ONE ASPECT OF THERMAL STABILITY 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, especially near cavity ends, there is a possibility for runaway in the field distribution and related thermal-stress effects. It can, in principle, finish with 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 increases 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 imprescriptibly 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. It this report the stability of the longitudinal field distribution in time for RFQ without resonant coupling is considered with respect 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 $E_{sm} \sim 1.8 E_k \approx (25 \div 32) \frac{MV}{m}$, 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.

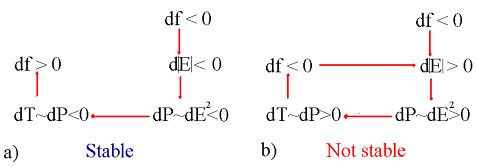

Figure 1: Thermal stable (a) and unstable (b) chain.

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.
As it is shown in [10], without resonant coupling 4-vane RFQ cavity is thermal unstable.

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

As one can see from (1), the negative local frequency deviation $\delta f_0 < 0$ at the cavity end leads to the local field increasing $\delta|\vec{E}| = |\vec{E} - \vec{E}_0| > 0$.
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.

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. 2a,

* paramono@inr.ru

[6]), the undercut with a moderate tip ($N2$ in Fig. 2b, [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. 2c) and inclined ($N4$ in Fig. 2d) outputs of the vane cooling channel.

For all undercut options the maximal value of magnetic

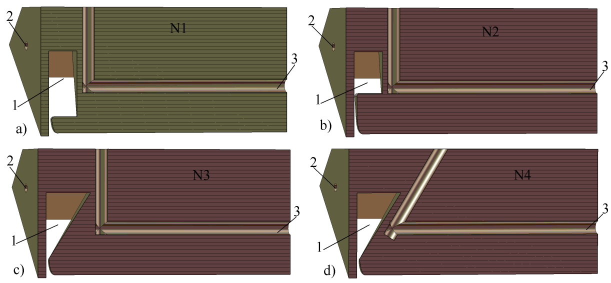

Figure 2: Different options for vane undercuts and cooling channels. 1 - vane undercuts, 2 - the channels for cavity body cooling, 3 - the vane channel.

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. 2. All options, shown in Fig. 2, were tuned for 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% ($P_a = 0.03 P_p$) and the average flow velocity $V_{av} = 1.5 \frac{m}{sec}$.
The undercuts with small and moderate tips ($N1$ and $N2$ in Fig. 2a,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. 2d. In more details the temperature distributions are presented in [10].
The distributions of the thermal induced displacements and related frequency shift δf_0 values are shown in Fig. 3. 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

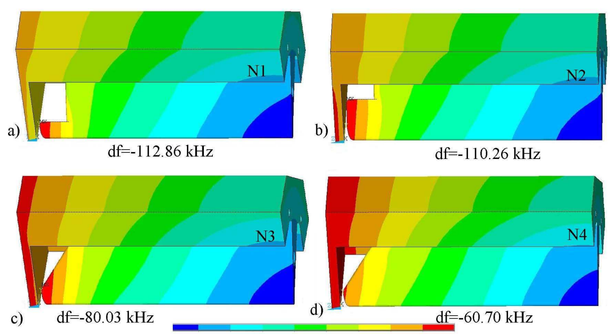

Figure 3: The displacements distributions and induced frequency shift values for different undercuts options.

Fig. 3 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

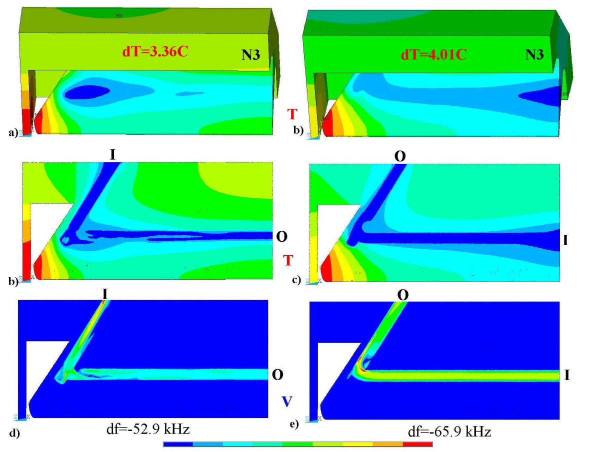

Figure 4: The temperature distributions at the surface (a,b), in the middle of the vane (c,d) for different directions (e,f) of the cooling liquid.

be even decisive. In Fig. 4 the temperature distribution are shown for water flow direction from the cavity end and for reverse case, calculated with the extended procedure [9] starting from CFD simulations. The water input from the RFQ end results in colder vanes and reduced frequency shift. Considering in this approach more longer RFQ part, we can obtain hot region in the cavity middle and even get $\delta f_0 \geq 0$ for RFQ end with respect regular part.
Depending on the design and cooling particularities, ends 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. The precise consideration is too complicated and we can detect qualitative dependencies.
Assuming the instability development as $\delta f_0 \sim A_0 e^{\zeta t}$, and considering the sequence $d(\delta f_0) \sim \delta x \sim \delta T \sim \delta P \sim \delta E \sim \delta f_0$, in [10] the instability increment ζ is estimated as:

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

where where α and E_c are the linear expansion coefficient and Young module for copper, $D_c = \frac{K_c}{\rho_c C_c}$ is the thermal diffusivity for copper, K_c, ρ_c, C_c are the heat conductivity, density and specific heat values for copper, respectively. The increment value ζ scales fasr with the cavity oerating frequency f_0, $zeta \sim f_0^4$.

The time scale of instability can be shorter, than the time

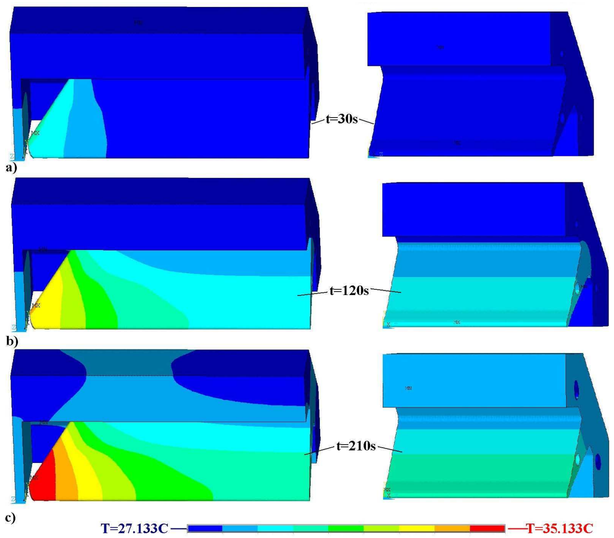

Figure 5: The transient temperature rise at the cavity and (left column) and regular RFQ part (right column) for closed vane channel.

constant of the cavity for RF power input. From Fig. 5 one can see, that local heating, for example at the cavity ends, is faster than more uniform heating of RFQ regular part.

In the frame of presented physical model, instability started 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 to total cavity. Most likely candidates are cavity ends, due to stronger effect on field distribution higher in (1) and essentially different $\frac{\partial f_0}{\partial P_a}$ value. Detuning of the segment near cavity middle at least generate 4 times lower field perturbations, have slower thermal transient and $\frac{\partial f_0}{\partial P_a}$ for middle RFQ is normally assumed for the total cavity.

The cavity tuning for frequency and field distribution is at RF power signal level, when thermal effects are absent, and results fix the initial distribution of local cavity parts detuning. With introducing RF power, sufficient for thermal effects, this distribution changes.

The RFQ cavity input and output ends, as a rule, have different 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 even 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.

During the stable operation for each P_a value there is the total frequency shift of the cavity, which should be eliminated by frequency control system. But this system, as a rule, operates for whole cavity and can not preserve the balance of detuning. The balance of detuning is also specific for each P_a value. Due to different $\frac{\partial f_0}{\partial P_a}$ values, with P_a increasing this balance will become weaker and at some value $P_a = P_a^{cr}$ 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. But original reason of instability in RFQ cavity without resonant coupling is in dispersion properties of such cavity. For stable operation with the high dissipated RF power and in CW regime, 4-vane RFQ cavity should be equipped with coupling cells to have the dispersion and stability properties of compensated structures.

In this work we can not estimate P_a^{cr} value - too many variables from cavity design, cooling, tuning and control.

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.

REFERENCES

[1] M.J. Browman, L.M. Young. Coupled RFQ's as Compensated structures, Proc. 1990 Linac, p. 70, 1990

[2] V. Paramonov, Stability of Normal Conducting Structures Operation ... Proc. 2008 Linac Conf., p.61, 2008

[3] L.M. Young, J. M. Potter. CW Side Coupled Linac for the Racetrack Microtron. Proc. PAC 1981, p. 3508, 1983.

[4] B.P. Murin (ed), Ion Linear Accelerators, v.2, Atomizdat, Moscow, 1978, (in Russian)

[5] E.A. Knapp et al., Coupled cavity model for standing wave accelerator tanks. Rev. Sci. Instr., v. 38, p. 1583, 1967.

[6] A. Ueno, Y. Kondo, RF-Test of a 324-MHz, 3-MeV, H- RFQ Stabilized with PISL's, Proc. 2002 Linac, p. 545, 2002

[7] G. Romanov et al., The Fabrication and Initial Testing of the HINS RFQ. Proc. 2008 Linac, p. 160, 2009

[8] S. Kim et al., Stabilized operation of the SNS RFQ, Phys. Rev. STAB, v. 13, 070101, 2010

[9] A. Skassyrskaya et al., The complete 3-D rf-thermal-structural-rf analysis ... Proc. 2002 Linac, p. 216, 2002

[10] V. Paramonov, Possibility of Thermal Instability for 4-Vane RFQ Operation. Proc. 2010 Linac, TUP060, Tsukuba, 12-17 Sep., 2010.