Properties of High Current RFQ Injectors

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Abstract

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 like a heavy ion injectors for a cyclotron, and the status of the work on high current high duty factor RFQs will be discussed.

1. Introduction

Injectors are combinations of an ion source, a low energy beam transport line (LEBT), a preaccelerator, a Cockroft Walton Cascade or a RFQ, and an intermediate matching section (IMS) which matches the beam to a following structure e.g. an Alvarez-accelerator. This preinjector defines the phase space density for the following stages in which the effective emittance will only grow. Emittance and beam current have to be optimized in the design of a high intensity accelerator. The injector is the bottleneck, because focusing forces are weak and the defocusing effects and nonlinearities caused by space charge are strongest at low energies,.

The development of the RFQ-structure was a major step for the improvement of linac injectors. It replaced C.W. Cascades in most old and all new high intensity accelerator designs giving the option for higher overall transmission and reduced emittance and made it possible to design and test injectors with up to 100% duty factor. While the injectors for synchrotrons work at low duty factors of 10^{-6} to $5*10^{-3}$ the high power linacs like used at LAMPF and ISIS (duty factors 10^{-1} and $2.5*10^{-2}$-) still employ C.W. injectors, but plans for modifications and improvement by use of RFQs are in progress. High current and high duty factor Injectors are not operational yet. For special ion sources like for polarized protons and for heavy ions with high charge states RFQs allow the use of complicated bulky sources, which are installed on "low" voltage platforms (20-100kV) like at the Saturne heavy ion injector, at MSI Stockholm and at CERN. Future high current linacs for neutron sources (e.g. ESS) and for material modification (ATW, APT, Trispal) have to rely on RFQ high current injectors

The possibilities of the RFQ structure to bunch and accelerate low energy high current ion beams opens new parameter spaces for accelerator designs. The variety of RFQ-accelerators covers the full ion mass range from H to U, frequency range from 5-500 MHz and duty factors up to 100%. The physics of transport and acceleration of high current ion beams in RFQs have been solved to such extend, 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 by RFQs as shown schematically in Fig.1.

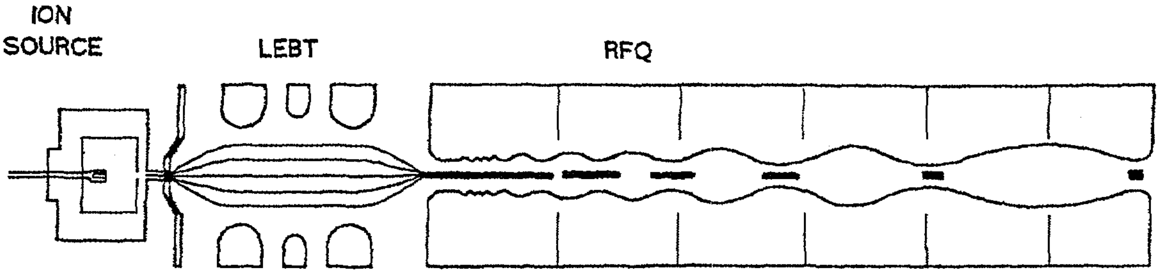

Fig. 1 Scheme of a RFQ injector

2. Radio Frequency Quadrupoles

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 the focusing gradients $G\ X{*}U_Q/a^2$; ($X<1$ for modulated electrodes) determine the acceptance in a low current application. A maximum voltage U_Q 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. Besides the choice of U_Q 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) and the beam properties.

The optimum frequency can be determined by many factors. In smaller projects it is the availability of transmitters or a postaccelerator to match. Lower frequencies give stronger focusing, less difficulties with power density and mechanical tolerances and generally a higher current limit. Higher frequencies, for which 4-Vane RFQ structures are employed, are favourable for compact designs with highest brilliance e.g. because the charge per bunch and the frequency jump to a final linac stage are smaller. Fig.2 shows the current limit in proton-RFQs considering a maximum phase advance per cell and V=2 Kilp. as sparking limit, for proton beams from 50 keV to 2 MeV. The parameters of existing RFQs fit into this curve, assuming that the operational current is normally 50% of the current limit. Similar curves describe optimization of structures at lower frequencies for heavy ions with respect to maximum acceptance or highest accelerating efficiency.

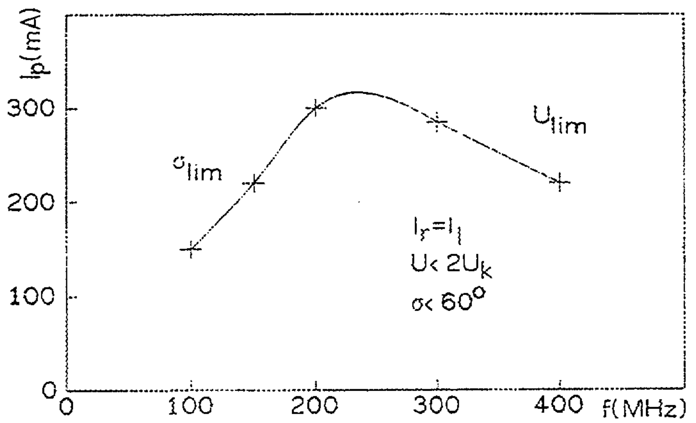

Fig. 2 Proton Current as function of the operating frequency

The rf-structure has to generate the quadrupole-fields with high efficiency and stability. The four-vane structure is mostly used for light ions. It consists of a TE_{210} like cavity loaded with four vane shaped electrodes. Optimizing results in a cloverleaf like cavity, with small quadrupole pole tip radius. It can be described as four weakly coupled cavities driving the quadrupole electrodes, which are sensitive to perturbations of the symmetry. The four rod cavity shown schematically together with a four vane structure in fig. 3, consists of a linear chain of stems carrying the electrodes, which form a chain of coupled $\lambda/2$-resonators.

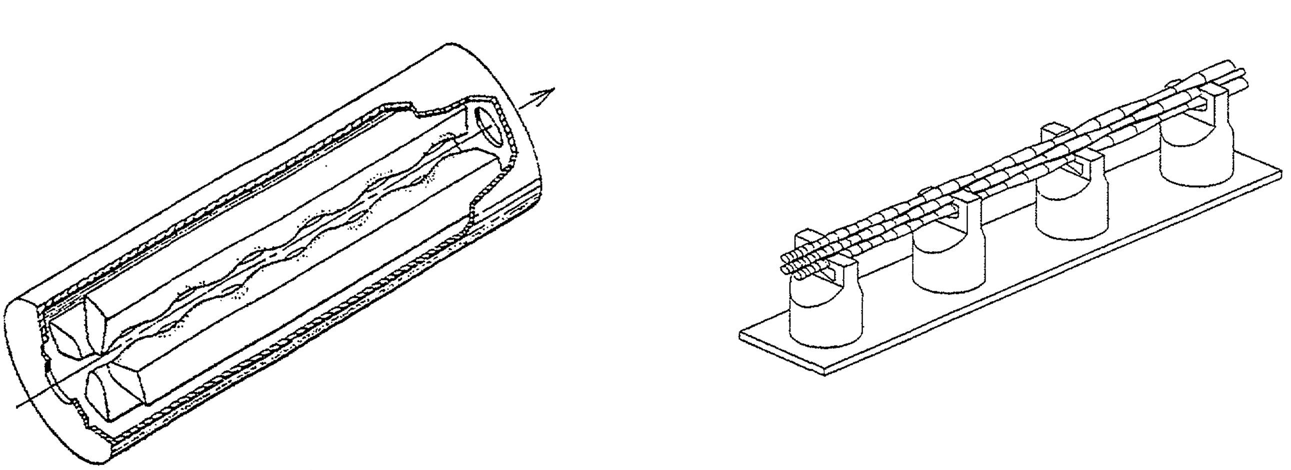

Fig.3 Scheme of four-vane and four-rod RFQ structures

This resonator has advantages especially at low frequencies, therefore it is used for heavy ion applications mostly. Generally, the rf-power N needed is independent of the frequency while the acceptance and the max. ion current are proportional to the electrode voltage resp. N^2, which is not a big issue in pulsed injectors with low average power. High duty factor operation is the actual area of development. A first class of structures, which might be used as SNS-linac injectors with duty factors of up to 10%, are being designed now, still more difficulties can be expected for cw-RFQs. One way to solve the power density problem are cryogenic structures, like at the GTA project at LANL where a 2.5 MeV RFQ was operated successfully at 20K temperature. The technology developed for this NPB program (electroformed, one block, 425 MHz 4-vane-RFQs) was also applied for Grumman's CWDD RFQ and the (room temperature) SSC injector.

3. Applications

The variety of RFQ-accelerators, which have been designed and built, covers the full ion mass range from H to U, frequency range from 5-500MHz and duty factors up to 100%. The physics of transport and acceleration of high current ion beams in RFQs have been solved to such extend, 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 by RFQs.

The standard application is the operation as preinjector for an Alvarez linac feeding a synchrotron. These systems are comfortably matched to ion source and RFQ designs, because they have a low duty factor, which allows pulsed, high power density operation. Examples are the injectors at BNL, DESY and CERN, where the LinacII injector was replaced by an RFQ, with peak currents of 200mA (10^{-4} duty factor)

Heavy ion RFQs have been built e.g. at LBL, INS, ITEP, GSI, Saclay and IAPF for atomic and nuclear physics research. They can be distinguished e.g. by the lowest specific charge they can accelerate and by the duty factor of the operation. Storage ring and synchrotron injectors have a favourable low duty factor. New machines are the new HIMAC injector at NIRS, which is very similar to the TALL-RFQ at INS, the heavy ion linac at TIT, operating at 80MHz, and the new injectors at CERN and Saclay

The RFQ2 at the Saturne complex is a four-rod structure (200MHz) for ions with q/A>0.25 from a EBIS ion source accelerating to 200 keV/u. 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 built at IFN Legnaro is a symmetric 4-rod RFQ with small vanes, like investigated at CRNL and IAPF. Less complex but still more difficult is the high duty factor HLI-RFQ at GSI, which has been upgraded to 25% duty factor by improving the cooling and the alignment of the electrodes. The HLI-RFQ is 3m long (designed for 108.5MHz and U^{28+} ions q/A=0.117), it 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, for which technical problems like cooling and thermal stress control dominate, while for synchrotron injectors this is no major concern.

The mechanical design of the four-rod-HLI-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 case of problems with high duty factor operation, which is required for the HLI-RFQ. Fig. 4 shows the final particle design parameters along the RFQ structure, table I 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 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%.

With this efficient cooling, the temperature of the rods is now raised by 6 degrees only at full field level and no mechanical or thermal problems have been observed. The maximum power load of the RFQ has been raised to 175 kW / 25% df and a large number of user beam times have been successful, e.g. with 100% availability for the long periods of the production of superheavy ions or ^{100}Sn.

General features of the proposed accelerators for radioactive beams are a final energy of appr. 10MeV/u for all ions up to mass 240u starting with singly charged ions from a complex target-ion source - high resolution mass separator system which gives a starting energy of 100 keV for all ions. The optimum

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

Table I Main Parameters of the HLI-RFQ

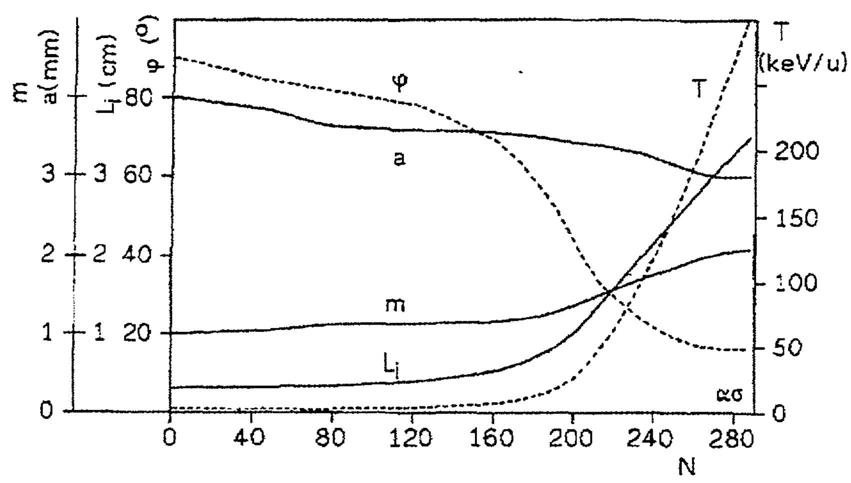

Fig 4 HLI-RFQ Design

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.

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 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 (corresp. 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. At TRIUMPF a maximum mass of m=60u and for REX-Isolde at CERN a mass of m=40u and a reduced duty factor of 25% is planned, together with an EBIS-type ion „collector-charger“ to give a reasonable size of the project. At REX, HLI-RFQ type structures will be employed together with spiral resonators, which have been used and tested at the MPI Heidelberg postaccelerator and TSR-ring injectors. For heavy ions with lower charge to mass ratios an even lower frequency has to be chosen, to give adequate focusing and space charge beam transport.

The 27 MHz High-Current Heavy-Ion Spiral-RFQ, first introduced as a prototype for the injector of the planned HSI (High Current Injector), has been tested for beam acceleration and rf-performance. This four-rod-RFQ consists of 231 accelerator cells which represent the matching and bunching section of the projected injector and accelerates ion beams from 2.2 keV/u to 17.6 keV/u. The rod-electrodes are supported by a resonator structure consisting of 20 spiral shaped stems. Fig. 5 shows a schematic view of a 4-stem Spiral-RFQ, fig. 6 shows the experimental set up at the GSI test injector.

The RFQ has been set up at the Test-Injector stand. The Ar^+ beam was extracted from a CHORDIS (Cold or Hot Reflex Discharge Ion Source) and injected into the RFQ by a five-lens beam line. The maximum achieved beam current was 8 mA for Ar^+ at design rf-level. This is the space charge limit for the RFQ calculated by PARMTEQ code assuming ideal electric field distribution. The peak bunch current was 30 mA. Extrapolation to U^{2+} ions would lead to a pulse beam current of 24 mA (i. e. a peak bunch current of 90 mA). The emittances were in good agreement with the expected values. Figs. 7 and 8 show the pulse beam current and the peak bunch current for Ar^+.

For accelerating ions with yet a higher mass-to-charge ratio higher electrode voltages (and so rf-levels) are required. The ability of the RFQ to operate under such conditions has been tested. The maximum applied power was as high as 260 kW at a duty cycle of 0.4 %. The electrode voltage, measured with an rf-pickup probe calibrated with Ar^+ beam, was 175 kV. This leads to a very high maximum electric field gradient of 340 kV/cm, corresponding to a Kilpatrick value of about 3. The Rp-value is 520 kΩ·m, which confirms previous low level measurements. The RFQ behaved stable, no excessive sparking and no ponderomotive effects could be observed. Adequate cooling of the RFQ structure ensured that the resonance frequency showed no drift. Higher rf-levels could not be applied because of the limited rf-amplifier power. In the next future the RFQ will be used to provide a high current He^{+}-beam for experiments in plasma physics

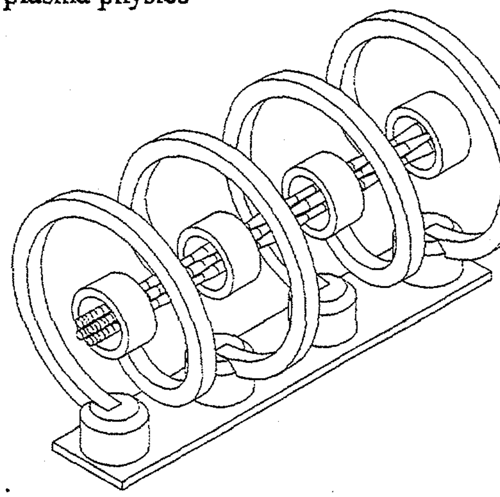

Fig. 5 Scheme of a 4-stem Spiral-RFQ.

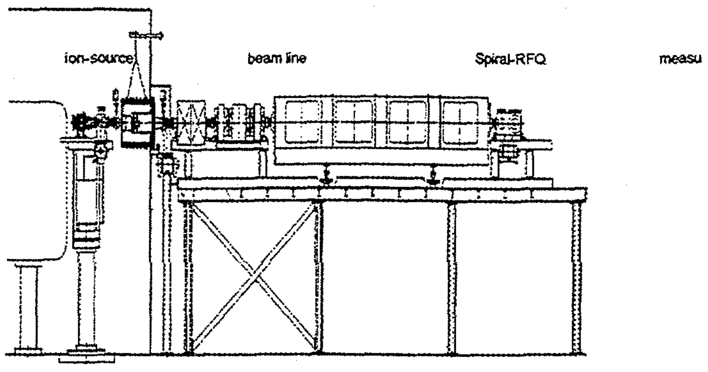

Fig 6 View of the experimental setup

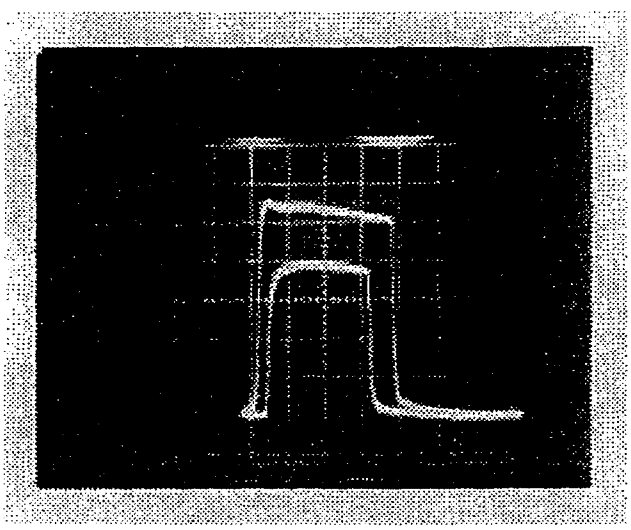

Fig. 7 Pulse beam current for Ar^{+} at RFQ input (upper) and RFQ output (lower). The scale is 2 mA/div. vertically and 1 ms/div. horizontally.

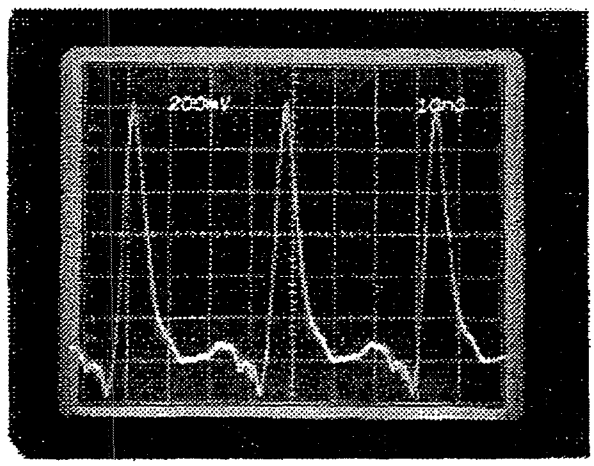

Fig. 8 Bunch current at RFQ output The scale is 4 mA/div. vertically and 10 ns/div. horizontally.

RFQs have been regarded as possible replacement for Tandem injectors for postaccelerators very early. But the first one to be be built was a superconducting heavy ion linac bypassing the EN-Tandem for Uranium beams. At the 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 and 7gap resonators, will provide up to three orders of magnitude increase in intensity which is especially important for laser cooling experiments. A prototype RFQ, which is based on the GSI HLI design, has been operated successfully at MPI.

A more complex system has to be used for a cyclotron injector RFQ. The ISL at the HMI Berlin (the former VICKSI machine) is an isochronous cyclotron with four separated sectors. It has an external injection of beams with variable energy from either a CN-Van-de-Graaff or an 8UD-Tandem.

Figure 9 shows the layout of the accelerator complex and its major facilities. The operating frequency of the RFQ must be synchronized with the cyclotron frequency, which for RFQs normally means a fixed output energy per nucleon. This would be a possible solution only for fixed energy cyclotrons. The fixed velocity profile is typical for RFQs. It can only be changed by changing the Wideröe resonance condition: $L = \beta_p\lambda_0/2 = v_p/2f$, in our case by varying the resonance frequency of the cavity: $v_p \sim f$, $T \sim v_p^2$: (VE-RFQ).

To change the frequency of the 4-Rod-RFQ, a type of RFQ resonator developed in Frankfurt, the resonator can be tuned inductively. Figure 10 shows the way of tuning by a movable tuning plate, which varies the effective length of the stems.

The VE-RFQ was developed at first for the application as a cluster postaccelerator at the 0.5 MV Cockroft-Walton facility at the IPNL in Lyon (France). It was designed for E_{in}=10 keV/u and an output energy between E_{out}=50 and E_{out}=100 keV/u for m=50u. Real heavy and low velocity particles are accelerated in the second VE- RFQ, with energy range from 2 eV/u to 1keV/u for singly charged metallic clusters up to mass m=1000u (frequency range from 5 to 7 MHz).

The third VE-RFQ is a first combination of an ECR ion source with an VE-RFQ has been built for the IKF 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 has 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 a SS-Cyclotron which 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 and E_{in}=360 keV/u (max. accelerating voltage U_m=2.9 MV, at cyclotron frequencies of 10 to 20 MHz.

The ISL tandem injector will be 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 will be split into two RFQ stages. Each stage with a length of 1.5 m consists of a ten stems 4-Rod-RFQ-structure. With a rf-power of 20 kW per stage an electrode voltage of 50 kV is possible. In the first mode of operation both RFQs accelerate, the output energy of the cyclotron is between E_{out}=3-6 MeV/u with a harmonic number of 5 for the cyclotron. For the low energy beam only RFQ 1 accelerates while RFQ 2 is detuned to transport the beam. In this mode the energy range of the cyclotron is between E_{out}=1.5-3 MeV/u. The cyclotron works on the harmonic number 7. In both modes the RFQs are tuned to the eighth harmonic of the cyclotron.

The ECR-source is mounted on the 200 kV platform, formerly used for the tandem, as indicated in fig. 9. The vertical beam is bent 90 °, passes through the buncher-chopper-system and will be

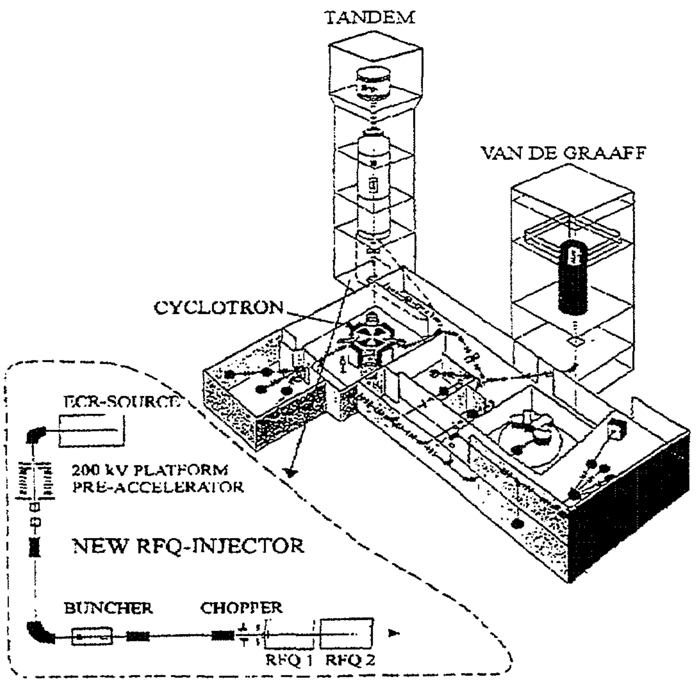

Fig. 9 Modification at the HMI-ISL facility

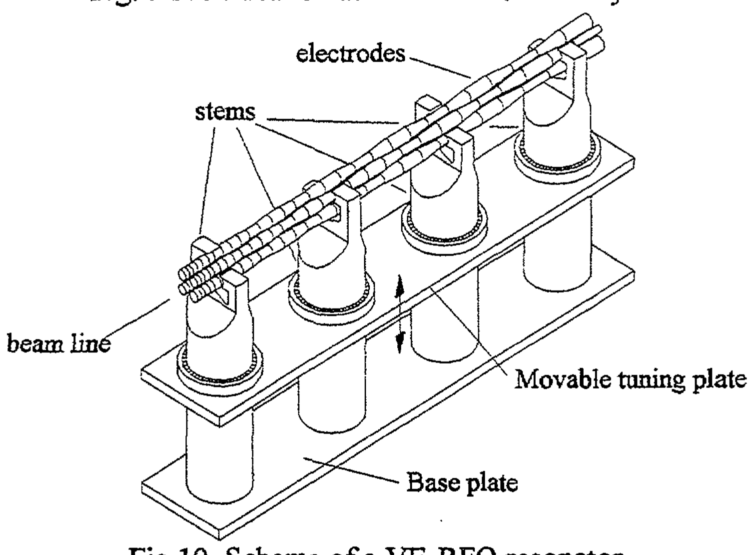

Fig 10. Scheme of a VE-RFQ resonator

injected into the RFQs. The final matching into the RFQ will be done by a triplet lens approximately one meter before 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.

These accelerator developments are concentrated on low current beams, but use 100% duty factor RFQ-structures. The proton (H^-) accelerators with RFQs (CERN, BNL, DESY, IHEP) are generally low duty factor injectors for synchrotron injection. The high duty factor (5%) machines LAMPF, ISIS don't have RFQs yet.

A big push was given by the development of high brilliant beams for ATS, GTA and CWDD. To achieve high duty factors with very compact "light" system design cryogenic operation was chosen, the RFQ structures were electroformed 4-vane cavities with stabilizers, which achieved very good flatness and field stability. The actual development is towards RFQs using a furnace brazed structures to combine the quadants with high precision, up to 8m length are planned (fig 11). On this basis structures for the LANSCE upgrade of LAMPF will be built.

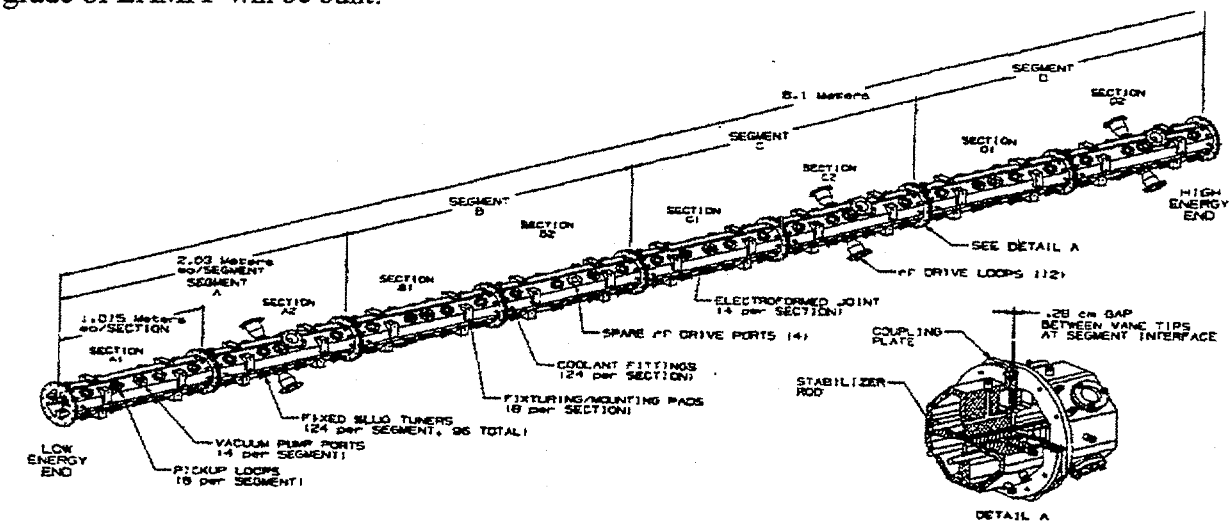

Fig. 11 The APDF 350 MHz -RFQ cavity

The CWDD project being set up at ANL, for which Culham did built the dc-injector and Grumman the cryogenic RFQ (350 MHz), was designed for a 2MeV, 80mA D^- RFQ beam. The RFQ has been set up and tested. ANL is now converting that accelerator to AWCL, a room temperature linac for neutron radiography. CRNLs RFQ1 project has achieved a great success by accelerating a 1.2 MeV, 70 mA, 100% duty factor beam. The hardware is now set up at LANL, where this work is continued, especially the ECR-high-current source is obviously an important part, which will be used in high current projects also.

Actual work is concerned with development of linacs for future Tritium breeding and waste transmutation linacs (ATP, ATW, and Trispal in France), which are planned for cw operation, hadron facilities and spallation sources, e.g. to upgrade LAMPF and to built a European Spallation source ESS, both with a beam power of 5MW (5-10% duty factor). For this beam power and use of H^- for storage ring

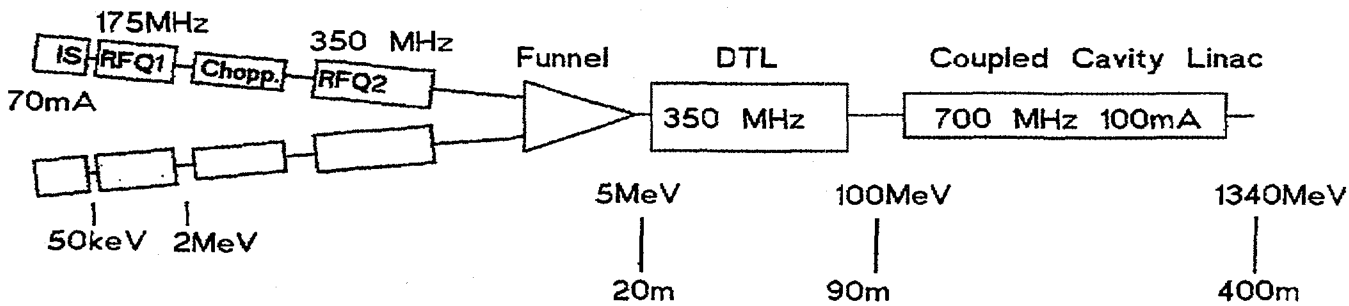

Fig. 12 Scheme of a high current ESS-injector linac

or RCS injection, the injector combines two branches with 50 mA beams. Fig 12 shows a scheme of an ESS-injector.

The RFQ injector for the ESS linac provides a bunched beam of 107 mA at 5 MeV. This can be achieved by a system of two 175 MHz RFQ lines, each with a current of 54 mA, whose beams will be combined in a funnel section. For a proper operation of the compressor rings the linac beam must be chopped with a 60 % duty factor at the ring revolution frequency of 1.67 MHz which implies beam pulses of 360 ns and gaps of 240 ns during the macro pulse of 1.2 ms.

The RFQs are planned to be split into two sections to allow at large beam pulse separation at rep. frequency of 175 MHz. The design of the RFQ has been optimized for a normalized input emittance of 1π mm mrad with respect to a small output emittance growth and a reduced output divergence of the beam to match to the chopping line. The RFQ-structures have a length of 2.9m each and structure power of 350 kW and 700 kW.

High duty factor operation is an important design feature for a number of new RFQ injector applications. The main points for realizing a cw-RFQ structure is determination of power loss distribution and appropriate cooling of the critical parts for preserving the delicate electrode alignment. For the test of new cooling concepts for high duty factors a small high power resonator with a resonance frequency of 211 MHz, has been built as shown in figure 13. The electrodes are cooled with a large amount of water per time (35 l/min), by omitting additional cooling pipes beside the electrodes and stems, but using integrated pipes with wide cross sections inside the electrodes. Investigations of temperature distribution have been done with the code MAFIA. In first tests 20 kW (c.w.) were achieved in thermal stable operation (limited by the rf-supply), which corresponds to 65 kW/m.

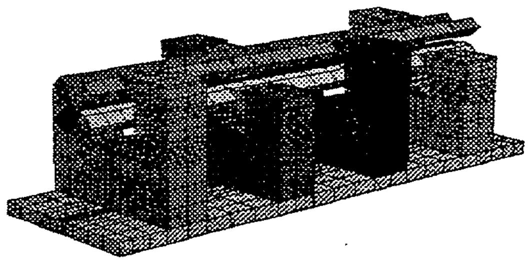

Figure 13: The 216 MHz-Structure

Another proposal with high beam power is IFMIF, a fusion material irradiation accelerator for 35 MeV deuterium to generate neutrons. The injector parameters are similar to the FMIT experiment, but without a funnel section at the moment. The resulting current of one unit is 125-250mA. Groups from Europe, Japan, USA and Russia are involved in this study.

If the perveance of the ion source or the transport capability of the accelerator system is not sufficient, two beams can be combined into a single beam with same emittance, if the frequency of the accelerator is doubled at the same time, as shown schematically in fig.14.

The current limit for RFQs is proportional to the ion velocity, so at higher energies the beam current can be multiplied easily. Funneling makes use of this fact, but has to be done with a well bunched beam, which is needed for low emittance growth in a system of dipoles, quadrupoles, rebunchers and a deflecting (funneling) rf-cavitiy (Fig. 15). A successful experiment has been made at LANL with a single leg (one branch) of a funneling system with a 5 MeV H^- beam. A smaller experiment, splitting a RFQ beam with a rf-deflector has been done at Frankfurt. Now, in the framework of the Heacvy Ion Inertial Fusion (HIIF) study, we work on a funnel experiment to study the beam physics effects in such systems

HIIF injector linacs start with a set (e.g. 16) of low frequency RFQs, because of the small values of the current limits of linear accelerators in the low energy part. For a higher ion energy, the frequency is

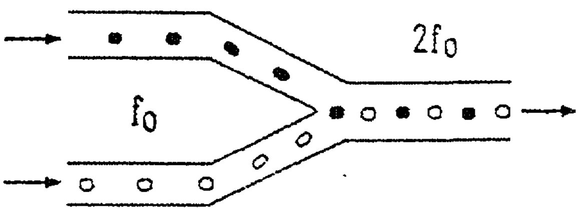

Fig. 14 Funneling scheme

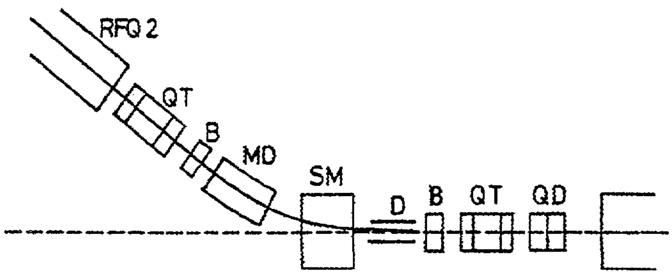

Fig 15 Funneling line

increased to reach a better accelerator efficiency. The accumulation of ion beam current in such a driver linac is done by multiple stages of funneling: in each stage the accelerator frequency is doubled and two beams with 180 degrees phase shift are combined to fill all the rf-buckets of the high frequency accelerator stage. In the ideal case, there is no change of the emittance and beam current and brightness are doubled.

The electrode geometry of the multi-gap deflector consists of some capacitors divided by spaces or sections with larger aperture with equal length. In this geometry the particles will see the deflecting field in one direction several times but the deflection in the opposite direction is always less. The scheme of the multi-gap deflector electrode geometry and the behaviour of the particles along the deflector are shown in figure 16. Figure 17 shows a plot of the two-beam RFQ structure.

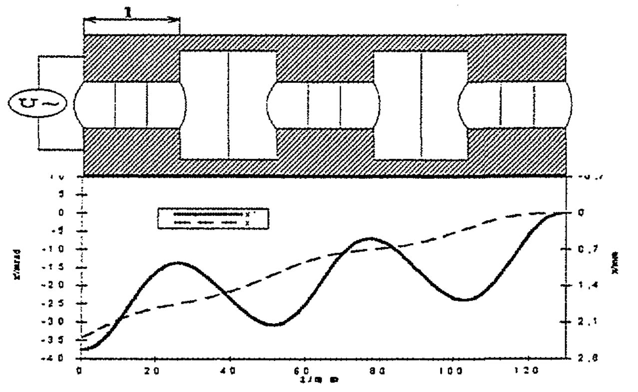

Fig. 16 Scheme of the multi-gap deflector electrode geometry and the behaviour of x' and x.

two-beam RFQ	He^+	Bi^+
f_0 [MHz]	54	27
Voltage [kV]	10.5	180
Rp-value [kΩm]	150	250
Q_0-value	2000	3000
T_{in} [keV]	4	230
T_{out} [MeV]	0.16	12.54
Length [m]	2	16
Angle between beam axes [mrad]	76	76
rf-deflector		
f_0 [MHz]	54	27
Voltage [kV]	6	273
Length [cm]	54	233
Length [$\beta\lambda/2$]	21	39
Beam separation at input [mm]	40	44

Table II Parameter of the Funneling experiment

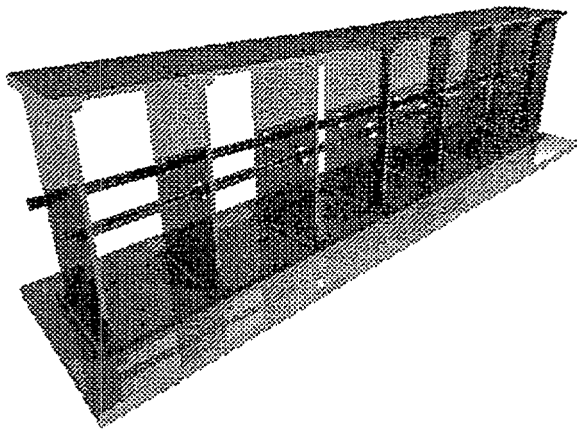

Fig. 17 Plot of the twin beam RFQ

The funneling experiments will be carried out with He^+-ions to facilitate ion source operation and beam diagnostics. Two small multicusp ion-sources and electrostatic lenses, built by LBNL, will be used. The ion-sources and injection-lens will be attached directly on the front of the RFQ with an angle of 76 mrad. Behind the RFQ the funneling deflector will be placed before the beam crossing. Beam diagnostics in front of and behind the RFQ and behind the funneling deflector are in preparation. In table II, the main parameters of the experiment with He^+ and a first HIIF funneling stage for Bi^+ are shown. With this experiment, studies of transmission, symmetry and emittance growth in nonlinear funneling fields can be done.

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Numerous papers and colleagues should be cited, who contributed to the RFQ development, mentioned in this paper. I would like to mention the two basic papers, from which all RFQ work started. In addition I want to acknowledge the contributions of „my students" and the positive effect of provencale air, âme and rosé to the études at JES7.

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