RECENT PROGRESS IN RFQs[×]

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Radio Frequency Quadrupole (RFQ) structures are the new standard solution for low energy ion accelerators. Applications can be distinguished by the ion beam energy and current, the emittance, the duty factor, and the specific charge of the ions chosen, which leads to the different techniques of beam dynamics and rf-structure design. New developments in RFQ design and a survey of projects will be presented.

INTRODUCTION

The concept of spatially homogenious strong focusing proposed by Kapchinskij and Teplyakov [1] has closed the low velocity gap of high frequency accelerators. The work triggered a large number of research activities starting with the thorough work at Los Alamos [2]. While the first aim was the improvement of injectors for high energy accelerators, applications for heavy ions and polarized beams were seen early too .
The capability of conventional accelerators is limited with respect to low energy and high current beams. The solution was an increased focusing strength by the application of electrical rf focusing. Electrical focusing forces are velocity independant and if rf-fields are applied, higher voltages (gradients) than in a dc quadrupole system can be reached giving a stronger focusing channel with bigger acceptance and higher current transport capability.
Introducing the mechanical modulation of the electrodes as indicated in Fig. 1 adds an accelerating axial field component, resulting in a linac structure which accelerates and focuses with the same rf fields.

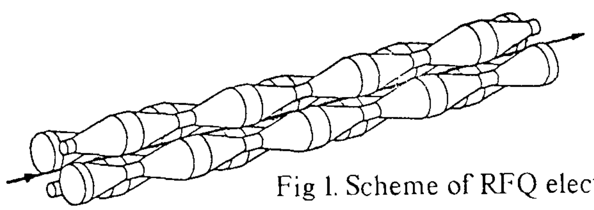

Fig 1. Scheme of RFQ electrodes

Because the focusing structure is homogeneous the accelerating and focusing cells can be very short, which means the beam aperture can be even larger than the cell length or the operating frequency can be high at a given beam energy.
In a general sense the RFQ has to be treated as a beam transport element and acceleration is introduced as a perturbation. This is especially true for the critical first part of the RFQ where the electrode modulation and the acceleration are very small.
Short cells make it possible to apply the concept of adiabatic bunching, also proposed by Kapchinskij, where stable phases and accelerating fields are changed very slowly according to the increasing particle velocity to keep for instance the phase space bucket and the length of the ion bunch constant . By this means a dc beam from an ion source can be transformed into a bunched beam with a minimum of emittance growth and particle loss.

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Properties of the RFQ and the various research activities are described extensively in various articles for instance by R. Stokes, H. Klein, S. Schriber and J. Staples [3-6] . Thus the following paper concentrates on recent developments in the fields of particle dynamics, rf, and mechanical design of RFQ's.

BEAM DYNAMICS

Beam dynamic schemes for the RFQ have been studied in detail and applied in a large number of RFQ projects. The basic principle remains the same: For a given injection energy and frequency the focusing gradients G ($G = X \times U_Q/a^2$; $X < 1$ for modulated electrodes) determine the "current transport" capability or 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 phase advance per cell σ_r 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 choice of aperture a, modulation m and the cell lengths L_C along the RFQ, define the electrode shape (pole tips) and the beam properties.
In the LANL design procedure a radial matching (RM) section is followed by the shaper (SH) which linearily changes the longitudinal phase advance σ_L to the value at the entrance of the adiabatic buncher (AB). Here the bucket width and height or bunch length and σ_L are kept constant with increasing particle energy W. In the final accelerator section (ACC) m and φ_s are kept constant as in a normal linac. The aperture a now can be adjusted to keep σ_r or the gradient G constant along the RFQ. RFQs designed with this procedure give bunched beams with a smaller emittance as the classical preaccelerator buncher schemes and still transmit approximately 95% of the beam.
For higher currents and smaller emittances (same electrode voltage) a longer shaper section, a smaller modulation and a higher starting energy for the accelering section have to be chosen which results in a smoother acceleration . This leads to an increased length of the RFQ structure which is proportional to power consumption and costs. For studies of the dependance of emittance growth on RFQ and beam parameters T. Wangler first used lower starting energies for the accelerator section and larger phases φ_s to improve the designs for high brightness beams. J. Staples designed the BNL and CERN O- RFQ with longer shaper sections, shorter bunchers and longer accelerator sections starting also with larger phases and resulting in a shorter and more efficient structure.
For the CRYRING project and the RFQ's designed for the GSI an attempt was made to minimize the energy spread and simultaneously keep the RFQ short by varying the parameters with respect to a constant σ and current limit I_{lim} without the different RFQ sections (SH, AB, ACC). Even the need of a short RFQ is more important for smaller projects, where the price of the injector is not negligible, the variations of the design procedure resulted in a shorter RFQ and a higher current capability as well. This is demonstrated

in fig. 2 which shows the current limits as calculated with modified "Wangler fomulae" for all cells of the HERA RFQ for comparison.
The new designs were verified with PARMTEQ which is the reference code for RFQ's. Even with special features the new electrode designs give comparable results: improved beam quality or a shorter RFQ .

RF – DESIGN

The RFQ electrodes have to be periodically charged by a rf current source which normally is one type of resonator for instance the 4-Vane-, double H-, Split Coaxial- or the 4-Rod-$\lambda/2$ resonator. They operate at the edge of the passband (except short one cell cavities or "sparkers") and have a common tuning sensitivity which is proportional to $(L/\lambda_0)^2$ (λ_0= rf-wavelength).
All those resonators are heavily loaded by the quadrupole electrode capacity which degenerate the cavity in the first order to an inductivity. The shunt impedance R′ ($R' = U_Q^2 \times L_c/N$) is inversely proportional to the surface resistance (including contacts) and to the square of the electrode impedance $R' \sim (R_S \times \omega^2 C_Q^2)^{-1}$. The electrodes are characterized by the ratio of the beam aperture to the radius of the pole tips .
The 4-Vane structure, which is mostly used for light ion injectors, consist of a TE_{210} cavity loaded with vane shaped electrodes. Optimization for a 4-Vane cavity leads to a cloverleaf structure with circular quadrants and a small pole tip radius. It can be described as four cavities driving the electrodes. The 4-Vane structure is sensitive to pertubations of cavity symmetry because the four quadrants are weakly coupled.
A special problem is the tuning of the end cells because the azimuthal symmetry has to be maintained whilst the natural TE_{211} mode is shifted to the TE_{210} mode (flat field). This normally leads to a significant Q degradation. Values between 50 and 90% of the theoretical Q values have been achieved after tuning.
The double H structure can be described as aysmmetric 4-Vane RFQ. It can be supplied with vane shaped as well as with rod type electrodes and finger drifttubes. It is mechanicly delicate but nevertheless operates very successful in the Serpuchov injector since 1983.
The Split Coaxial resonator developed by R.W. Müller is especially suited for low frequency operation with heavy ions. It is a TEM like cavity in which the field has been flattened by introducing spears which carry finger drift tubes. The structure is asymmetric which means one electrode is on ground potential and the axis potential oscillates with +/- $U_Q/2$. It has favourable rf properties and has been operated also with vane and rod electrodes (P. Leipe, S. Arai) as low power proton models for Heavy ion RFQ's.
The 4-Rod structure developed in Frankfurt consists of coupled $\lambda/2$ oscillators in an linear arrangement and although the current densities at the electrode supports are relativly high the efficiency does not fall short compared with the 4-Vane resonators. The conically shaped electrodes (fig. 1) which have already been proposed by Kapchinskij can have a cooling bore and allow high duty cycle operation. Resonators between 20 and 220 MHz with spiral shaped and straight stems were operated succesfully.
Fig. 3 shows the shunt impedance R′ as function of the frequency of different RFQ's, which should be on one line if geometrically scaled.

FIELD STABILIZATION

For beam dynamics field amplitudes and rf phase along the accelerator structure must be kept constant. Therefore rf stability during operation and tuning tolerances are very important for the design of rf structures. The 4-Vane structure is very sensitive to perturbations of cavity symmetry because the four quadrants are only weakly coupled.
Several schemes for improvement of azimuthal stability have been proposed. At first a slot coupled resonant coaxial manifold was applied to distribute the rf power equally (J. Potter) and comparable but different an external manifold with a multidrive system (S. Gordiano). But mostly vane coupling rings (VCR) which correspond to magnetron straps connecting the electrodes with same poplarity directly have been used (H. Schneider, H. Lancaster) since. They work very efficiently, but they drive the 4-Vane cavity below cut-off.
Appliing the VCR method in the end cells only and using them for frequency tuning in addition, as first

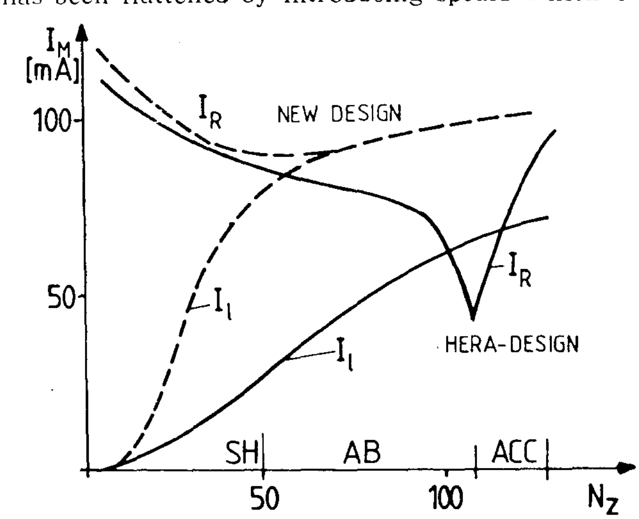

Fig. 2 Current limits along the RFQ

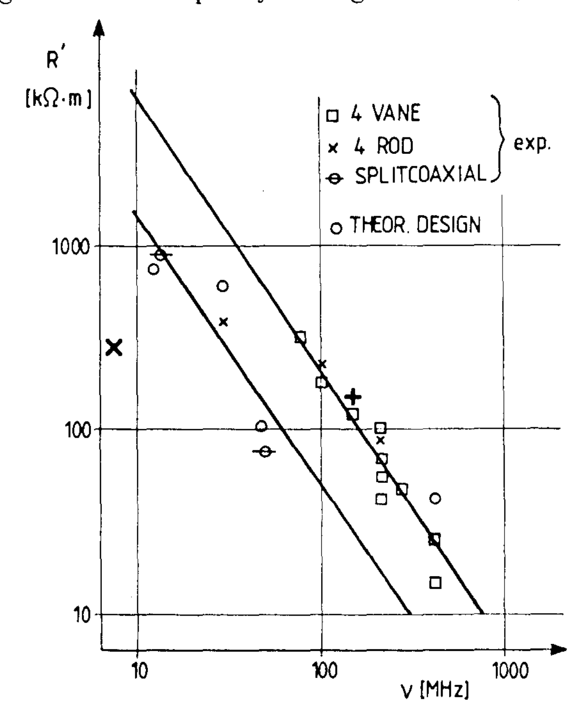

Fig.3 RFQ Impedance as function of frequency

planned for the HERA RFQ, is a possible solution only for short cavities. For the CRNL RFQ R. Hutcheon has solved the problem by compensating the local perturbation by the VCR's individually.
Dipole shifters (DS) as proposed by W. Pirkl are placed in the symmetry planes in the RFQ ends and stabilize the 4-Vane by resonantly perturbating the dipole modes. They have been successfully applied in the BEAR RFQ (LANL) which is short enough to be stabilized only from both ends.
Inductively coupled short resonant transmission lines. (RLC) were successfully applied at the HERA RFQ. These resonant loop couplers convert the operational cut off mode to a $\pi/2$ mode (resonant coupling) and can be applied for longer cavities too by coupling from outside the cavity. Longitudinal stabilization with RLCs which is of the same importance for all structures has up to now been realized only on low power level.

SPARKING

Besides the choice of injection energy and operating frequency the electrode voltage is a starting parameter for the particle dynamics design. T. Wangler and P. Junior have shown, that the current which can be accelerated is proportional to the maximum voltage U_O which therefore should be close to the breakdown voltage U_B. The new design schemes have only changed the proportionality factor. The breakdown voltage is compared with a semiempirical breakdown criterion (Kilpatrick limit) and given in units of the "Kilpatrik voltage" U_K resp. field strength E_K.
The sparking voltage or the enhancement factor for the breakdown voltage depend on frequency, gap geometry, surface treatment, gas pressure and electrode material and duty cycle. The mechanism is thought to be ignited by x-rays, secondary electron emission and hydrogen impact. Kilpatricks Criterion for the breakdown voltage can be approximated for typical RFQ parameters by:

$$U_K[\mathrm{kV}] = 10\cdot(1+g[\mathrm{mm}])\,(1+1.5\cdot 10^{-3} f[\mathrm{MHz}]).$$

Voltages U_K up to two times "Kilpatrik" can be applied in cw operation, whilst higher values up to $5\times U_K$ can be reached in pulsed operation depending on pulse lengthes and repetition rates.
Because sparks occur in a probability process the number of sparks per time should be proportional to the area which has the minimum distance and to the time of the operation of the rf-pulse. Therefore validity of extrapolation of results from "sparkers" is limited. To reduce secondary electron emission, the surfaces should be either clean or coated, which is done during conditioning.
The electrode area with minimum distance can be influenced by the particle dynamics design. A small capacity or having the minimum aperture only in a small part of the RFQ are advantageous in this respect. Constant aperture designs have a higher X-ray level and will tend to spark earlier. There could even be magnetic insulation to prevent electrons from crossing the gaps. This is a rather unpractical provision although inhomegenous stray magnetic fields are of some advantage.

MECHANICAL DESIGN

The mechanical design is important for the alignment and tuning procedures and determines the reliabilty of the RFQ operation. So questions of mechanical design should early interfere with the particle dynamic design as well as the rf design.

Although the first RFQ projects have been very successful they showed problematic points also, like long time stability, the rf-contacts, erosion, cooling, tuning, stabilisation and rf drive.
A lot of changes have been made since, mainly to simplify manufacturing, tuning and operation. Low duty factor cavities are simpler, the contacts and the tuning influence only the rf-power consumption. High duty cycle or CW cavities are by far more difficult. Contacts should be avoided and a better shunt-impedance eases rf power demands and cooling as well.
The general trend is a reduction of complexity of the mechanical design. L. Hansborough, J. Potter and R. Hamm reduced the number of parts by making vanes and parts of the outer conducter out of one piece and screwing the assembly together on large well defined planes. Even one piece designs e.g. electron welding of the RFQ after alignment and remachining as proposed by E. Boltezar or copper forming procedures as done for the BEAR-RFQ are applied. Fig. 4 shows the cross section of an new LBL- RFQ indicating the reduced complexity. This RFQ is a future proton injector (0.8 MeV/50 mA) for the BEVALAC linac. It shall be testet soon by AccSys. The RFQ was made out of copper plated aluminium which is easier to machine, has less internal stresses and is light weighted and cheaper. The weight of course is a major point for the "esoteric" BEAR application.

Originally the 4-Rod RFQ was aimed to simplify the mechanical reqirements but it is not at all "easy to manufacture". The conversion to linear stem arrangements, the new modified stems and electrode supports are thought to be rf - as well as mechanical improvements. The cavity does not determine the frequency because only approximately 5% of the power is dissipated on the tank wall. Thus cooling is simple and ports for pumping and tuning do not have to be compensated or precisely aligned. For the EBIS/ECR combinations high pumping speeds for UHV and even "baking" procedures are proposed.
The design of the RFQ can be divided into three parts: the particle dynamics, the rf- and the mechanical design. The quality of the design is determined by the proper mixture of these ingredients of this delicate "eutectic".

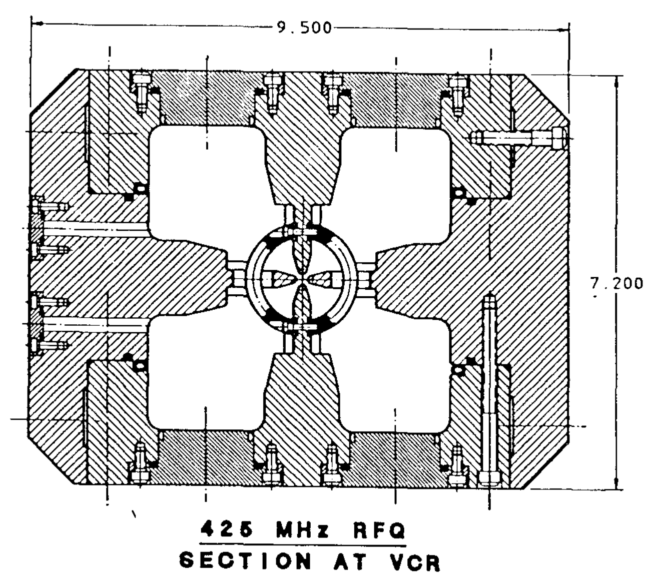

Fig.4 Cross section of LBL RFQ

HIGH CURRENT INJECTORS

The development of low energy high current accelerators was pushed by the demand for improved injectors for high energy synchrotrons. Therefore the first application of RFQs has been seen in the replacement of Cockroft-Walton injectors in high energy labs. The proton current can be in the order of 100 mA, the output energy is about 1 MeV. The number of the RFQs being proposed for this application is big, but the number of routinely operating RFQs is still small.

The first RFQ operating as injector for a high energy system was the URAL 30 linac at IHEP (USSR), which was tested since 1977 and started routine operation in 1983 as injector at a proton current of 80 mA. The peak current of the injector RFQ is 130 mA. The 3 MeV experimental RFQ structure at ITEP has a peak current as high as 250 mA (75% transmission). At 100 mA the transmissin is as high as 97%.

Comparable structures have been the POP prototype RFQ, the ATS- RFQ (LANL), which achieves currents in the 80 to 120 mA region but is not used as high energy injector but for "esoteric applications", and the CERN RFQ I prototype which accelerates also up to 80 mA protons.

The BNL- RFQ built by LBL will be the next real operational RFQ. It has a design current of 50 mA H^- and started operation in 1987. Now the C.W. -injector was replaced during an AGS heavy ion run and H^- operation with the RFQ is scheduled for November.

The RFQs built for HERA (a 4-Vane and a 4-Rod RFQ shown in fig. 5) accelerate up to 50 mA H^- and are operating since 1987. The Alvarez injector linac and the HERA rings to follow are not yet ready.

An interesting application is the RFQ built by AccSys, which serves as an injector for the medical synchrotron built by FNAL for the Loma Linda Hospital and accelerates 25mA protons up to 2 MeV.

The first to pass the URAL RFQ also in beam current will be the CERN RFQ II for LINAC 2, which is designed for a current of 200 mA (750 keV) with high transmission and special regard to minimum emittance growth (M. Weiss). It shall be ready for first tests in 1989. This is a clear sign of the importance of the RFQ for high brightness high current injectors but also for the time needed for prototypes and developement before commisioning of operational accelerators.

These injectors typically are pulsed with several Hz and pulse lengthes of up to 500 μsec. So the average power of these structures is rather low and cooling and power deposition are not very important. This is totally different for projects where a high duty factor operation or even cw operation of the RFQ injector is planned.

The first RFQ designed for cw operation was built for the FMIT project at LANL. It successfully accelerated up to 40 mA H_2^+ ions to 2 MeV.

A project, which has been less ambitious in time schedule is commisioned now. The CRNL RFQ 1 planned first as cw prototype for an injector for an accelerator breeder has been built and tested successfully in cw rf operation (R. Hutcheon, G. McMichael). The first beams have been accelerated but the transmission is still low due to problems with the ion source and the injection part. But the problems with the cavity power and the field stabilization obviously have been solved successfully. Fig. 6 shows a view of the CRNL RFQ.

LOW CURRENT RFQ's

Most of the RFQs built up to now can be classified as low current accelerators with negligable influence of space charge. The first ones have been the Berkeley Local Injector (J. Staples, R. Gough) for heavy ions, the Brookhaven RFQ for polarized protons (S. Gordiano), and the Saclay RFQ (M. Olivier) built in collaboration with Los Alamos. They are operating routinely and very reliable.

A similar structure was the CERN "oxygen" RFQ built by LBL, which finished the first set of experimental runs at CERN in the last year. Being a very small structure, it demonstrated the suitibility of the RFQ's for heavy ion acceleration at high energy labs.

LITL and TALL are two successful RFQs built in INS for heavy ion acceleration and are also working with higher duty cycle, the average power can be 25 kW. The huge TALL machine (0.8 MeV/amu, 100 MHz, L= 7.2m, e/m > 1/7) will be copied for application as injector for the medical heavy ion synchrotron at NIRS (Y. Hirao).

Both, the RFQ injector for CRYRING, which will be finished by end of this year, and the new GSI "low current" RFQ injector are being built in Frankfurt.

They belong to the same group of RFQ's as the Saclay RFQ which was the first EBIS-RFQ combination. They combine very efficient sources for highly charged heavy ions with an RFQ, followed by a linac and a heavy ion (storage) ring. The GSI project differs by the use of an ECR source and the duty cycle of up to 50 % envisaged. The combination with these advanced ion sources is clearly one important future RFQ application, because these sources hardly could mounted on the high voltage platform of a normal classical injector.

LOW FREQUENCY HEAVY ION RFQ's

Another kind of RFQ are low frequency high current heavy ion accelerators, as being planned for the possible application of heavy ion fusion drivers. For low charged heavy ions typically Xe or Bi or U^{1+} or U^{2+} the rf frequency has to be in the 10 to 30 MHz region, because of the low starting or input energy and the space charge at these energies. GSI and ITEP have built and operated prototypes to study the special problems of high current heavy ion beams.

The GSI MAXILAC is a five cell Split Coaxial RFQ (length 9 m). It accelerates up to 5 mA Ar^{1+} and up to 2 mA of U^{4+} from 2.5 MeV/amu to a an energy of 45 keV/amu.

The ITEP heavy ion RFQ accelerator is a helix driven 4-Rod structure with 12m length with a frequency of 6.9 MHz. It accelerates 10 mA Xe^{2+} from 0.96 keV/nucleon to 36 keV/amu.

Work has started for a possible 27 MHz heavy ion injector for the UNILAC and SIS accelerator system. The design aims at an U^{2+} beams of 25 mA and an output energy as high as 210 keV/nucleon corresponding to a total accelerating voltage of 25 MV.

CONCLUSIONS

Considerable progress concerning particle dynamics-, rf-, and mechanical design of RFQ's has been made in the last few years.

Table 1a shows characteristic parameters for some of the RFQ's which "recently" were completed. The list is not complete. It doesn't include the RFQ's at KEK and ICR and all the noumerous RFQ studies and model, prototype, "sparker" tests, beam dynamics studies, and

beam transport experiments for instance at Trieste, Beijing, at INS, Texas A+M, and Frankfurt as well as the RFQ's built by SAIC, Boeing, and Grumman.
Projects which will be completed soon like the CERN RFQ II and several heavy ion RFQ's are compiled in Table Ib under "near future RFQ's". Table Ic gives characteristic parameters of RFQ projects which are in the design phase like the GSI high current injector and and a new CERN heavy ion injector. Especially the neutral beam heating (NBH) RFQ which is planned by a collaboration headed by ORNL for the ITER Tokamak reactor indicates the next step in RFQ developement which will be necessary to realize a multibeam 2 MeV D^+ accelerator with approx. one Ampere per beamlet.
For reference some of the "old" RFQ's, those which are operating since longer time and have been reported for instance at the linac conference at SLAC are collected in Table Id. Not mentioned are the industrial applications and energy variation, staging, funneling, deccelereating with RFQ's about which hopefully will be reported in future.

REFERENCES

Comprehensive lists of references are given in the review papers [3,4,5,6]

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TABLE I

	Ion	T MeV /amu	f MHz	L m	I mA des./ex	U_Q kV	DF %	R' kΩm
			a) "recent" RFQs					
BNL/LBL	H	0.75	200	1.4	50/60	81	.7	55
AccSys PL2	P	2.0	425	1.6	25/25	64	3.	45
BEAR/LANL	H^-	1.0	425	1.0	30/25	44	.025	27
CRNL RFQ 1	P	0.6	365	1.5	70/	78	100	65
HERA RFQ 4-V	H^-	0.75	202.5	1.2	20/54	70	.025	75
HERA RFQ 4-R					20/36			85
CERN O-RFQ	O^{6+}	0.14	202.5	.86		36	.025	55
			b) "near future" RFQ's					
CERN RFQ 2	P	0.75	202.5	1.7	200	178	.0025	
LBL	P	0.8	400	1.0	50	72	0.7	
AccSys D1	D^+	.45	425	.75	20	45	3.	
IMPL	B^+	.03-0.14	17-100	2.5	10	35	25	
CRYRING	Ne^{5+}	0.3	108.5	1.55		70	0.1	
GSI LCI	U^{28+}	0.3	108.5	2.8		80	50.	
TALL II	Li^+	0.8	100	7.25		81	10	
LYON Cluster	$M50^+$	.05-.1	80-110	3		100	25	
			c) "future" RFQ					
GSI HC I	U^{2+}	0.21	27.15	36	25	180	1	
CERN HI	U^{35+}	0.1	101.25	1.4		80	0.05	
NBH OR	D^+	1.0	27.0	6.5	1000	400	100	
EHF/SSC	H^-	2.	50/400	4.2	50	140	2.5	
			d) "old" RFQs					
ITEP	P	3.0	148.5	4.9	250	185	.001	110
URAL 30	P	0.635	148.5	1.35	130	164	.003	150
LANL ATS	H^-	2.0	425	2.9	100	111	1.0	25
CERN RFQ 1	P	0.52	202.5	1.38	85	108	0.05	80
LBL LI	S^{4+}	0.2	200	2.25	2.5	70	0.2	55
INS TALL	Li	0.8	100	7.25		81	10	190
SACLAY	Ne^{5+}	.183	200	2.3		73	.025	50
MAXILAC	Kr^+	.045	13.1	9.4	5	105	5	800
ITEP HI	Xe^{2+}	.36	6.1	12	10	190	1	290
FMIT	D^+	1.0	80	3.9	40	180	100	240

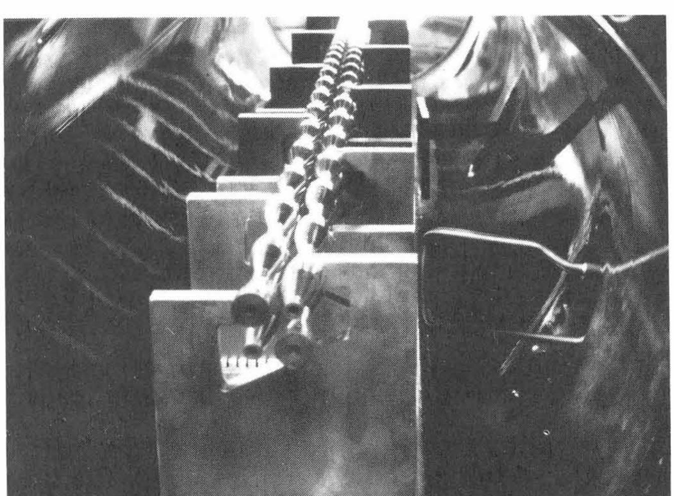

Fig. 5 View of the 4-Rod HERA RFQ

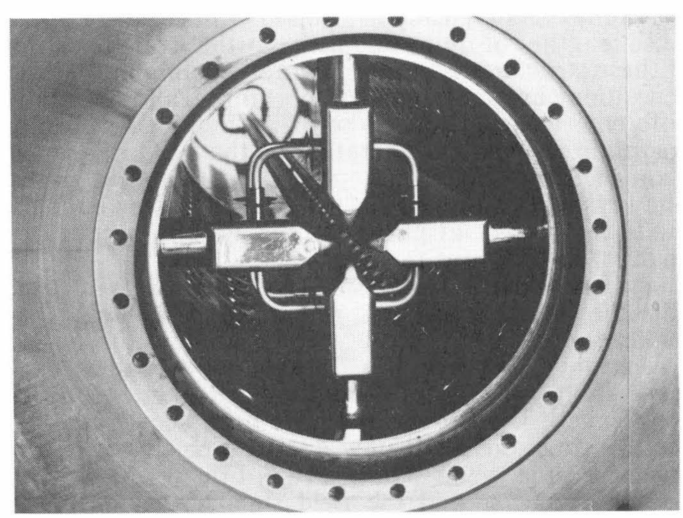

Fig. 6 View of CRNL cw RFQ 1