ACCELERATION OF RADIOACTIVE IONS AT REX-ISOLDE*

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Abstract

REX-ISOLDE is an experiment at ISOLDE/CERN where radioactive ions, which are produced by bombardment of a thick target with 1.4 GeV protons from the PS Booster, are post-accelerated with a 9 meter linac for experiments in nuclear-, astro- and solid state physics. For the efficient acceleration to energies between 0.8 and 2.3 MeV/u (in the first stage), the principle of charge breeding of the radioactive ions was introduced at REX. Therefore a Penning trap for accumulation, cooling and bunching is used in combination with an electron beam ion source for charge breeding. The Linac itself consists of a 4-Rod RFQ, an IH-drift-tube accelerator and three seven-gap split-ring resonators. In October 2001 the first radioactive beam has been accelerated successfully at REX. We give an overview of the performance of the REX-ISOLDE charge breeder and accelerator and of current and planned measurements. Further, the future plans for an energy upgrade of REX-ISOLDE by integrating additional IH cavities are described.

1 INTRODUCTION

Radioactive ions, which are produced with the ISOL (**I**sotope **S**eparation **O**n**L**ine) method, exist as a matter of principle after extraction from the online source and mass separation mostly in a 1+ charge state. The post-acceleration of these ions can principally be done in two different ways. One possibility is a low frequency machine for low charge states, which accelerates to energies, which are reasonable for stripping. Downstream the stripper a more efficient acceleration of the remaining, stripped fraction of the beam is possible. This principle surely reduces the effort in ion source development and in handling of highly charged ions in the LEBT region. On the other hand the pre-stripper LINAC will be large and cost intensive. The system has also a low flexibility since the maximum A/q of the pre-stripper accelerator defines the maximum mass of the ions, which can be accelerated. It is not possible to extend the mass range by changing the charge state.

The second principle for the post-acceleration of radioactive ions is to increase the charge state of the ions before the acceleration. This can be achieved by using an appropriate ion source as a charge state breeder. The charge breeding requires an immense effort (dependent on the type of ion source, which is used) concerning the accumulation and cooling of the beam. Also - dependent on the type of charge breeder - the accelerator might only work in pulsed mode. The required breeding times of presently 20ms to 200ms restrict (together with the diffusion time from the ISOL target) the acceleration of extremely short lived isotopes.

The great benefit of the charge breeding is that the resulting system is very flexible concerning the mass range, which can be covered. The second advantage is that the accelerator becomes very short from the beginning. Also the efficiency of that system might be steadily improved, by improving its subcomponents, such as the ion trap or the charge breeder. Finally the beam emittance, which is delivered by the charge breeders can be optimized to very small values. As a rule it is smaller than the emittance of stripped beams. At REX-ISOLDE at CERN the principle of charge breeding was realized for the first time [1]. The main reason to follow that scheme was the mentioned flexibility in ion species. Further there were limitations concerning the available room for the accelerator in the ISOLDE hall.

The main aim of REX-ISOLDE (in its first stage) is to deliver post accelerated radioactive ion beams with a variable energy between 0.8 and 2.2 MeV/u, whereby the full variety of ions available at ISOLDE should become accessible in form of accelerated beams for experiments. The charge state breeder, consisting of a Penning Trap and an EBIS (Electron Beam Ion Source), allows the acceleration of ions with $A < 50$ to energies at the Coulomb barrier with a LINAC of only 9 m length. It defines the time structure of the beam delivered to the LINAC and it adjusts the A/q of the ions below 4.5, which is the maximum A/q that can be accelerated with the REX structures. Fig. 1 shows a schematic of REX-ISOLDE in its current stage.

The beam line between the EBIS and the LINAC includes a mass separator, which separates the highly charged radioactive ions from the residual gas ions, which are always present in the ejected EBIS beam. Isotopes from the EBIS could be separated by the REX mass separator with a resolution of $(A/q)/\Delta(A/q)=100$. Beam optics calculations of the separator have shown a resolution of 110 for an injected beam with $\varepsilon = 10\ \pi$ mm mrad at 5 keV/u. The total transmission of the mass separator is (dependent on the charge state) in the range of 75-90%.

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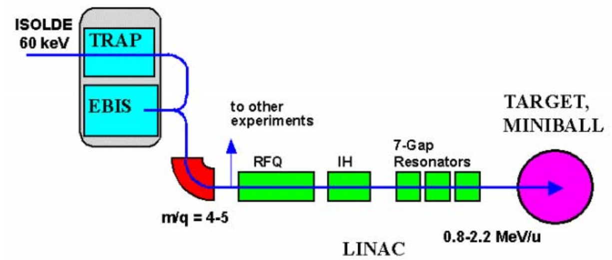

Figure 1: Schematic setup of REX-ISOLDE.

The linear accelerator of REX-ISOLDE consists of three different resonator types [2]. A 4-rod RFQ and an IH-DTL accelerate the ions to an intermediate energy of 1.2 MeV/u where they are further accelerated or decelerated by three 7-gap resonators of the split ring type. The section of the three seven gap resonators allows an energy variation of the whole system of 0.8 to 2.2 MeV/u. All structures operate at 101.28 MHz, which is half of the CERN proton LINAC frequency. The maximum duty cycle is 10%. The macrostructure of the accelerated ions have a typical bunch width of 10-50 μs, whereby a slower EBIS extraction (500 μs) is at the moment under investigation. The pulse distance is 20 ms (for the light ions). The calculated bunch length will have a pulse width depending on the final energy between 1.3 ns at 2.2 MeV/u and 13 ns at 0.8 MeV/u at the target. The expected energy spread of the beam at the target will be 1.5% at 2.2 MeV/u and 5% at 0.8 MeV/u [3].

2 STATUS OF REX-ISOLDE

2.1 Status of the experiments

The systematic study of nuclear structure at REX-ISOLDE is divided in three blocks: Coulomb excitation reactions, transfer reactions and fusion-evaporation reactions. In October 2001 REX-ISOLDE started working as an accelerator for radioactive ions from ISOLDE. In two commissioning beam times during fall 2001 the whole system - charge breeder and accelerator – proved the ability of producing in this first tests energies of 2 MeV/u for ^{24}Na with A/q=4. During this commissioning beam time radioactive sodium beams (^{24}Na, ^{26}Na) have been transmitted on a ^{58}Ni target for Coulomb excitation experiments and on a ^{9}Be-target to study neutron pickup reactions. For that purpose a temporary target set-up including a Si-strip-detector and one MINIBALL triple cluster detector has been installed.

During the shutdown period 2001/2002 the third seven gap resonator was taken into operation and REX-ISOLDE reached for the first time the design energy of 2.2 MeV/u. Switching the 7-gaps to 0° phase enables to reach an energy of even 2.3 MeV/u. Also during that period the MINIBALL detector array was completely installed for measurements comparable to the commissioning runs, but now with the full equipment covering a mass range from ^{24}Na to ^{28}Na.

For a Lithium run after the Na beamtime in May 2002, a second beamline was installed in the target area. With the successful acceleration of $^{9}Li^{2+}$ to 2.3 MeV/u REX-ISOLDE proved for the first time operation at the maximum A/q of 4.5 at design energy. Figure 2 shows a picture of the target area with the MINIBALL and the second beamline.

Figure 2: The target area of REX-ISOLDE. The MINIBALL is at the end of the 65° beamline. At the 20° beamline the target chamber for the Li run has been removed and was replaced by an emittance scanner (background right hand side) for commissioning measurements.

2.2 The Charge State Breeder

The REXEBIS has produced the first charge bred ions in May 2001. It has delivered stable $^{39}K^{10+}$ and $^{23}Na^{6+}$ beams from the REXTRAP test ion source. Stable beams from ISOLDE have been used to breed $^{27}Al^{7+}$- and $^{23}Na^{6+}$-ions and to accelerate them for detector tests. With radioactive $^{26}Na^{7+}$ and $^{24}Na^{7+}$ beams (about $5*10^5$ p/s) γ-spectra have been taken during the commissioning beamtimes. For further measurements with the MINIBALL in 2002, $^{25}Na^{7+}$, $^{27}Na^{7+}$ and $^{28}Na^{6+}$ beams have been produced with comparable intensities. During a Li run $5*10^8$ p/s of $^{9}Li^{2+}$ were extracted from the EBIS. In general the charge breeder of REX-ISOLDE is the first charge state booster that breeds intensities of some pA of radioactive ions for post acceleration with a LINAC.

A breeding efficiency with the EBIS of about 15% in one charge state could be reached for Na and K. Including the trap efficiency of about 40% the overall breeder efficiency in one charge state is about 6%. In fig.3 a current charge state spectrum of ^{26}Na is shown (breeding time: 18 ms). The Figure shows the very small background contamination from residual gas ions produced in the EBIS. This low background allows the identification of very low intensities (down to 100 fA) of charge bred radioactive ions.

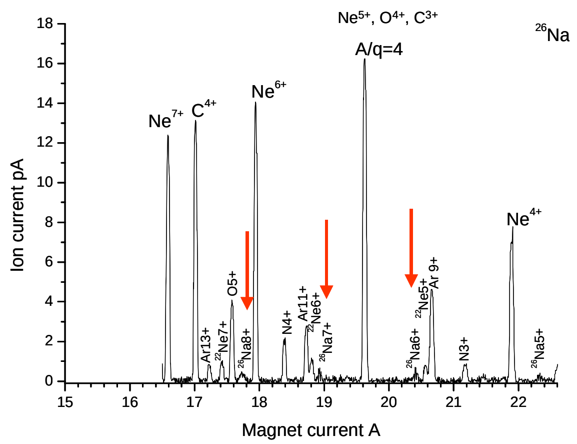

Figure 3: Charge state spectrum of ^{26}Na

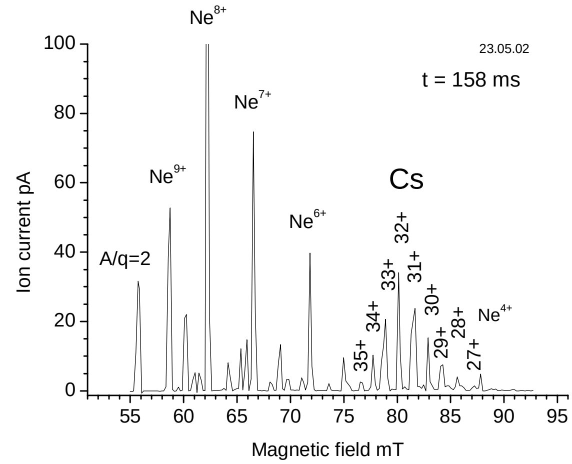

Figure 4: Charge state spectrum of ^{133}Cs

During the Na beamtime in May 2002, the EBIS could deliver a whole series of Sodium isotopes from ^{24}Na to ^{28}Na in charges states which produced A/q values of 3.5 to 4. For $^{27}Na^{7+}$ the stable $^{27}Al^{7+}$ from the ISOLDE could be used as a pilot beam. Li had to be used in a 2+ state, even if the EBIS can produce easily 100% of $^{9}Li^{3+}$. The reason is, that an A/q of 3 is impossible to separate from the strong $^{12}C^{4+}$ background. So the measurements had to be done at the maximum A/q of 4.5.

In connection with the energy upgrade of REX-ISOLDE (see next section) and the planned acceleration of isotopes in the mass range of the Uranium fission products, measurements have been done to test the breeding efficiency of the EBIS in the vicinity of A=150. Therefore a ^{133}Cs beam from the test source of REXTRAP was injected into the EBIS. At a breeding time of 80 ms the maximum charge state was 26+. The acceleration tests had to be been done with $^{133}Cs^{32+}$ (A/q=4.16). For this charge state, the breeding efficiency was only about 1%. The currents for the test measurements were about 10 pA at a repetition rate of 12.5 Hz. Earlier measurements with Cs have shown a maximum charge state at 32+ for a breeding time of 160 ms. Fig. 4 shows a spectrum for the charge breeding of ^{133}Cs.

Another point to mention in connection with the switching to heavier isotopes is the test of a new cooling method, the so called rotating wall principle, in the REXTRAP. Since the breeding times in the EBIS are nearly a factor of ten longer than for the lighter elements, a more efficient trapping and cooling mechanism than the conventional side band cooling is needed to store the larger amount of ions in the trap for a longer time. First tests with the rotating wall principle look very promising . But for some isotopes in the higher mass range the yields will be so small, that also at higher storage times the conventional cooling technique will be sufficient.

2.3 The Accelerator

A test ion source has been installed to allow measurements at the LINAC independent from the charge breeder. This off-line ion source is a small 2.45 GHz rf-source, which can deliver ions of all gaseous atoms with currents up to 100 μA. The source has been mounted (in straight line with the beam axis of the REX accelerators) in front of the bending magnet of the separator. Without any additional beam optics it delivered 80 nA of He^{1+}, which is a reasonable current for emittance measurements.

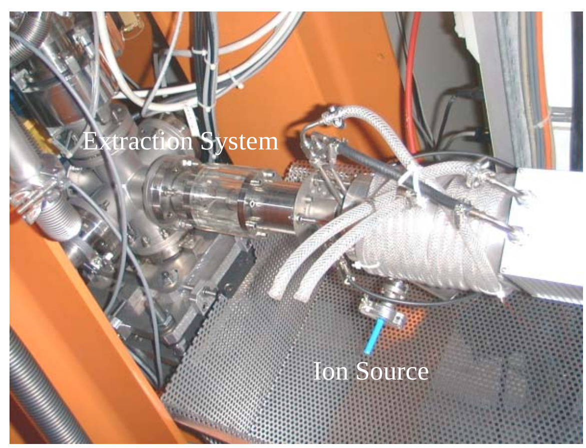

Figure 5: The REX test ion source mounted on the separator magnet. The plasma chamber and the extraction electrode is inside the transparent flange. The rectangular box on the right hand side houses the magnetron.

Since the required pressure for operation of the source was much too high, it is at the moment modified with a smaller extraction hole. Also an einzellens will be added to increase the current to several μA. Figure 5 shows a picture of the test source mounted to the separator magnet.

Tests with the RFQ have already shown a transmission of about 90% and the design energy spread of ±1.5%. Our new measurements therefore are focused on the rebuncher section and on the 7-gap resonators. For injection into the IH-structure the rebuncher had to be tuned to the right phase and amplitude. Therefore measurements of the beam energy and the energy spread in dependence on the rebuncher acceleration phase and amplitude have been carried out. The measurements have been done with a rest gas beam from the EBIS with A/q = 4. At the accelerating /decelerating phase the maximum energy shift was about 20 keV/u, which correspond to 80 kV effective acceleration voltage. At 20 kW rf-power the resulting shunt impedance is 35.25 MΩ/m, which is in round terms in agreement with low level measurements, where 38.4 MΩ/m were found. With the right phase setting full transmission through the IH-structure could be reached at 1.5 kW rf-power in the rebuncher. Fig. 6 shows the behaviour of the energy peak of the beam from the IH-DTL at different power levels. The peak reaches its maximum intensity and design energy spread (± 0.75%) at 1.5 kW. This means (at a Transit time factor of 0.67) an effective voltage of 69 kV in the rebuncher. This is in very good agreement with the TRANSPORT calculations where 70 kV have been fitted to match the RFQ beam to the IH structure.

Behind the 7-gap resonators the energy spread was measured as a function of the phase of 7-gap III, while the resonators I and II operated at a slightly negative phase. Here we reached the design energy spread of ±0.85% at 2.3 Mev/u (see fig. 7). The exact phase relations between the three resonators will be studied in detail together with the corresponding radial emittance.

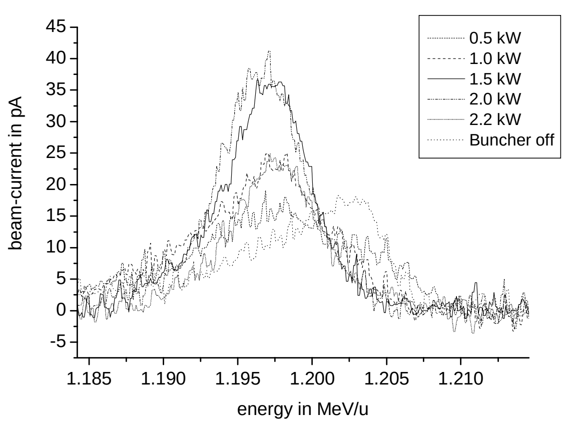

Figure 6: Energy peak behind the IH-DTL at different rebuncher voltages.

However, in the May beamtimes the REX-ISOLDE LINAC could accelerate charge bred ions of ^{23}Na - ^{28}Na and ^{9}Li to 2.3 MeV/u with a transmission through the LINAC of about 70% and a transmission to the target of typically 50 – 60%. At the current beamtime we reached 85% to the target. It could be shown that the whole LINAC follows very accurately a linear scaling of all elements with the A/q of the ions.

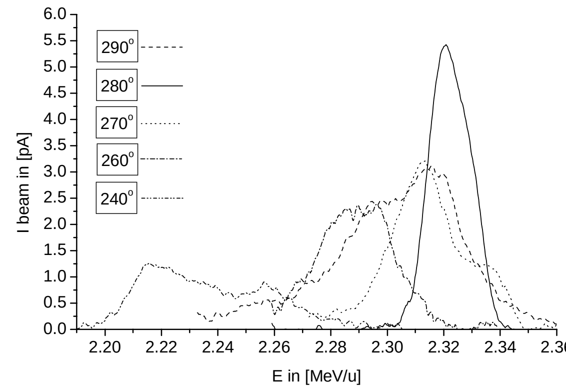

Figure 7: Energy peak at maximum energy behind the 7-gap resonators for different phases of 7-gap III.

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The latest result of the REX LINAC is the acceleration of about 10 pA $^{133}Cs^{32+}$ to 2.3 MeV/u. The LINAC was working with a duty cycle of 5% (50 Hz, 1 ms), while the beam was extracted with 12.5 Hz and pulse lengths of 80 µs. After scaling of settings for A/q=4 and short optimisation we reached a transmission of more than 50% through the whole LINAC at the first shot.

3 THE PLANNED ENERGY UPGRADE AT REX-ISOLDE

3.1 Energy Upgrade to 3.1 MeV/u

If the full range of isotopes from ISOLDE shall come into reach for nuclear physics experiments with Coulomb excitation and transfer reactions, higher beam energies are required. An increased energy of about 3 MeV/u would allow to study nuclear reactions up to mass A=85 on deuterium targets. A beam energy of 4.2 MeV/u would be suitable up to mass A=145. Therefore we want to increase the maximum particle energy at the target in the near future in a two-step upgrade of the REX LINAC to about 4.3 MeV/u. This means that additional cavities have to be integrated in the existing REX setup.

A concept is to use 7-gap resonators to gain effective acceleration voltage, but to stay flexible in the transit time factor. For experiments with radioactive ions at the Coulomb barrier, 7-gap resonators are used at REX-ISOLDE and will be used for the MAFF project. For MAFF, IH-resonators are planned to establish the energy variation, because of the high shunt impedance and the flexibility of the drift tube structure, which can be easily changed to adjust a different velocity profile [4]. Since

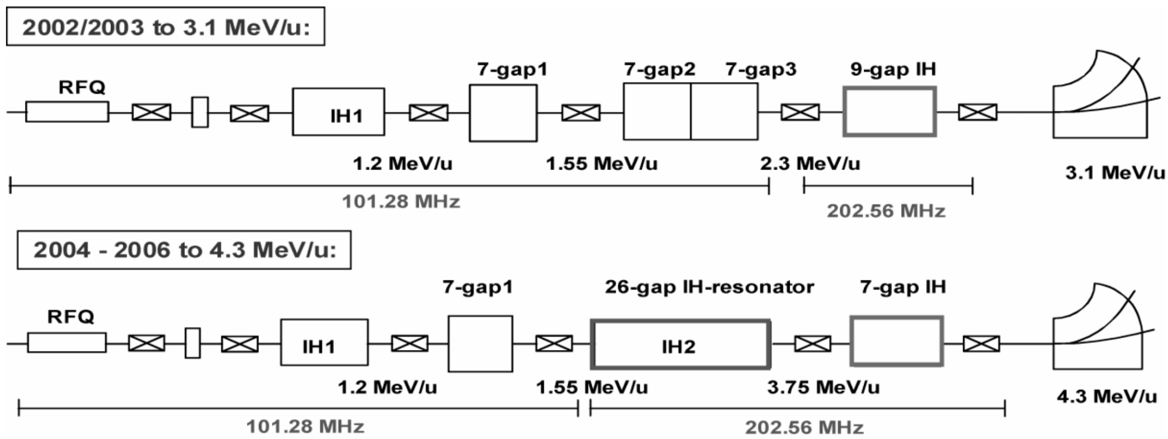

Figure 8: Schematic overview of the planned upgrade for REX-ISOLDE. In the shut down period 2002/2003, the IH-9-gap structure will be added. In 2005/2006 the last two 7-gap resonators will be replaced by an IH 26-gap resonator and the IH-7-gap resonator.

the final authorization to operate the Forschungsreaktor München II (FRM II), is delayed, a proposal was made to modify the prototype of the IH-7-Gap resonator for the MAFF LINAC in such a way, that it could be used as post accelerator for a twofold energy upgrade at REX [5]. Simulations using the Codes MAFIA for the resonator design and LORASR for the beam dynamics have shown that the desired energy increase can be reached at the given resonator frequency of 202.56 MHz using the prototype resonator tank designed for MAFF. Fig. 8 shows the principle of the two-step upgrade. For the first upgrade to 3.1 MeV/u the drift tube structure has to be exchanged by 8 smaller drift tubes of the same basic design. The 7-Gap IH structure would be turned into a 9-Gap structure. Like the original drift tube structure all units are built identical. To adjust for the new cell length at REX-ISOLDE energies of 2.3 MeV/u – 2.5 MeV/u, the length of the drift tubes is shortened and the radii and the holding rods are thinner to match the required frequency by reducing the capacity. In order to focus the beam onto the target an additional magnetic quadrupole triplet lens is required. The beam dynamics of the injection into the 9-gap resonator, of the resonator itself and of the transport towards the target has been calculated with COSY infinity and LORASR. A beam of 2.25 MeV/u from the original REX 7-gap resonators has been matched to the 9-gap resonator. The LORASR calculation delivers a final energy of 3.0 MeV/u at -10^{o} synchronous phase. For A/q = 4 an effective voltage of 2.85 MV is required.

3.2 Energy Upgrade to 4.3 MeV/u

For the second upgrade, planned for 2004-2006, it is proposed, that the last 2 split ring 7-gap structures of REX-ISOLDE will be replaced by a cavity similar to tank2 of the MAFF-LINAC, which is an IH-cavity with 26-gaps. This accelerator will raise the energy from 1.55 MeV/u to 3.75 MeV/u. The final step to 4.2-4.3 MeV/u will be done with the original MAFF IH-7-Gap resonator. Though the original design of the 7-Gap resonator will work fine, further tuning to optimize the structure in respect to beam quality instead of a wide range of energy variation is advisable in that case.

4 CONCLUSIONS AND OUTLOOK

The beamtimes in 2001 and 2002 until now, which have taken place at REX-ISOLDE were very successful and can be seen as a proof of principle for the charge breeding and post acceleration of radioactive ions. The data of the Na and Li beamtimes in 2002 is still analyzed. First preliminary physics output - especially concerning the halo nucleus ^{10}Li - is present and currently discussed.

In general REX-ISOLDE has initiated intensive investigations of ion sources from the ECR and EBIS type for charge breeding [6].

The energy upgrade of REX will follow a two step plan. With the increased spectrum of post accelerated radioactive ions REX-ISOLDE will remain a unique facility for nuclear physics experiments during the next decade.

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