

POSSIBILITY OF THERMAL INSTABILITY FOR 4-VANE RFQ OPERATION WITH HIGH HEAT LOADING

V.V. Paramonov*

Institute for Nuclear Research of the RAS, Moscow, Russia

Abstract

Due to dispersion properties, 4-vane RFQ cavity without resonant coupling is a thermally unstable structure. With deterioration of balance for local detuning there is a possibility for runaway in the field distribution and related thermal effects. It can result, in principle, in irreversible plastic deformations and cavity frequency shift. Both the increment and the threshold of instability are proportional to the average dissipated RF power. This possibility is more probable for long RFQ cavities. Also particularities for the cavity ends design are important. Some general features of this effect are discussed and illustrated with simulations.

INTRODUCTION

The Normal Conducting (NC) RFQ cavity is now the indispensable part of the hadron's linac. For proton linac 4-vane RFQ with operating TE_{210} mode is now prevailing. The sensitivity of the field longitudinal distribution to the shape deviations in such cavities strongly depends on the relative RFQ length $\frac{L_c}{\lambda_0}$, where L_c is the RFQ length and λ_0 is the operating wavelength. To reduce it for long RFQ cavities, $\frac{L_c}{\lambda_0} \geq 5$ the resonant coupling with special coupling cells was proposed [1], providing for RFQ properties of compensated structure in the field distribution sensitivity and stability. The shorter RFQ cavities, $\frac{L_c}{\lambda_0} \leq 5$, as a rule, are without coupling cells. In this report the stability of the longitudinal field distribution in time for RFQ without resonant coupling is considered with respect to thermal induced geometry perturbations.

OPERATING REGIME STABILITY

In modern proton linac's RFQ operate with the frequency $f_0 \sim (324 \div 402.5)MHz$, maximal electric surface field $E_{sm} \sim 1.8E_k \approx (25 \div 32)\frac{MV}{m}$, which corresponds to the maximal magnetic field at the regular RFQ surface $H_{sm} \sim 5.2\frac{kA}{m}$. It results in the pulse heat dissipation is of $P_p \approx 100\frac{kW}{m}$. Even for operation with duty factor $d_f \sim (1 \div 6)\%$ the average heat dissipation $P_a \sim (1 \div 6)\frac{kW}{m}$ is significant for thermal effects. The temperature of the cavity increases and f_0 decreases due to the cavity expansion. For the fixed cooling conditions the cavity frequency shift df_0 is linearly proportional to P_a . Suppose a steady-state high RF power operation with a reference field distribution in the cavity is achieved. Let us suppose a small local temperature deviation $\delta T > 0$ at

the cavity surface due to some reasons. It may be either cooling fluctuation or electric discharge. This local temperature deviation leads to the local cavity expansion and local frequency change δf . The local frequency change δf immediately results in the change of the field distribution along the cavity and the change of the field in place of local heating. Depending on the cavity dispersion properties, two options, shown in Fig. 1, are possible.

In the first case, Fig. 1a, the local field relatively decreases.

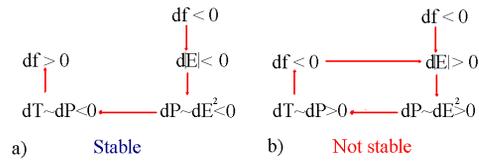


Figure 1: Thermal stable (a) and unstable (b) chain.

The local RF power dissipation decreases, the local temperature decreases, the local frequency increases, canceling or reducing initial frequency deviation δf . It is the stable case. After some time the cavity returns to operation with the reference field distribution.

In the second case, Fig. 1b, the local field, together with the local RF power dissipation, relatively increases, the local temperature increases, the local frequency decreases, amplifying initial local frequency deviation δf . Self-amplifying runaway starts and in the cavity itself there is no physical mechanism, which can stop it.

The thermal stability of operation for multi cells NC cavities was considered in [2]. All time the compensated structures can be tuned for stability conditions by appropriate choice of the stop-band width, [3], [2]. The simple multi cells structure with operating 0-mode and positive dispersion is unstable. RFQ cavity has no marked cells, but operating mode TE_{210} is zero type mode and dispersion for TE_{21n} modes is positive.

The deviation of the quadruple field longitudinal distribution along RFQ is the result of TE_{21n} modes superposition. The field distribution \vec{E} in the cavity with a small dimension deviation ΔV can be described as [4]:

$$\vec{E} = \vec{E}_0 + \sum_n \frac{\vec{E}_n f_n^2 \int_{\Delta V} (Z_0^2 \vec{H}_0 \vec{H}_n^* - \vec{E}_0 \vec{E}_n^*) dV}{W_0 (f_0^2 - f_n^2)}, \quad (1)$$

where $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$, $\int_V Z_0^2 \vec{H}_n \vec{H}_m^* dV = \int_V \vec{E}_n \vec{E}_m^* dV = \delta_{nm} W_0$ and V is the cavity volume, \vec{E}_0, \vec{H}_0 are the electric and the magnetic field distributions for operating TE_{210}

*paramono@inr.ru

mode and $f_n, \vec{E}_n, \vec{H}_n$ are the frequency and fields distributions for TE_{21n} mode. The similar relation for description of a field perturbation in the chain of coupled cavities is given in [5] with a matrix form.

In 4-vane RFQ without coupling cells the frequency and field distribution along the cavity for TE_{21n} mode are:

$$f_n^2 \simeq f_0^2 + \left(\frac{nc}{2L_c}\right)^2, \quad \vec{E}_n \simeq \sqrt{2}\vec{E}_0 \cos\left(\frac{n\pi z}{L_c}\right), \quad (2)$$

where c is the velocity of light. Transforming (1) with suggestion the volume deviation ΔV is placed at $z = z_0$, taking into account (2) and using frequency perturbation theorem, one can get:

$$\vec{E} \simeq \vec{E}_0 - \sum_n \sqrt{8}\vec{E}_0 \frac{\delta f_0}{f_0} \left(1 + \frac{4L_c^2}{n^2\lambda_0^2}\right) \cos\left(\frac{n\pi z_0}{L_c}\right). \quad (3)$$

As one can see from (3), the negative local frequency deviation $\delta f_0 < 0$ at the cavity end leads to the local field increasing $\delta|\vec{E}| = |\vec{E} - \vec{E}_0| > 0$. Without resonant coupling 4-vane RFQ cavity is thermal unstable.

Most dangerous is the detuning of the cavity ends, $z = 0, L_c$. This effect linearly rises with the cavity length $\frac{L_c}{\lambda_0}$, because the relative detuning $\frac{\delta f_0}{f_0}$, caused the same absolute local deviation δf_0 is inverse proportional to L_c . The dependence of $\frac{\delta|\vec{E}|}{|\vec{E}_0|}$ increasing on the cavity length $\frac{L_c}{\lambda_0}$ is shown in Fig. 2, assuming the detuning $\delta f_0 = -10^{-3}f_0$ of the cavity part with $0.1\lambda_0$ at the cavity end $z = 0$.

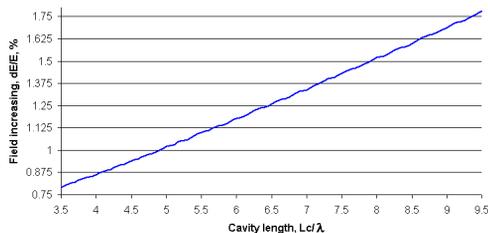


Figure 2: The longitudinal field distribution sensitivity to the RFQ end detuning δf .

RFQ ENDS DETUNING

The RFQ vanes have undercuts in the cavity ends to return magnetic field flux, to tune the cavity frequency and tune longitudinally the field distribution. Different shapes are known - the undercut with a small tip ($N1$ in Fig. 3a, [6]), the undercut with a moderate tip ($N2$ in Fig. 3b, [7]) and mostly distributed undercut with inclined tip, see, for example SNS RFQ, [8]. The last one can be realized both with vertical ($N3$ in Fig. 3c) and inclined ($N4$ in Fig. 3d) outputs of the vane cooling channel.

For all undercut options the maximal value of magnetic field and related dissipated heat density takes place at the cavity ends. Additionally, the vane cooling channel may be at enlarged distance from the undercut tip, as one can see from Fig. 3. All options, shown in Fig. 3, were tuned for

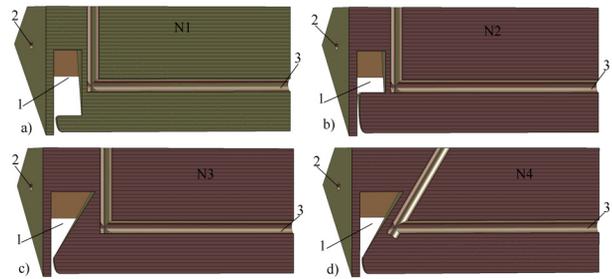


Figure 3: Different options for vane undercuts and cooling channels. 1 - vane undercuts, 2 - the channels for cavity body cooling, 3 - the vane channel.

operating frequency and a flat field distribution along the cavity. Initial thermal-stress analysis has been performed according [9] in engineering approach assuming the duty factor of 3% ($P_a = 0.03P_p$) and the average flow velocity $V_{av} = 1.5 \frac{m}{sec}$. The temperature distributions are shown in Fig. 4.

The undercuts with small and moderate tips ($N1$ and

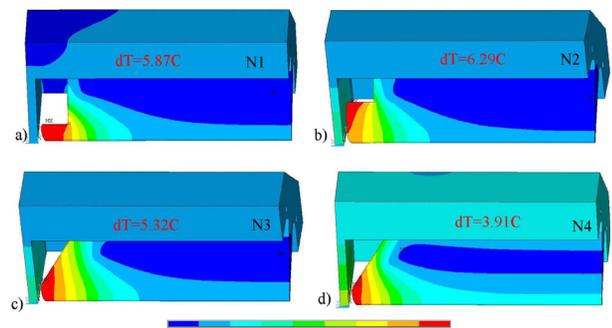


Figure 4: The surface temperature distributions and maximal temperature rise dT values at the vane undercuts for different cavity end design.

$N2$ in Fig. 3a,b) have the larger surface temperature rise $dT = T_{max} - T_w$ with respect to the temperature of cooling liquid. The smallest dT value has the undercut with inclined tip and inclined channel output, $N4$ in Fig. 3d. The distributions of the thermal induced displacements and related frequency shift δf_0 values are shown in Fig. 4. For δf_0 value definition it is assumed, that the detuning is localized near cavity end at the length $0.1\lambda_0$.

Even from the qualitative displacement distributions in Fig. 5 one can see the significant difference between options $N1, N2$ and $N4$ - small and moderate tips move to the cavity end plate. For the inclined undercut with inclined channel the plates moves from the tip, decreasing capacitance. More detailed analysis shows for all undercut both longitudinal and radial ($dr < 0$) displacements. The minimal δf_0 value provides $N4$ option due to better cooling and smaller induced displacements.

The direction of cooling water is very important and can be even decisive. In more details it is presented in [10].

Depending on the design and cooling particularities, ends

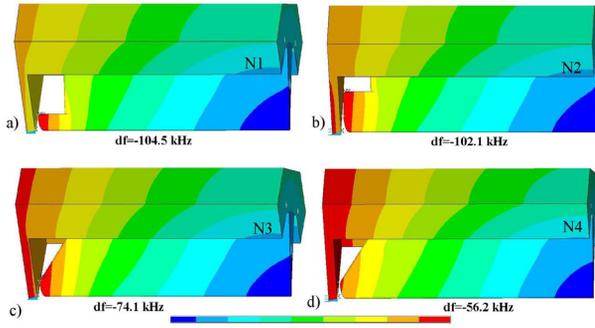


Figure 5: The displacements distributions and induced frequency shift values for different undercuts options.

of RFQ cavity have different values for 'power sensitivity' $\frac{\partial f_0}{\partial P_a}$, which is **not the same** as for regular RFQ part.

INCREMENT AND THRESHOLD

The instability is the result of the coupled RF - thermal - stress - RF interaction and the increment value ζ depends on both cavity RF parameters and cavity material thermal and mechanical properties, details of the design.

Assuming the instability development as $\delta f_0 \sim A_0 e^{\zeta t}$ we get $\frac{d\delta f_0}{dt} = \zeta \delta f_0$. Let us consider the sequence $d(\delta f_0) \sim \delta x \sim \delta T \sim \delta P \sim \delta E \sim \delta f_0$. From (3) it follows $\delta P \sim P_a \frac{L_c^2}{\lambda_0^2} \frac{\delta f_0}{f_0}$. From the equation for thermo-elastic deformations follows $\delta x \sim \frac{\alpha}{E_c} \delta T$, where α and E_c are the linear expansion coefficient and Young module for copper. The time scale of the instability is defined by the slowest process in the sequence - heat propagation, which qualitatively describes by thermal diffusivity $D_c = \frac{K_c}{\rho_c C_c}$, where K_c, ρ_c, C_c are the heat conductivity, density and specific heat values for copper. The dimensions of cavity parts x_i are also important, [10]. Because instability is related to local effects, it depends on the local RF power loss density $P_a^s \sim \frac{P_a}{x_i^2}$. But instability location is not known directly and outside the cavity we see the total average power P_a . For this reason we use more usual P_a term in ζ value estimation. The time scale of instability is shorter, than the time constant of the cavity for RF power input, [10]. Summarizing, we can write expression for instability increment as:

$$\delta f_0 \sim A_0 e^{\zeta t}, \zeta \simeq B_0 \frac{P_a}{x_i^2} \frac{L_c^2}{\lambda_0 c V} \frac{\alpha D_c}{E_c}, \quad A_0, B_0 = const \quad (4)$$

In the frame of presented model, instability starts when there is a powerful RF supply to support essential thermal effects, and one part of the cavity has the negative local frequency detuning with respect total cavity. Most likely candidates are cavity ends, due to stronger effect on field distribution higher in (3) and essentially different $\frac{\partial f_0}{\partial P_a}$ value. The cavity tuning for frequency and field distribution is at RF power signal level, when thermal effects are absent. The RFQ cavity input and output ends, as a rule, have dif-

ferent design and may have different fields values. If after tuning the ends are not balanced in frequency detuning and one end has initial $\delta f_0 \leq 0$, will be startup instability simultaneously with RF power switch on.

For balanced ends and correct cooling scheme there is a power range $0 \leq P_a \leq P_a^{cr}$ for RFQ stable operation, when the balance of local detuning is preserved. There are a lot of operating 4-vane RFQ's, but not with very high average RF power. But, due to different $\frac{\partial f_0}{\partial P_a}$ values, with P_a increasing this balance can become weaker and at some value $P_a = P_a^{cr}$, which depends on cavity design, cooling, tuning and control, will be violated - one cavity end will get negative detuning. It will be start of instability.

In frame of presented model, the instability threshold depends on the average power, dissipated in the cavity. Additional heat sources at the 'weak' cavity part, like electric breakdowns and particle losses [8], can provoke instability or decrease threshold slightly. In more details instability threshold is discussed in [10].

SUMMARY

Consideration shows, that due to dispersion properties, 4-vane RFQ cavity without resonant coupling has the property of thermal instability. If instability started, the cavity has no own mechanism, except inelastic (irreversible) deformation to stop it. Both the increment and the threshold of instability depend on the average RF power, dissipated in the cavity and can limit possible duty factor value for each particular design. Control system for longitudinal field distribution together with fast movable tuners can dump instability.

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