Recent High Power RFQ Development

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Abstract. RFQs as injectors for high power linacs have to deliver high current ion beams at cw operation. The development of the 4-Rod RFQ structure has led to interesting solutions, which will be discussed with actual projects as examples. The properties and limits of our designs will be discussed.

1. Introduction

Accelerators have been developed as tools for atomic, nuclear and particle physics. From these technologies numerous applied researches 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 modest like for spallation sources with beam powers of up to 1 MW 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 prototypes 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.

Today RFQs are the new standard injector for a number of projects. The development of the 4-Rod RFQ structure has led to interesting applications. We gained lots of experiences especially in the field of cw operation recently. Cooling techniques have been derived for thermal loads of more than 60 kW/m. All major parts of the RFQ resonator, electrodes, stems, base plate and even the tank itself have to be cooled very efficiently at such high power devices. Recent work on the SARAF - 175 MHz cw RFQ, the GSI - high charge state (HLI) injector upgrade, the FRANZ - 175 MHz RFQ, and the RFQ for the MSU-CW post-accelerator are examples that will be discussed in detail. Furthermore we will provide an outlook on our future plans on high power RFQs. All recent RFQ systems have been designed and built in close collaboration with NTG-Company.

2. 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 I, input and output energy $W_{\mathrm{in,out}}$ 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 $\Delta\varepsilon$ 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 at 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 $\lambda/2$-resonators in π-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 approximately 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.

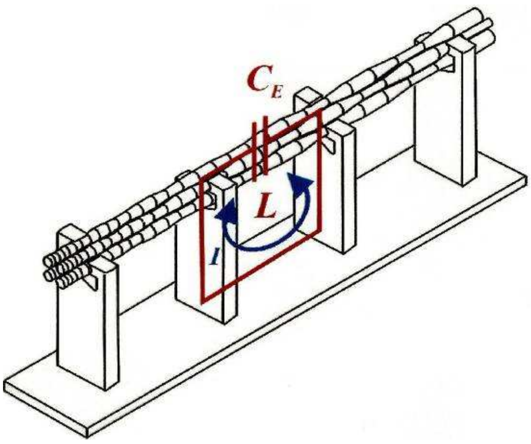

FIG. 1. Scheme of a 4-rod-RFQ.

3. RFQ Projects

The following Chapter will describe a choice of our RFQ projects with special respect on high power applications.

3.1. SARAF-250kW-CW-RFQ

This is the most recent high power RFQ set into operation at the SOREQ institute Israel [4]. It is a 4 m long structure operated at 176 MHz for acceleration of protons and deuterons up to 1.5 MeV/u for rare isotope production. Exceeding 60 kW/m it is by far the highest thermal load that has been realised with a 4-rod-RFQ so far. Beam tests with protons have already been accomplished successfully. The structure is now being conditioned for deuteron operation. 190 kW (47.5 kW/m) cw have been reached at stable operation up to now, which already exceeds the ever reached thermal load on a 4-rod structure by a factor of 2.4. At 250 kW the structure is conditioned to 85%. The target of 250 kW at 100% duty cycle should be met soon. This groundbreaking 4-rod design will serve as a prototype for upcoming high power applications.

FIG. 2. The SARAF-RFQ.

TABLE I: SARAF-RFQ PARAMETERLIST.

Parameter	***Value***
frequency f_0 [MHz]	176
input energy W_{in} [keV/u]	20
output energy W_{out} [keV/u]	1500
max. mass to charge ratio A/q	2
inter electrode voltage V_{el} [kV]	65
electrode length [cm]	390
duty factor [%]	100
thermal load [kW/m]	62.5

3.2. HLI for GSI

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, U^{28+}) 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 project. 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 was the injection with a rather step angle because of the low injection energy. A new ECR ion source with higher frequency will now provide 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 60 kW can be applied and an optimized cw injector for "superheavy production" can be built. 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.

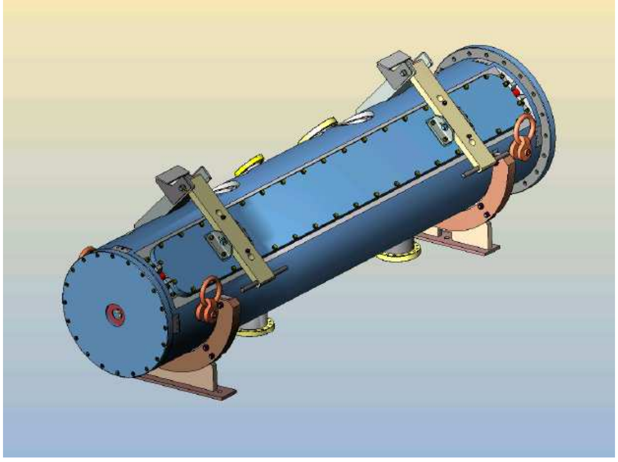

FIG. 3. Setch of the new HLI-RFQ for GSI.

TABLE II: HLI RFQ PARAMETERLIST.

Parameter	HLI	HLIn
frequency f_0 [MHz]	108.48	108,48
input energy W_{in} [keV/u]	2.5	4
output energy W_{out} [keV/u]	300	300
max. mass to charge ratio A/q	8.5	6
inter electrode voltage V_{el} [kV]	85	55
input emittance $\varepsilon_{rms,norm.,in}$ [mm mrad]	0.07	0.1
output emittance $\varepsilon_{rms,norm.,out}$ [mm mrad]	0.12	0.1009
electrode length [cm]	305	199.5
duty factor [%]	25	100
thermal load [kW/m]	7	28

3.3. FRANZ-RFQ

The Frankfurt Neutron Source at the Stern-Gerlach-Zentrum (FRANZ) [5] will provide a short 175 MHz linac sequence consisting of a 1.75 m long 700 keV 4-rod type RFQ [6] followed by a 60 cm IH-DTL [7] for proton acceleration up to 2 MeV. 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 the coupling [8].

The coupling of different rf-components is very attractive for most recent accelerator development. It leads to more compact devices using a common rf-amplifier and control system. Thus the overall size and the costs of the set up can be reduced drastically.

Many examples are planned or already in existence. For instance a coupled RFQ-drifttube combination that has been developed for medical application at the HICAT (Heavy Ion Cancer Therapy) center in Heidelberg by the IAP, where a 4-rod-RFQ and a 2 gap rebuncher sequence are merged [9]. This concept has been applied recently to other treatment facilities by industry several times [10, 11]. Coupled CH-DTL cavities are a major achievement in the development of the FAIR Proton Injector at GSI [12, 13].

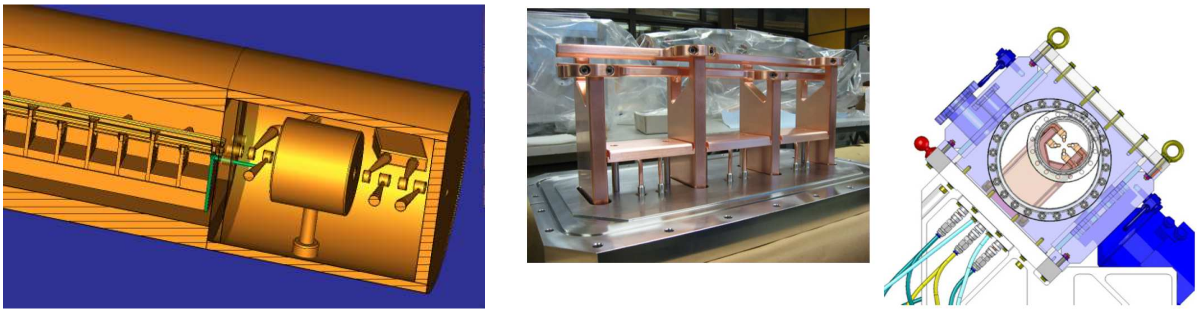

FIG. 4. From left to right: The RFQ-IH-DTL-combination, 4-stem-model of the rf-structure, scetch of the FRANZ-RFQ.

TABLE III: FRANZ RFQ PARAMETERLIST.

Parameter	***Value***
frequency f_0 [MHz]	175
input energy W_{in} [keV/u]	120
output energy W_{out} [keV/u]	700
max. mass to charge ratio A/q	1
inter electrode voltage V_{el} [kV]	75
electrode length [cm]	175
beam current [mA]	150-200
duty factor [%]	100
thermal load [kW/m]	65

3.4. MSU Post-Accelerator RFQ

A complete Radio Frequency Quadrupole system presently is designed and fabricated for NSCL [14]. 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 electrodes 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 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.

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.

TABLE IV: MSU RFQ PARAMETERLIST.

Parameter	***Value***
frequency f_0 [MHz]	80
input energy W_{in} [keV/u]	12
output energy W_{out} [keV/u]	600
max. mass to charge ratio A/q	5
inter electrode voltage V_{el} [kV]	87
electrode length [cm]	3.35
duty factor [%]	100

4. An RFQ Tandem for the EURISOL post-accelerator

Within the framework of the EURISOL design study it was our task to develop a normal conducting RFQ accelerator for the post accelerator [15]. Compared to the other structures discussed above, this one has the highest mass to charge ratio of $A/q = 7$. This would tend to rather high inter vane voltages, which on the other hand is of course limited due to the maximum affordable thermal load. On the basis of experiences with projects like the SRARAF RFQ and others, a good compromise was found with $V_{\mathrm{el}} = 60$ kV. The thermal load would be with approximately 30 kW/m only half as much as what was proposed for SARAF and is even 37% below of what has been reached at maximum so far. This, from the current perspective rather conservative design value, gives some headroom to go for even higher A/q-values. Together with an output energy of 560 keV/u and the need for as less losses as possible due to activation of the structure, an RFQ-tandem with two times 4 m long 4-rod-RFQ structures is proposed. A direct transition between the RFQs is foreseen, there are no additional beam transport elements in between. The matching between the two RFQ sections causes no beam losses.

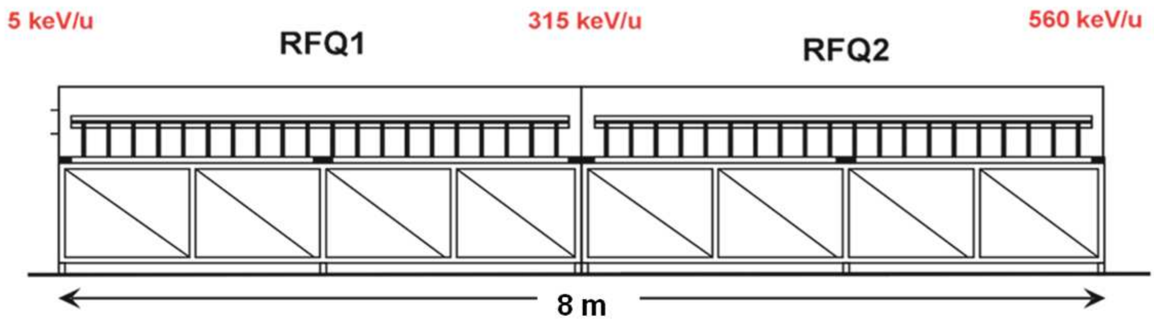

FIG. 5. The EURISOL normal cnducting RFQ tandem.

TABLE V: EURISOL RFQ-TANDEM PARAMETERLIST.

Parameter	***NC-RFQ1***	***NC-RFQ2***
electrode length l_{el}	391 cm	390 cm
frequency f_0	88 MHz	88 MHz
mass over charge A/q	7	7
input energy W_{in}	5 keV/u	319 keV/u
output energy W_{out}	319 keV/u	560 keV/u
minimum aperture a_{min}	3.3 mm	4.4 mm
electrode Voltage V_{el}	60 kV	60 kV
rf-power P_{rf}	120 kW	120 kW
duty cycle	cw	cw
input emittance $\varepsilon_{rms,n}$	0.1 mm mrad	0.105 mm mrad
Transmission	99.9 %	99.9 %
transversal emittance growth	5%	1%
energy spread DW	1.5 %	1.3%
phase spread Dj	15°	15°
thermal load [kW/m]	30 kW/m	30 kW/m

4. Conclusion

These projects show the wide range of applications we worked and work on. Besides these high power 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 required for IFMIF and similar ADS-projects in Asia and Europe comparable with the LANL LEDA projects 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.

Appendix 1: References

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