TEST MEASUREMENTS WITH THE REX-ISOLDE LINAC STRUCTURES*

O. Kester, D. Habs, T. Sieber, S. Emhofer, K. Rudolph, LMU München, Garching Germany
R. von Hahn, H. Podlech, R. Repnow, D. Schwalm, MPI- K, Heidelberg, Germany
U. Ratzinger, A. Schempp, J.W. Goethe-Universität, Frankfurt, Germany
and the REX-ISOLDE collaboration

Abstract

The Radioactive Beam Experiment (REX-ISOLDE) [1,2] is a pilot experiment at ISOLDE (CERN) testing the new concept of post acceleration of radioactive ion beams by using charge breeding of the ions in a high charge state ion source and the efficient acceleration of the highly charged ions in a short LINAC using modern ion accelerator structures. In order to prepare the ions for the experiments singly charged radioactive ions from the on-line mass separator ISOLDE will be cooled and bunched in a Penning trap, charge bred in an electron beam ion source (EBIS) and finally accelerated in the LINAC. The LINAC consists of a radio frequency quadrupole (RFQ) accelerator, which accelerates the ions up to 0.3 MeV/u, an 20 gap interdigital H-type (IH) structure with a final energy between 1.1 and 1.2 MeV/u and three seven gap resonators, which allow the variation of the final energy between 0.8-2.2 MeV/u. A variety of tests with REXTRAP, REXEBIS and the LINAC structures have been done, in order to study their capabilities. An emittance meter for beam intensities down to 0.5 nA and a test beam line for the front part of the REX-ISOLDE LINAC have been built up in order to measure beam emittances of the different components, beam energy, energy spread and transmission of the LINAC structures. The results of these measurements and the first tests at CERN are presented.

1 INTRODUCTION

REX-ISOLDE is in its first stage an experiment at the existing radioactive beam (RIB) facility ISOLDE at CERN [3]. A variety of experiments in nuclear physics, atomic physics and solid state physics is planned with neutron rich light nuclei up to mass A=48 [4]. For the experiments a very compact post accelerator is being built, up using the new concept of charge breeding of the singly charged radioactive ions [5]. REX-ISOLDE is the first RIB experiment using a device with buffer gas cooling for accumulation and bunching of ions and a high performance ion source like an EBIS for charge multiplication of the ions. A bunched 5 keV/u beam of highly charged ions is then accelerated in a 4-rod RFQ-LINAC to 0.3 MeV/u. In the following IH-structure and the three 7-gap resonators the ions are further accelerated to a tunable final energy between 0.8 MeV/u and 2.2 MeV/u (fig.1). After a momentum analysis in a dipole magnet, which can switch the beam to different ports, the ions are transported to a target, which is surrounded by a highly efficient detector system.

The demands to the charge breeder and the LINAC are high efficiency, good beam quality and maximum flexibility in the final energy. Therefore test measurements have been done in order to determine the beam quality and transmission after each part of the experiment. For the measurements of the beam quality an emittance meter has been developed, which uses the slit grid method and can measure down to beam intensities of 0.5 nA. In addition in each section of the LINAC there are beam diagnostic systems, which can determine intensity, shape and position of the beam over a large range of intensities (100 particle/s – 1 nA) [6]. For higher beam intensities a Faraday cup can be used which is mounted in the same vacuum housing as the low intensity device.

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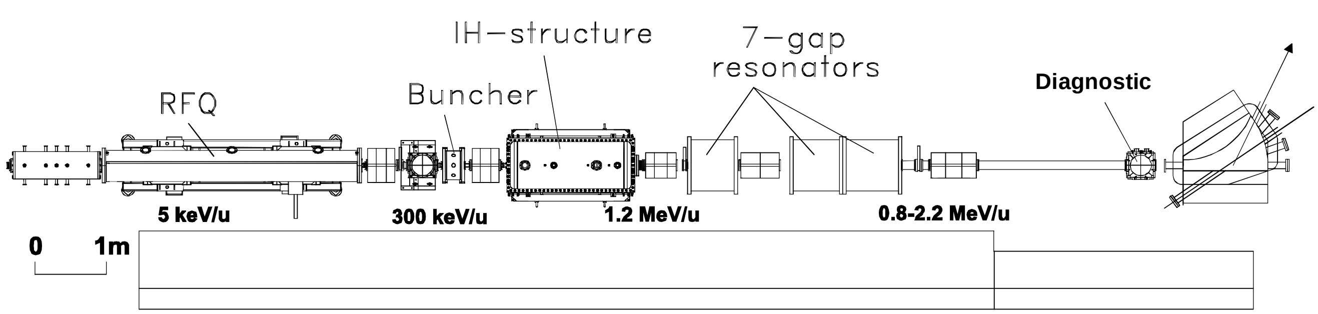

Figure 1: Lay-out of the REX-ISOLDE linear accelerator

2 THE CHARGE BREEDER

The scheme of REX-ISOLDE is pursued in several steps fulfilling separated functions. The 1^+ beam is first bunched in a Penning trap and its phase space is reduced by cooling to < 3 π mm mrad (60 keV) which is the acceptance of the EBIS. In the EBIS the singly charged ions are then converted to highly charged ions (A/q <4.5) by bombarding them with an intense electron beam. Bunching of the radioactive beam is required in the proposed acceleration scheme, because charge-state breeding in the EBIS requires a typical time of about 20 ms and the LINAC operates with a duty factor of 10%. For the low-intensity radioactive beams it is furthermore advantageous to compress the ions in short pulses in order to increase the signal to background ratio in the measurements. In the first capture and cooling tests with the REX-trap efficiencies of about 50% and emittances in the order of 2 π mm mrad have been measured [7]. With higher buffer gas pressure a capture efficiency of about 100% is expected

In the REXEBIS [8] the 0.5 A electron current is compressed by the magnetic field of 2 T into a current density larger than 200 A/cm^2. The electron beam has an energy of 5 keV. The isotopes used at the REX-ISOLDE experiments will require breeding times between 5 and 20 ms to reach a charge-to-mass ratio larger than 1/4.5. To assure a high efficiency, the injection, breeding and extraction have been extensively simulated. With the high quality beam from the trap an injection and capture efficiency in the EBIS of about 95% is expected. This will be tested when the mass separator [9] operates, which is now being installed. The mass separator is an achromatic system using a Nier spectrometer setup. Thus the acceptance of the mass separator in restricted to 10 π mm mrad, if the mass resolution shall exceed 150. Therefore measurements have been performed, in order to check the emittance of the extracted ion beam out of the EBIS.

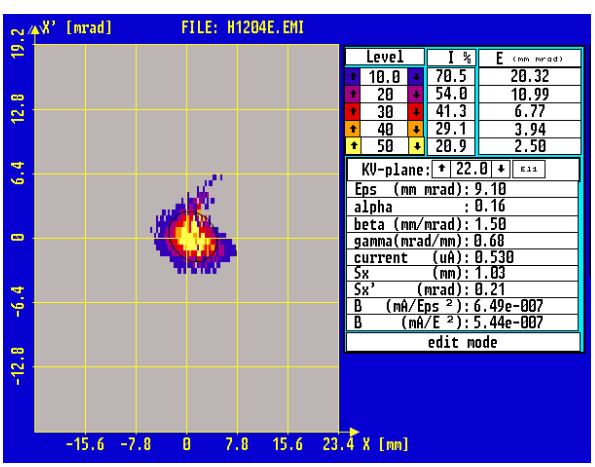

Figure 2: Measured beam emittance from the REXEBIS with 1ms confinement time and 20 kV platform potential.

Due to the poor vacuum in the emittance meter and the source, the compensation time was around 1 ms. Staying below this value with the confinement time the emittance of the ion beam exeeds 9 π mm mrad (fig.2). In order to get information about the beam quality under better vacuum conditions, the emittance measurements will be redone.

3 THE REX-ISOLDE LINAC

The REX-ISOLDE LINAC consists of different types of modern ion accelerator structures [10]. A 4-rod RFQ and an IH-structure accelerate the ions to an intermediate energy between 1.1 and 1.2 MeV/u. The 7-gap resonators allow the variation of the target energy. The structures operate at 101.28 MHz and with a duty cycle of 10%. All structures are driven with 100 kW power amplifiers which allow a maximum reflected power of 6 kW. In order to meet the required 95% overall transmission efficiency, the acceptances of all structures are larger than 0.6 π mm mrad normalized (x and y). This acceptance is about 20 times larger than the measured EBIS emittance.

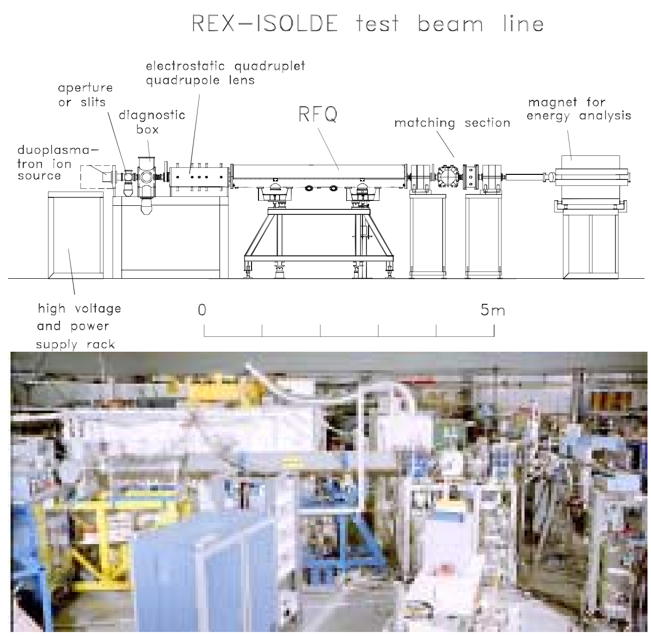

Figure 3: Foto and scheme of the REX-ISOLDE test beamline at Munich

3.1 *The emittance meter*

The emittance measurements at the REX-ISOLDE beam line require a very sensitive system with high resolution. To meet these requirements a modular system with only one slit and one grid from the company NTG together with very sensitive current amplifiers (down to 5 pA) from the university of Heidelberg have been chosen. Using a grid and an L-shaped slit arrangement, which is driven under 45° towards the x and y axis through the beam axis, allows the measurement of emittance in x- and y-direction at the same z-position. The dynamic range of the amplifiers allows measurements of beam currents between 0.5 nA-1 mA. Due to the modular design, the distance between slit and grid can be modified in order to adapt the resolution for higher beam energies.

3.2 The REX-ISOLDE test beam line

In order to test the RFQ and the matching section, a test beam line had been installed at the Munich tandem laboratory which is shown in fig.3. The RFQ injection part was a duoplasmatron ion source, a diagnostic box and an electrostatic quadrupole quadruplet lens. For beam analysis behind the RFQ the whole matching section was built up together with a 90° bending magnet for energy analysis. This magnet was replaced by the emittance scanner after the energy measurements were completed. The injection system of the RFQ was examined with the emittance meter to determine the correct lens voltages for optimum matching of the beam to the RFQ acceptance. The measured injection emittances fit remarkably good to the calculated phase spaces from COSY infinity.

3.3 The REX-RFQ

The measurements with the REX-RFQ are the most elaborate concerning the properties of this machine [11]. In the first experiments the cavity parameters have been determined which are shown in table 1.

Table 1: Key parameter of the REX-ISOLDE RFQ

Q-value	4050
Rp-value [kΩm] perturbation Capacitor X-ray Spectroscopy Beam Tests	 150 145 146.5
flatness	< 1.5 %
Final energy spread	±1.4 %
U_{design}	9.33 *A/q

At the transmission measurements, the injected beam was in both directions convergent, fitting accurately into the acceptance of the RFQ. The injected emittances were about 30 π mm mrad at an energy of 5 keV/u. The beam current was 1 µA. The current was measured with the two identical Faraday cups of the REX-diagnostic boxes before and behind the RFQ. The error - due to source instabilities and secondary electron effects - is 1%. With this accuracy, no beam losses could be observed, starting at a voltage of 33 kV (Design voltage for A/q=4 of 37.3 kV). The measurement of the time structure of the RFQ-bunches was achieved with a fast 50Ω Faraday cup. From PARMTEQ and TRANSPORT calculations we expected a phase spread of the bunches of ±14° at the RFQ-exit and a phase spread of ±35° behind the drift to the place of measurement. The measured peak bunch current was 100 µA, which was (with a pulse current of 20 µA and a duty cycle of 10%) in excellent agreement with the designed bunching factor of 12 and the calculated bunch-broadening during the 1.85 m drift. The length of the bunches in time was (FWHM) ~2 ns, a value which fits very well to the theoretical data (1.9 ns).

In fig.4 emittance measurements of the RFQ are shown for different injection emittances. In the upper graphics the injection emittance was about 100 π mm mrad in the lower ones about 10 π mm mrad for a 5 keV/u He^+ beam. The measurements have proven that a small injected emittance is preserved during the acceleration. The emittance of the EBIS beam will be below 10 π mm mrad at 5 keV/u. The measurements showed, that a small RFQ input emittance can be delivered to the IH-structure.

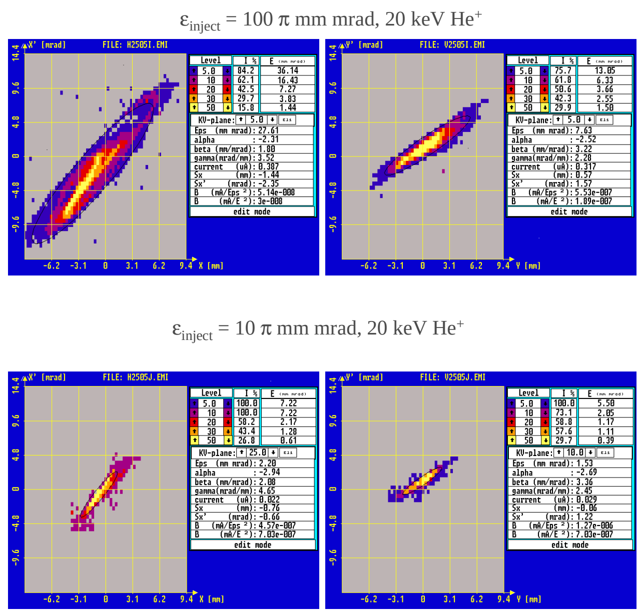

Figure 4: Measured beam emittances from the RFQ for different injection emittances.

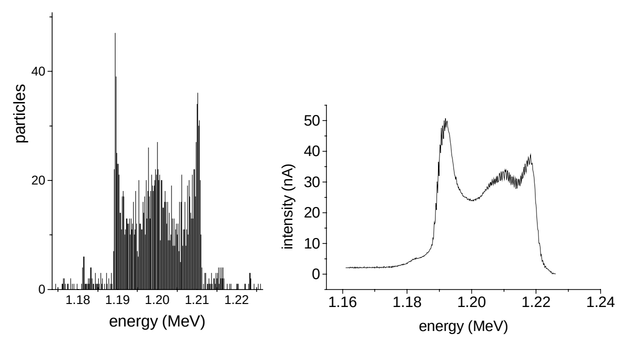

Figure 5: Measured energy spectrum (right) in comparison with PARMTEQ calculations for the design rod voltage.

For the Energy measurements, a magnet with a maximum field of 1T was installed in a distance of 2 m behind the RFQ. With 1 mm slits before and behind the magnet, the resolution of the system was ~0.1%. The error of the absolute energy is – due to problems with the calibration of the magnet – estimated to 1%. In order to verify and to improve the rf-measurements of the Rp-value, we varied the rf-power, until the energy peak was symmetric and in best agreement with the PARMTEQ design calculations. Fig.5 shows the spectrum measured at 28.35 kW compared to the PARMTEQ calculation for an elecrode voltage of 37.3 kV. The Rp-value derived from this measurement is 146.5 kΩm. The measured energy spread is ±1.4%.

3.4 The matching section

The beam dynamics concept [12] of the IH-structure requires a convergent in transverse and longitudinal direction. Therefore a section consisting of two magnetic quadrupole triplet lenses and a three gap split ring re-buncher has been insertet between RFQ and IH-structure. The first lens produces a waist in front of the re-buncher. The second triplet matches the beam to the IH-structure acceptance. Fig.6 show the beam envelope in the section together with the drift towards the emittance scanner. In addition the expected emittances at the position of the emittance meter are shown in comparison with the measurements. The settings of the lenses have been derived from simulations with TRANSPORT, for a matched beam to the entrance of the IH-structure. The measurements in fig.6 show that the matching of the transverse phase spaces can be easily achieved with the two lenses. For the emittance measurements the buncher was driven with 2 kW rf-power and with the correct phase. The defocusing effect of the buncher gaps has been taken into account in the simulations.

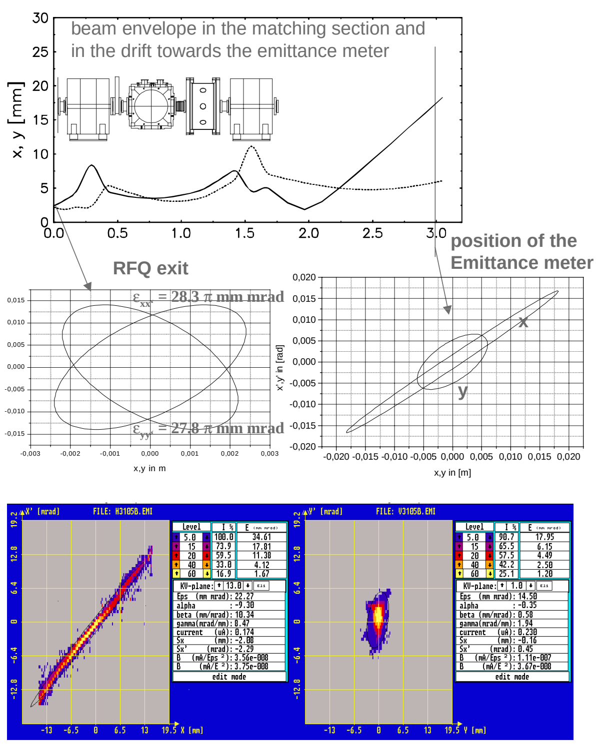

Figure 6: Calculated beam envelope in the matching section and towards the emittance meter and resulting emittances in comparison with measurements.

The measurement of the longitudinal beam parameters was done by the analysis of the beam energy distribution. The buncher has to reduce the phase spread of ±35° at the buncher entrance to the required ±10° at the IH-structure entrance. TRANSPORT calculations require a total buncher cavity voltage of 72 kV which correspond to 2 kW rf-power. From calculations an energy spread of the beam behind the re-buncher of ±2.8% was expected. The measured energy spread shown in fig.7 at the bunching phase (336° relative to the RFQ pick up signal) is ±3.2%. It seems that the power level can be reduced slightly, but the final adjustment will be done by transmission measurements through the IH-structure in the beam line at CERN.

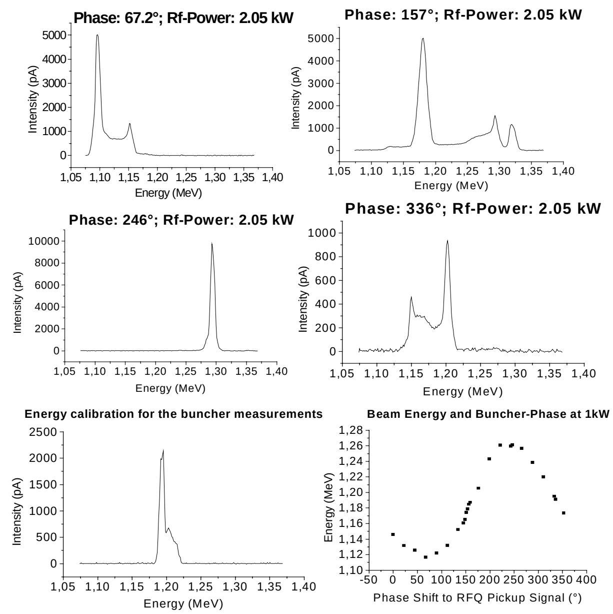

Figure 7: Energy spectra of the re-buncher at different phases relative to the RFQ pick up signal. The figures at the bottom show the energy peak out of the RFQ and the energy gain of the beam in dependence on the buncher phase.

3.5 The REX-IH-structure

The IH-cavity serves as the booster section of the REX-ISOLDE LINAC [4]. The resonator will accelerate the ions up to 1.2 MeV/u applying 5 MV resonator voltage. The length of the cavity is only 1.5 m. In order to increase the range of energy variation of the 7-gap resonators, the final energy of the IH-structure can be varied down to 1.1 MeV/u by changing the gap voltage distribution due to capacitive plungers. Low level measurement have been done to determine the shunt impedance and the cavity quality factor. The Q-value is 16500 and the shunt impedance is 330 MΩ/m. Thus the 5 MV resonator voltage will be adjusted with only 60 kW rf-power. Due to the method of switching between different gap voltage distributions via plungers, parasitic resonances could occur, while driving the plungers to the final positions.

These positions have been determined and switching between the modes will be done without rf-power in the cavity.

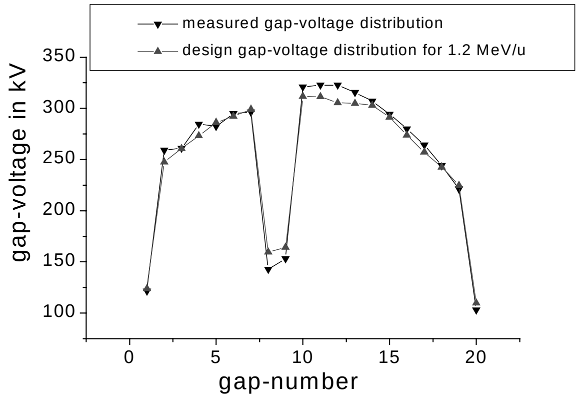

Figure 8: Perturbation measurement of the gap voltage distribution for the 1.2 MeV/u mode

Fig.8 shows the measured gap voltage distribution for the higher final energy of 1.2 MeV/u in comparison to the design voltage. The measured distribution fits with an accuracy of 2% to the design values. Beam dynamics calculations with LORASR and the measured gap voltages show no significant changes in the beam quality in comparison with the design voltage distribution. Nevertheless the discrepancies of the gap voltages for specific gaps result from irregularities in the copper plating of the drift tubes. In addition, due to a thicker copper layer on the drift tubes, the gap voltage distribution for the 1.1 MeV/u mode could not be adjusted at the required frequency of 101.28 MHz. Therefore a new drift tube structure is in preparation, which will be installed in the beginning of next year.

3.6 The 7-gap resonators

For the variation of the beam energy, three 7-gap spiral resonators are used which are similar to the structures of the Heidelberg high current injector [13]. From experience with those structures the design voltage of the REX-ISOLDE structures was 1.74 MV at an power level of 90 kW. The synchronous particle velocities were chosen to 5.4%, 6% and 6.6% c. After tuning of the eigenfrequency of the push-pull mode the rf-parameters have been determined via beam tests, which are shown in table 2. A $^{32}S^{7+}$ dc-beam from the MPI-Tandem accelerator had been used to examine the maximum resonator voltage [14]. The injection of a dc-beam into an rf-cavity leads to an energy modulation of the ions with two peaks which correspond to the ions which gain or loose the maximum possible energy in the cavity. The injection energy had been chosen according to the synchronous particle velocity of the cavity under examination.

The values determined by beam tests are slightly lower than the values determined by low level measurements due to heating effects of the copper surface which might reduces the conductivity. However, all three cavities exceed their design voltage at the 90 kW power level. The beam quality of the resonator triplet will be determined, when the first beam tests with the whole LINAC at CERN will be carried out.

Table 2: rf-parameters of the REX-ISOLDE 7-gap cavities determined with beam tests

Resonator	5.4%	6.0%	6.6%
Z in [MΩ/m]	62.5	59.7	59.5
Q	5560	5280	5030
U_{max} in [MV]	1.77	1.81	1.88

4 CONCLUSION

For REX-ISOLDE modern ion accelerator structures are used to accelerate neutron rich rare isotopes with masses < 48 from the online mass separator ISOLDE over a distance of only 9 m to energies at the Coulomb barrier. This new kind of combination of different well known structures used at REX-ISOLDE leads to extensive tests and beam measurements in order to explore the properties of the elements and the potential of the whole system. The test measurements which have been done so far show that all structures exceed their design values in beam quality, transmission and efficiency. Thus the whole system, which is now being installed at the ISOLDE hall can be run at the end of the year in order to investigate the charge breeding efficiency as well as the beam quality of the IH-structure and the 7-gap resonators.

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