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PROGRESS IN NORMAL CONDUCTING RFQs IN FRANKFURT*

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Two Heavy Ion RFQs[1–3] have been built for the UNILAC at GSI, a new high charge state injector (HLI) and a prototype of a new high current injector (HSI). Both can be seen as branches of actual RFQ development. The HLI-FQ aeeelerates U^{28+}ions from an ECR-ion source from 2.5 keV/u to 300 keV/u with a high duty cycle of now 25% at an operating frequency of 108.5 MHz. The Spiral-RFQ for the HSI accelerator accepts low energy (2.2 keV/u). high current (25 mA) beams with low charge states (U^{2+},Xe^{+}) at an operating frequency of 27 MHz. Results of structure development and beam experiments for both structures are discussed which can be seen as model for the first crucial part of a RFQ for low charged radioactive beams concerning low frequency operation, high duty factor and beam dynamics properties.

KEY WORDS: RFQ, low-beta accelerators, low q/A beams, normal-conducting accelerator structures

1 INTRODUCTION

The GSI accelerator system[4,5] consists of the new 18 Tm heavy ion synchrotron SIS and the experimental storage rin ESR, both fed by the old UNILAC.

With these new rings and the UNLAC injector it is possible to accelerate all elements up to Uranium to energies above 1 GeV/u. The SIS and the ESR are now working for more than two years.

Two new injectors HSI (Hochstrominjektor) and HLI (Hochladungsinjektor) have been planned to fill the SIS ring with short bursts of high current heavy ion beams and to continue providing low current high duty factor beams for the nuclear physics research program at the UNILAC.[6]

The high charge state injector HLI[7] consists af a combination of an ECR ion source, a 4-Rod-RFQ and an IH-structure, both operating at a frequency of 108.5 MHz. The HLI enables direct injection of U^{28+} into the Alvarez part of the UNILAC at an energy of 1.4 MeV/u without stripping. This injector is designed for a beam current of 5 μA for the heaviest ions. The HLI is succesfully working and delivering beams for experiments since June 92.

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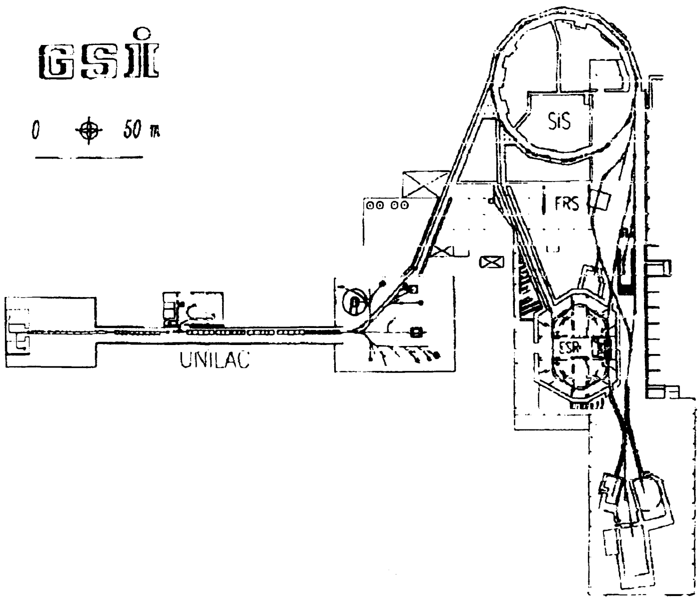

FIGURE 1: Plan view of the GSI accelerator facility

The high current injector HSI is designed to fill the SIS up to its space charge limit and will accept e.g. U^{2+} or Xe^{+} beams with currents as high as 25 mA at low initial particle energies of 2.2 keV/u. The Spiral-RFQ-accelerator is working at the (UNILAC)-Wideroe frequency of 27 MHz, which allows a beam transfer without frequency jump. Presently a gas stripper at 216 keV/u is planned which will produce a reasonable fraction of the necessary charge state of U^{10+} for acceleration in the second Wideroe part of the UNILAC. The second as gas stripper at 1.4 MeV/u provides the U^{28+} beam for postacceleration in the Alvarez-part of the UNILAC and injection into the SIS. Figure 1 shows a layout of the GSI accelerator system with the HLI and the planned HSI injector.

2 THE SPIRAL-RFQ-PROTYPE

A prototype of the Spiral-RFQ[8–10] has been built for both, rf and beam test purposes. The structure length is 4 meters but nevertheless the electrodes consist of the first 231 RFQ-cells, one third of the HSI's total cell number. These 231 cells cover the crucial low-energy part of the HSI-RFQ, where the dc-beam is converted into a bunched beam. Therefore the 4 m prototype can give relevant information on beam properties e.g. on emittance growth. A survey over the main parameters of the RFQ-Prototype is given in Table 1.

A rectangular vacuum chamber made of Aluminium has been chosen or the Spiral RFQ. Eight large lids give easy access and simplify the mountins and adjustment of the RFQ electrodes. The structure has been aligned with an opto-mechanical system.

TABLE 1: Main Parametes of the Spiral-RQF

f	27.1 [MHz]	length	3.95 [m]
cells	231	Rp	520 [kΩm]
T_{in}	2.2 [keV/u]	T_{out}	17.6 [keV/u]
ϕs	39[°]	a	6.0 [mm]
m	1.458	a_N	0.9 [π mm*mrad]
U_{el}	1.51 A/q [kV]	I	0.23 A/q [mA]

The rod-electrodes are fixed on electrode carriers, each about 100 mm long and with precisely milled washers to the spiral supports which allow an alignment with a precision of approx. 0.1 mm, less than 3% of the aperture radius. Figure 2 shows a scheme of a spiral-RFQ resonator cell.

The field distribution along the beam axis has a maximum deviation of less than 2%. With the existing equipment rf-tests have been performed up to 35 kW pulsed input power (67 kV) and 7.2 kW in cw operation. No mechanical and cooling problems could be observed despite the design which was for a duty factor of less than 1% (average power of 2 kW). From beam- and rf-measurements an Rp-value of 520 KΩm could be determined, which has been checked with x-ray spectroscopy at higher field levels.

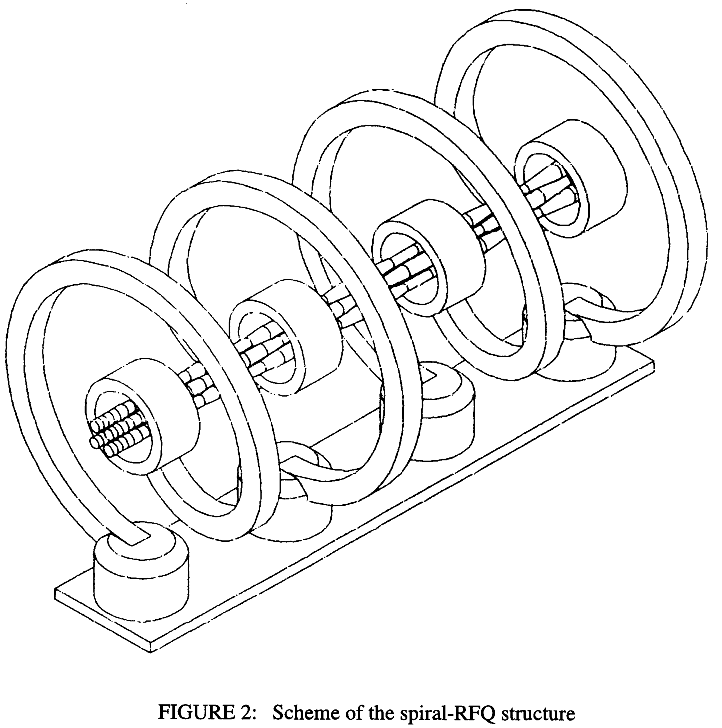

FIGURE 2: Scheme of the spiral-RFQ structure

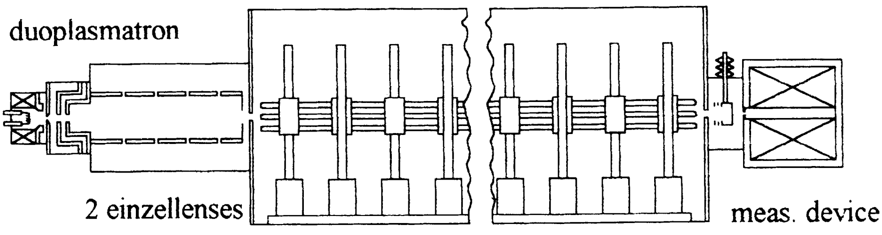

FIGURE 3: Scheme of the experiment set up for beam tests

These first beam experiments have been done at the Institut für Angewandte Physik. Due to the limited rf-power and extraction voltage light ions (He^+) have been used for the experiments. The corresponding electrode voltage and beam current are 6 kV and 0.8 mA respectively. Figure 3 shows a scheme of the experimental setup.

The beam from a duoplasmatron source was matched into the RFQ by two electrostatic einzellenses. For beam analysis an emittance-measurement-device, a fast Faraday-cup and an analysing magnet had been installed. The maximum transmitted beam current was 980 μA, but due to the input emittance with the typical aberrations of einzellenses the transmission at design voltage has been less than 40%. PARMTEQ calculations with this input emittance delivered transmission curves which are in good agreement with the measurements. Figure 5 shows the calculated transmission curves vs. electrode voltage for the design input emittance ($\varepsilon_{\text{norm}} = 0.3\pi$ mm mrad, $\alpha_x = 0.8$, $\beta_x = 0.1$ mm/mrad), the emittance with the aberrations of the einzellenses ($\varepsilon_{\text{norm}} = 0.5\pi$ mm mrad, $\alpha_x = 0.8$, $\beta_x = 0.04$ mm/mrad) and the measured transmission. N^+ in the beam, caused by a leaky valve in front of the ion source, is responsible for the tail of the measured transmission curve. The calculated tranpsport of N^+ is shown in Figure 4 too.

In Figure 5 the measured energy spectrum is plotted for the design voltage. Calculations give much smaller energy spread ($\varepsilon_{\text{design}}$), but the results of the measurements can be reproduced with good accuracy, if the measured emittance is used as input for the calculations. The He^+ experiments have been finished successfuly. In a next step, the RFQ has been installed at the high current injector test stand at GSI where it will be tested with heavy ions, a high current source and a magnetic injection system to check the full specifications. Presently the RFQ is mounted at GSI and vacuum- and rf-plumbing are completed.

3 THE HLI-RFQ

The new "High Charge State Injector (HLI)" for the UNILAC has been built to provide 2 to 20 MeV/u beams for the low energy program of GSI. It consists of an ECI-source which accelerates from 5 keV/u to 300 keV/u for injection into the following IH-structure that further accelerates the beam to 1.4 MeV/u which is the proper energy for the injection into the first Alvarez part of the UNILAC,[5,6] as schematically shown in Figure 6.

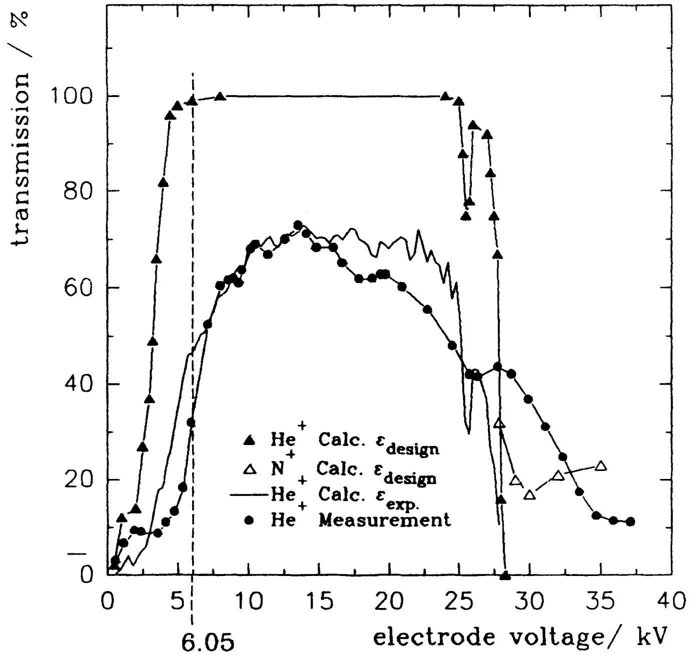

FIGURE 4: Calculated and measured transmission curves

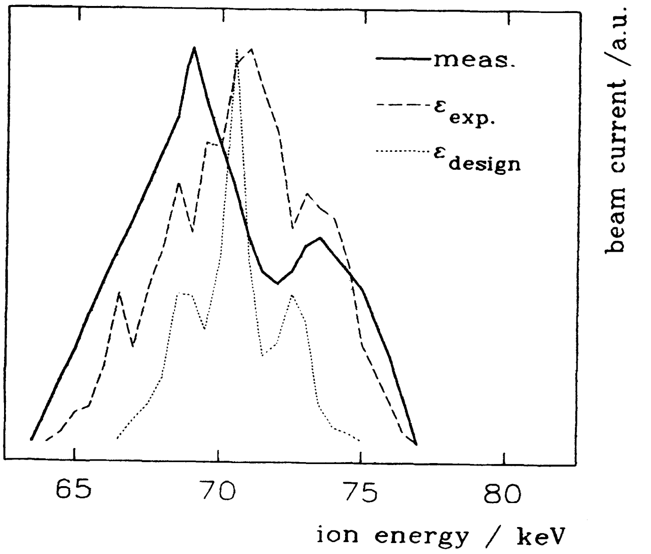

FIGURE 5: Measured and calculated energy spread

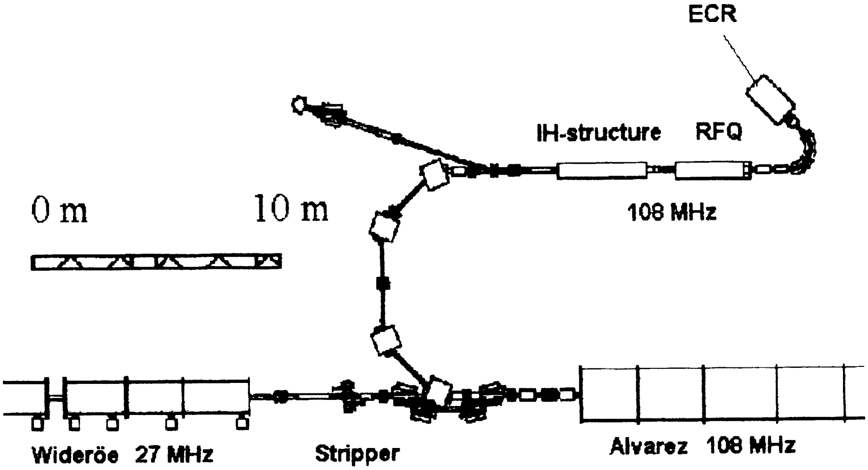

FIGURE 6: Layout of the HLI-injector of GSI

The resonator consists of four rods arranged as a quadrupole. Diagonally opposite rods are connected by spirally shaped stems or in case of higher frequency with straight stems that are positioned on a common base plate. The quadrupole field between the electrodes is achieved by a $\lambda/2$-resonance which results from the electrodes acting as capacitance and the stems acting as inductivity. When the structure frequency and electrode voltage have been chosen to give good focusing properties, the length has to he optimized with respect e.g. to the beam emittance, the power consumption and the beam transmission.

The mechanical design of this type of accelerator structure allows cooling of all components. The stems, the electrodes, and the tuning blocks are mounted into the tank by screws to be able to change components in ease of problems with high duty factor operation, which is required for the HLI-RFQ. Figure 7 shows the final particle design parameters along the RFQ structure, Table 2 summarizes characteristic parameters. The slow increase of the ion energy T as function of RFQ cell number N is demonstrating the fact that a significant

TABLE 2: Main Parameters of the HLI-RQF

f	108.5 [MHz]	length	2.95 [m]
cells	287	Rp	175 [kΩm]
T_{in}	2.5 [keV/u]	T_{out}	300 [keV/u]
fs	18[°]	a	3.0 [mm]
m	2.1	a_N	0.5 [π mm*mrad]
U_{el}	9.4 A/q [kV]	transmission	> 90%

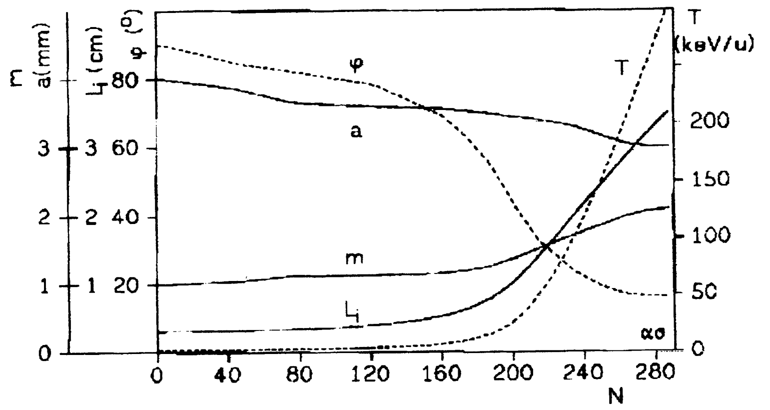

FIGURE 7: Beam dynamics layout of the HSI-prototype-RFQ

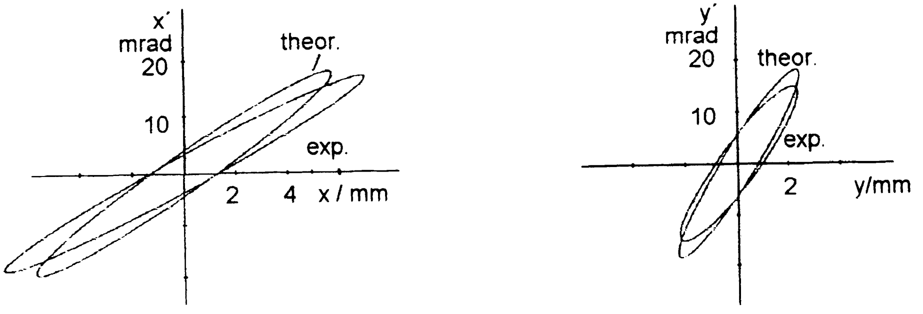

FIGURE 8: Measured and calculated beam emittances at the HLI-RFQ

part of the structure is required for bunching. After the RFQ had been assembled, aligned and tuned the field flatness was examined and optimized under low power conditions. The field variation along the axis was less than 5%.

The first beam tests showed encouraging results.[11,12] The output beam had the proper bunch structure and ion energy. The width of the bunch, measured by time of flight measurements with two probes, was less than 1 nsec. The energy of the ion beam and the radial emittance was in good agreement with the theory as shown in Figure 8. A closer inspection of the output beam showed a lower transmission of only 40–50%. Experiments with reduced input emittance and with Helium at increased electrode voltage resulted in the required transmissions values of 90%. A first realignment of the electrodes improved the transmission. For an emittance of $\varepsilon = 115\pi$ mm mrad (design value) the transmission now was 94%. For the experiment, the emittance was changed by an aperture in the injection beam line. Also rf-operation revealed some problems: rf-operation was stable with very little multipacting at low levels and a quick thermal equilibrium at power levels up to

130 kW (25% d.f.) with small frequency shifts. At high power levels, an rf modulation caused by ponderomotoric forces was observed, which was qualitatively similar to the effects studied at spiral loaded cavities.[13] This effect was characterized as mechanical oscillations of the electrode ends, which were excited at the pulse repetition frequeney. Its resonance is at 178 Hz at which it shows strong amplitude resp. forward power modulations, if the tank amplitude is kept constant during the pulse by the control system. Even the pertubation could be controlled at 50 Hz repetition rate and design field value, this effect makes it difficult to achieve 50% df without additional mechanical stabilisation of the electrodes. An improved feedback system would solve this problem as well, but it would not be ideal for routine operation.

With an improved cooling tube for the electrodes, which gives a stiffer system at the same time, and a better alignment the operational properties have been improved. Figure 9 shows the improved transmission curve. The temperature of the rods is now raised by 6 degrees only at full field level and the mechanical oscillations are suppressed. The maximum power load of the RFQ has been raised to 175 kW/25% df and several U^{28+} user beam times have been successful, at least from the accelerator point of view.[14]

5 RFQS FOR THE ACCELERATION OF RADIOACTIVE BEAMS

General features of the proposed accelerators for radioactive beams at ISL are a final energy of 10 MeV/u for all ions up to mass 240u starting with singly charged ions from a complex target-ion source — high resolution mass separator system with gives a starting energy of 100 keV for all ions. The optimum postaccelerator should be able to accelerate all these ions with 100% transmission without emittance growth. It would work with 100% duty cycle (DC or CW mode) and have a microstructure with 10 MHz beam bunch repetition rate.

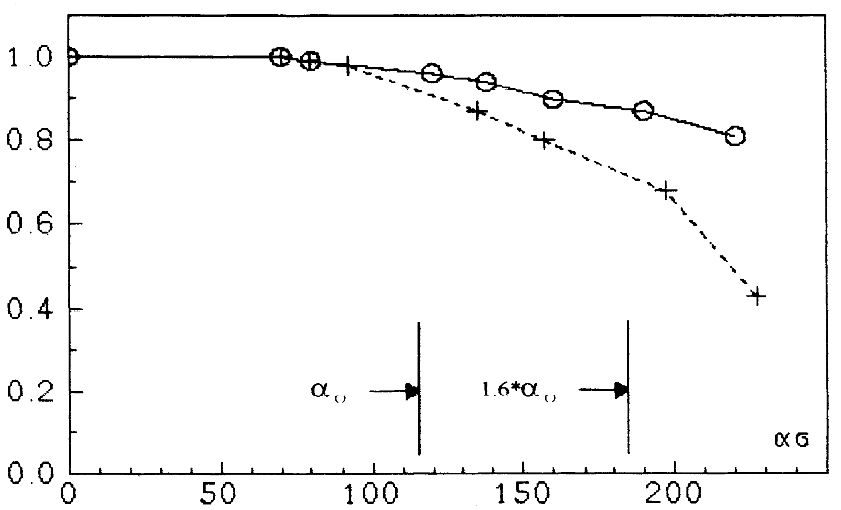

FIGURE 9: Transmission curves for the HLI-RFQ

To put the problems of the low energy part into a proper perspective a comparison with the HILAC or UNILAC parameters shows the step ahead in expected performance. Aside from the duty factor problem which will dominate all the linac engineering, the low specific charge q/A of the ions to be accelerated is the most difficult input parameter for the beam dynamics design. While the UNILAC starts with charge state $q = 10$ for the heaviest ion ($q = 28$ at the new HLI injector), the ISL machine will start with singly charged ions, which means all focusing and accelerating gradients should be increased by a factor of ten (A/q) to give the same beam dynamics. Such parameters are not assumed even in the most optimistic designs. Therefore restrictions in the mass range and/or duty factor are made in most cases.

ISL will make use of the full mass range. The design of the prestripper part of the linac which accelerates the single charged ions $q/A \geq 1/240$ from 100 keV to 100 keV/u for which a sufficient stripping efficiency is assumed to increase the charge state to $q/A > 1/20$ is shown in Figure 10a. To match the beam from the mass separator to the input of the first rf-linac structure with its inherent velocity profile, the first RFQ is being installed at a HV-platform. Lowering the injection energy of the RFQ to 1 keV/u the platform voltage could be reduced to 140 kV max. A short rf-cavity then has to match the energy of the beam from the platform to the input of the second RFQ. Its total "voltage gain" of 22 MV shows the scale of the machine, which can be compared to the "high current injector" planned at GSI for the pulsed injection into the SIS.

The HV-platform posos some problems concerning the radial and axial matching into the first and second RFQ. It could be omitted like shown in Figure 10b, if a special energy matching cavity is put in front of the RFQ1. Another simplification is the skipping of adiabatic bunching part in the first RFQ which has been done for the cluster-RFQ and the cyclotron injector at HMI.[15,16] For low current application, this option can be used but would need a HV-platform for the ion source or a 140 kV cavity and a drift of appr. 3 m in case of the 100 keV beam of ISL. Using an external (harmonic) buncher results in a compact solution for RFQ1 which should operate at 10 MHz to provide the beam mictrostructure and the strong focusing at low energy.

The matching into the first RFQ is somewhat complicated because the energy matching cavity will change the bunching and the radial matching for RFQ1, which is an interesting optimization problem. The structure for the 10 MHz-RFQ could be a modification of the Spiral-RFQ built for GSI or a twin-line 4-rod structure like the one being built for heavy clusters (operating frequency 5 MHz).[17] The RFQ1 would be 4.5 m long and needs about 50 kW rf-power.

In the reference design worked out at the Oak Ridge an LBL workshops, the second RFQ would work at 50Hz which would enable the application e.g. of superconducting RFQs, which would be saving power consumpion. But unfortunately the jump from 10 to 50 MHz for such low specific charges is not possible at these low energies.

Applying the adiabatic damping in classical accelerators, the frequency can be doubled if the energy has been increased by a factor of $T_f/T_i = 6.5$. In our designs, at least a factor of $T_f/T_j = 10$ would be applied, because of the parameter variations in the RFQ. A factor of 5 in frequency would require a factor of appr. $T_f/T_i = 70$ in energy to ensure proper phase width acceptance. In addition, the focussing strength of the "high frequency" (50 MHz) is limited. A electrode voltage e.g. of $U = 400$ kV would be needed to give the same phase

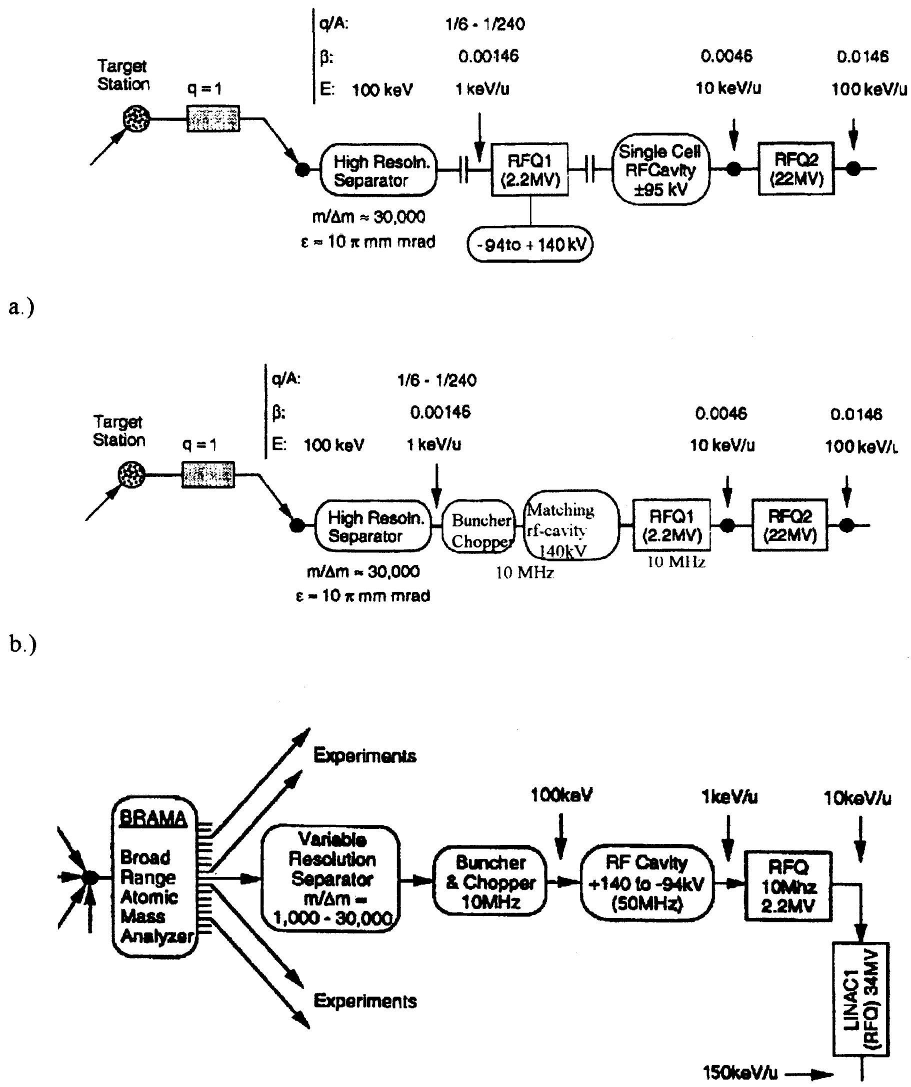

FIGURE 10: Layouts of the injector for heavy tadioactive beams

advance per cell as in RFQ1. The maximum field strengths are 90 MV/m (8.5 U_k) which comes close to the best values obtained in short prototype tests, but are unreasonable for longer structures like RFQ2, which would be approximately 5.5m long.

It would be more realistic to switch to 20 MHz for RFQ2, with still a modest power of 20 kW/m but a length of 24 m for a final energy of 100 keV/u. Going to 30 MHz would not reduce the length, but nearly double the power load and increase the peak fields by 50%. At

50 MHz, the phase advance per cell would be too small ($\sigma < 5°$) and the power loss rather large ($P = 60$ kW/m).

These design considerations for the prestripper part will have to modified by the optimization of the complete system. It is likely that the dominant role of the losses and the emittance growth caused by the strippers will make discussions about some percentage savings not useful, even if it is a multiplying factor in the overall transmission.

Less universal but more effective in terms of acceleration would be to start with a higher charge state as with an ECR source. The broad charge state spectrum and the large emittance of these sources is a disadvantage but the accelerator design would be straightforward either following the GSI-HLI injector or the ANL-ATLAS designs.

An alternative solution especially suited for lighter radioactive ions is discussed at MPI Heidelberg and MSI Stockholm. As demonstrated for "normal" ions the EBIS ion source can be operated in a special mode where ions are collected successively ionized and extracted in a pseudo cw mode.[18]. Measurements at MSI have demonstated an efficiency of 14%,[19] that means that the amount of input ions to ions in a single charge state is as high as for the passage of a single stripper. The limits for heavier masses have to be evaluated but the accelerator part is rather simple, e.g. standard postaccelerator systems like MPI, ANL and pulsed operation with e.g. 25% d.f. is also matched to the ion source program.

The prestripper part of the ISL accelerator would indeed be another class of machine, and the restriction to lighter masses ($A/q \leq 10$) e.g. at TRIUMPF[20] leads to more classical solutions too.

The basic design parameters for singly charged radioactive heavy ions ($m = 240u$) discussed above result in a large, long accelerator but the parameters for a injector with good beam emittance and high transmission like the focusing strength, the field gradients, and the ratio of power/length are feasible.

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