FIELD STABILIZATION OF RFQ STRUCTURES

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Abstract

RF stability and tuning tolerances seem to be bottlenecks of RFQ projects. In this paper several methods of field stabilization, which should facilitate construction, tuning and operation, are discussed. Results of first experiments are presented.

Introduction

The RFQ has been established as the new preacceleration system for light as well as for heavy ions[1]. Fields of development are the beam dynamics aspects of electrode design determine the beam properties and the RF design of the cavities providing the necessary focussing and accelerating fields.

The main parameters are determined by the specific application and the beam dynamics requirements. The cavity must be optimized after choice of ion species, duty cycle and energy range.

RF aspects concerning resonator design are the choice of type of cavity for design frequency and energy range and aspects of cooling, alignment, tolerances and operation stability. The most common RFQ structures for light ion acceleration is the 4 vane structure, which has been developed in an RF manifold driven version in Los Alamos[2,3]. For high duty cycle operation and long structures severe thermical problems arise resp. in case of heavy ions a different kind of resonator has to be chosen.

A basic problem is the choice of structure parameters, which provide a constant accelerating and focussing field distribution like used in the beam dynamic design codes, which in addition should be reached in a simple and effective way and should stay stable also in presence of thermal as well as beam loading. The RFQ field distribution is a complex function of electrode capacities, quadrant inductances, perturbations and losses. The field can be expanded in terms of normal modes of the ideal cavity. The contribution of a neighbouring mode is inversely proportional to the frequency separation

$$\frac{|E_n - \bar{E}_0|}{E_0} \sim (|\omega_n^2 - \omega_0^2|)^{-1}$$

The influence of the next neighbouring mode normally is dominant, so especially for long cavities (or systems with many cells) the specific design must maximize the frequency difference to the next mode to give a stable field distribution in the wamted mode (in this context problems of overlapping of modes due to losses and induced phase shifts due to power flow will be neglected).

The 4 vane RFQ is a structure operating at cut-off-frequency in 0-mode and azimuthally in π-mode. So very small frequency seperation and group velocity being the main problem of this structure. Especially field unflatness caused by fabrication and tuning tolerances set a limit of the applications of the 4 vane RFQ. To improve tolerances, these group velocities must be made sufficiently high or, in an equivalent description, the coupling between cavities or the frequency separation between neighbouring modes must be increased. Solution can be coupling resonators like the manifold or vane coupling rings for the azimuthal stabilization.

The basis for the investigations has been the work on coupled cavities and field stabilization schemes for high energy structures and the work on 4 vane RFQ structures in Los Alamos[4,5]. Some ideas for field stabilization have already been discussed with the manifold driven RFQ[2].

The schemes proposed here for stabilizing of fields in the RFQ can be divided up into schemes, which increase the coupling between cells or parts of the structures and secondly connecting cells by additional resonant coupling devices and making use of $\pi/2$-mode operation.

Coupled Cavities

The coupled circuit model has been an effective tool for the understanding of the RF properties of accelerating structures. With impedance or chain-matrix representation of coupled resonators especially dispersion properties, effects of tuning, perturbations and tolerances can be calculated. The 4 vane RFQ cavity can be described by a 3-dimensional array of discrete resonators represented by their resonance frequencies ω_i and the coupling strength γ between them (stored energy normalization will be used). In a first step the influence of higher longitudinal modes will be neglected. But as shown in fig. 1 also for one cross section a 9x9 matrix has to be used for the manifold RFQ system with coupling cells, which only can be solved numerically. J. Potter and R. Hutcheon have developed methods of solving the problem of detecting tuning errors and by using three-dimensional lumped circuit descriptions of the 4 vane RFQ[6,7] resulting in very sophisticated tuning procedures but not changing tuning sensitivity. In the following effects will be demonstrated with a minimum number of cells, in which case the behaviour can be shown easily.

The tolerances of two coupled cavities expressed by the ratio of normalized currents in the cavities can be easily derived from the impedance-matrix A

$$A = \begin{pmatrix} \alpha_1 & \gamma \\ \gamma & \alpha_2 \end{pmatrix} \qquad \alpha_i = 1 - \frac{\omega_i^2}{\omega^2} \qquad I_0 \ (1,1)$$

$$\alpha_{0,\pi} = \pm\gamma \qquad I_\pi \ (1,-1)$$

$$\text{cell frequency} \quad \omega_i = (L_i C)^{-1/2}$$

$$\gamma = M_{12}/\sqrt{L_1 L_2}$$

The frequencies of $0,\pi$-mode are determined by det A = 0. A frequency shift of $\Delta\alpha_{1,2} = \pm\varepsilon$ causes the current tilt to be $\Delta I = \pm\varepsilon/\gamma$. Unfortunately the coupling γ between two adjacent quadrants and also between the RF manifold and the RFQ is weak.

So the aim was to increase this coupling strength between the existing manifold and the 4 vane cavity system. Besides distribution of RF power from the waveguide to the RFQ with minimum field perturbation[7] the inherent stability of the coaxial manifold can be used to improve the field distribution in the RFQ itself.

Another way of increasing the coupling is the use of same coupling rings used by LBL[8] similar to the magnetron straps[9]. For next neighbour coupling the tridiagonal matrix elements now are: $a_{ii} = \alpha_i - g$; $a_{i,i+1} = g + \gamma$. The matrix shows the normal transformatoric coupling $\gamma = M/L$ and in addition "galvanic" coupling with $g = L/(2L+L_c)$ (L_c = inductance of coupling ring). The dispersion relation

$$\omega_a^2 = \omega_0^2/(1 - g + (g + \gamma)\cos\phi)$$

shows that a low impedance L_c does not influence the 0-mode but drives all other modes towards higher frequencies. The stabilizing effect is vanishing for higher values of L_c.

For a ring of 4 cavities representing the RFQ with shortening rings the matrix is

$$A_4 = \begin{pmatrix} \alpha-g & \gamma & g & \gamma \\ \gamma & \alpha-g & \gamma & g \\ g & \gamma & \alpha-g & \gamma \\ \gamma & g & \gamma & \alpha-g \end{pmatrix}$$

$$\omega^2 = \omega_o^2/(1 - g + \gamma\cos\phi + g\cos2\phi)$$

Because of the flux distribution in the 4 vane RFQ the condition $\Sigma I_i = 0$ does not allow azimuthal 0-mode.

Increase of "normal" coupling strength can be achieved to some extend by increase of the slot area, which would disturb the fields in the RFQ.

Loop arrangements should be able to tie a larger part of the flux in neighbouring cavities together. They fit into existing RFQ-manifold schemes, because they can be orientated differently on both connected cavities.

Fig. 2 shows possible arrangements of azimuthally coupling with loops respectively loop coupled lines. There are schemes mounted on the vanes but also arrangements like RF power loops from the tank outside. Calculating the coupling strength of such loops[10] the resulting coupling strength is clearly higher than for coupling slots

$$\gamma_{Loop} = \frac{F_L^2}{F_{Cav}^2} \cdot \frac{L_{Cav}}{L_{Loop}} \qquad L_L \cong \mu_o \frac{R}{2} \ln \frac{4R}{r}$$

but the value of 1 % for a loop with 10 % of the quadrant area is not really satisfying. The impedance of the loops is still too high to couple enough energy into the next cell. This can be achieved by making the loop respectively the slot resonant. Resonating slots have been suggested very early by J. Potter, but the capacities have to be very big, so mechanical design is difficult and in addition the net coupling is still small[2]. Using a similar method by inserting a $\lambda/4$-oscillator in the slot[11] gives the same properties. Loops can be made resonant very simple by adding a mid-capacity or adjusting resonant length. With resonant coupling the field distribution in the RFQ is tightly attached to the longitudinal and transverse stability of the fields in the manifold. So tolerances relax to the requirements of beam dynamics.

Properties of resonant coupling have been discussed for almost all high energy structures[12-17]. Treating the coupling element as a separate cell (ω_C, α_C) the simplest matrix is:

$$A_3 = \begin{pmatrix} \alpha_o & \gamma & 0 \\ \gamma/2 & \alpha_C & \gamma/2 \\ 0 & \gamma & \alpha_o \end{pmatrix} \quad \begin{matrix} \omega_C = \omega_0 \\ \text{Solutions} \\ \alpha_{0,\pi/2,\pi} = -\gamma,\ 0,\ +\gamma \end{matrix}$$

$$I_o(1,1,1),\ I_{\pi/2}(1,0,-1),\ I_\pi(1,-1,1)$$

An important property of the $\pi/2$-mode, which can be used for definition of resonant coupling is that in case of perturbations (e. g. $\alpha_o = \pm\varepsilon$) the currents stay constant, while there is current in the nominally unexcited cell: $I_o(1,-\varepsilon/\gamma,1)$. This can be used for definition of resonant coupling. As can easily be seen from A_3, There is no tilt as in $0,\pi$-mode, but changing the frequency of coupling cell produces a tilt proportional to γ^2. In the context of frequency separation (group velocity) the operation in $\pi/2$ has maximum $\Delta\omega$ and in addition contributions of neighbouring modes cancel because of symmetries.

Fig. 3 shows the net frequency separation as function of coupling cell frequency. Compared to the case of a nonresonant coupling element ($\omega_C \gg \omega_o$) where the coupling constant is γ^2, now for $\omega_C = \omega_o$ the coupling is γ. So varying the frequency of the coupling cell ω_C without changing the intrinsic geometrical coupling (size of slot, loop, aperture, etc.) will change the effective coupling γ in a wide range ($\gamma \to \sqrt{\gamma}$). So all loop schemes presented (fig. 2) can be made resonant. According to the formula for γ_L that can be done with help of a tuning capacity or inductance outside the quadrants (fig. 2c,d).

Measurements on a loop coupled coaxial resonator system with a loop (half) area of 10 cm² result in a coupling strength of 17 %. Fig. 4 shows the loop and frequencies of the 3 resonator systems as function of loop frequency. The 90° loop (fig. 5) was tuned with a capacity paddel in the coupling slot.

Azimuthal stabilization has been tested on the cloverleaf-RFQ-model described in [2]. Dipole modes have been shifted away more than 50 MHz compared to the normal value of approximately 1 - 2 MHz just by "connecting" opposite quadrants with small loops and a line with total length of $\cong \lambda/2$ corresponding to scheme of fig. 2d.

The loops can be used to make the coupling slots between the manifold and the RFQ resonant. In two slots of the same RFQ-model two resonant loops (same size as above) had been inserted at both ends of one quadrant and tuned with slot capacity to the RFQ frequency of 315 MHz. Fig. 6 shows the experimental arrangement. The RFQ was detuned by moving the end tuners on one side of the cavity, being only 0.2 mm away from short for $\Delta\nu$ = 5 MHz[17]. The coupling constant of the manifold loop RFQ-system was 23.8 %, which is in good agreement with theory, because the coupling is proportional to the number of parallel coupling cells $\gamma_{eff} \sim \sqrt{n}\cdot\gamma$. For comparison in fig. 7 the detuning without resonant loops is shown, which gives a field tilt of up to 1:5. Thus by stronger resp. resonant coupling the stability could be improved considerably. But there still is the somewhat inflexible coupled cavity system being very bulky for low frequencies and having stored energy in the manifold.

For the RFQ without manifold other stabilizing schemes have to be used.

Longitudinal Stabilization

The 4 vane RFQ cavity is operated in TE_{210}-mode, to which a TE_{211} can be transformed by proper terminating the "4 vane line". With fig. 8 such TE-lines near cut off can be described by the dispersion relation

$$k_z^2 = \frac{L_1}{L_o}\left(1 - \frac{\omega^2}{\omega_o^2}\right) = R/Z \ ,$$

in which the longitudinal inductance L_1 is deduced from the transmission line properties of the electrode region[7], while L_o is the quadrant inductance giving the resonance frequency. So the frequencies of the next higher mode are determined by the ratio L_1/L_0. With an appropriate chain matrix representation of the RFQ-line a simple matrix formulation can be found using methods of particle dynamics[8]. For the circuit in fig. 8 the longitudinal 0-mode frequency for open circuit boundary conditions ($\cos\mu = +1$) leads to $R/Z_i = 0$, which can be fulfilled for $R \to 0$ or $Z_i \to \infty$.[1]

To achieve a flat field distribution 0-mode must be obtained for all cells. But any nonuniformity will lead to a voltage drop at R, the longitudinal impedance of the line, which can not be changed ($Z_{1,2} = Z_o \pm \varepsilon$; $I_R = \varepsilon/R$).

A solution will be an increase of coupling strength by bypassing R with a low impedance R' (like in case of shortening rings) or by making R or R' resonant.

For structures working near cut off the dispersion curve has a parabolic shape, it starts with zero group velocity and with small mode separation. Using these general properties J. Potter has given a formula for tolerances for structures working at band edge[6,19], which does not include effects of dipole modes. Realization of such a resonant by-pass could be done in several ways. Fig. 9 shows several versions of transmission lines parallel to the vanes. A single cell could be described as a capacitively coupled λ/2-line attached to the vane. Any imbalance would excite the "stabilizing bar", the chain of bars or the transmission-line along the vane and power flow would equalize the fields along the structure. The line could be coupled either capacitively or inductively again via loops from the RFQ outside. By proper terminating the stabilizing line it can be kept free of stored energy. Chain matrix description of a transmission-line parallel to the RFQ-line (fig. 10) leads to 4x4 matrices as basic cells

$$\begin{pmatrix} 1+R_1/Z_1 & (2+R_1/Z_1)/Z_1+R_o/Z_c^2 & -R_o/Z_c & -(2+R_1/Z_1+R_o/Z_o)/Z_c \\ R & 1+R_1/Z_1 & 0 & -R_1/Z_c \\ -R_1/Z_c & -(2+R_1/Z_1+R_o/Z_o)/Z_c & 1+R_o/Z_o & (2+R_o/Z_o)/Z_o+R_1/Z_c^2 \\ 0 & -R_o/Z_c & R_o & 1+R_o/Z_o \end{pmatrix}$$

$$\vec{E} = (I_1, U_1, I_o, U_o)$$

With asymmetry in the TE-line $R_o/Z_o \rightarrow R_o/Z_o \pm \varepsilon$ and $\cos\mu = 0$:

$$E_\varepsilon(1/Z_c, \varepsilon \cdot Z_c/R_o, 0, 1)$$

The eigenvector $\vec{E}$ shows the properties of this stabilized cell. 0-mode in the lower part can be provided also in case of different Z_o resonators, which represent tuning or machining errors along the structure. Assuming an internal π-mode of the stabilizing line, there is a stabilizing current through the coupling impedance Z_c just like in the case of the simple circuit of fig. 8. The strength of such a system is limited by the coupling impedances Z_c. Because 0-mode is preserved independently of the tuning of the TE-line parts, an imbalance is just resulting in some power in the coupling cell, such a system corresponds to resonant coupling (π/2-mode) operation of a coupled cavity system. Comparison with the 0-mode-λ/2-RFQ studied in Frankfurt[20], which can be represented by two parallel TM-lines, shows that the stabilizing effect given by two transmission lines and the quadrupole electrodes acting as stabilizing impedances is very strong. The eigenvector shows that in case of asymmetry $Z_{1,2} = Z_c \pm \varepsilon$ there will be no net current but longitudinal currents within the cell

$$E_\varepsilon = \left(\frac{\varepsilon}{R_o}\ ,\ -1\ ,\ -\frac{\varepsilon}{R_o}\ ,\ 1\right)$$

Since in the chain matrix description the basic cell contains all information, the stabilizing effect will be present also in a chain of cells (numerically properties of neighbouring modes could be determined as well).

Turning the loop (180 °) would stabilize a π-mode operation like for azimuthal quadrant stabilization or in case of 0-mode changes the transmission-line from a stabilizing line to a driving line like a 4 vane resonator with a manifold. This shows a simple way of testing the principle: The existing manifold could be modified by changing the position and angle of the coupling slots to convert the driving manifold to a stabilizing manifold[19,21].

Fig. 11 shows a scheme of the experimental arrangement. Asymmetric detuning with the end-tuners of only one side up to Δf= - 2 MHz didn't change the field flatness at all. For greater detuning the limited coupling strength of the slots couldn't provide enough power flow as indicated by the eigenvector I_ε. The experiments showed that such a system stabilizes the fields but again the coupling must be made stronger. Replacing the slots by coupling loops would provide such strong coupling.

Conclusions

Some possible schemes for azimuthal and longitudinal field stabilization of RFQ resonators have been discussed. They use low impedance and resonant coupling devices to connect the different parts of the RFQ structure . Tests with cold models show promising results.

Up to now only shortening rings have been tested in high power tests at low duty cycles. Some of the new schemes, especially those, which do not interfere with the vane, will undergo high power tests in future.

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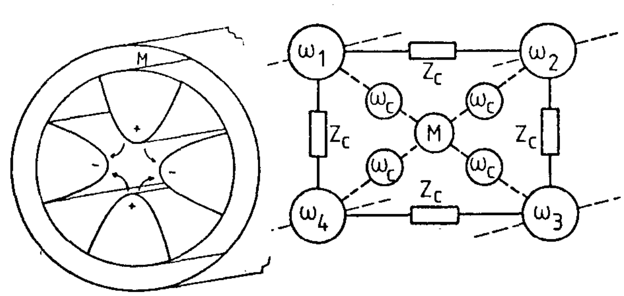

Fig. 1 Scheme of an RFQ resonator system

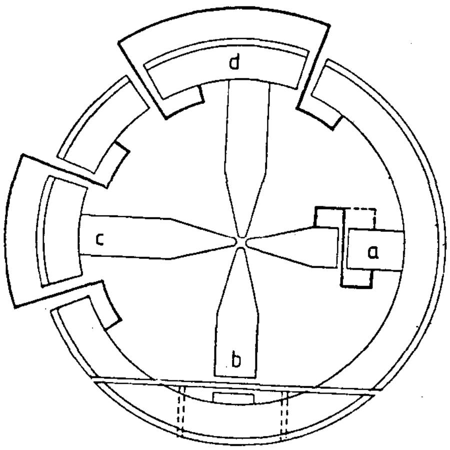

Fig. 2 Azimuthal stabilization loop schemes

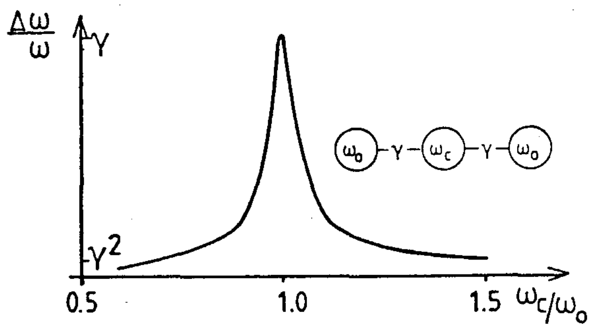

Fig. 3 Coupling strength as function of coupling cell frequency

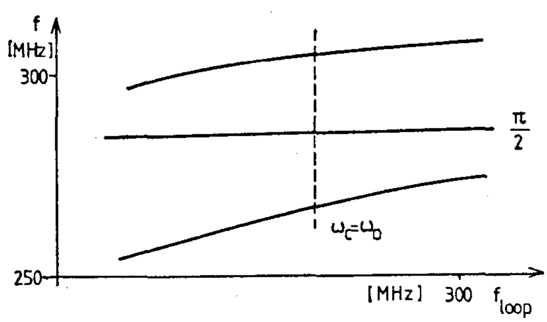

Fig. 4 Mode frequencies of loop coupled coaxial resonators

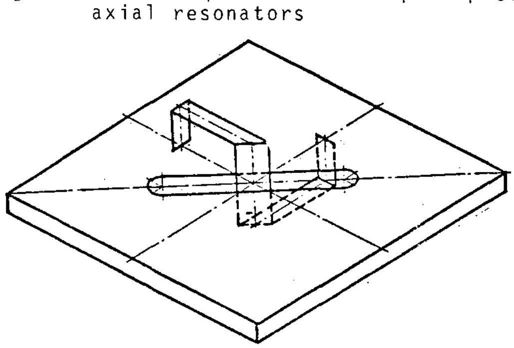

Fig. 5 Sketch of orthogonal loop in a coupling slot

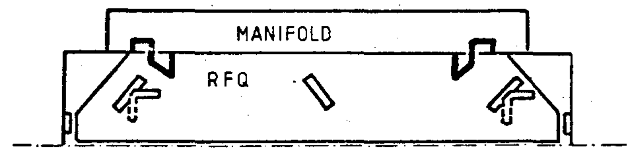

Fig. 6 Experimental set-up for resonant loop coupled RFQ-manifold

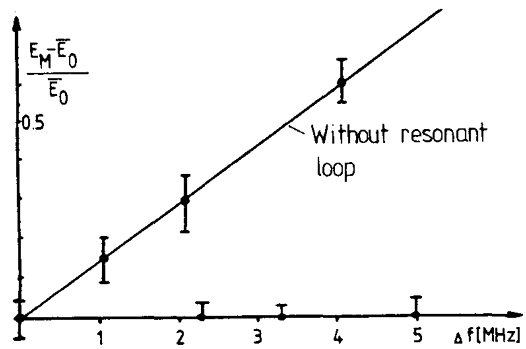

Fig. 7 Field tilt versus detuning frequency

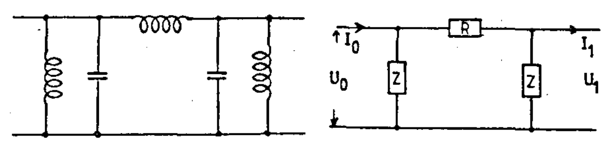

Fig. 8 TE-mode circuit

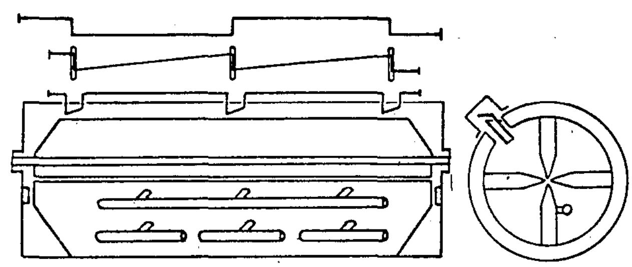

Fig. 9 Longitudinal stabilization schemes

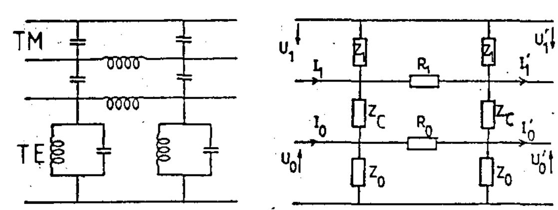

Fig. 10 TE-stabilization network

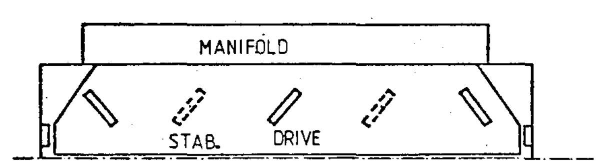

Fig. 11 Manifold as stabilizing coaxial line