STATUS OF REX-ISOLDE*

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Abstract

After commissioning of the radioactive beam experiment at ISOLDE (REX-ISOLDE) and the γ-Detector array MINIBALL first series of physics experiments have been performed in 2002 and 2003. The REX-ISOLDE charge state breeder adjusts the charge-to-mass ratio of isotopes from the whole nuclear chart to the LINAC requirements. A variety of isotopes from different mass regions of the nuclear chart have been charge bred with REXEBIS [1] to the required $A/q < 4.5$. A variety of tests with REXTRAP, REXEBIS and the LINAC structures have been done, in order to study the beam parameters, transmission efficiency and upgrade options. The LINAC now consists of six resonators and one re-buncher cavity. The beam energy, which can be delivered towards the target areas, can be varied between 0.8 and 2.2. An additional boost to 3 MeV/u is now possible because of the upgrade with a 202.56 MHz IH-cavity developed for the MAFF project. In addition beams from the RFQ at 0.3 MeV/u have been used for solid state physics experiments. The present status of the projects and the commissioning measurements will be presented.

INTRODUCTION

Radioactive ion beam (RIB) facilities give rich opportunities for nuclear structure research as well as for nuclear astrophysics and applied physics. RIB facilities drive the increasing understanding of the evolution of nuclear structure and the growing wealth of nuclear structure data. As yet only relatively small part of the nuclear landscape has been explored, especially on the neutron-rich side where the limit of stable nuclei is only known for the lightest elements. The European nuclear physics community, represented by NuPECC, has identified the need for a second generation of Radioactive Ion Beam (RIB) facilities in Europe. The design of such a second generation RIB facility, based on the ISOL technique, has been investigated, under the auspices of the EU Fifth Framework as the RTD proposal EURISOL [2]. Therefore huge effort is spent on extrapolation from running RIB facilities and present techniques towards those new intense ISOL facilities like EURISOL or RIA [3]. Running ISOL facilities in Europe that provide post accelerated RIBs for nuclear physics experiments are ARENAS (Leuven), ISOLDE (CERN) and SPIRAL (GANIL). Preparation work for future facilities is carried out by those facilities, which is important for the EURISOL design study.

The Radioactive Beam Experiment at ISOLDE, REX-ISOLDE, delivers post accelerated beams of exotic isotopes for nuclear physics research and it has been the dominant experiment in the past two ISOLDE running periods [4]. REX-ISOLDE profits from the vast experience of ISOLDE in production of radioactive beams of more than 600 isotopes from 72 elements. In addition the resonant ionisation laser ion source (RILIS) can provide beams with high selectivity, even isomeric beams. Since end of 2001 the LINAC provides radioactive beams from the ISOLDE online separators with energies of 2.2 MeV/u towards two target stations. One target station is used for the efficient γ-ray MINIBALL array [5] and the other target station is dedicated for smaller experimental set-ups. In order to make the full variety of beams from ISOLDE available for nuclear physics experiments the method of charge breeding of the singly charged radioactive ions has been employed [1]. Hence the concept of REX-ISOLDE is based on a large Penning trap which accumulates the radioactive ions from the ISOLDE mass separators and allows phase space cooling of the RIBs. The prepared ions are then injected into an Electron Beam Ion Source (EBIS), which raises the charge state of the radioactive ion to an $A/q < 4.5$. The extracted highly charged ions are charge state selected with subsequent acceleration in a short LINAC

THE LOW ENERGY SYSTEM

The low energy part of REX-ISOLDE has several tasks. The low energy part transports the 60 keV beam from the ISOLDE main beam line towards the accelerator and prepares the ion beam for injection into the LINAC. The size of the post-accelerator needed to bring the unstable nuclei to the energies required to study nuclear reactions depends linear on the charge state of the radioactive ions. 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.

The principal scheme of the charge multiplication (charge breeding) in case of REX-ISOLDE is shown in fig.1. An EBIS delivers high charge states and is employed as breeder for the radioactive isotopes at REX-ISOLDE. The ISOLDE beam can not be injected into the Electron Beam Ion Source (EBIS) with high efficiency without any beam preparation, because of the small

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transverse acceptance of the electron beam confining the injected ions. Thus an beam emittance cooler was required for beam preparation at REX-ISOLDE. A large Penning trap, the REXTRAP [6], was therefore installed in front of the REXEBIS. It accumulates, bunches and phase space cools the continuous ISOL-beam within 10-20 ms the beam from ISOLDE. Bunches of 10 σs length and transverse emittance of 10 mm·mrad for 80% at 30 keV are extracted from the trap. A considerably higher injection and trapping efficiency into the EBIS is obtained compared with beam emittances up to 30 mm·mrad (at 60 kV) from the ISOLDE target ion source. The extracted pulse is transferred to the EBIS via a transport line, and because of the buffer gas pressure (~10^{-3} mbar of Ne or Ar), several stages of differential pumping have to be inserted into the transport line to ensure a high vacuum inside the EBIS.

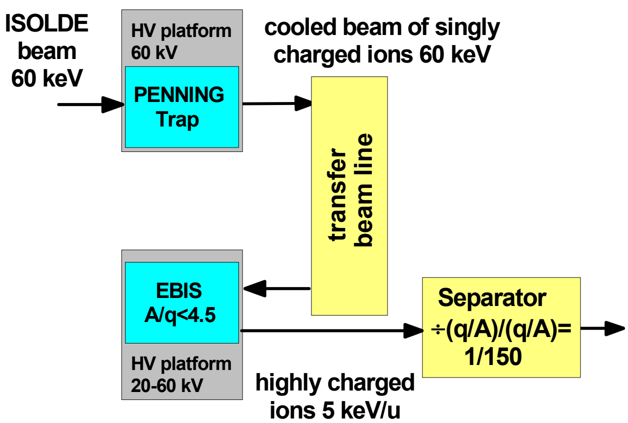

Figure 1: Schematics of the REX-ISOLDE low energy system.

The operation parameters of REXTRAP and REXEBIS are summarized in table 1. An offline ion source for injection of stable alkaline isotopes into REXTRAP is available for tuning of the low energy system of REX-ISOLDE. All elements except for He can be handled by the trap with transmission efficiencies up to 45%. Space charge effects start occurring for more than 10^5 ions per pulse, with an efficiency decrease and emittance increase [7]. At present the Penning trap-EBIS concept has a limited ion throughput of ~10^8 ions/s. Because of the pulsed beam injection into the EBIS, its platform-potential can be ramped between injection and extraction and thereby the potential of the ISOL production part is decoupled from the injection. In addition the injection energy into the RFQ can be adjusted according to the chosen A/q-value. Within the past running periods of ISOLDE, a variety of nuclides has been charge bred, as shown in table 2. Stable ions have been used for pilot beams to tune the accelerator and to test the breeding capabilities of the REX-ISOLDE charge state breeder. High currents of several nA of He^+ from the EBIS were used for intensive studies of the beam dynamics of the accelerator structures.

Table 1: Operation parameter of REXTRAP and REXEBIS

REXTRAP	
magnetic field	3 T
buffer gas pressure	10^{-2}-10^{-4} mbar
cycle time	10-20 ms
trap length	0.9 m
mass resolution	~ 300
REXEBIS	
magnetic field	2 T
electron current	200-300 mA
electron beam energy	4-5 keV
confinement length	0.8 m
max. current density	150-200 A/cm^2

To prepare for the energy upgrade of the LINAC, heavier elements have been charge bred in REXEBIS, because with the energy upgrade experiments with heavier isotopes become possible. With Caesium the charge state 32 could be produced as the maximum of the charge distribution using an extended breeding time of 160 ms. Radioactive ions from $^{9}Li^{2+}$ to $^{156}Eu^{28+}$, have been delivered to experiments at MINIBALL and the second beam line. In addition $^{138}Ba^{26+}$ and $^{153}Sm^{28+}$ have been produced using breeding times of 18 ms and 38 ms respectively. The Samarium and Europium ions (A/q = 5.46) have been accelerated in the RFQ for ion implantation into Silicon Carbide as radiotracers.

Table 2: Isotopes that have been charge bred in the REX-ISOLDE charge state breeder

Stable	Radioactive
$^{7}Li^{2+}$	$^{9}Li^{2+}$, $^{11}Li^{3+}$
$^{23}Na^{7+}$	$^{24-29}Na^{7+}$
$^{27}Al^{8+}$	
$^{24}Mg^{8+}$	$^{30}Mg^{8+}$
$^{39}K^{10+}$	
	$^{74,76}Zn^{18+}$
$^{84}Kr^{20+}$	$^{88}Kr^{21+}$
$^{133}Cs^{32+}$	
$^{138}Ba^{26+}$	
	$^{153}Sm^{28+}$
	$^{156}Eu^{28+}$

The efficiency of the breeding system of interest is the ratio between the number of ions injected into the RFQ and the number of ions injected into the Penning trap. The trap efficiency does not exceed 50% and is somehow the bottleneck of the system. For high intensities (>10^5 ions/s) the efficiency drops down to 4%, dependent on the species and the intensity. Therefore the rotating wall cooling method [8] is under study to be applied for REXTRAP. The transmission from trap to EBIS is about 90%. The mass separator transmission is about 80%. The maximum ratio of ions in one charge state for light ions, if no charge state at shell closure is selected, is about 30%. This should give 20% efficiency in one charge state. Until now the efficiency after the trap to the analyser

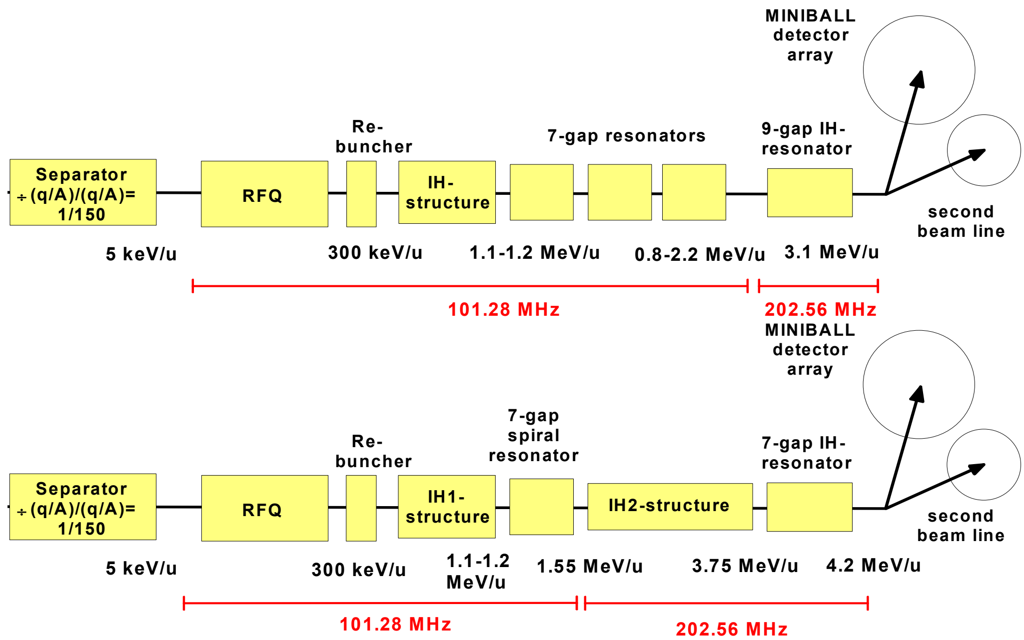

Figure 2: Schematic of the present REX-ISOLDE LINAC structure (upper panel) and of the planned upgrade to energies above 4 MeV/u (lower panel).

magnet is 5-10%. At higher intensities the efficiency can drop to as low as 2% due to space charge effects in REXTRAP. To this value the trap efficiency of ~45% should be included. Thus the injection and trapping efficiency in REXEBIS is only 30-50%. The injection efficiency can be improved by using a partially compensated electron beam as Coulomb target [9], which will be explored in the EURONS project within the EU 6th framework programme. However the charge state breeder is a major component for the success of the REX-ISOLDE experimental programme.

THE REX-ISOLDE LINAC

The linear accelerator of REX-ISOLDE is composed of modern ion accelerator structures. 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. All structures operate at 101.28 MHz, which is half of the CERN proton LINAC frequency. One 202.56 MHz IH-cavity with nine gaps has been added in order to boost the energy to 3 MeV/u. The cavity is shown in fig.3. The maximum duty cycle of the cavities is 10%, the typical duty factor at operation is 5%. The maximum A/q of the ions can be 4.5. The linac composition is sketched in Fig.2. The actual beam and rf parameter of the structures are summarized in table 3. The acceptance of the cavities is calculated for 95% transmission.

The macrostructure of the accelerated ions have a typical bunch width of 15-50 σs, whereby a slower EBIS extraction (500 σs) is possible, but not yet in use. The time span between the macro pulses is 20 ms for the light ions with A < 50 and 40-100 ms for heavier ions. The beam quality in front of the linac has been analysed via emittance measurements close to the mass slit of the separator. The LINAC tune has been examined via energy spectra taken from each cavity.

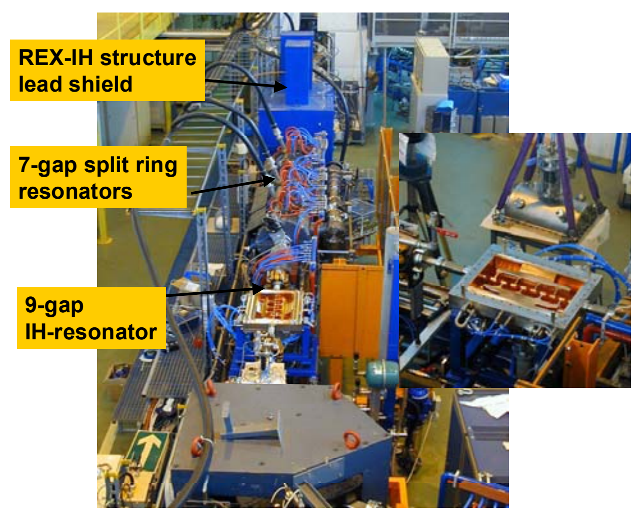

Figure 3: Picture of the REX-ISOLDE LINAC in its present set-up including the 9-gap IH-structure.

Two EBIS operation modes have been tested, one with highly charged ions from residual gas and one using He-ions to reach higher beam currents needed for emittance measurements of the linac at higher energies. The geometrical emittance of the REXEBIS has been measured as ~10 mm·mrad (95%) for highly charged ions at 20 kV extraction voltage, which corresponds to 5 keV/u. The value of the emittance is dependent on the ion neutralization of the electron beam and on the ion species, especially the mass. Fig. 4 shows emittance measurements of the EBIS beam behind the A/q-separator mass slit for different degrees of compensation and for different ion species. For emittance measurements of the

LINAC beam, a beam intensity of several nA was required. Therefore He-gas has been injected into the EBIS and the electron beam has been neutralized. For such increased compensation level with low charged ions like He^+, the emittance amounts to 35-70 mm·mrad (0.11-0.23 mm mrad normalized). For operation with radioactive beam the emittance correspond to the measured EBIS emittance of 10 mm mrad.

Table 3: Measured beam parameter of the REX-ISOLDE LINAC structures

	RFQ	Buncher	IH	7-gap	9-gap IH
f_{inject}# [MeV/u]#	0.005	0.3	0.3	1.1-1.2	2.25
η_{inject}#	0.0033	0.0254	0.0254	0.049-0.051	0.069
f_{exit}# [MeV/u]#	0.3	0.3	1.1-1.2	0.85-2.3	2.9-3.0
$\eta_{extract}$#	0.0254	0.0254	0.049-0.051	0.043-0.07	0.079
$\zeta_{xx'}$, ζ^n [mmmrad]	200 (0.66)	---	25.3 (0.643)	40 (2)	20 (1.4)
$\zeta_{yy'}$, ζ^n [mmmrad]	200 (0.66)	---	25 (0.636)	52 (2.55)	20 (1.4)
Q	3400	3500	16200	5370	10100
R_p, Z_{eff} kTm, MT/m	146	20	215	60	165

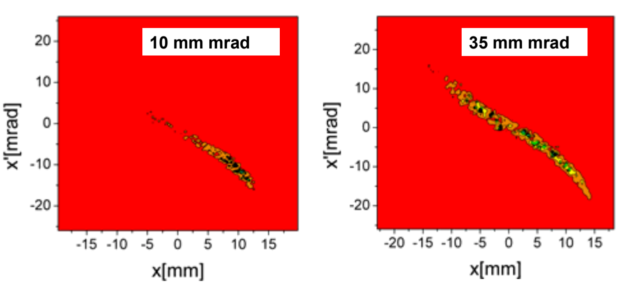

Figure 4: Right: Typical EBIS emittances of 10 ϕ mm mrad for highly charged ions from REXEBIS. Left: The electron beam has been neutralized with light ions (He).

The past two running periods commissioning measurements have been carried out with the LINAC structures in order to improve the beam quality especially the energy spread of the beam [10]. The commissioning measurements comprise scans of the beam energy spread and emittance measurements of the different structures. Due to the very low intensities from the REXEBIS, bunch length measurements could not be performed so far. Therefore the longitudinal emittance of the beam from the different cavities has been calculated and the energy spreads have been determined. The phases have been adjusted in two steps. First the beam energy has been maximized for given amplitude, to define the 0^o-synchronous phase. Then the required phase according to the design calculations has been set and the energy spectrum has been measured and compared with calculated values. The energy measurements of the IH-structure have been presented in [10]. As an example of additional energy measurement the beam energy spectrum from the first 7-gap resonator at 1.55 MeV/u is shown in fig.5. The beam energy spreads of all cavities are summarized in table 4 for the settings of the 2.9 MeV/u accelerator tune. The measured values are in good agreement to the design values of the simulation calculation. The discrepancy results mainly from the tune of the re-buncher cavity.

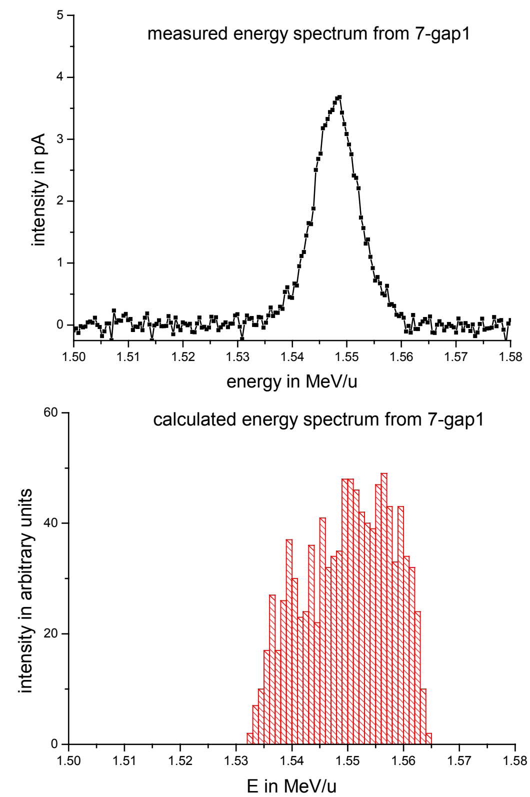

Figure 5: Comparison of the measured and calculated energy-spectra of the first 7-gap resonator.

Table 4: Measured and calculated energy spread of the beam from the different LINAC structures. The phase are adjusted for 2.9 MeV/u final energy

	phase	E-spread calculated [%]	E-spread measured [%]
RFQ	--	±1.5	±1.4
Buncher#	-90°	±3.2	±3.0
IH#	0°	±1.0	±0.85
>-gap1#	-20°	±1.1	±0.75
>-gap2	-20°	±0.8	±0.7
>-gap3	-20°	±0.7	±0.65
9-gap IH	0°	±0.5	±0.65

In addition transverse emittances from different cavities of the front part of the REX-ISOLDE LINAC have been determined in order to evaluate the transverse emittance growth. In fig.6 the emittance of the IH-structure is shown. The injected normalized emittance has been 0.26

mm mrad and 0.2 mm mrad respectively. The normalized emittance from the IH-structure is 0.29 and 0.21 mm mrad respectively. Thus an emittance growth of about 10% occurs in the IH-cavity. The difficulties of the emittance measurements are the very low beam intensity of about 1nA, which is the limit of the Munich emittance meter. In addition the angular resolution has been only 0.5 mrad, which put large error bars on the measured values of 20%, which is in the range of the emittance growth.

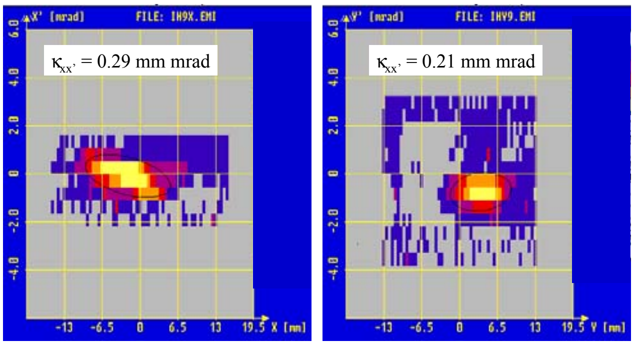

Figure 6: Normalized emittances from the IH-structure. A 1nA He^{+}-beam has been used for the measurements.

The emittances of the IH-structures and the 7-gap split-ring structures cavities will be measured before the next shut down period, with higher angular resolution. However the beam measurements reveal the proper tune of the LINAC for energies above 2.2 MeV/u and a small emittance growth so far, which corresponds to the small spot size at the MINBALL target position.

FURTHER UPGRADE PLANS

To use the full range of isotopes from ISOLDE for nuclear physics experiments with Coulomb excitation and transfer reactions, higher beam energies are required. An increased energy of 3 MeV/u allows studies of nuclear reactions up to mass A=85 on deuterium targets. An even higher beam energy above 4 MeV/u would be suitable up to mass A=145. Therefore a study of a further energy upgrade of the REX-ISOLDE LINAC has been launched. A major change of the LINAC structure will be required in order to reach energies of approximately 4.2 MeV/u and beyond. The proposed structure is sketched in fig.2. Thus two of the 7-gap spiral resonators with 101.28 MHz resonance frequency have to be replaced by a 1.5 m IH-cavity with 202.56 MHz resonance frequency to boost the energy to required region of 3.75 MeV/u. Then a 7-gap IH-resonator of the MAFF type cavity can be used to accelerate to final energies above 4 MeV/u.

The first 7-gap split ring structure will be used to prepare the beam for injection into the 28 gap 202.56 MHz IH-structure. The synchronous phase of the 7-gap resonator will be adjusted to -20^{o}, which allows a exit energy of 1.53 MeV/u and a phase spread of $\pm 10^{o}$ at the entrance of the 202.56 MHz structure. The cavity will boost the energy to 3.75 MeV/u which requires 10.14 MV effective acceleration voltage for ions with A/q = 4.5. With an effective shunt impedance of 180 MT/m, which is feasible for such cavities, an rf-power of 380 kW would be require. Results from beam dynamics calculation with LORASR are shown in fig. 7 concerning the development of the longitudinal phase space. A phase spread of $\pm 8^{o}$ and an energy spread of ±0.6% and a small emittance growth of 10% will be expected for the 3.75 MeV/u beam. The beam energy can be varied in the range of ±0.5 MeV/u via the 202.56 MHz 7-gap resonator of the MAFF type, which presently serves as 9-gap booster cavity at REX-ISOLDE.

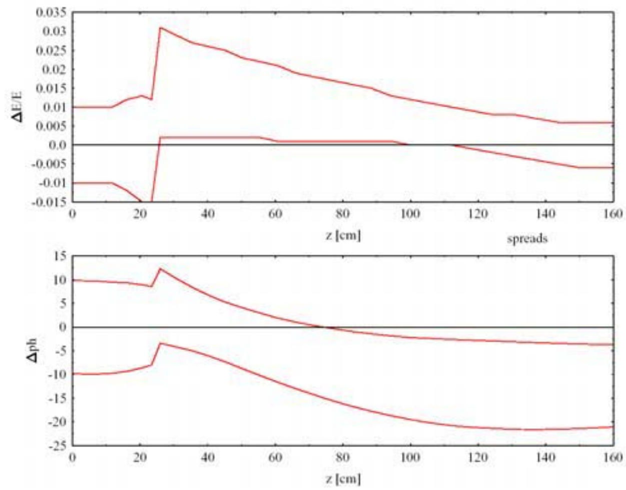

Figure 7: Development of phase and energy spread in the 28 gap 202.56 MHz IH-cavity for the energy upgrade above 4 MeV/u.

REFERENCES

[1] F. Wenander, Proc. of the RNB6, ANL, Chicago, USA, Sept. 2003, accepted for publication in Nucl. Phys. A
[2] http://www.ganil.fr/eurisol/index.html
[3] RIA white paper: http://www.sc.doe.gov/production/henp/np/projects/docs/ria-whitepaper-2000.pdf
[4] O. Kester and D. Habs, Nuclear Physics News 13, No.3 (2003) p.25
[5] J. Eberth et al., Prog. in Part. and Nucl. Phys. 48 (2001) 389.
[6] P. Schmidt, Nucl. Phys. A701, (2002) 550c
[7] F. Ames et al., Hyperfine Int. 132 (2001) 469-472
[8] K. Reisinger, "Emittance measurements on the sideband cooling technique and introduction of the rotating wall cooling technique at REXTRAP", Diploma thesis, TU München, July 2002
[9] R. Becker and O. Kester, "The EBIS/T as a Coulomb Target for Ions", EBIS/T 2004, Tokyo, Japan, 2004, to be published in AIP conference proceedings.
[10] S. Emhofer et al., "Commissioning results of the REX-ISOLDE LINAC", PAC'2003, Portland, Oregon, USA, May 2003, p.2872
[11] O. Kester et al., "An energy upgrade of the REX-ISOLDE LINAC", PAC'2003, Portland, Oregon, USA, May 2003, p.2869