RF-QUADRUPOLE INJECTORS FOR CYCLOTRONS

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Rf-linacs as injectors limit the energy variablity of a cyclotron because of their fixed velocity profile, output energy per nucleon and frequency. These restrictions don't apply if they can be operated with a variable frequency. Examples are the new injectors for the RILAC and the RRC at RIKEN and the ISL heavy ion cyclotron at HMI, which employ variable energy 4-rod-RFQs. Properties of these injectors and possible applications will be discussed.

1. Introduction

RFQ linacs are efficient, compact low energy ion accelerator structures, which use electrical rf focusing and are able to capture, bunch and transmit high current ion beams. The capabilities of the RFQ structure to adiabatically bunch and accelerate low energy high current ion beams open new parameter spaces for accelerator designs.

The variety of RFQ-accelerators covers the full ion mass range from H to U, frequency range from 5-500MHz and duty factors from below 0.01 up to 100%. The physics of transport and acceleration of high current ion beams in RFQs have been solved to such extent that the best beams, which can be produced by ion sources and transported in a LEBT, can be captured and transmitted with very small emittance growth[1,2,3].

The RFQ basically is a homogeneous transport channel with additional acceleration. The mechanical modulation of the electrodes, as indicated in figure 1, adds an accelerating axial field component, resulting in a linac structure which accelerates and focuses with the same rf fields. For a given injection energy and frequency f the focusing gradient $G = X{*}U_Q / a^2$ (U_Q = electrode voltage, a = beam aperture, $X < 1$ for modulated electrodes) determines the acceptance in a low current application. Generally, a maximum voltage U_Q has to be applied at a minimum beam aperture a, because the radial focusing strength is the limiting factor. The highest possible operating frequency should be chosen to keep the structure short and compact.

RFQs are very attractive for low energy ion accelerators e.g. for applications with high current beams or in combination with sources such as an ECR, because the source can be close to ground potential and is easy to operate and to service. The RFQ concept of spatially homogeneous strong focusing employs strong focusing with rf-electrical focusing which is independent of velocity and therefore the acceleration can start at a low energy with short cells. This allows a large number of cells and an adiabatic capture of the dc-beam from the ion source.

Heavy ion RFQs can be classified by the lowest specific charge they can accelerate and by the duty factor of the operation. The choice of the operating frequency f and the electrode voltage U_Q together with the "RFQ design", the values of the aperture a, the modulation m and the length L_C along the RFQ, determine the electrode shape (pole tips) and the beam properties.

The choice of operating frequency depends on many factors. In smaller projects it is the availability of transmitters or a postaccelerator to match. Lower frequencies give stronger focusing, allow lower electrode voltages and thus less difficulties with power density and mechanical tolerances, and have generally a higher current limit. High frequencies ($f > 200$MHz) used for 4-vane RFQs for light ions (P, H^-, D), are favourable for compact designs with highest brillance, e.g. because the charge per bunch is smaller. 4-rod structures at lower frequencies around 100 MHz have enough acceptance for highly charged heavy ions like from ECR sources, while for lower ion charge $q{*}e_o$ to mass $A{*}u$ ratios ($q/A < 1/10$) lower frequencies have to be used, e.g. approx. 10 MHz for singly charged Uranium beams at energies below 0.1MeV/u.

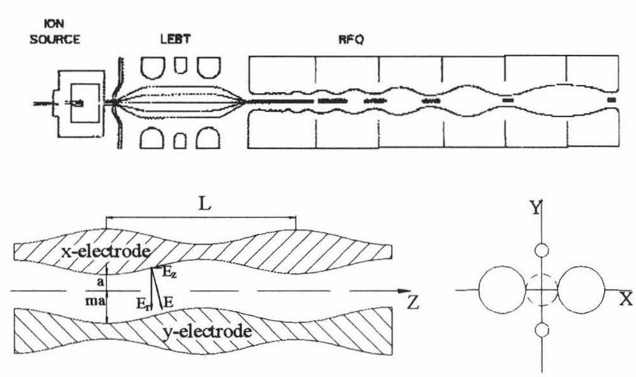

Fig 1: Scheme of RFQ-injector and modulated electrodes.

2. RFQs as cyclotron-injectors

A first proposal to use an RFQ to improve the axial injection system of a compact cyclotron was made by Hamm[4]. To inject in a Separated Sector Cyclotron (SSC), the RFQ has to provide a bunched beam at a well defined injection energy given by the inner radius of the SSC. The operating frequency of the RFQ must be synchronised with the cyclotron frequency, which for RFQs normally means a fixed output energy per nucleon, which would be matched to fixed energy cyclotrons. To keep the energy variability of the cyclotron it is necessary to have an injector which has also a variable energy and frequency. Variable Energy (VE)-RFQs have a fixed ratio of output to input energy given by the length of the first and last modulation cell. This is similar to the energy gain factor of a SSC which makes them well suited as injectors [5].

There are two choices for the frequency of a cyclotron injector. One choice is the rather low frequency of the cyclotron resonators, which is straightforward and uses compatible equipment, but gives huge resonators and causes problems with mechanical stability.

Alternatively a harmonic of the cyclotrons frequency can be taken, for a compact and efficient RFQ design. To get a high transmission of the system, a beam prebunched with the cyclotron frequency should be injected.

Generally, the rf-power N needed to drive the RFQ resonator is independent of the frequency, while the acceptance and the ion current increase in proportion to the electrode voltage and the square of the rf-power N, which is not a big issue in pulsed injectors with low average power. High duty factors up to cw operation, which are essential for cyclotron injectors is still a field of RFQ-development. Generally, cw designs have a low electrode voltage to keep a low average power consumption per length, which is a key parameter of RFQs, because e.g. of the mechanical tolerances of the quadrupole electrode alignment.

3. RIKEN - RFQ

The RIKEN accelerator research facility has an intermediate energy heavy ion accelerator complex consisting of the K-540 MeV ring cyclotron (RRC) with two injectors, an AVF K-70 MeV cyclotron for light ions and a frequency tunable Linac (RILAC) for heavy ions. Since the facility became fully operational in 1990 new programs have requested further improvements of the experimental facilities and the accelerators [6].

The RILAC injector consists of a Cockroft-Walton dc-preinjector (CW) and six accelerator units of Wideroe type, which are required to be tunable in frequency to match the RRC parameters. The frequency range covers 17-45 MHz, the maximum acceleration voltage is 16 MV. In this injector mode ions with mass to charge ratio smaller than 28 can be accelerated from energies between T_i = 9.3 - 53 keV/u up to T_f = 0.7-4.0 MeV/u [7]. For the heaviest particles at the highest RILAC frequency the Cockroft-Walton injector provides ions from an ECR source with maximum voltage of 450 kV. The new RFQ-preinjector for higher currents will be used alternatively to this injector and therefore has to match the beam parameters at the first unit of RILAC [8].

The most important problem to be solved is the frequency tuning of 17-40 MHz. Using the same basic concepts which were used in the RILAC tanks, a compact low frequency RFQ-structure could be built.

Like at GSI, the RILAC tank is an asymmetric Wideröe structure, in which each second drift tube is connected to ground (outer conductor) to ease the installation of quads, while the other drift tubes are connected to the open end of a single radial λ/4-line, for which the drift tube capacity acts as capacitive load. The frequency tuning is done by changing the effective length of the λ/4-line with a movable shorting plate as illustrated in fig.2.

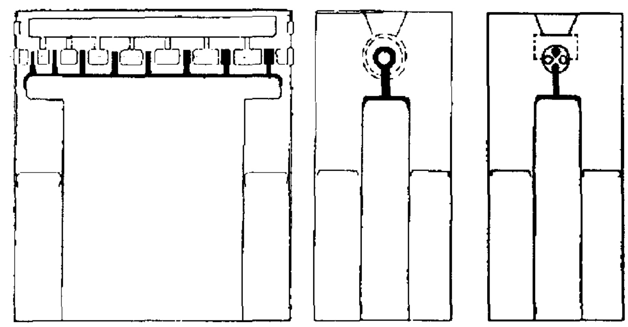

Fig. 2: Scheme of asymmetric RILAC - drift tube structure and added 4-rod-RFQ-electrodes.

Instead of alternate drift tubes in the RILAC tanks, in the RFQ resonator two of the four quadrupole electrodes are connected to the λ/4 line, two to the tank. To achieve the necessary mechanical stability the two "hot" electrodes are part of a conductor tube and the two (grounded) horizontal vanes are connected to two long copper bars fixed at the tank end flanges as indicated in fig. 3. Characteristic for such a structure is that the beam axis is on $\pm U_Q/2$. Checking the current and the magnetic field distributions, the resonator arrangement could also be described as folded coaxial resonator (FC-RFQ).

The resonator is shortened by the high capacitive load (appr. 250 pF/m) and the fact, that the diameter of the radial λ/4 stub line is smaller than in the RILAC tanks to increase the line impedance. Thus the length of the radial stub line is reduced from 4 m to 80 cm for the lowest frequency. To ensure mechanical stability, the electrode line is supported by ceramic pillars.

Critical point in these VE-RFQ structures is the operation at the highest frequency, where the power consumption and the losses in the ceramic are maximum. In addition the voltage distribution along the electrodes is somewhat unflat, because the ratio of lengthes of the stub line to the electrodes is small.

The maximum vane voltage in the RIKEN-RFQ is 36.6 kV. The required rf-power of 26 kW is fed in capacitively, close to the electrode line.

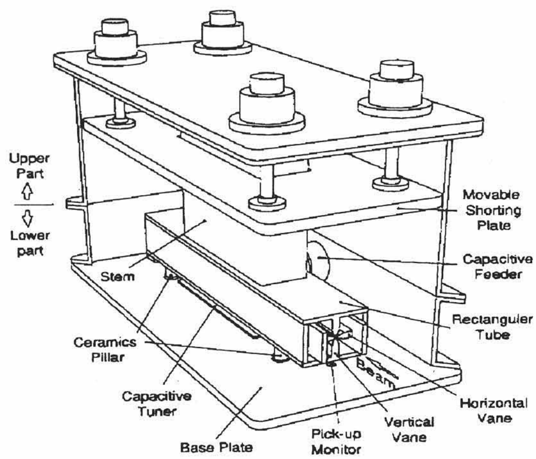

Fig. 3: Schematic drawing of the RIKEN-RFQ resonator.

The beam dynamics design results in RFQ-electrodes with a length of 1.42 m, with high acceptance and good transmission. The parameters of the RIKEN-RFQ are summarized in table I.

The RFQ has been built and successfully tested with Ar^{3-11+} and O^{5+} beams [9]. It will be installed at the RILAC injector in 1996, the injector layout is shown in fig. 4.

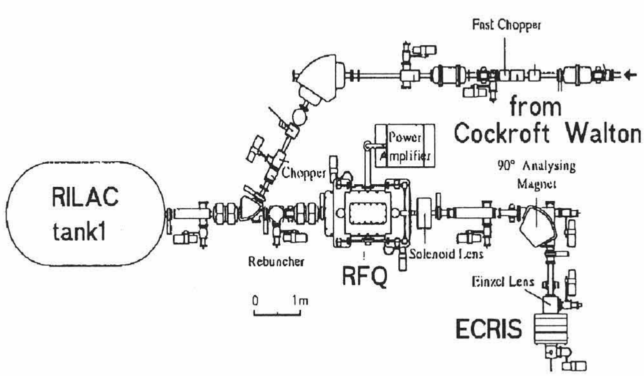

Fig. 4: RILAC-injector layout.

Table I: Parameters of the RILAC-RFQ injector.

RILAC-RFQ	
min./max. E_{in}	0.24/1.17 [keV/u]
min./max. E_{out}	10.7/53 [keV/u]
Energy gain factor	45
Stroke of tuner	79 [cm]
Charge-to-mass-ratio	28/238-1/7
Frequency	18-40 [MHz]
Electrode voltage (max.)	33.6 [kV]
Length/diameter	1.7 / 1 x 0.7 [m]

4. HMI - RFQ

The ISL [10,11] heavy ion cyclotron at the HMI Berlin (the former VICKSI machine) is an isochronous cyclotron (K=134 MeV), which had external injection of beams with variable energy from either a CN-Van-de-Graaff or an 8UD-Tandem accelerator. A new injector with an ECR source together with two VE-RFQs is under construction, which will replace the 8UD-Tandem injector to meet the demands of solid state physics users. Fig. 5 shows a scheme of the heavy ion accelerator complex with the new RFQ-injector in the encircled area.

The design of the new RFQ injector is based on the development of the variable energy 4-rod-RFQ, which was at first applied as a cluster postaccelerator at the 0.5 MV Cockroft-Walton facility at the IPNL in Lyon (France) [12], designed for an output energy between E_{out} = 50 - 100 keV/u for m < 50 u operating at 80-110 MHz to cover the VHF range, for which transmitters were easily available.

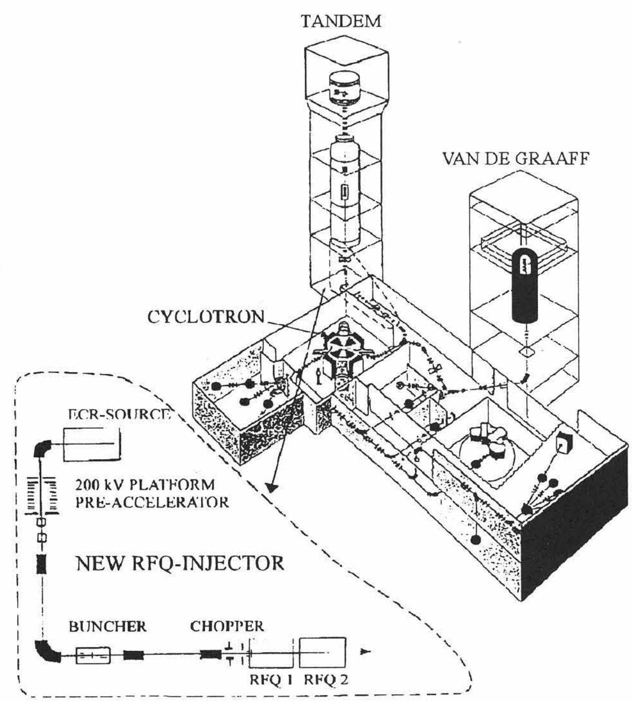

Fig. 5: The ISL accelerator at HMI.

The 4-rod RFQ structure consists of a chain of straight stems as electrode supports, opposite pairs of electrodes being connected to each second stem. This arrangement forms a chain of interlaced λ/2 oscillators, operating in a π-mode to produce the axissymmetric quadrupole fields [13]. The stems represent the inductivity the electrodes the capacity of this coupled transmission line resonator. This structure is very stable in respect to rf operation because neighbouring modes are clearly separated and all major current conducting parts can easily be cooled.

The frequency is tuned by a movable shorting plate along the structure, as indicated in fig. 6, which changes the effective length of the stems. The structure has been designed for a tuning range of $f_h / f_l = \sqrt{2}$, which gives a very stable mechanical structure and keeps the tight tolerances of the electrode positions.

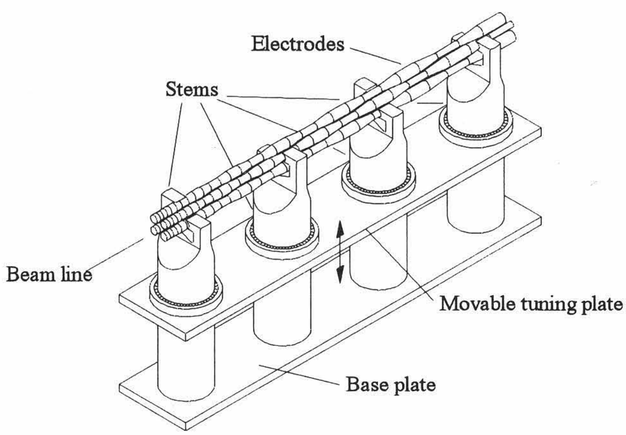

Fig. 6: Scheme of the VE-RFQ at HMI.

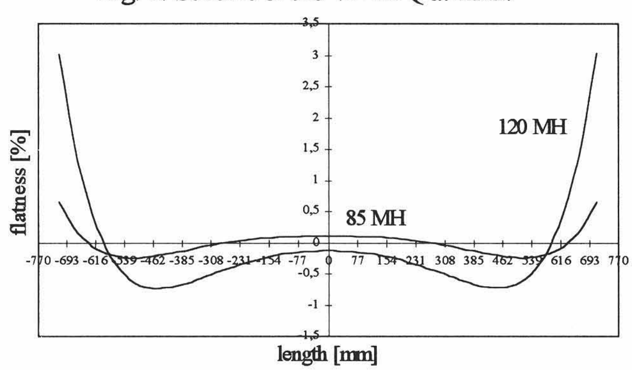

Fig. 7: Voltage distribution for highest and lowest tuner positions.

Fig. 7 shows the voltage distribution for lowest (85 MHz) and highest position of the tuner (120 MHz), indicating that the field unflatness stays very small.

To cover the energy range of 1.5-6 MeV/u the injection energy E_{in} of the ISL must be between E_{in} = 90 keV/u and E_{in} = 360 keV/u, at cyclotron frequencies of 10 to 20 MHz. To stretch the energy range without changing the basic structure design, the injector is split into two VE-RFQ stages. Each stage with a length of 1.5 m consists of a ten stem 4-rod-RFQ-structure tunable between 85 MHz and 120 MHz. With an rf-power of 20 kW per stage an electrode voltage of 50 kVcan be achieved. In the first mode of operation both RFQs accelerate, the output energy of the cyclotron is between E_{out} = 3 MeV/u and E_{out} = 6 MeV/u with a harmonic number of 5 for the cyclotron. In the second mode RFQ_2 has the same frequency as RFQ_1, but is detuned in phase and the energy range of the cyclotron is between E_{out} = 1.5 MeV/u and E_{out}= 3 MeV/u (harmonic number 7). In both modes the RFQs are tuned to the eighth harmonic of the cyclotron frequency. Characteristic data for the ISL-RFQ injector are given in table II.

The RFQ-output emittance depends strongly on the input conditions. For matched input beams with $\Delta E/E <$ 1,5 %, normalized emittance $\varepsilon_n < 0.5\ \pi$mm mrad and a bunch length $\Delta t < 1$ ns a transmission of 95 % is expected. To reach this beam quality it's necessary to have a buncher-chopper system between the ECR and the RFQs [14].

The ECR-source is mounted on the 200 kV platform, formerly used for the tandem. The vertical beam is bent by 90°, passes through the buncher-chopper-system and will be injected into the RFQs. The final matching into RFQ_1 will be done by a triplet lens. The beam from RFQ_2 is transported into the injection beamline of the cyclotron, to which a rebuncher has been added to make a proper time focus for the cyclotron.

Figure 8 shows the region (arrow) with a proper phase for the transport with RFQ_2. The figure shows E_{out} as a function of the input phase of RFQ_2. Fine tuning of the output energy can be done by adjusting the phase of RFQ_2 in the transport mode.

The RFQ-electrode- and the mechanical design of the RFQ has been done. The RFQ-system is being manufactured by NTG [15]. The tank is now ready for copper plating, first test electrodes have been manufactured. Assembly and first rf-tests are scheduled for early 1996.

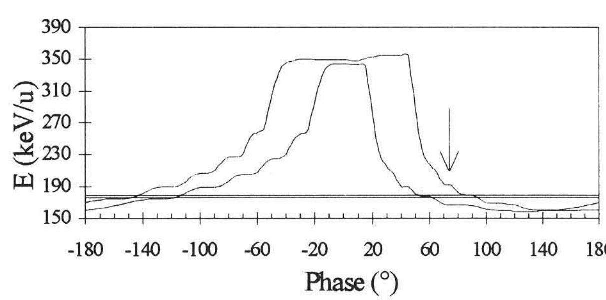

Fig 8: Output energy as function of the phase of RFQ_2.

Table II: Parameters of the HMI-RFQ injector.

HMI - RFQ:	
min./max. E_{in}	15.16/29.72 [keV/u]
min./max. E_{out} RFQ 1	90.98/178.35 [keV/u]
min./max. E_{out} RFQ 2	178.35/355.09 [keV/u]
Energy gain factor RFQ 1	6
Energy gain factor RFQ 2	1.96
Charge-to-mass-ratio	1/8-1/4
Frequency	85-120 [MHz]
Electrode voltage (max.)	50 [kV]
Length/diameter	3/0.5 [m]

5. Conclusions

The RFQs for RRC at RIKEN and the ISL at HMI are the first of their kind. They represent two different solutions to the problems given by the special requirements of injection into a cyclotron. Replacing the Cockroft-Walton as preinjector the RIKEN machine uses the RILAC frequency and fully bunches the dc-beam and accelerates to the input velocity of the linac. The maximum accelerator voltage is 450 kV. A single post coaxial resonator is used to tune the frequency from 18-40 MHz and a folded coaxial electrode arrangement provides the quadrupole fields. RF and beam tests have been successful.

The HMI machine uses a prebunched beam and operates at cyclotron harmonic. The frequency of the multistem resonator can be tuned from 85-120 MHz. It is split into two cavities and uses the second RFQ for beam transport in the low energy mode. The maximum accelerating voltage is 2.8 MV, the small longitudinal emittance is focused to the cyclotron with a separate buncher.

The examples presented show, that the prejudice of RFQs not being suited for cyclotron injection has to be reconsidered.

High energy cyclotrons use smaller cyclotrons as injectors, which cannot be replaced by RFQs. But the replacement of static preinjectors is a field where RFQs can provide higher currents at comparable beam emittances which makes them attractive e.g. for ECR-injectors and high power accelerators like the spallation source type of machines.

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References

1. I.M. Kapchinskij and V. Teplyakov, Prib. Tekh. Eksp 119, No.2 (1970) 17
2. K.R. Crandall, R.H. Stokes, T.P. Wangler, Linac 79, BNL 51134 (1979) 205
3. A. Schempp, Adv. of Acc. Physics a. Technologie 12, World Scientific (1993) 194
4. R.W. Hamm et al., Proc. 9th. Cyclotron Conf. Caen, France (1981) 359
5. A. Schempp, Habilitationsschrift, Universität Frankfurt am Main (1990)
6. Y. Yano et al., EPAC 4, World Scientific (1994) 515
7. M. Odera, LINAC 84, GSI 84-11 (1984) 36
8 O. Kamigaito et al., Jpn. J. Appl. Phys. 34 (1994) 537
9. A. Goto et al., Proc. PAC 95, Dallas, USA,IEEE(1994)
10. H. Homeyer. W. Pelzer, Vorschlag zur Realisierung eines Ionenstrahllabors im HMI (ISL-Berlin), HMI-Berlin, 1992
11. H. Homeyer, K. Ziegler, NIM B64 (1992) 937
12. M.J. Gaillard et al., Z.Phys. D26, (1993) 347
13. A. Schempp, NIM B40/41 (1989) 937
14. W. Pelzer, A. Schempp NIM A 346 (1994) 24
15. Neue Technologien, D-63571 Gelnhausen