RADIO-FREQUENCY QUADRUPOLE LINACS

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Abstract
Radio-Frequency Quadrupole (RFQ) linacs are efficient, compact, low-energy ion structures, which have found numerous applications. They use electrical RF focusing and can capture, bunch, and transmit high-current ion beams. Some recent developments and new projects such as heavy-ion injectors replacing Tandems as injectors for cyclotrons and linacs, RFQ post-accelerators, and the status of the work on high-energy implanters and small neutron sources are discussed.

1. INTRODUCTION

Injectors are combinations of an ion source, a Low-Energy Beam Transport (LEBT) system, an electrostatic pre-accelerator or an RFQ, and an intermediate section that matches the beam to a following structure, for example an IH- or an Alvarez accelerator.

The pre-accelerator defines the phase space for the following stages, in which the effective emittance will possibly increase. In the design of a high-current accelerator, the emittance and the current have to be optimized. The injector is the bottleneck because focusing forces are weak and the defocusing effects and non-linearities caused by space charge are strongest at low energies.

The development of the RFQ structure with its ability to bunch and accelerate low-energy, high-current ion beams opens new parameter possibilities for accelerator designs.

The variety of RFQ accelerators covers the full ion mass range from hydrogen to uranium, in the 5–500 MHz frequency range and duty factors up to 100%. The physics of the transport and acceleration of high-current ion beams in RFQs has been solved to such an extent that high-brilliance and high-current beams produced by ion sources and tranported in an LEBT can be captured, bunched, and transmitted with very small emittance growth by RFQs, as shown schematically in Fig. 1

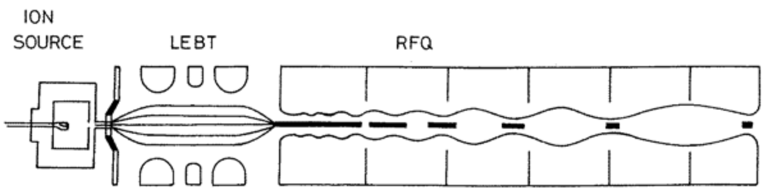

Fig. 1: Layout of an RFQ injector

Basically the RFQ is a homogeneous transport channel with additional acceleration. The mechanical modulation of the electrodes as indicated in Fig. 2 adds an accelerating axial field component, resulting in a linac structure that accelerates and focuses with the same RF fields.

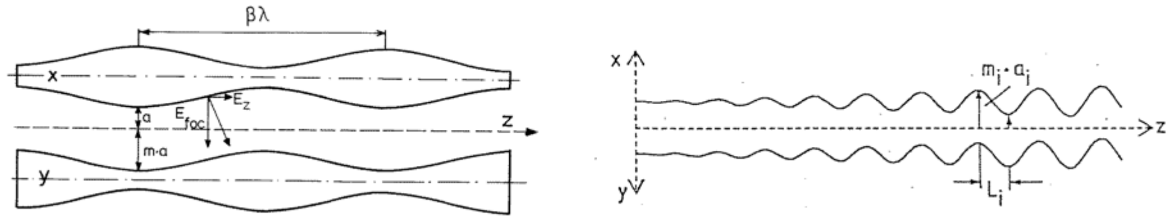

Fig. 2: RFQ electrodes

For a given injection energy and frequency the focusing gradients $G = X^*U_0/a^2$, ($X < 1$ for modulated electrodes) determine the acceptance in a low-current application. A maximum voltage U_0 has to be applied at a minimum beam aperture a if the radial focusing strength is the limiting factor. The highest possible operation frequency should be chosen to keep the structure short and compact. After the choice of U_0 and operating frequency, the 'RFQ design', the values of aperture a, modulation m, and the lengths L_C along the RFQ determine the electrode shape (pole tips), the ratio between accelerating and focusing fields, as indicated in Figs. 2 and 3, and hence the beam properties.

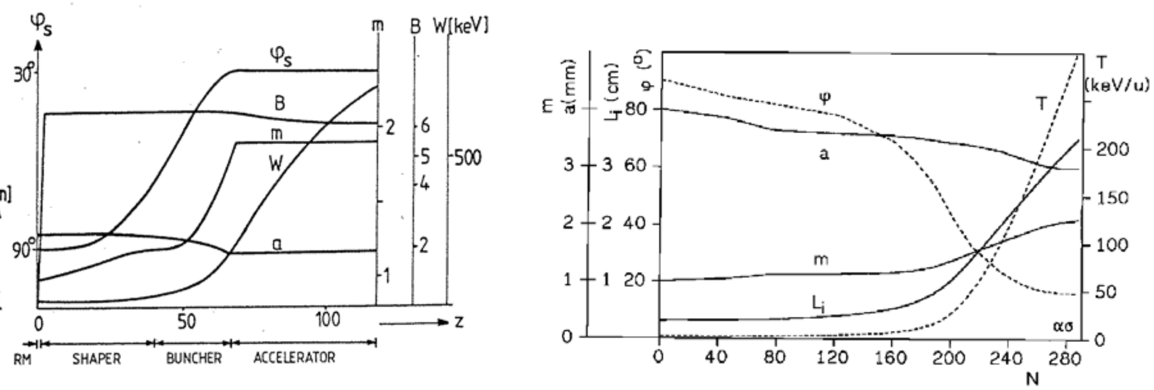

Fig. 3: Electrode designs of the first DESY RFQ and the GSI–HLI RFQ

The optimum frequency depends on many factors. In smaller projects it is the availability of the transmitters or a matching post-accelerator. Lower frequencies provide stronger focusing, less difficulties with power density and mechanical tolerances, and generally a higher current limit. Higher frequencies are favourable for compact designs with highest brilliance because the charge per bunch and the frequency jump to a final linac stage are smaller, but the currents are limited by the maximum focusing fields and sparking.

The RF structure has to generate the quadrupole fields with high efficiency and stability. The four-vane structure, which is mostly used in proton and H^- acceleration, is basically a TE_{211}-mode structure, in which the resonator has been loaded with electrodes to increase the quadrupole field, as shown in Fig. 4. The end region has to be modified to allow the magnetic fields to turn around and to shift the mode into a TE_{210} with a constant quadrupole field along the structure. Radio-frequency stability and thermal symmetry of the cavity, which can also be treated as four weakly-coupled resonators, are the reason for very tight mechanical tolerances that are a particularly limiting factor in high duty factor operation.

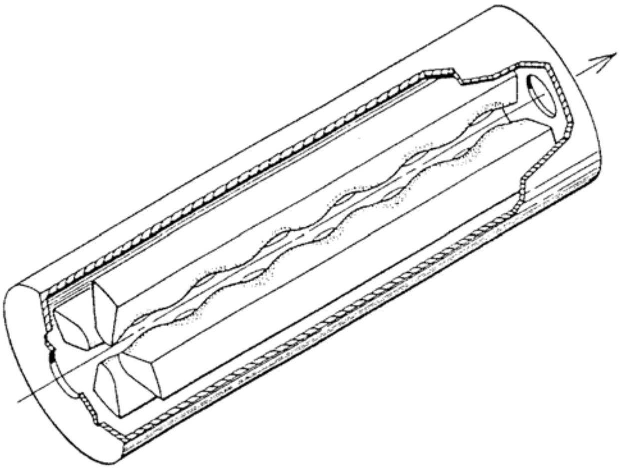
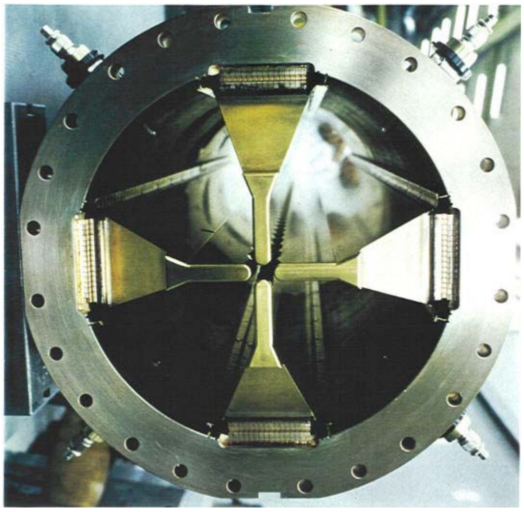

Fig. 4: The four-vane RFQ and a view of the CERN RFQ2 structure

The four-rod structure, shown in Fig. 5, consists of a linear chain of stems that form a chain of strongly coupled $\lambda/2$ resonators. By the direct connection of the electrodes with the same polarity, dipoles cannot be excited and tolerances are less stringent. The length of the stems can be changed to give compact resonators with rather low frequency that can also be used for low frequencies for low charge-to-mass-ratio heavy ions.

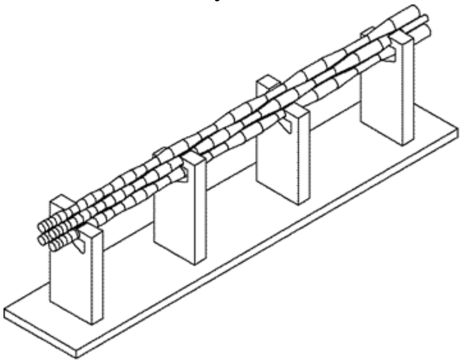


Fig. 5: The four-rod RFQ and a view of the DESY RFQ2 structure

The RFQ rods are driven by periodically arranged support stems that exite the electrodes in a TE_{210}-like mode. Inherently there are some longitudinal currents on these rods and a few per cent voltage modulation between the support stems. Like the azimuthal symmetry, this cannot be changed (improved or made worse) by tuning or heating during operation.

The rod electrodes can have a circular cross section (as used in the first low average power structures), parallel cooling channels, or a vane-tip shape to give a good approximation to the ideal two-term potential. In any case, as long as the field coefficients are calculated correctly, the electrode shape has no influence on the beam properties.

Generally, the required RF power N is independent of the frequency, whilst the acceptance and the maximum ion current are proportional to the electrode voltage and N^2, which is not a big issue in pulsed injectors with low average power. High duty factor operation is the present area of development. A first class of structures, which will be used as spallation source-linac injectors with duty factors of up to 10%, is presently being built, but more difficulties still have to be resolved for Continuous Wave (CW) RFQs.

2. RFQ APPLICATIONS

The standard application is operation as a pre-injector for an Alvarez linac feeding a synchrotron. These systems are easily matched to ion sources and RFQ designs because they have a low duty factor, which allows pulsed, high power-density operation. Examples are the injectors at BNL, DESY, CERN, IHEP and KEK. Higher duty factors have been favoured by the development of high-brilliance beams for ATS, GTA and CWDD, based on the LANL developments in structures and beam dynamics. The final version of this injector is an RFQ for 8 MeV protons, which is made of eight resonantly-coupled pieces, as shown in Fig. 6, each individually furnace-brazed, aligned, and tuned.

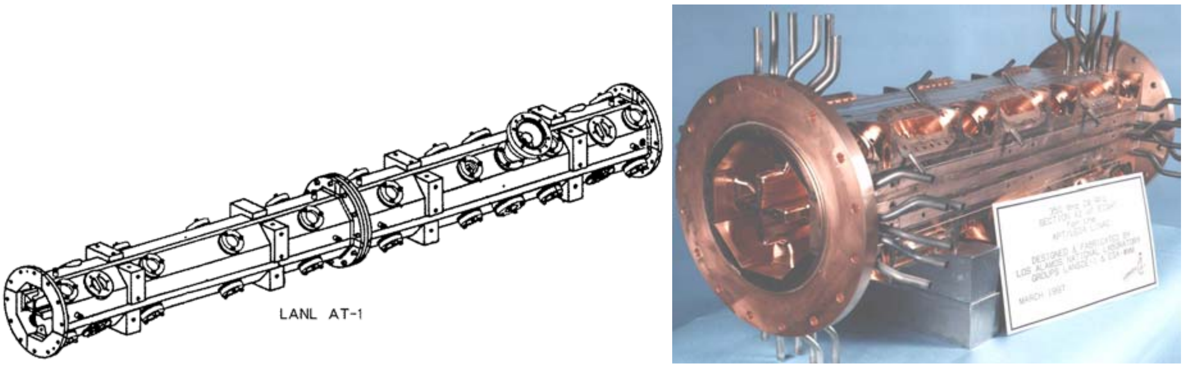

Fig. 6: The segmented CW RFQ and a view of a brazed LEDA RFQ prototype module

The LEDA RFQ is a part of the front-end demonstrator for a future accelerator-driven system, for example to transmute nuclear waste. It has successfully accelerated output beams of 100 mA in CW operation.

Somewhat smaller, but not unimportant, are projects which can be grouped as spallation neutron sources: designs for 5 MW (5–10% duty factor) have been made for H^- beams of 30–100 mA for new machines (ESS, NSNS, JHP) and the upgrade of existing high-power linacs like LAMPF and ISIS. The beam dynamics design has matured to rather small emittance growths (10–20%) which stretch the limits of simulation results. The advances in structure development are slow and reflect the limits of the technology. Present examples are the new ISIS injector and the RFQ for SNS, which uses non-resonant magnetic stabilizers as shown in Fig. 7.

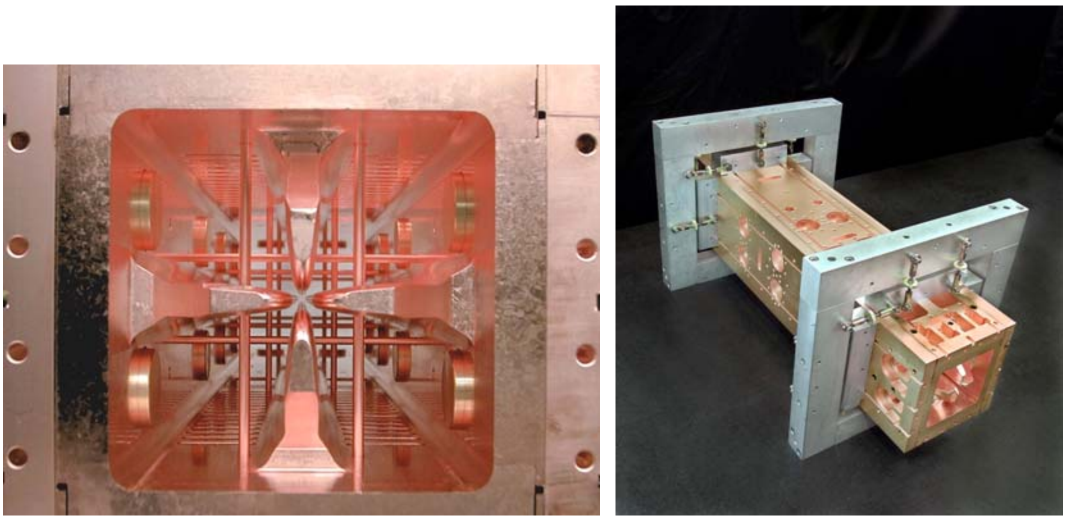

Fig. 7: The LBNL SNS RFQ

Short prototype RFQs for even higher duty-factors and CW operation have been set up in CRNL, LANL, KEK, JAERI and also in IAPF. A parallel development aims to build a 120 mA, 35 MeV, CW deuterium accelerator (IFMIF) for material testing of fusion devices.

3. HEAVY-ION ACCELERATORS

RFQs are also very attractive for low-energy, heavy-ion accelerators. They cannot replace static injectors and Van de Graaff generators in terms of energy resolution and beam quality, but are favoured for applications using high-current beams or combined with sources like an ECR, because the source can be close to ground potential and is easy to operate and service. The RFQ concept of spatially-homogeneous strong focusing proposed by Kapchinskiy and Teplyakov employs strong focusing with RF focusing that is independant of velocity, so the acceleration can start at low energy with rather short cells. This allows adiabatic capture of the DC beam from the ion source.

Heavy-ion RFQs have been built at LBL, INS, ITEP, GSI, Saclay and IAPF, for example, for atomic and nuclear physics research. They can be distiguished by the lowest specific charge they can accelerate and by the operational duty factor. Storage-ring and synchrotron injectors have a favourably low duty factor. New machines are the new HIMAC injector at NIRS, which is very similar to the TALL RFQ at INS, and the new injectors at CERN, MPI Heidelberg, and LMU Munich.

The RFQ of the CERN Pb injector is fed by a pulsed ECR source and operates at 101 MHz. It is designed to accelerate Pb^{25+} ions from 3 to 250 keV. The RFQ was built at INFN Legnaro, and is a symmetric four-rod RFQ with small vanes (Fig. 8), similar to those investigated at CRNL and IAPF.

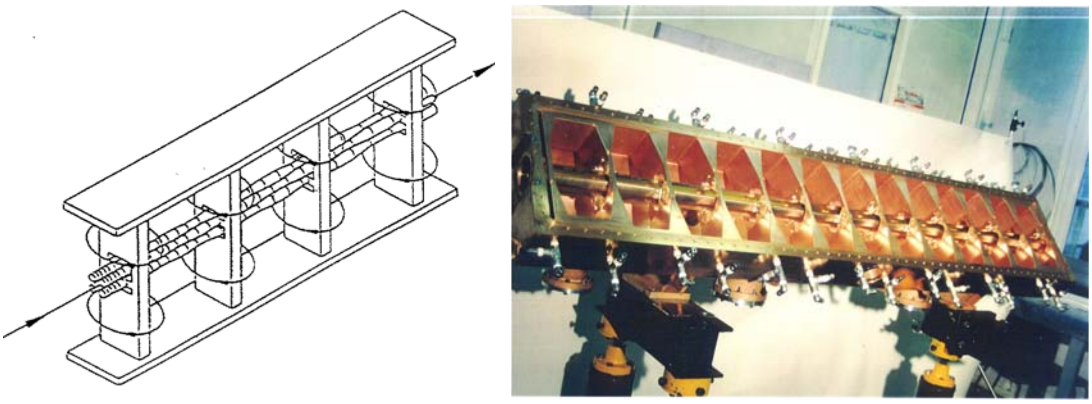

Fig. 8: The CERN heavy-ion RFQ

Less complex is the high duty factor HLI RFQ at GSI, which routinely operates at 25% duty factor. The HLI RFQ is 3 m long (designed for 108.5 MHz and U^{28+} ions $q/A = 0.117$) and accelerates from 2.5 to 300 keV/u. The high RF efficiency (figure of merit: shunt impedance) of the HLI RFQ is important for high duty factor structures in which technological problems like cooling and thermal stress control dominate, whereas this is not a major concern for synchrotron injectors.

The high-current injector at GSI has been designed for U^{4+} ions. The layout consists of an RFQ (2.2–120 keV/u, length 9.2m) for 15 mA beam current and an IH structure (0.12–1.4 MeV/u).It operates at 36 MHz, without an intermediate stripper as in the previous designs for U^{2+}, which had a spiral RFQ (27 MHz) injecting into the existing Wideröe part of the UNILAC. The IH RFQ with a special matching section for a bunched output beam (Fig. 9) consists of 10 modules (Fig. 10) with a length of 0.92 m each. It has been commissioned successfully.

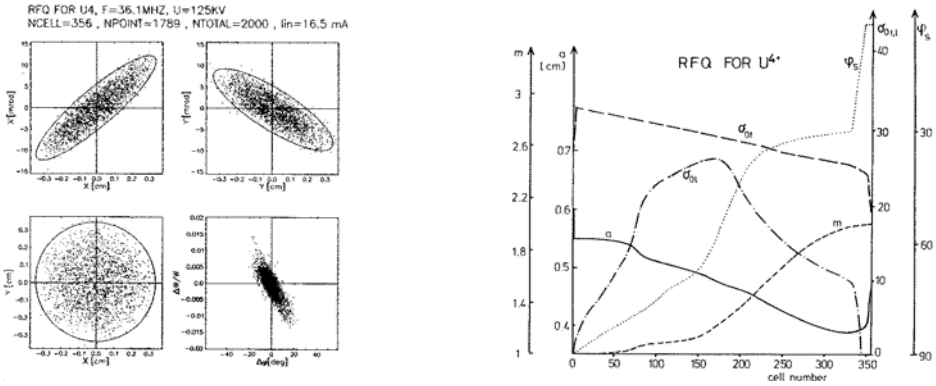

Fig. 9: The design for the GSI–HSI RFQ

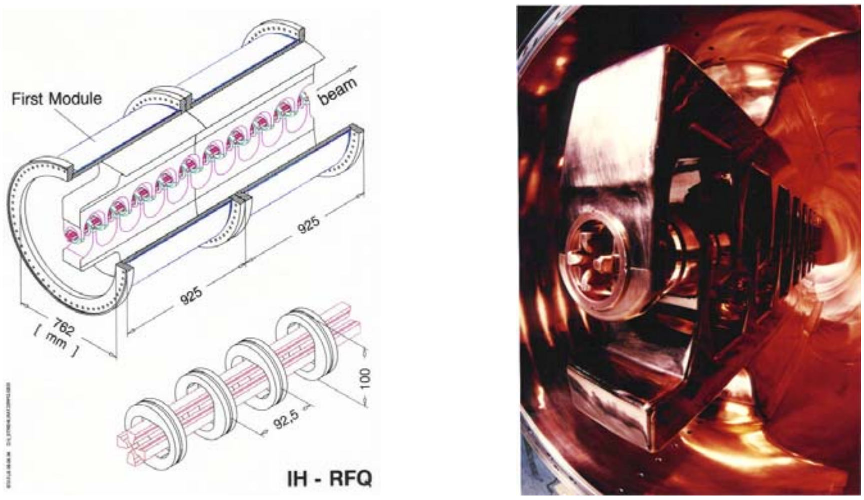

Fig. 10: The structure of the GSI–HSI RFQ

Van de Graaff Tandem machines have been the workhorse for nuclear physics research. Their limitations are low currents and low energy per nucleon for the heaviest ions, which led to the various heavy-ion RF accelerators and Tandem post-accelerators. An RFQ, although a low-velocity structure, can be applied as a post-accelerator for a Tandem installation if very heavy particles and a fixed output energy/u are not a restriction for the experiments.

For some time RFQs have been regarded as possible replacements for Tandem injectors for post-accelerators, but the first to be actually built was a superconducting heavy-ion linac bypassing the EN Tandem for uranium beams at ANL.

At MPI, Heidelberg, many experiments at the TSR storage ring were limited by the low currents delivered by the MP Tandem. A high-current injector for singly-charged light ions, consisting of a CHORDIS source, two RFQs, which are based on the GSI HLI design, and seven-gap resonators, as shown in Fig. 11, provides an increase in intensity higher by up to three orders of magnitude, and this is especially important for laser cooling experiments. A much more difficult task is to design an RFQ as the injector for a cyclotron. A first project was the conversion of the ISL at the HMI, Berlin (the former VICKSI machine), which is an isochronous cyclotron with four separated sectors. It had external beam injection with variable energy from either a CN Van de Graaff or an 8UD Tandem.

To inject into a separated-sector cyclotron, 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 synchronized with the cyclotron frequency, which for RFQs normally means a fixed output energy per nucleon, which could be a possible solution only for fixed energy cyclotrons.

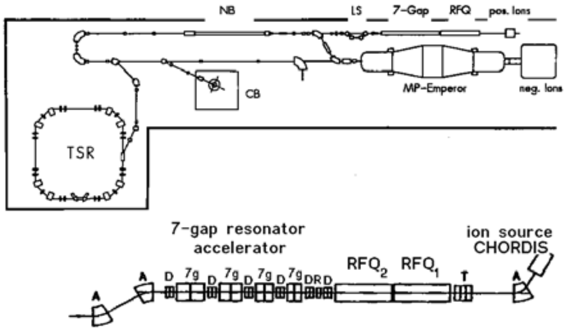

Fig. 11: The TSR injector at MPI

A fixed-velocity profile is typical for RFQs. It can only be changed by varying the cell length L or the frequency f. The possibility of changing the Wideröe resonance condition, $L = \beta_p \lambda_0/2 = v_p/2f$, has been used for RFQs with variable energy (VE RFQ). For this reason it is possible to change the output energy using the same electrode system by varying the resonance frequency of the cavity: $v_p \sim f$, $T \sim v_p^2$.

A type of RFQ resonator that can be capacitively or inductively tuned has been developed to change the frequency of the four-rod RFQ in Frankfurt. Figure 12 shows the method of tuning by means of a movable plate, which varies the effective length of the stems.

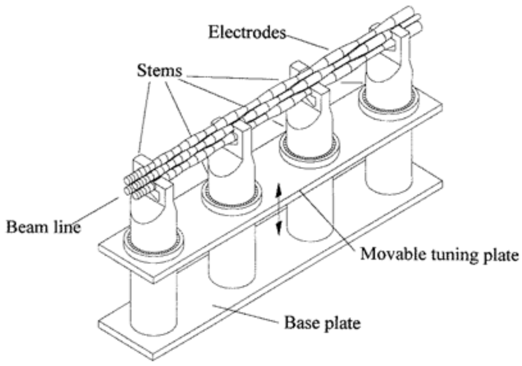

Fig. 12: The VE RFQ resonator insert

In Frankfurt the VE RFQ was first developed for application as a cluster post-accelerator at the 0.5 MV Cockroft–Walton facility at the IPNL, Lyon, France. It was designed for an input energy E_{in} = 10 keV/u and an output energy between E_{out} = 50–100 keV/u for m = 50 u. Heavy and low-velocity particles are accelerated in the second VE RFQ, with an energy range of 2–10 keV/u for singly-charged metallic clusters up to mass m = 1000 u (frequency range 5–7 MHz).

Another VE RFQ combined with an ECR ion source was built for the IKF at Frankfurt. The design values are a minimum specific charge of 0.15, an output ion energy of E_{out} = 100–200 keV/u, a maximum electrode voltage of 70 kV, and a structure length of 1.5 m. 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 an SS-Cyclotron, and makes them well suited as injectors. To cover the energy range of 1.5–6 MeV/u, the injection energy of the ISL must be between E_{in} = 90–360 keV/u (maximum accelerating voltage U_m = 2.9 MV), at cyclotron frequencies of 10–20 MHz.

The ISL tandem injector at HMI in Berlin, as shown in Fig. 13, has been replaced by a combination of an ECR ion source on a 200 kV platform, which will produce highly charged ions with charge-to-mass ratios between 1/8 and 1/4, and a VE RFQ. To stretch the energy range the RFQ is split into two RFQ stages. Each stage has a length of 1.5 m and consists of a ten-stem, four-rod RFQ structure. With an RF power of 20 kW per stage an electrode voltage of 50 kV is possible. In the first mode of operation both RFQs accelerate and the output energy of the cyclotron is between 3–6 MeV/u with a harmonic number of 5 for the cyclotron. For the low-energy beam only RFQ1 accelerates, while RFQ2 is detuned to transport the beam. In this mode the energy range of the cyclotron is between E_{out} = 1.5 to 3 MeV/u. The cyclotron works on the harmonic number 7. In both modes the RFQs are tuned to the eighth harmonic of the cyclotron.

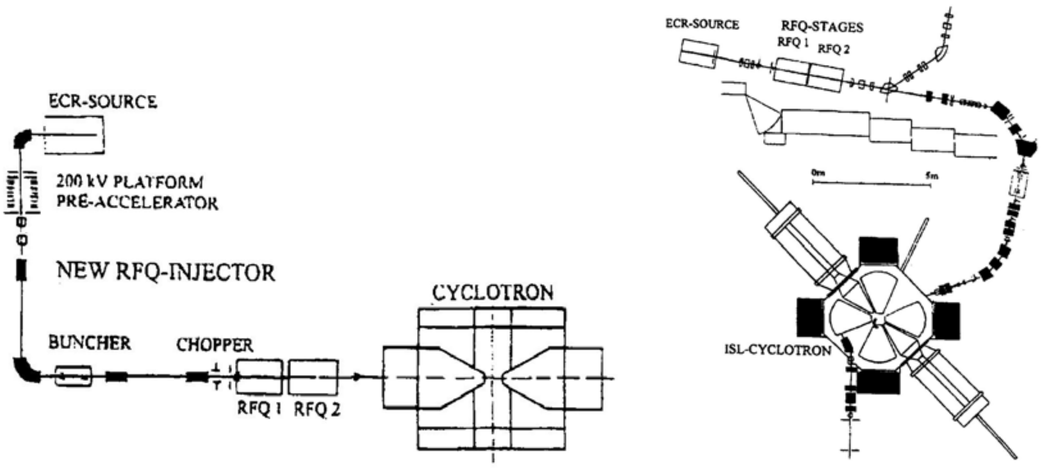

Fig. 13: The VE RFQ injector at ISL

The ECR source is mounted on the 200 kV platform formerly used for the Tandem. The vertical beam is bent through 90°, passes through the buncher–chopper system, and will be injected into the RFQs. The final matching into the RFQ will be by a triplet lens approximately 1 m in front of the RFQ to allow for diagnostics and a Faraday cup. The beam from the RFQ 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. The RFQ output emittance depends largely on the input conditions. For matched input beams with $\Delta E/E \leq 1$, normalized emittance $\varepsilon_n < 0.5$ mm mrad, and a bunch length $\sigma_t < 1$ ns a transmission of 100% is expected. To reach this beam quality it is necessary to have a buncher–chopper system between the ECR and the RFQ. As with the cluster linac at IPNL, there is no bunching in the RFQ. To save length and power the RFQ starts with stable phase $\varphi_s = 50°$ and at ISL the bunching is done by an existing bunching stage left over from the Tandem injector.

At RIKEN a similar problem had to be solved. The injector was formerly a variable frequency Wideröe-type linac. The 450 keV CW injector has now been replaced by an RFQ that is tunable from 8–28 MHz to match the VE linac and RRC cyclotron. An asymmetric four-rod-type RFQ, excited by one λ/4 resonator is used for this large frequency range. The electrodes must be supported by ceramic stems and, especially for the higher frequencies when the electrodes themselves are a major part of the λ/4 line, the tuning is difficult and the field distribution becomes unbalanced. This system matches the RIKEN linac very well and increases the experimental possibilities.

4. NEW DEVELOPMENTS

There are a number of studies making use of RFQ ion injectors and the proposals to build accelerators for radioactive beams seem to be of the highest interest in nuclear physics research. The typical RB facility starts from an ISOLDE type of ion source with singly-charged ions. To obtain a reasonable amount of ions, CW operation is planned. This favours superconducting structures. However, the low-energy part must use much lower frequencies for RF acceleration than is suitable for SC cavities, so room is left for NC RFQ structures to accelerate and form the beam, as shown in Fig. 14 for the ISAC-

RB accelerator at TRIUMF. The various systems can be distinguished by the heaviest mass number planned to be used and the accelerator system to be employed. For masses between 30 and 60 u, INS, TRIUMF, and ANL all have normal conducting RFQ linac-based systems.

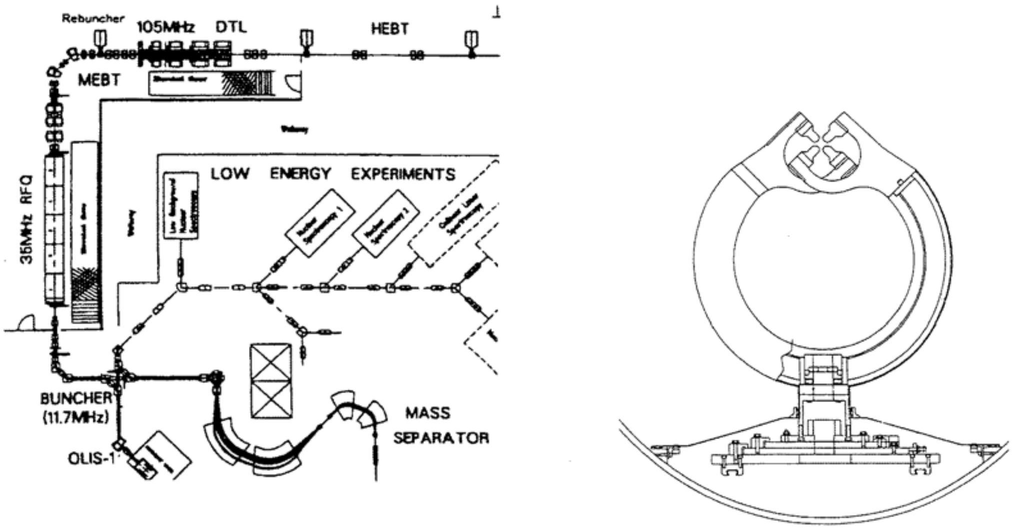

Fig. 14: TRIUMF RB accelerator

A very interesting concept is being pursued by groups from LMU Munich and MPI. It consists of a Penning ion trap followed by an EBIS ion collector–charge breeder with pulsed extraction, and a small compact pulsed accelerator of the MPI high-current injector or post-accelerator type to be installed at the CERN ISOLDE facility, as shown in Fig. 15 (see also Fig. 16).

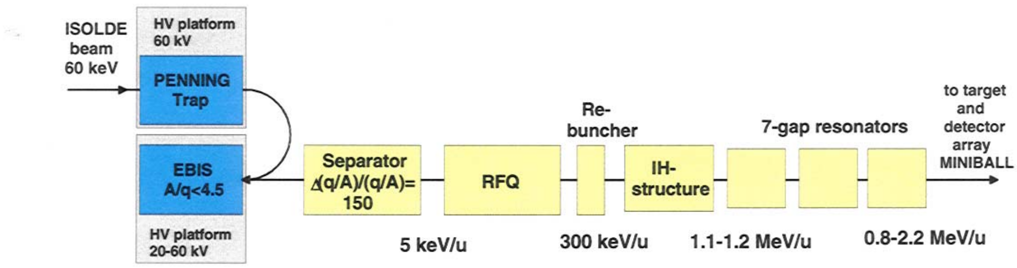

Fig. 15: The REX-ISOLDE principle

There are many applications of RFQs in industry. The first group is used for material improvement such as ion implantation in silicon, together with machines for 1 MeV boron and 6 MeV phosphorus. A second group are involved in the medical field, for example parts of PET isotope production units and medical synchrotrons such as Loma Linda and NIRS. New projects for using these therapy machines are presently under discussion at GSI, CERN, and Prague. Another application of high-current RFQs is as a compact radiation source for radiography with neutrons or resonant X-rays similar to those proposed for material detection.

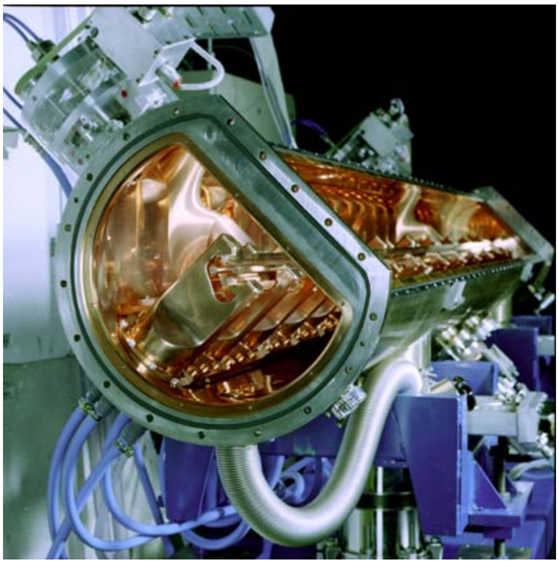

Fig. 16: The REX-ISOLDE RFQ

New developments in particle dynamics designs aim to reduce emittances while at the same time reducing the voltage and RF power requirements, but with only a minor reduction in beam quality. This would be especially important for high duty factors and industrial applications.

The matching between RFQ stages and the following accelerator stage has also been improved. The first step is optimization of the end cell to shape the transition fields. Recent designs also shape the bunch to make it appear that it has drifted longitudinally (e.g. the HSI project at GSI) and focus it longitudinally and radially (e.g. the funnel experiment at IAPF).

5. CONCLUSIONS

There are many new developments in the field of RF ion accelerators that will promote new experimental parameters for atomic and nuclear physics. Injectors into cyclotrons, Tandem replacements, and new compact ion accelerators are attractive applications of RFQs.

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