OVERVIEW OF RECENT RFQ PROJECTS *

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Abstract

RFQs are the new standard injector for a number of projects. The development of the 4-Rod RFQ structure has led to interesting developments, which will be discussed with actual projects as examples. Recent work on the FAIR - p linac, the GSI - high charge state injector upgrade, the GSI - HITRAP, the new BNL - EBIS-RFQ, and the RFQ of the MSU-CW Reaccelerator will be presented and the status of these projects will be discussed.

INTRODUCTION

Accelerators have been developed as tools for atomic, nuclear and particle physics. From these technologies numerous applied research did develop. The "production" of secondary particles as purpose of a facility was another big step in accelerator technology, because the production rates can be increased by optimizing the beam energy and target arrangement and of course by increasing the beam current to the target.

In case of heavy ion beams the duty factor of the machines had to be large because of the limits of sources for (multiple charged) heavy ions. For protons and deuterons the beam currents from ion sources could be pushed up to the 100 mA region, so the duty factors of the accelerators could be modes tlike for spallation sources with beam powers of up to 1MW and the synchrotron injectors, drivers for neutron production or for sources of radioactive beams with beams of some kW.

Accelerators for radioactive beams have low power beams but require high duty factors for compensation of the low production rates.

The Frankfurt IAP was involved in the planning phase for GSI and the cooperation with GSI in the 70s by post accelerator structure applications (helix, spiral) could be kept up until today with respect to the FAIR project.

A big step were the new ideas about RFQs in the late 70s for low energy acceleration [1,2].

Application for heavy ions and lower frequency and the need for practical solutions led to the development of the 4-rod RFQ structure. First prototyps and beam tests were rather simple, but the big point was the chance to develop and built structures for other labs, at first GSI, DESY and MSI, which pushed the development and besides beam dynamics, the importance of issues like rf- and mechanical technologies and reliability.

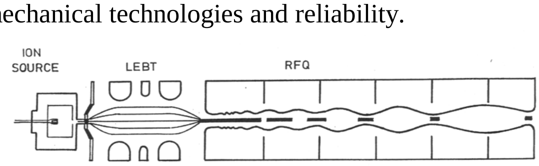

Figure 1: Scheme of a RFQ injector.

*supported by the BMBF

RFQ DESIGN

The design of RFQs is at first the choice of basic parameters like frequency, input output energy, which are mostly determined by the application or the ion source or the following bigger accelerator system.

Next steps in the beam dynamics design is the choice of electrode voltage U, beam current, input and output energy and emittances ε and the cell parameters along the RFQ: cell length L_i, aperture a_i, modulation m_i. The result is an RFQ with certain total length L and power consumption N which adiabatically bunches and focuses the dc beam from the ion source with small Δε and high transmission [3].

RFQ design is sometimes treated as being completed, when the beam dynamics design is finished. Especially for high power beams it is crucial to have a balanced design which takes into account the special rf-problems as well as the engineering to ensure tolerances, to handle the rf-losses, the beam with losses, the diagnostics and also maintenance possibilities and control.

While for smaller neutron generators RFQ aspects can dominate the choice e.g. of the frequency and length and rf-power consumption to simplify alignment and tuning, for bigger projects the optimization of the total accelerator, the availability of power sources and naturally costs will set some design input parameters and e.g. will increase the frequency to lower the charge per bunch, to avoid funneling and ease emittance growth and matching problems or reduce crucial beam losses.

Reducing losses and emittance growth and high duty factors or beam powers require even new solutions and prototype developments not showing up in beam dynamics simulation which sometimes are described as "physics design".

To generate the quadrupole fields we use the 4 rod RFQ structure, which we have developed in Frankfurt It can be described as a chain of interlaced λ/2-resonators in π–0-mode. The electrodes can be typical rods, or small vane shaped electrodes. with unchanged rf-properties. The radial dimensions of the 4-rod RFQ are appr. half as for a 4-Vane TE_{210}-structure at the same frequency. Beam dynamics and experimental results for emittances and transmission are the same as for 4-Vane RFQs.

While the power consumption is also roughly the same, there are some advantages because the 4-rod structure cannot show dipoles and longitudinal coupling is stronger

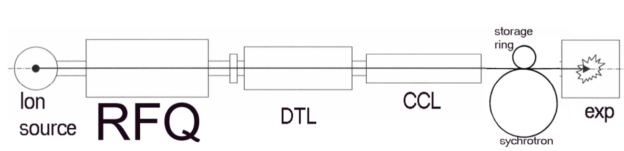

Figure 2: Accelerator system.

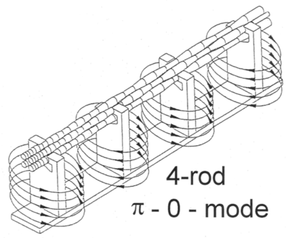

Figure 3: Scheme of a 4-Rod-RFQ resonator insert.

The rf-fields are confined in the resonant insert. A change of tank dimensions results in very little change of the frequency, so ports in the tank and e.g. the top lid along the tank do not change fields and coupling in the structure. So long RFQs can be aligned, tuned and inspected through such a top lid and tank contacts are not critical because less than 10% of the rf-power is dissipated in the tank , most of it close to the insert.

RFQ PROJECTS

One of the early RFQ- projects was the HLI injector RFQ for GSI. This HLI (108.5 MHz, 2.5keV/u-1.4 MeV/u, U28+) was the first ECR-RFQ-IH combination, which was built and operated. The duty factor was 25%, so also from the duty factor point of view it was a very advanced. It served as example for the Lead Injector of CERN and many other heavy ion machines. Also the injector for the HIT medical synchrotron is a scaled version of the HLI.

The HLI is operating since 1991 routinely with various ions and charge states. Not optimal were the injection with a rather step angle because of the low injection energy.

A new ECR ion source with higher frequency will give higher charge states and beam currents. The extraction energy can be higher and with that the matching problem can be reduced. The maximum cw-power of 60kW can be applied and an optimized cw injector for “superheavy production” can be built [4]. This HLIn is now under construction. Its design is close to the old one, cooling and mechanics are improved using the operational experience.

New beam dynamics design results in a much shorter cavity. The beam should have very small emittance and nearly no emittance growth. The RFQ should be operational in 2009.

Med-RFQ

In a collaboration with the GSI in Darmstadt an RFQ-Drifttube-Combination for the Heidelberg cancer therapy center HICAT has been designed, built and successfully tested with a H-beam at the IAP Frankfurt. The integration and combination of both an RFQ and a rebunching drifttube unit inside a common cavity forming one single resonant RF-structure has been realized for the first time with this machine.

The 217 MHz RFQ [5] is a part of the HICAT accelerator complex, which consists of a RFQ-IH-linac for pre-acceleration of $^{12}C^{4+}$ up to 7 MeV/u.

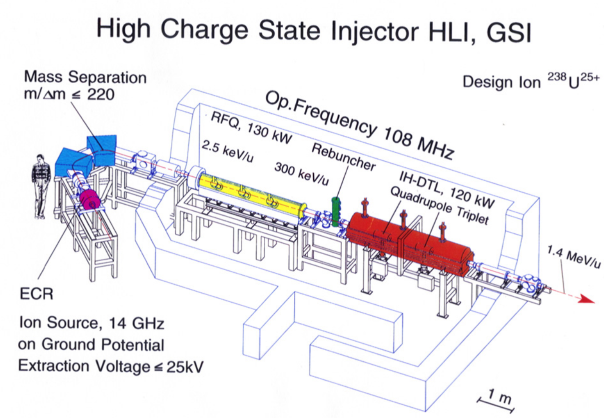

Figure 4: The HLI-injector of GSI.

Table 1: HLI-RFQ Parameters

PARAMETER	HLI	HLI-n
Frequency [MHz]	108.48	108.48
A/q	8.5	6
Input Energy [MeV/u]	0.0025	0.004
Output Energy [MeV/u]	0.3	0.3
Inter-ElectrodeVoltage[kV]	85	55
εin norm., rms [π mm mrad]	0.07	0.1
εoutx. n., rms [π mm-mrad]	0.12	0.1009
Electrode Length [cm]	305	199.5
Duty factor [%]	25	100

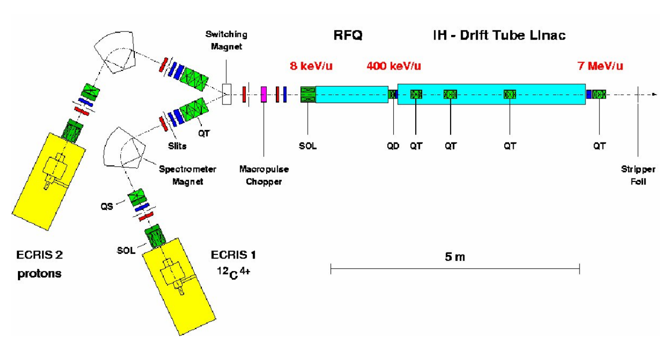

Figure 5: Layout of the HICAT injector.

Table 2: Med-RFQ Parameters

Operating frequency	216.816 MHz
Ion species	$^{12}C^{4+}$, protons
Length of tank	1.40 m
# of RFQ cells	219
Input/output energy	8 / 403 keV/u
Input emittance	$\varepsilon_{x,y}$=150 π mm mrad
Electrode voltage	70 kV
Power consumption	165 kW

In the following synchrotron ring-structure completely stripped $^{12}C^{6+}$ ions are accelerated to final energies between 50 and 430 MeV/u. This linac has been set up and tested at Heidelberg. Also the Synchrotron and the huge Gantry are operational. First patient treatment is planned for Dec.08.

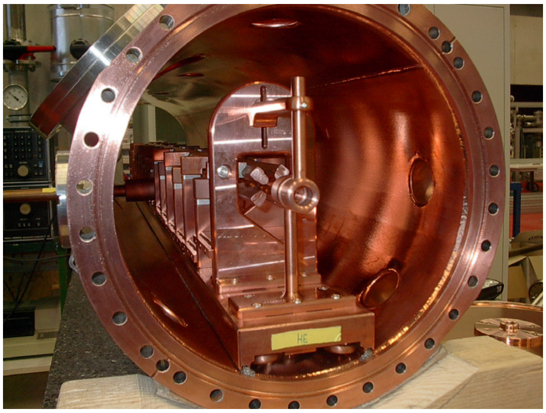

Figure 6: View of the HIT-RFQ with rebunching section.

Three new Med-RFQs have been built by industry since. We have supported by aligning and tuning these twins of the Heidelberg HIT-RFQ, which can be treated as prototype for a chain to clones come?

HITRAP-RFQ

The HITRAP-linac at GSI will decelerate ions from 5 MeV/u to 6 keV/u for experiments with the large GSI Penning trap. The ions, provided by the GSI accelerator facility, will be decelerated at first in the existing experimental storage ring (ESR) down to an energy of 5 MeV/u and then injected into a new IH decelerator and decelerated to 500 keV/u. The following 4-Rod RFQ will decelerate the ion beam from 500 keV/u to 6 keV/u. The properties of the RFQ decelerator and the status of the project will be discussed.

The design of the HITRAP 4-rod-RFQ is closely related to the design of the 108 MHz structure of the GSI-HLIn LINAC. The low A/q allows a short structure of 127 cells that is only 1.9 m long. A maximum rod voltage of 77.5 kV is required. The 45° phase spread of the ion bunches extracted from the IH-structure needs to be matched to the RFQ acceptance of 20°. Thus, in the matching section between IH-structure and RFQ two gap-1o8 MHz spiral Rebunchers will be installed [6,7].

GSI Proton-Linac

To provide sufficient primary proton intensities a new proton linac is planned for the antiproton physics program for future Facility for Antiproton and Ion Research (FAIR) at GSI-Darmstadt. The proposed linac consists of an ECR proton source, a RFQ, and a normal conducting CH-structure. It will have a final energy of 70MeV and deliver an output current of up to Ip= 90 mA. The operation frequency will be 325 MHz. The RFQ will accept a beam at 95 keV and accelerate to 3 MeV for injection into the IH-type DTL.

BNL-EBIS-Linac-RFQ

The new EBIS preinjector at BNL will accelerate ions from the EBIS source with specific mass to charge ratio of up to 6.25, from 17 keV/u to 2000 keV/u to inject into the Booster synchrotron, expanding experimental possibilities for RHIC and NASA experiments [8].

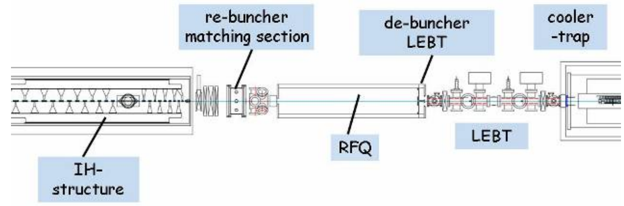

Figure 7: The RFQ section of the HITRAP decelerator.

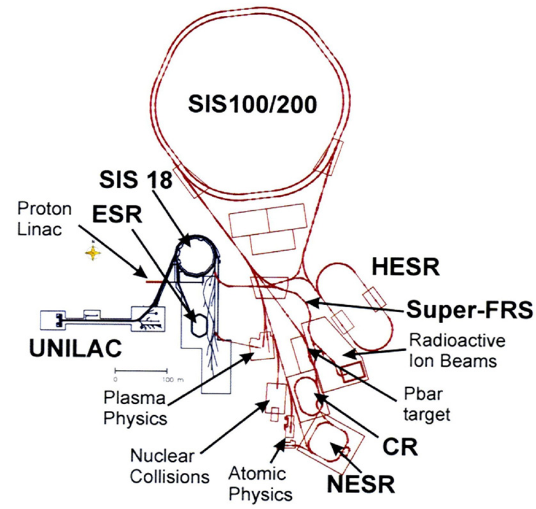

Figure 8: The FAIR project at GSI.

Table 3: Basic Proton-RFQ Parameters

Frequency	325 MHz
Input energy	95 keV
Output energy	3.0 MeV
Beam current	70/90 mA
output emittance rms norm.	0.4 π mm mrad
energy spread rms	150 deg keV
Electrode voltage	80 kV
RFQ length	3.22 m

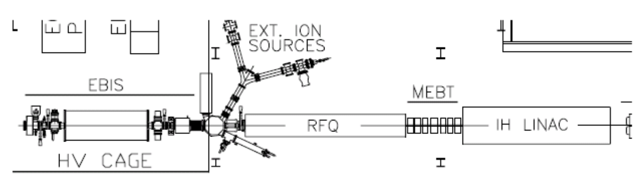

Figure 9: Layout of the EBIS Linac at BNL.

Table 4: BNL-RFQ Beam Dynamics Design Parameters

Frequency	100.625 MHz
Input energy	17 keV/u
Output energy	0.3 MeV/u
Mass to charge ratio	6.25
Beam current	10 mA
Outp trans. emitt rms norm. 90%	< 0.38 π mm mrad
Output long. emittance 90%	< 220 deg keV/u
Transmission	98%
Electrode voltage	70 kV
RFQ length	3.1 m

The RFQ has been designed and manufactured. The resonant insert has been aligned with a precision of ±0.03 mm and the flatness is better than ±2%. Tuners and rf-coupler have been built, tested and matched. Vacuum tests have been done and the EBIS-RFQ has been prepared for transport to BNL in the week before LINAC 08 [9].

Franz RFQ

The Frankfurt Neutron Source at the Stern-Gerlach-Zentrum (FRANZ) will comprise a short 175 MHz linac sequence consisting of a 1.75 m long 700 keV 4-rod type RFQ [10] followed by a 60 cm IH-DTL for proton acceleration up to 2 MeV to create a nsec pulsed high current beam on a n-target for n production.

The beam current is 200 mA at pulsed and up to 30 mA at c.w. operation. The aim is to have a very compact device driven by only one rf-amplifier to reduce costs and required installation space. A strong coupling between the RFQ and the IH resonators will be realized by a direct connection between the last stems of each resonator through the common end wall. The accelerators could also be driven separately by just removing these brackets. The distance between the end of the RFQ electrodes and the midplane of the first DTL gap is only 5 cm leaving some place for a x-y-steerer. Preliminary rf-simulations have been carried out together with accompanying measurements on rf-models.

The needed high average power levels require improved cooling of the RFQ-resonant insert. A short prototype has been built to develop a structure for such high thermal loads.

MSU-Reaccelerator RFQ

A complete Radio Frequency Quadrupole system presently is designed and fabricated for NSCL [12].. The 4-Rod RFQ structure matches the parameters given by the NSCL beam dynamics layout of the RFQ-electrodes, the 80.5 MHz structure is 3.35 m long and should need less than 150 kW rf-power. The rf-design has been made with the MWS-code and agrees with extrapolations from earlier experiments with 100 and 108 MHz RFQs.

The mechanical design was aiming at a solid structure, similar to the ones we had built recently. Changes had to be made to modify the structure following the request of a minimum number of brazings, water to vacuum and a less complex structure and the question of raw material availability.

Our new layout was using a rectangular cavity, where stems were inserted and sealed from the outside. We modified the cooling of the elctrodes with a cooling tube outside the stem. By this we had only one braze (the rectangular tube-electrode connection and a plug at this end of the electrode). The cooling tube than runs along the stem outside and is sealed at the base plate outside. Another new feature is the use of a thick wall Al-tank with welded stainless steel flanges, which avoids copper plating and cooling problems at high duty factors.

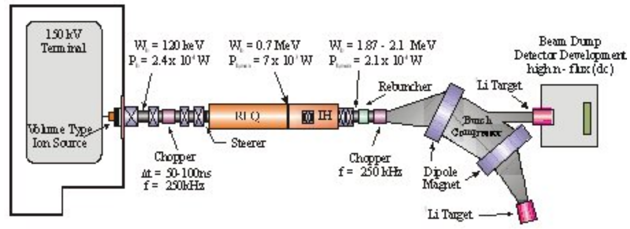

Figure 10: Layout of the FRANZ accelerator

Table 4: FRANZ-RFQ Parameters

Frequency	175 MHz
Input energy	120 keV
Output energy	0.7 MeV
Beam current	150/200 mA
output emittance rms norm.	0.1 π mm mrad
Long. Emittance	20keV*30degr.
Electrode voltage	75 kV
RFQ length	1.75 m
cell number	95

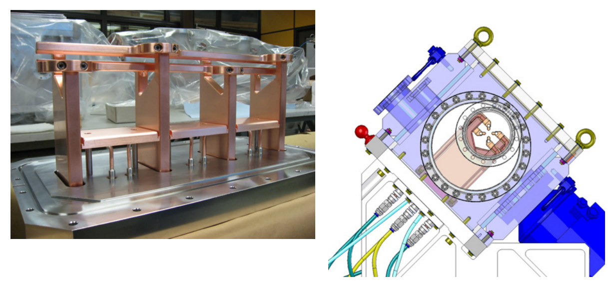

Figure 11: Prototype high power RFQ insert and tank.

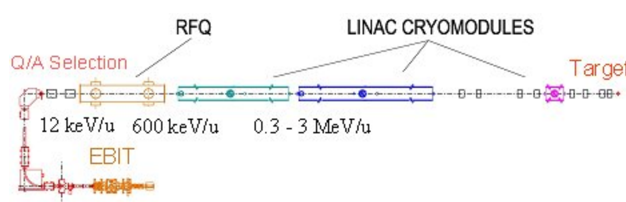

Figure 12: Layout of the MSU reaccelerator.

Table 5: MSU-RFQ Parameters

Frequency	80 MHz
Input energy	12 keV/u
Output energy	0.6 MeV/u
Charge to mass ratio	> 0.2
output emittance rms norm.	0.1 π mm mrad
Long. Emittance	30keV/u*degr.
Electrode voltage	87 kV
RFQ length	3.35 m
cell number	93

By plugging in the electrode support stems from the outside, all cooling drills are without brazes of the stem and the cooling can be plugged on via Festo/Rectus standard connectors.

Funneling-RFQ

Funneling is a method to increase beam currents in several stages. The maximum beam current of a linac is limited by the beam transport capability at the low energy end of the linac: For a given ion source current and emittance the linac current limit is proportional to $\beta = v/c$ for electric and to β^3 for magnetic focusing channels and ideal emittance conservation. The funneling scheme is making use of the higher current limits at higher beam energies.

The Frankfurt Funneling Experiment is a prototype of such a stage. The experimental setup consists of two ion sources with electrostatic lens systems, a Two-Beam RFQ accelerator, a funneling deflector and a beam diagnostic system. The two beams are bunched and accelerated in a Two-Beam RFQ and the last parts of the RFQ electrodes achieve a 3d focus at the crossing point of the two beam axis. A funneling deflector combines the bunches to a common beam axis.

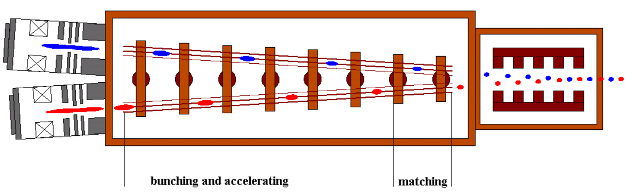

Figure 13: Scheme of the experimental setup.

The two-beam RFQ accelerator consists of two sets of quadrupole electrodes arranged with an angle of 75 mrad in one common resonant structure (fig. 2) [1]. The beams are bunched and accelerated with a phase shift of 180°. The quadrupole sets with a total length of approx. 2 meter are divided into two sections: The first section bunches and accelerates the beam to a final energy of 160 keV. The matching section focuses the beam longitudinally and radially to the beam crossing point at the deflector with low acceleration to 179keV.

The experiments have shown, that the system does funnelling, but beam emittances have to be better to reduce losses. At present the ion sources are improved and the section in front of the deflector is redesigned to give a better focusing at the funnelling section [12].

Other projects are the Saraf-RFQ for the SOREQ sc-linac for 40 MeV p,d beams, were we designed, tuned an CW-RFQ in collaboration with NTG [13]. This cw-RFQ at 175MHz has accelerated protons to 1.5 MeV and now is conditioned for 250 kW cw-operation.

The MAFF-RFQ, an IH-RFQ designed and built by the Munich group for the acceleration of radioactive beams with A/q=6.3 at 100MHz from 3keV/u to 300keV/u, has been set up and beam tests are prepared [14].

For RIKEN we have built a 2 m long RFQ at 100 MHz, which was successfully accelerating a C^{6+} beam of more than 50mA, proving the direct injection scheme with a Laser ion source [15].

CONCLUSIONS

These projects show the wide range of applications we worked and work on. Besides these projects we have done preliminary designs for advanced medical injectors and compact heavy ion machines and n-generators as well as for high power accelerator projects like IFMIF.

The range of parameters which is characteristic for IFMIF and similar ADS-projects in Asia and Europe comparable with the LANL LEDA project, is requiring power loads and structure length, as basic critical parameters, and efforts in engineering which we cannot provide. Our limited resources force us to work on compact machines.

ACKNOWLEDGEMENTS

I want to thank my colleagues and our RFQ-group for help and good teamwork, which is necessary for successful projects and thesises. I have to thank the partners in our collaborations for entrusting us with such work, for patience and understanding which sometimes is necessary, because of the special style of University people, old and young ones, and for the Germanenglish.

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