DESIGN OF COMPACT RFQs

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RFQs are favourable injector structures for high current beams as well as for low current beams e.g. heavy ions. The design of an RFQ consists of three parts, which are normally treated separately. A new concept for the particle dynamic design, the rf-structure, and the mechanical design of RFQs is presented.

Introduction

The concept of spatially homogenious strong focusing proposed by Kapchinskij 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. While the first aim was the improvement of injectors for high energy accelerators, application in other fields e.g. for heavy ions and polarized beams was seen early too.

The capability of conventional accelerators is limited in respect to low energy and high current beams. A possible solution for low current accelerators, "low current" means a negligable influence of beam space charge forces on beam dynamics, is the choice of a lower operating frequency for which the rf defocusing is weaker and longer drift tube magnets are allowed. For beams with significant space charge defocusing the velocity dependent magnetic focusing forces are prohibitive for low velocity ions. The minimum velocity now is given by the maximum dc extraction and dc-column voltage which are inversely proportional to the current.

A first step in solving these restrictions was the application of electrical quadrupole focusing which had not been applied due to technical problems with feedthrougs and sparking. The second step was the application of electrical rf-focusing which solves some of the technical problems by generating the high voltages necessary only close to the electrodes. Kapchinskij now introduced the mechanical modulation of the electrodes and added an accelerating field component and by this got the first structure which accelerates and focuses with the same fields. Fig.1 shows an example of modulated electrodes.

Electrical focusing forces are velocity independant and if rf-fields are applied, higher voltages than in a dc quadrupole system can be reached giving a stronger focusing channel. 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 ore the operating frequency can be higher at a given beam energy. This saves possible frequency changes by overcoming the critical low energy part of the accelerator.

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 first part of the RFQ where the modulation and acceleration are very small.

Short cells made 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 constant. By this a dc beam from an ion source can be transformed into a bunched beam with minimum emittance growth and particle losses.

Beam Dynamics

Beam dynamic schemes for the RFQ have been studied in detail and applied in a large number of RFQ projects. The basic principles remain the same: For a given injection energy and frequency the focusing gradients G ($G = X*U_Q/a^2$; X< 1 with modulation) 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 phase advance per cell σ is the limit. The highest possible operation frequency should be chosen to keep the structure short and compact. Beside the choice of U_Q and operating frequency the "RFQ design", the choice of a, modulation m and the cell lengthes L_C along the RFQ, defines the electrode shape (pole tips) and with that the beam properties.

In the LANL design procedure for which the HERA RFQ design is shown as example in Fig.2., a Radial Matching (RM) section is followed by the Shaper (SH) which linearily changes the longitudinal focusing frequency 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 paticle energy W. In the final Accelerator Section (ACC) m,φ_s are kept constant as in a normal linac. The aperture a now can be adjusted to keep a constant radial focusing frequency σ_r or focusing force B along the RFQ.

RFQs designed with this successful procedure give bunched beams with a clearly smaller emittance as the classical preaccelerator-buncher schemes and still transmit appr. 95% of the beam.

For higher currents and smaller emittances a longer shaper secion, a smaller modulation and a higher starting energy T_{AB} for the accelering section have to be chosen which in general results in a smoother acceleration. This leads to an increased length L_C of the RFQ structure.

For the CRYRING project an attempt has been made to change the design procedure in a way to minimize the energy spread and simultaneously keep the RFQ short. With a constant electrode voltage U_Q the rf-power consumption, the size of the rf transmitter and the cost of the RFQ structure are proportional to the length of the RFQ.

The need of a short RFQ is more important for smaller project where the price of the injector is not negligible. The variations of the design procedure also indicated a higher current capability. This is demonstrated in Fig.3 which shows the current limits as calculated with modified "Wangler fomulae" for all cells of the HERA RFQ design.

Looking carefully to the reasons for particle losses in high current designs the current limit I_M had more importance as a constant focusing frequency σ_r. Even the current limit I_M is a quantity defined for periodic channels only. Fig.3 indicates a bottleneck which seems to limit the overall performance. This coincided nicely with the maximum accelerated beam current at DESY (for some time).

The dashed curve demonstrates how the current limit of the RFQ can be increased by approx. two without changing the electrode voltage and the final apertures. The number of cells is sligthly smaller, whilst the length is larger (10%) in this case. Keeping the tank length constant (L=118cm) and starting with a higher injection energy (30keV), which is more appropriate for higher currents, and a higher electrode voltage (100 kV) (this is no problem for the low duty cycle of proton injectors) allows an accelerated beam of 100mA (current limit 190mA in LANL notation). This gives a large safety margin for acceleration from H^- soures.

This new design has been checked with PARMTEQ. Application for high current heavy ion acelerators, for which the beam current could also be increased by a significant factor, leads to improved designs (U^{2+}, U_Q=150 kV, T_i=2.5keV/N, f=27.1MHz, I_M= 60 mA) at higher operating frequencies than originally were planned.

RF Design

The electrodes have to be periodically charged by a rf current source which normally is one kind of resonator e.g. the 4Vane-, double H-, Split Coaxial- or the 4Rod-$\lambda/2$ 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 $(L_c/\lambda_o)^2$ (λ_o= rf-wavelength).

They all are heavily loaded by the quadrupole electrodes which degenerate the cavity in the first order to an inductivity. The shunt impedance R' ($R'=U_Q^2*L_c/N$) is inversely proportional to the surface resistance (including contacts) and to the square of the electrode impedance $R' \sim (R_S*\omega^2 C_Q{}^2)^{-1}$.

The electrodes are characterized by the ratio of beam aperture to the radius of pole tips. So optimisation for a 4Vane cavity

leads to a cloverleaf structure and a small pole tip radius. Frequency and Q values can be computed by SUPERFISH which is an advantage. But the real capacity of the electrodes as well as the real inductivity of a cavity with rf- and pumping ports and especially with ends cannot be calculated precisely.
Thus for tuning to the operating frequency a change of vane position or cavity volume is necessary. A special problem is the tuning of the end cells because the azimuthal symmetry has to be kept while 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 4Vane cavity has the special problem, that dipole modes can easily be exited. Thus stabilizing with Vane Coupling rings (VCR), prosed by Schneider (LBL), and resonant Loop Couplers (RLC), which advantageously do not interfere with the vanes, have been used to stabilize the resonator. Now the RLCs have also been tested in the middle of a cavity, coupling via short transmission lines outside the cavity. Longitudinal stabilisation which is of the same importance for all structures has up to now been realized successfully only on low power levels. Tuning the 4Vane cavity is tedious and a stabilizing system eases the tuning and operating substantially.
The Split Coaxial resonator developed by R.W.Müller (GSI) is specially suited for low frequency operation with heavy ions. It is a TEM like cavity in which the field has been flattend by introducing spears which carry finger drift tubes. The structure is asymmetric that means one electrode is on ground potential and the axis potential is oscillating with +/- $U_Q/2$. It is essentially a $2\beta\lambda$ (focusing) structure, which is expected to be one reason for difficulties especially at the low energy end of the structure. It has been operated with vane and rod electrodes too and the efficiency was somewhat better with rods, due to the smaller capacity compared to finger electrodes.
The 4Rod - $\lambda/2$ RFQ structure developed since 1978, after the news about RFQs spread out (from LANL!), is based on the work on postaccelerator structures like helices and spirals. It is a structure also well suited for lower frequencies and heavy ions and has been operational at DESY as H^- injector without problems. The 4Rod structure consists of $\lambda/2$ 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 4Vane resonators.
The HERA 4ROD RFQ resonator has been further optimized for the CRYRING application now using basicly circular stems which converge to fingers carrying the rod electrodes. For heavy ion application a 27 MHz resonator has been built which uses supporting stems consisting of circular arcs forming on "open spiral" as shown in Fig.4. The tank diameter is only 50 cm. A split coaxial resonator is also suited for this frequency but the higher capacitive load favours the 4Rod cavity. Fig. 5 compares the shuntimpedance of different RFQs which should be on one line if geometrically scaled.

Sparking

Besides the choice of injection energy and operating frequency the electrode voltage is a starting parameter for the particle dynamics design. Wangler and Junior have shown, that the current which can be accelerated depends on the maximum voltage U_Q which therefore should be close to the breakdown voltage U_B. This 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. The mechanism is thought to be ignited by x-rays, secondary e^- emission and Hydrogen impact. Kilpatricks Criterion for the breakdown voltage can be approximated for the parameters of interest for RFQs by: $U_K[kV]=10\cdot(1+g[mm])(1+1.5\cdot10^{-3}f[MHz])$. Voltages U_K up to two times "Kilpatrik" can be applied in cw operation, whilst higher values can be reached in pulsed operation e.g. Gerhard and Kipper measured $U_Q=3.5U_K$ with the Spiral-RFQ shown in Fig.4 (3%d.c.).
Because sparks should in a probability process be proportional to the area which has the minimum distance and to the time of the operation ore the rf-pulse. Therefore extrapolation of results from "Sparkers" is limited. To reduce secondary e^--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

Mechanical design is most important for a reasonable alignment and tuning procedure and a reliable RFQ operation. So some mechanical aspects should early be entered into the particle dynamic design as well as rf optimisation.
3D vane tip milling, choice of rod or finger electrodes and high duty cycle operation are obvious examples where mechanical considerations enter early. Although the first RFQ projects have been very successful they showed problematic points also, like long time stability, the contacts, erosion, cw-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 contact and the tuning influence the rf-power consumption but this is not a major concern. High duty cycle or CW cavities are by far more unforgiving. A better shunt-impedance eases rf power demands and cooling as well.
The various labs have developed own methods and rules for construction. Fiducial notches, plated Vanes, VCRs, Manifolds, RLCs, 3Point adjustment, separate function design, shims or positioners, Window frames, rf-compensation of unsymetries, gold plating or even none of these don't keep the RFQ from working, but the details of the design are important for (long time) operation and also for beam properties.
The general trend is a reduction of complexity of the mechanical design. The LBL design keeps separate vanes while Hansborough, Potter and 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 Boltezar or copper forming procedures (LANL) are applied.
The use of 4Rod or Vane Electrodes (Leipe) in a Split Coaxial structure are a first similar measure to simplify mechanical properties. The 4Rod RFQ from the beginning was also aimed to simplify the mechanical reqirements but is still far from being "easy to manufacture". The conversion to linear stem arrangements, a base plate similar to the Girder in an Alvarez, the new modified stems and electrode supports are thought to be rf- as well as mechanical improvements.
For low frequency applications this corrensponds to the application of the "open spiral" design, as being applied in a number of Buncher Cavities for GSI (Häuser), and changes of the support and possible application of linear structures.
Another aspect influencing the quality of the design is the difference in "language" of users and people working on ion sources, particle dynamics, rf design or mechanical problems.
This is illustrated e.g. by the still unknown tolerance requirements with respect to particle dynamics, determining rf- and mechanical tolerances.
The possible future application of RFQs for NET and ITER (heating with MeV D-beams) also indicates the problems. The solutions will apply electrode voltages in the order of MV as indicated in Fig. 6 and MWs (cw) of rf and beam power. The problems can only be solved by interference of all RFQ aspects.

Acknoledgements:
Besides the basic RFQ literture cited here, there should be numerous papers and personal reports dealing with aspects of RFQ design. As a compromise, I just thank my friends for help.

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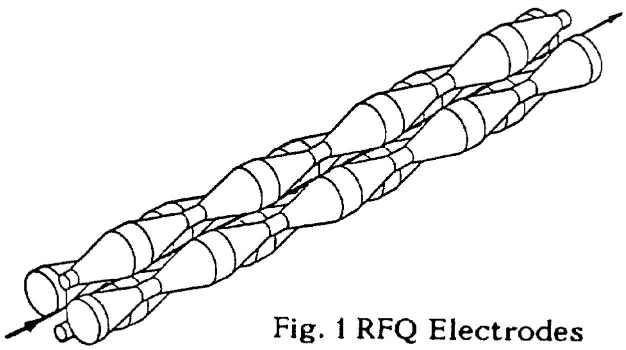

Fig. 1 RFQ Electrodes

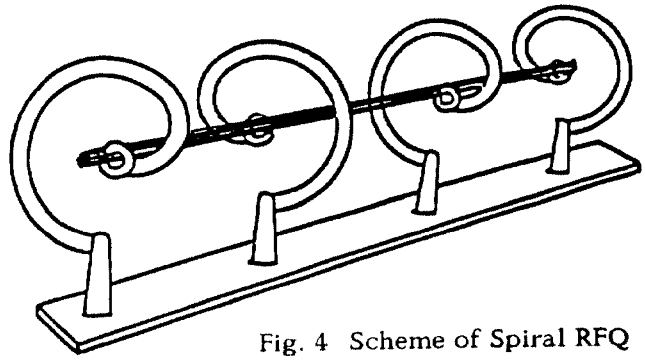

Fig. 4 Scheme of Spiral RFQ

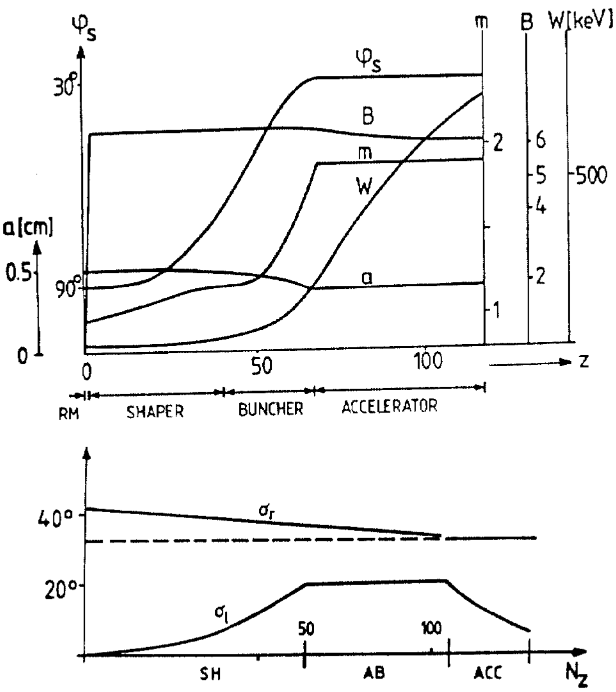

Fig. 2 HERA RFQ Design

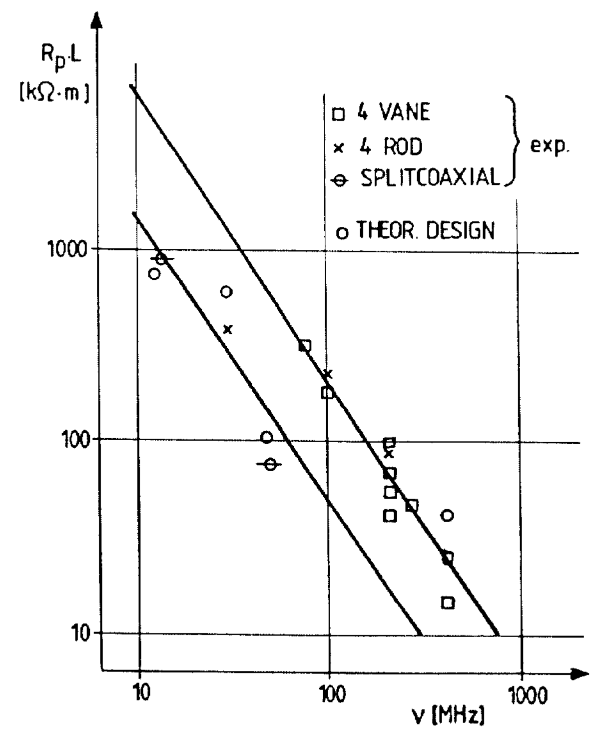

Fig. 5

RFQ Impedances as function of operating frequency

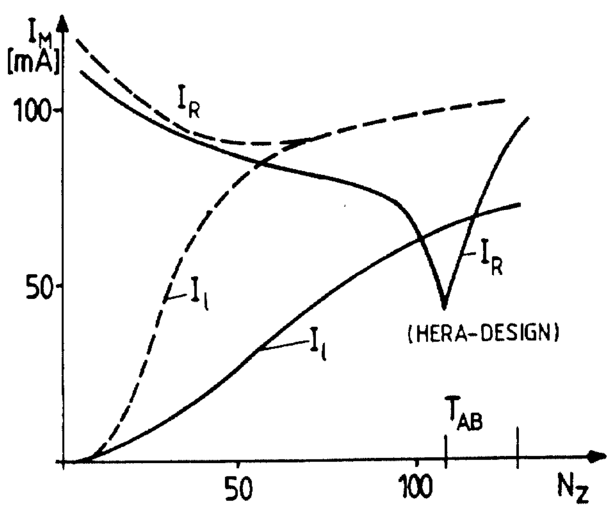

Fig. 3 Maximum current I_M along the RFQ

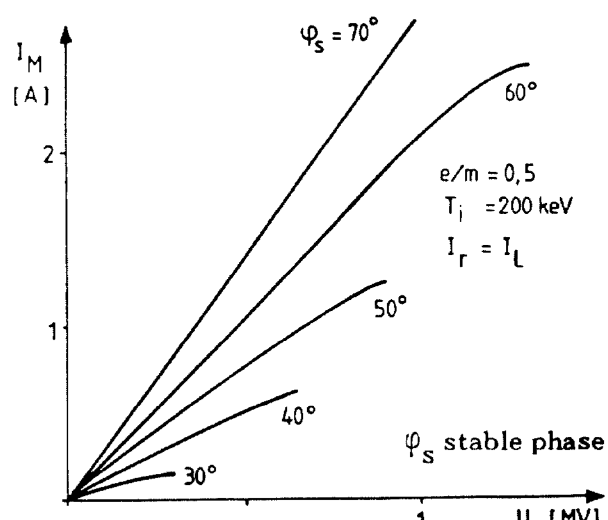

Fig. 6

Max current I_M as function of electrode voltage