VARIABLE ENERGY AND HEAVY ION RFQs[×]

Alwin Schempp

Institut für Angewandte Physik, J.W. Goethe Universität
D-6000 Frankfurt am Main, Postfach 111932, Germany

Abstract

RFQs are low energy rf accelerator structures which can efficiently transport and accelerate high current ion beams. RFQs have a fixed velocity profile and therefore fixed input and output energies per nucleon. The ion energy can be varied by changing the resonator frequency. This has been done for a 4-Rod-RFQ, i.e. the type of RFQ resonator developed in Frankfurt, which is well suited for such an application.

The status of two RFQ projects for cluster- and heavy ion acceleration with a possible variation of the output energy by a factor of two will be discussed together with work on fixed energy RFQs for heavy ions.

Introduction

In a Radio Frequency Quadrupole[1,2] (RFQ) structure acceleration is achieved by a geometrical modulation of quadrupole electrodes leading to axial components of the field. These electrodes are part of an rf resonator, excited in a TE_{210}- like mode to generate the necessary field distribution.

The mechanical modulation of the RFQ - quadrupole electrodes, as indicated in fig. 1, adds an accelerating field component to the focusing channel, resulting in a structure which accelerates and focuses with the same rf fields.

Electrical focusing forces are independent of the ion velocity v_p and if rf-fields are applied, higher voltages than in a dc quadrupole system can be reached, giving a very strong focusing with a large radial acceptance. Because the focusing structure is homogeneous the accelerating and focusing cells can be very short, which makes it possible to apply the concept of adiabatic bunching[3]. The phases φ_s between the particles and the rf- fields and the amplitude of the accelerating fields E_z are changed very slowly according to the increasing ion velocity v_p, transforming a dc beam from an ion source into a bunched beam with a minimum of emittance growth and particle losses.

The mechanical shape of the electrodes is characterized by the aperture radii a_i, the modulations m_i, and the modulation periods L_i, as shown in fig. 1. Together with the electrode voltage U_Q it determines the acceleration and focusing fields. Therefore a voltage as high as possible (close to the breakdown voltage) and an aperture as small as possible will be chosen for a high focusing strength $G \sim U_Q/a^2$ and a high ion current capability [3]: Limiting current $I_{lim} \sim U_Q^2 v_p |\varphi_s| / (a^2 f)$. For the same focusing strength the voltage U_Q which has to be applied to the quadrupole electrodes is proportional to the ratio of ion mass A to charge q: $U_Q A/q$.

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Thus the choice of the frequency f and the electrode voltage U_Q are starting parameters for the particle dynamics design.

The rf power N required to provide the design quadrupole voltage U_Q on the electrodes is proportional to the length L_s of the structure and depends on the type and parameters of the structure and the operating frequency f. The shunt impedance R′ which characterizes the rf efficiency of the accelerator structure is defined by: $R' = U_Q/N \times L_S$. R′ is roughly proportional to $f^{-1.5}$ while the cavity length L_S will be inversely proportional to the frequency [4,5].

The various applications of RFQ accelerators can be distinguished by the ion beam species, the ion energy and current, the emittance, the duty factor, and the specific charge of the ions, which lead to the different techniques of beam dynamics and rf-structure design.

The velocity profile is fixed and can be changed by varying the length L_i or the phases between groups of cells by breaking the structure into several individually driven and phased subunits like in postaccelerators[6] or with a variable frequency keeping the electrode structure unchanged. The second way of changing the Wideroe[7] resonance condition: $L_i = \beta_p \lambda_o/2 = v_p/2f$, is the way which has been used for compact ion RFQs with variable energy (VE-RFQ)[8].

The electrode and cavity design is based on the development of fixed frequency (energy) 4-Rod RFQs[9,10], which is well suited for low frequency heavy ion acceleration. Therefore, examples of recent developments of fixed energy heavy ion RFQ will be discussed at first.

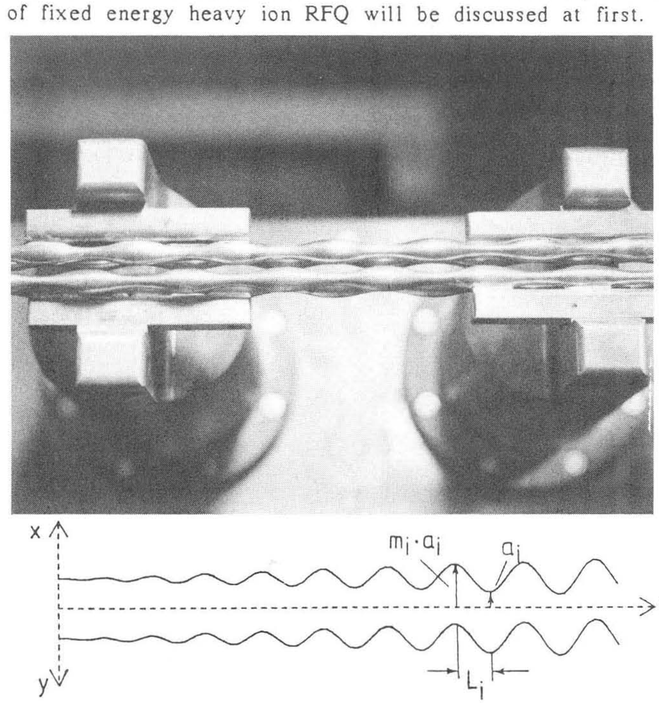

Fig. 1 Modulated RFQ electrodes

RFQ design examples

The 4-Rod RFQ rf-structure consists of coupled $\lambda/2$ oscillators in a linear arrangement as indicated in fig. 2, and although the current densities at the electrode supports are relatively high the efficiency does not fall short compared with other RFQs. The resonator is very stable in respect to rf operation because neighboring modes are clearly separated and all major current conducting parts can easily be cooled, which is important especially for high duty cycle operation and possible application for superconducting RFQ resonators[11,12].

The RFQ structure should be as short as possible to save rf power and costs proportionally. When the structure frequency and electrode voltage have been chosen to give good focusing properties, the length L_S has to be optimized in respect e.g. to the beam emittance, the power consumption and the transmission, which is the ratio of d.c. input beam versus output beam.

Fig. 3 shows the design parameters a,m, and L_i along the RFQ structure for the new HLI injector for the GSI[13,14]. The RFQ with a length of 2.9 m and an electrode voltage of 80 kV operates at 108.5 MHz and requires approximately 120 kW rf power with a duty cycle of up to 50%. PARMTEQ calculations show a radial emittance growth[15] of only 10% and a small longitudinal emittance of 8 ^{0}keV/u (90%, r.m.s.) which comes even close to values achieved for more linear bunching schemes. The slow increase of the ion energy T as function of the RFQ cell number N is demonstrating the fact that a significant part of the RFQ structure is required for bunching.

Fig. 4 shows the cross section of the tank which is of a coffin like design which facilitates installation, alignment and maintenance as well as the burial. Fig. 5 shows the low energy end of the cavity, which incorporates also beam diagnostic devices. The tank has been manufactured and will soon be copper plated. First operation is scheduled for spring of 1991.

Another fixed energy 4-Rod RFQ has been built for heavy ions (specific charge $q/A \geq 0.25$, energy 10 - 300keV/u) as injector for the storage ring CRYRING at the MSI Stockholm. The RFQ resonator has been designed, built, and tested in Frankfurt and is now installed at the injector beam line at MSI[16].

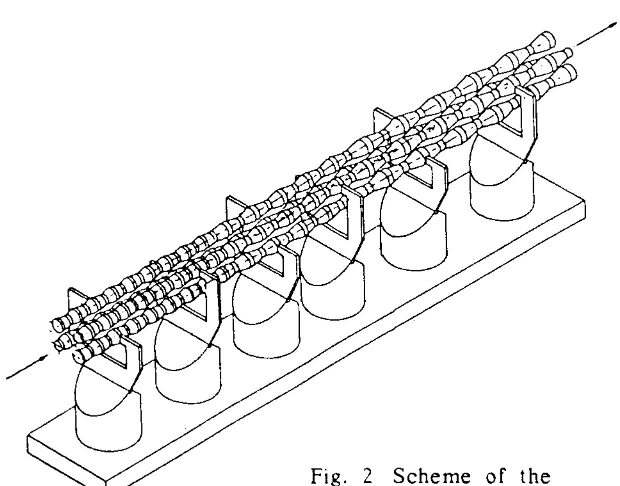

Fig. 2 Scheme of the 4-Rod RFQ structure

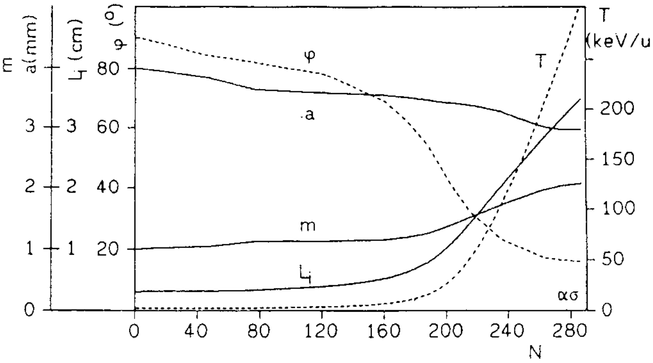

Fig. 3 Electrode design for the HLI-RFQ

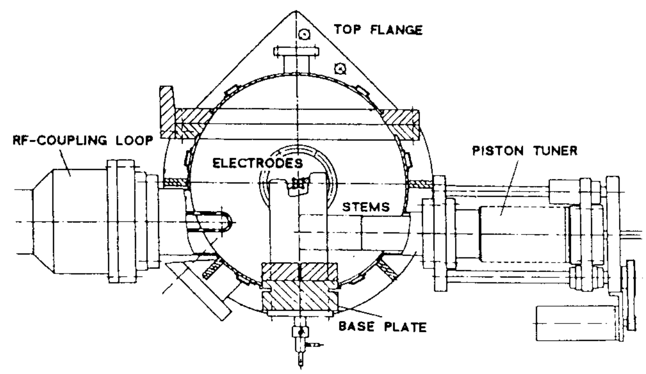

Fig. 4 Cross section of the HLI-RFQ

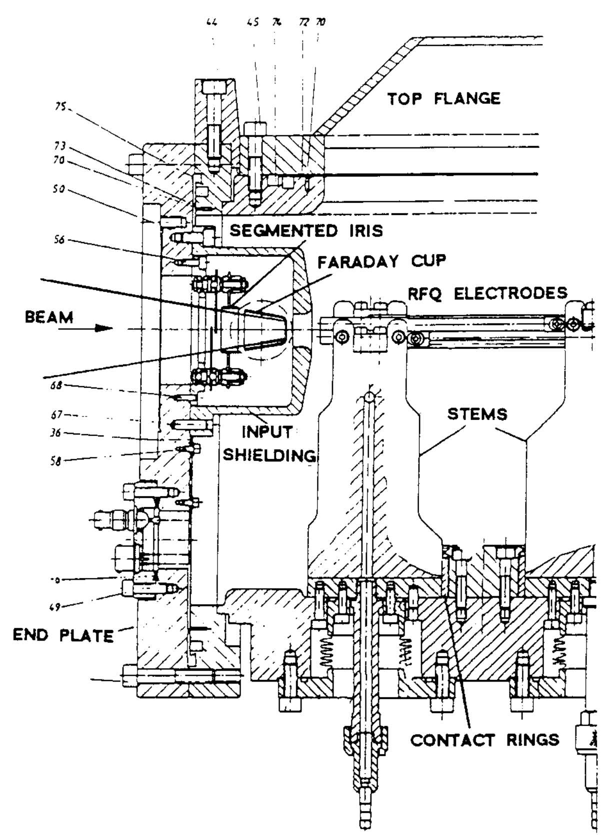

Fig. 5 Low energy end of the HLI-RFQ

Fig. 6 shows a view of this RFQ. Design features are a small size (tank diameter 35 cm at 108.5 MHz, length 1.54 m), a good rf efficiency and modest mechanical tolerances. The results of the beam tests were in very good agreement with PARMTEQ calculations. The rf-efficiency was better than expected so that also ions with smaller specific charge ξ/A can be accepted.

This experiments confirmed that the method of designing the electrode parameters along the RFQ without shaper, gentle buncher, and accelerator sections[4], can give shorter RFQ structures without drawbacks in beam quality .

Based on this results other heavy ion structures have been designed or will be built. There are plans for a new special injector for the TSR at the MPI Heidelberg[17] and for a new Lead-Linac RFQ for CERN[18], for which the HLI-RFQ and the CRYRING RFQ are valuable "prototypes". There is also a collaboration with GSI to built a prototype of a High current RFQ for U^{2+} (HSI) using the 4-Rod structure with spiral stems[19,20]. This HSI-RFQ is designed for the acceleration of up to 25mA U^{2+} ions from 2.5 to 20 keV/U. It will be 4 m long and operate at 27 MHz (1% df). First beam experiments are planed in the first half of 1991.

Variable Energy RFQs

The advantages of the RFQ structure are clear: low energy acceleration of ions from as low as 1 keV/amu up to approximately 1 MeV/amu with strong rf focusing and the possibility of high beam currents. The design of the RFQ has to be made for the heaviest particle to be accelerated and for fixed initial and final ion velocities v_p (or energy per mass unit u: T/u) A change of the output energy is possible by varying the resonance frequency of the cavity using the same electrode system: $v_p \sim f$.

Keeping the electrode voltage U_Q constant heavier particles with mass m = A×u and charge state q can be accelerated at a lower frequency with the same RFQ electrodes to the same final energy T_f : $T_f \sim A/q\, f^2$. To change the frequency of the 4-Rod RFQ the resonator can be tuned capacitively or inductively. For the first Variable-Energy- (VE-) RFQ structures to be built, the effective length of the driving conductor will be changed with movable shorts as indicated in Fig. 7, which results in a sufficiently large tuning range. Even though the problems with movable contacts exist, they are simpler to solve than for a comparable cavity resonator. In Frankfurt 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).

The upgrading of the Cluster Facility is being performed in a collaboration between IPN Lyon, KfK Karlsruhe and IAP Frankfurt[21,22].

For the Lyon postaccelerator an upper frequency of 110 MHz could be used because of the relatively high preaccelerator voltage of 500 kV and the restriction to cluster masses of 30 u resp. 50 u. The RFQ for postacceleration of clusters is designed for 10 keV/u injection energy and up to 100 keV/u (3MeV for m=30u, 5MeV for m=50u) final energy. A layout of the cluster accelerator is shown in fig. 8.

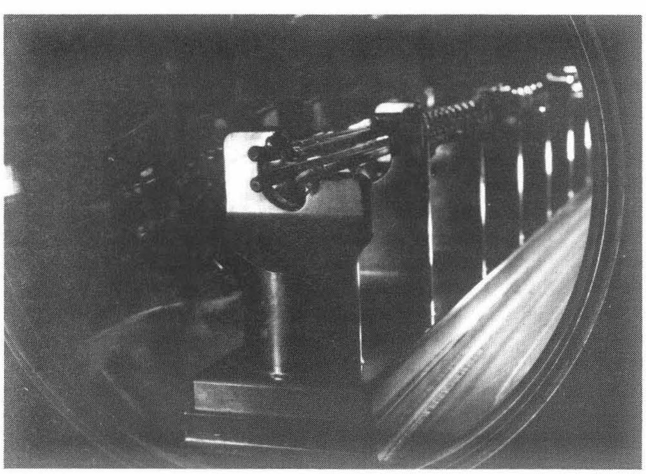

Fig. 6 View of the CRYRING RFQ resonator

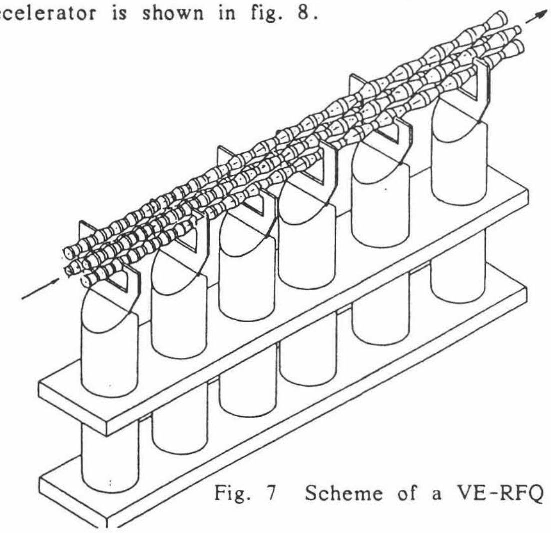

Fig. 7 Scheme of a VE-RFQ module

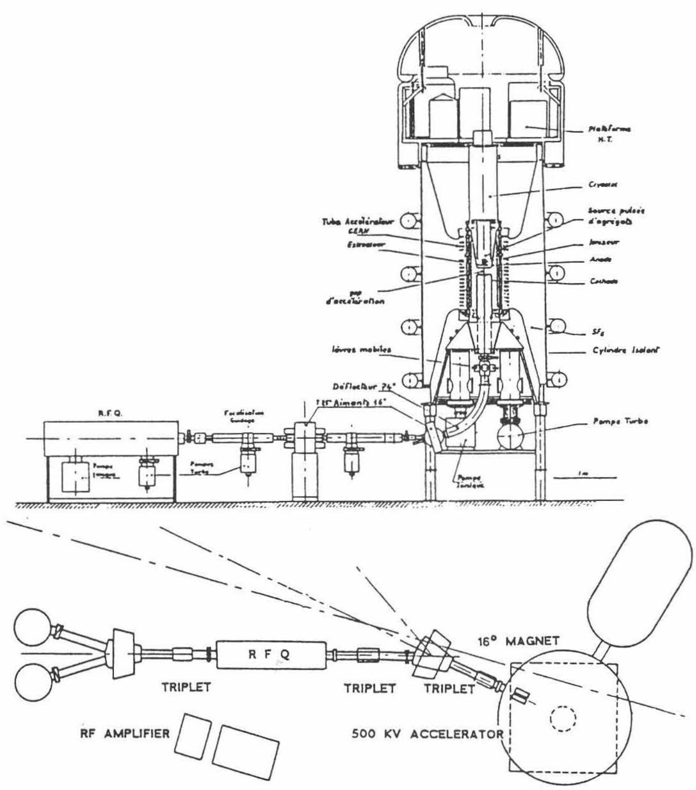

Fig. 8 Layout of the Lyon cluster accelerator

The beam is accelerated vertically, then bent into the horizontal direction by a cylindrical electrostatic deflector and a bending magnet which provides mass selection. The beam transport and matching into the RFQ is done by electrostatic quadrupole triplets, which are very effective at the low cluster velocities.

For energy variation the resonator can be tuned within an appreciable range to scan e.g. the FM range from about 80 MHz to 110 MHz corresponding to an energy change by a factor of approximately two.

The particle dynamics design for the heaviest particle resp. the minimum charge to mass ratio q/A necessary for acceleration is characterized by Fig. 9. Taking the "design particle" as reference, better q/A ratios or acceleration to lower energies requires only a lower voltage: $U \sim A/q \times f^2$. Compared to other RFQ designs [5] the buncher part has been skipped for a very effective acceleration, e.g. an average field strength of up to 2.5 MV/m, which is even higher than in classical ion accelerators. This is on cost of a relatively small transmission of appr. 25%.

The work on the Cluster injector and the beam lines is in progress. The RFQ is behind schedule, but has been successfully assembled and tuned and is beeing transported to Lyon for first beam experiments. The left part of fig.10 shows a view of the VE-RFQ.

The Lyon RFQ shows, that the design of variable frequency RFQs is not aiming at the highest beam currents and highest brilliance but on flexibility. A second system based on the 4-Rod principle, which has a larger frequency range resulting in an energy variation between 300 and 1500 keV is being developed by AccSys [23,24] as an ion implanter.

Another VE-RFQ is built for an ECR-RFQ combination at the IKF at the University of Frankfurt [25,26]. Interesting new experimental possibilities will be available for atomic physics as well as for ion implantation and materials characterization.

The basic parameters of this VE-RFQ are an output ion energy of T_f = 100 - 200 keV/u, the same frequency variation of f = 80-110 MHz, a minimum specific charge of q/A = 0.15, an electrode voltage of U_Q = 70 kV and a structure length of L_s= 1.5 m. The rf power consumption will be 60 kW (110 MHz).

The beam-dynamics design results in the energy/frequency plot of Fig.11. For a specific ion the electrode voltage can be lowered for obtaining smaller frequencies and energies according to $U_Q \sim A/q \times f^2$. While the radial phase advance per cell σ and the focusing strengh B will stay constant, the acceptance α and the maximum ion current I_r are smaller for lower frequencies because of the reduced voltage U_Q. Fig. 12 shows the possible range of improvement when the voltage U_Q is kept constant. Thus the focusing strengths can be improved resulting e.g. in a constant ion current for all frequencies. Fig.13 shows relative mass and energy ranges of a VE-RFQ and the extension for the constant voltage option. More detailed calculations about the beam dynamics properties are presented by Deitinghoff [27].

The tank of this RFQ has been manufactured and will be copper plated at GSI. The parts of the electrode insert are ordered, an existing transmitter will be modified. First beam tests are planed for 1991.

Conclusions

The results of the work on low-energy ion RFQs are showing that accelerators with fixed and variable energies can be built with properties matched for the specific application.

The fixed energy 4-Rod structure has shown convincing results. Operating experience with the VE-RFQ has to prove, if reliability and practicability belong also to its properties.

Table 1 Lyon cluster VE-RFQ parameters

Max. initial/final kinetic energy	10 /100 keV/u
Min. initial/final kinetic energy	5/50keV/u
Maximum kinetic energy for m=30u	3.0 MeV
Length/diameter of the structure	2.0/0.5m
aperture	3.1-2.5 mm
Number of cells/ modulation of electrodes	167/1.1-1.98
Frequency	80-110 MHz
Peak voltage/maximum field strength	80kV/ 42MV/m
Transverse phase advance per cell	8.2 -7.2 °
Synchronous phase	50-15.5°

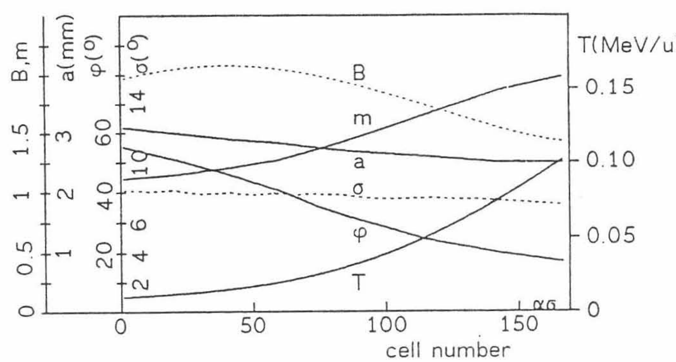

Fig. 9 Electrode parameters along the RFQ

Fig 10 View of the Lyon VE-RFQ

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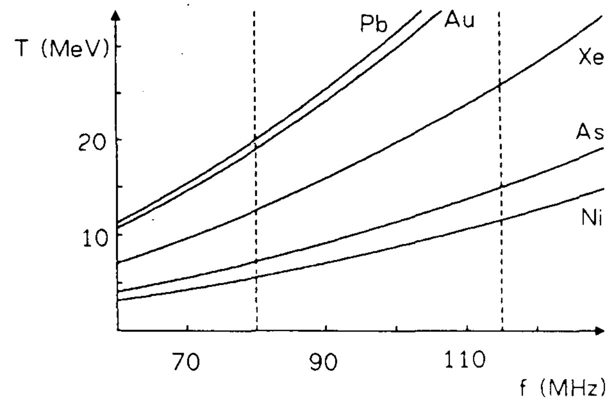

Fig. 11 Ion energy as function of RFQ frequency

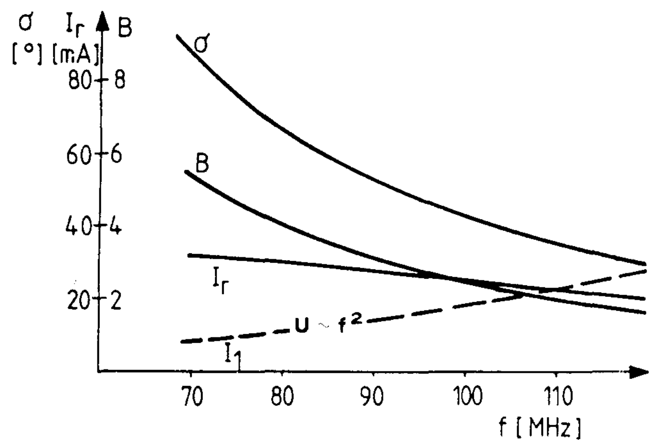

Fig. 12 Tune and current limit for constant electrode voltage

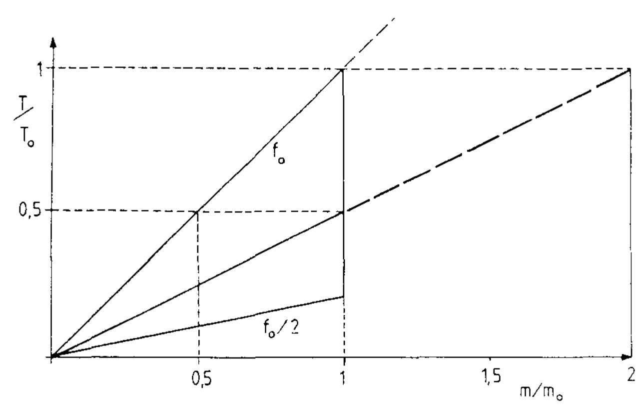

Fig 13 Energy mass plot for VE-RFQs