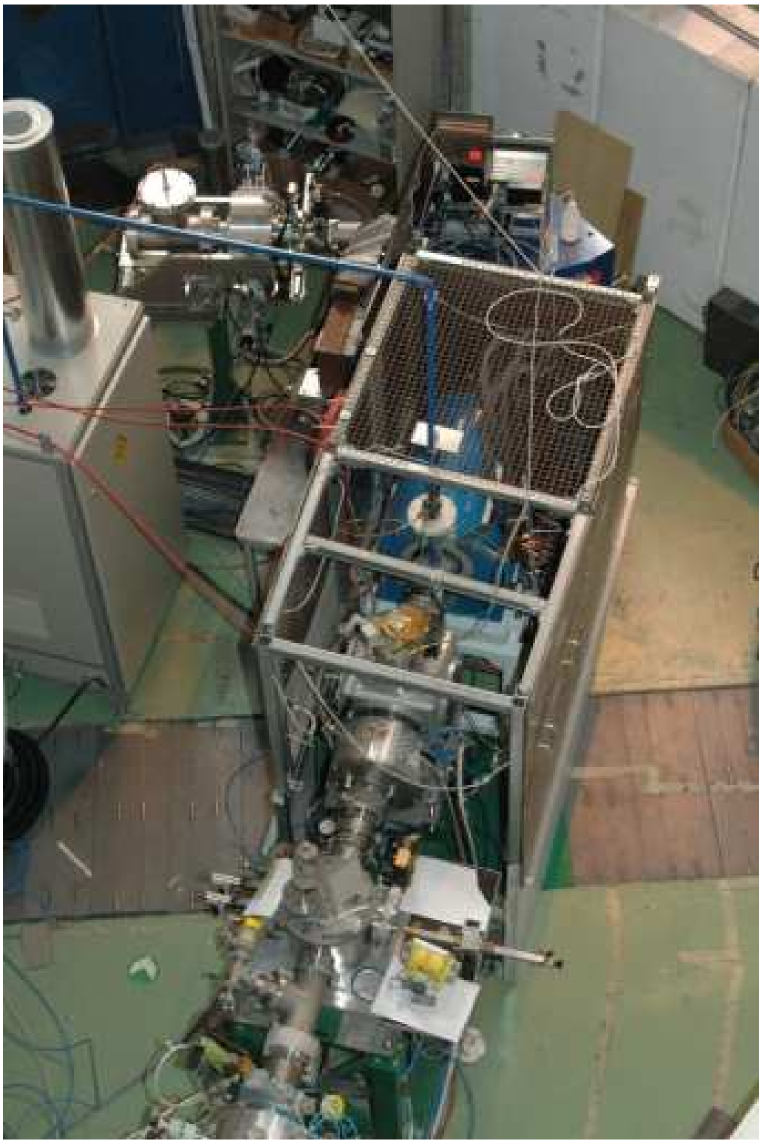

Figure 3: *Picture of ECRIS PHOENIX test bench at ISOLDE.*

pression of the isobaric contamination. We want to test the injection and the charge breeding of molecule fragments in the ECRIS Phoenix with SeCO, AlF, HfF_3, GeS, SnS and CO molecules.

6. The charge breeding of the NuPECC elements. We want to demonstrate the charge breeding of the following elements: Be, Na, Ar, Ni, Kr, Ga, Sn, Fr. Two important developments are strongly related to this project: extending the ECR charge breeding technique to light isotopes, and the reduction of the background for weak intensity beams. The first one will be studied by LPSC with Na ions before being tested at ISOLDE. The latter one shall be started this year with an improvement of the vacuum in the GHM beam line and the modification of some mechanical parts of the Phoenix booster. In this respect, an UHV ECRIS is being designed by LPSC.

In the next two years an ECRIS charge breeder at ISOLDE could be used together with an HV cage for boosting the energy of the primary beam coming from the production ion source to n-times the cage potential. This scheme is particularly of interest for astrophysics and solid state physics experiments which require a total energy of typically a few MeV. In a longer term perspective the same booster could be used in parallel with the EBIS at REX-ISOLDE. This latter

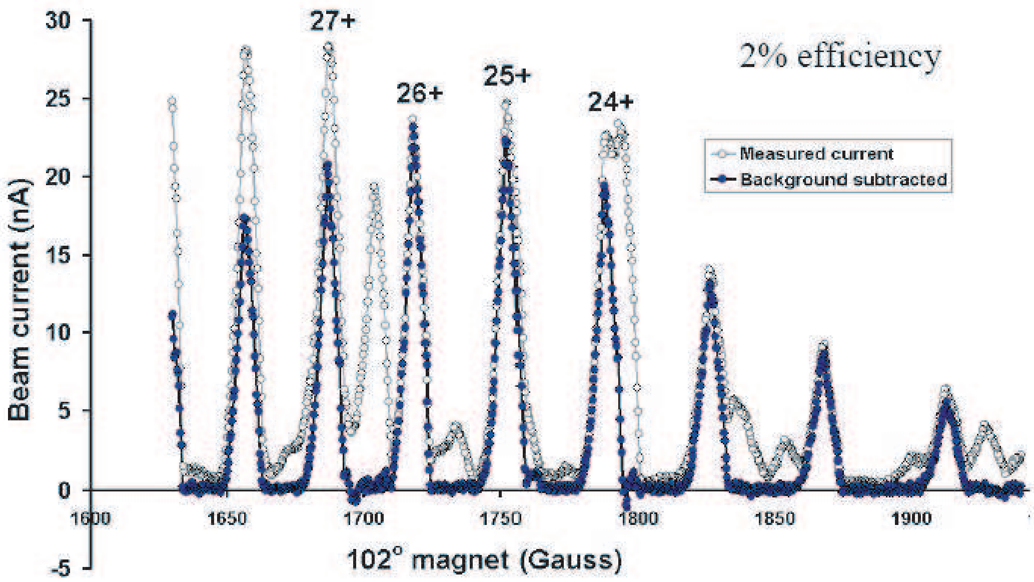

Figure 4: *Charge state spectrum of* ^{238}U *from the PHOENIX booster at ISOLDE.*

development is part of the HIE project. In general, the performances and the reliability of the ECR charge breeder for the astrophysics and implantation experiments, and as an alternative for the REXTRAP-REXEBIS combination, will depend strongly on the results obtained during the IS397 experiment.

4 Beam time Request

In total we require 20 shifts of radioactive beam time and 15 shifts of stable beam for commissioning and implementation of the afterglow method. Because of the big variety of fission fragments and NuPECC elements required for this experiment, the shifts could be distributed in parasitic mode during other running experiments, with UC_2 target and various ion source combinations. However, to keep the opportunity that all persons involved in the collaboration could be present at the same period we would like that some of the shifts with radioactive beam are grouped. In summary the table 1 presents the needs of the experiment in term of beam time for the different elements or isotopes proposed.

Table 1: *Beam time requirements*

Isotopes / Elements	Target / Ion source	Shifts parasitic mode	Grouped shifts
stable Ar, Kr, Xe isotopes	Plasma source with cold line	3	2
stable Na, K, Rb, Cs isotopes	W-surface ionizer	3	3
Molecular sidebands	various ion sources	4	-
^{88}Kr, $^{132,138-144}$Xe	UC_2/plasma source, cold line	3	3
^{98}Sr, ^{132}Cs, ^{132}Sn	UC_2/W-surface ionizer with RILIS for Sn isotopes	-	7
NuPECC elements	various target/ ion sources	7	-

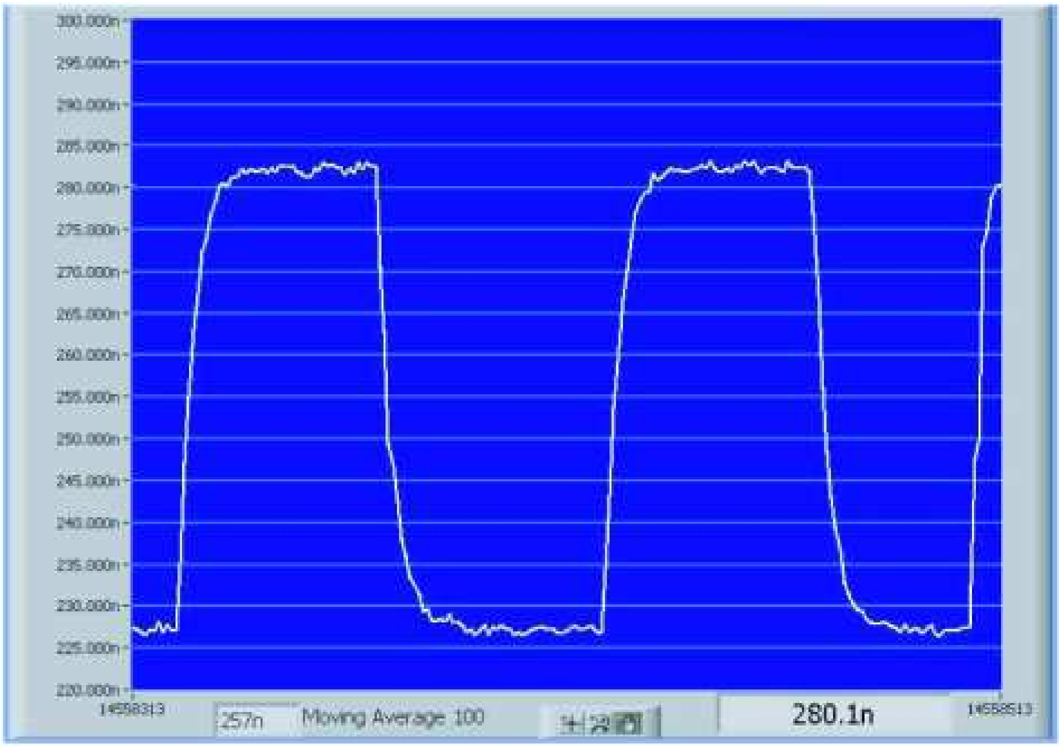

Figure 5: *Charge breeding time measurement with* $^{40}Ar^{7+}$*. The beam gate at GHM was successively opened and closed during 1s*

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