Status and First Results of REX-ISOLDE ◇

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In 2002 first experiments with radioactive nuclear beams have been carried out with the radioactive beam experiment at ISOLDE (REX-ISOLDE). Beams have been delivered to the γ-detector array MINIBALL and to small experiments in the second beam line at a maximum energy of 2.3 MeV/u. In addition commissioning of the LINAC has been performed in order to improve the beam quality and to reduce the beam energy spread. It has been demonstrated that ions with masses up to A=150 could be accelerated with an overall efficiency of 2-3% from ISOLDE target to the MINIBALL target. The new acceleration scheme using charge breeding of the radioactive ions in an Electron Beam Ion Source with a good efficiency of approx. 18% in one charge state has been demonstrated as well [1]. The charge breeding concept allows the acceleration of a variety of isotopes in very different mass regimes, which could be demonstrated with REX-ISOLDE [2].

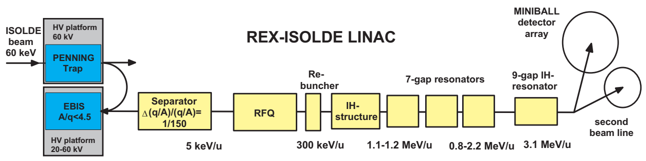

Fig. 1: Schematic of the REX-ISOLDE set up.

The concept of REX-ISOLDE (fig.1) comprises a large Penning trap for the accumulation of the radioactive ions that arrive continuously from one of the ISOLDE online separators. In addition, the REXTRAP improves the transverse emittance of the ion beam by applying buffer gas and sideband cooling techniques. Together REXEBIS and REXTRAP define the time structure of REX-ISOLDE and thus the repetition rate. Depending on the breeding time of the EBIS, the repetition frequency of REX-ISOLDE can be varied between 1 and 50 Hz. The latter is given by the maximum repetition rate of the LINAC. The EBIS has produced charge bred ions in May 2001 for the first time. Since then it has delivered charge bred beams from Li, Al, Na, K, Mg and Cs. The charge breeder of REX-ISOLDE is the first charge state booster using an EBIS. The EBIS is able to breed intensities down to 300-500 fA of radioactive ions for post acceleration with a LINAC. During the beam time with Na-isotopes in May 2002, the EBIS could deliver a whole series of Sodium isotopes from ^{24}Na to ^{28}Na in charges states which correspond to A/q values of 3.5 to 4. For ^{27}Na^{7+} the stable ^{27}Al^{7+} from the ISOLDE target could be used as a pilot beam. During a Li run, $5*10^8$ p/s of ^{9}Li^{2+} were extracted from the EBIS. 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 and the planned acceleration of isotopes in the mass range of Uranium fission products, measurements have been taken 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) at a breeding efficiency of 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.2). Another point to mention in connection with the change to heavier isotopes is the test of a new cooling method, the "rotating wall principle", in the REXTRAP. Since the breeding times of heavy isotopes 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. Storage times of more than 200 ms and storage capacities of $5*10^7$ particles could be reached with the rotating wall technique and an additional one order of magnitude can be obtained.

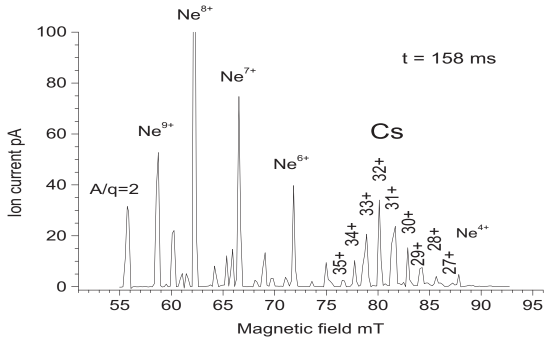

Fig. 2: Charge state spectra of ^{133}Cs for test of the REX-ISOLDE upgrade.

The electrode structure of REXTRAP has been changed in order to apply a rotating quadrupolar field in the transverse direction, which results in a better confinement of

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the ions [3]. The linear accelerator of REX-ISOLDE consists of three different resonator types. 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 ms, whereby a slower EBIS extraction (500 ms) is at the moment under investigation. The pulse distance is 20 ms (for the light ions). 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. First commissioning measurements have been done to examine the emittance of the injected beam into the RFQ. The emittance measurements with the Munich low intensity emittance meter [4] have demonstrated that the emittance of beams with highly charged ions from the EBIS have the expected value of 10 π mm mrad at 5 keV/u injection energy. In case the electron beam is maximum neutralized by rest gas ions the emittance grows by a factor of five [5].

Until now only the highest beam enery of 2.2-2.3 MeV/u has been required by experiments. The different LINAC structures have been tuned with rest gas beams from the EBIS with A/q=4 in order to determine the right amplitude and phase settings. In order to improve the beam quality of the REX-ISOLDE LINAC commissioning measurements have been carried out between the beam times. Tests with the RFQ have already shown a transmission of about 90% and the design energy spread of 3%. The measurements have been focused on the re-buncher section and on the 7-gap resonators. For injection into the IH-structure the re-buncher had to be tuned to the right phase and amplitude. Therefore measurements of the beam energy and the energy spread in dependence on the re-buncher acceleration phase and amplitude were required. At the accelerating /decelerating phase the maximum energy shift was about 20 keV/u, which correspond to 80 kV effective acceleration voltage. At 2 kW rf-power the resulting shunt impedance is 35.25 MΩ/m, which is in agreement with low level measurements, where 38.4 MW/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 re-buncher. For those measurements the IH-structure was turned on. The peak in the energy spectrum reached its maximum intensity and design energy spread (0.75%) at 1.5 kW as well. Assuming a transit time factor of 0.67 an effective voltage of 69 kV in the re-buncher is seen by the particles. This is in very good agreement with the TRANSPORT calculations where 70 kV have been fitted to match the RFQ beam into the IH-structure acceptance.

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 the design energy spread of 0.85% at 2.3 MeV/u (see fig.3) could be reached. At 2.3 MeV/u the 7-gap resonator phases have to be tuned close to 0^o and thus the energy spread becomes much larger than the expected 1.5%. Therefore the beam could not be focussed through a 5mm aperture in front of the target, because the magnetic bender in front of the target stations shuffels longitudinal energy spread into tranverse beam emittance due to the energy dispersion. That coupling of the longitudinal and transverse phase space can be reduced by adequate focussing and by the right choice of the resonator phases. The exact phase relations between the three resonators will be studied in detail together with the corresponding radial emittance. However, in May 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%. In the beam time in September with ^{30}Mg the beam could be delivered with smaller energy spread and could be focussed through the target aperture, due to slighly lowering the final energy and to adjust the 7-gap cavities 2 and 3 to negative synchronous phases.

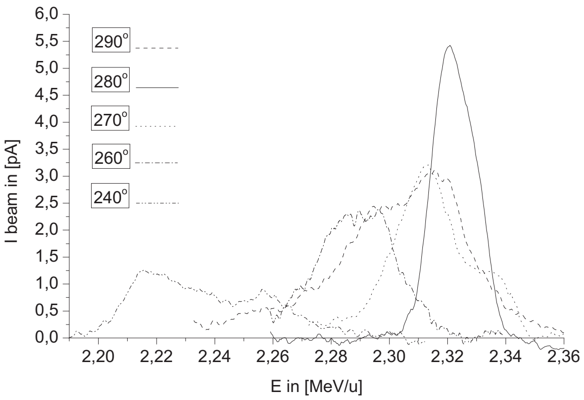

Fig. 3: Energy peak at maximum energy behind the 7-gap resonators for different phases of 7-gap III.

If the full range of isotopes from ISOLDE 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 approx. 4.2 MeV/u. This means that additional cavities have to be integrated in the existing REX set-up. One 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. 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. 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. 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 stems are thinner to match the required frequency by reducing the capacity. 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. The second step would be a mayor change of the LINAC structure, where two of the 7-gap resonators are substituted by a 26-gap 202.56 MHz IH-cavity, which boost the energy from 1.55 MeV/u towards 3.7 MeV/u. The final energy adjustment would then be done by a cavity similar to the MAFF 7-gap resonator [6]. A test beam line has been installed at the MLL, in order to perform beam tests with this IH-cavity. Experiments have been performed at the MLL using a O^{5+} beam from the tandem accelerator, in order to test the structure. The effective shunt impedance has been determined for the 7-gap using continuous beam and pulsed beam injection [7].

A systematic study of the structure of exotic nuclei is now possible at REX-ISOLDE. The nuclei that are accessible will be mainly investigated with standard nuclear reactions like Coulomb excitation, transfer, and fusion-evaporation reactions in inverse kinematics, allowing a detailed study of collective and single particle properties of nuclei far from stability. The cross sections for these reactions are rather high: about 1 b for Coulomb excitation and about 100 mb for neutron-pickup reaction from deuterium and ^{9}Be. First nuclear physics experiments with MINIBALL, a highly efficient and highly granular HPGe-array [8], using the radioactive beams provided by the REX accelerator were performed in 2002. The aim of the experiments was to commission the accelerator and the MINIBALL array and to start an investigation on the collective and single particle properties of the neutron-rich Na and Mg isotopes using Coulomb excitation on a Ni target and neutron-pickup reactions on ^{9}Be (^{9}Be,2α) and ^{2}H (d,p) targets. The neutron-rich Na and Mg isotopes are especially interesting, because of the rapid changes in nuclear structure around the N=20 nucleus ^{32}Mg. In addition, the Na and Mg isotopes are produced with high yields at ISOLDE. Only preliminary γ-spectra can be shown at this stage of the analysis. Figure 4 shows a spectrum taken with a ^{25}Na beam of 2.25 MeV/u incident on a deuterated polyethylene target (7 mm). The beam intensity was 3*10^6 /s on target and the measurement did take about 7 hours. The top panel shows the γ-spectrum in the energy range up to 800 keV.Sharp lines and broad structures can be seen. After correction for the Doppler shift (bottom panel) several lines show up or improve, clearly proving that these γ-rays were emitted by a fast moving source.

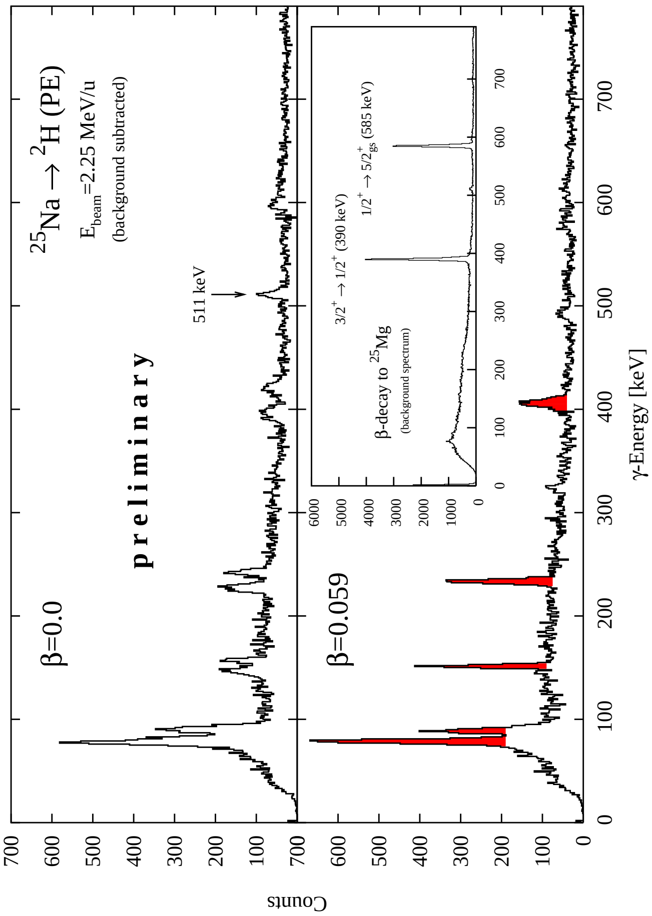

Fig. 4: Doppler corrected (bottom) and uncorrected (top) γ-spectra taken in 7 hours with a ^{25}Na beam (3*10^6 /s, E$_{beam}$=2.25 MeV/u) on a deuterated polyethylene target (7mm).

Presently only the detector (Ge-crystal) positions are used for the Doppler correction; the segmentation of the MINIBALL detectors and the available pulse shape data are not yet analyzed and should improve the Doppler correction considerably. The observed γ-rays do not necessarily originate from neutron-pickup, since other reaction channels cannot be excluded at this stage of the analysis. However the peaks at 151.1 keV and 233.6 keV are known transitions in the neutron-pickup product ^{26}Na. Moreover a state at 420(15) keV is known, but no transition has been observed so far. Therefore the line around 410 keV might be the transition of this level to the ground state. The spectra are background subtracted. A background spectrum is plotted in the inset, showing the well known β-decay γ-lines of ^{25}Na.

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