STABILITY OF NORMAL CONDUCTING STRUCTURES OPERATION WITH HIGH AVERAGE HEAT LOADING

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Abstract

Instead of proved application of superconducting structures for high energy part of intense linear proton accelerators, Normal Conducting (NC) structures are still considered for medium and low energy parts below $200MeV$. Operation with accelerating rate of $\sim 4\frac{MeV}{m}$ and duty factor $\sim 5\%$ results for standing wave NC structure in an average heat loading of $\sim 30\frac{kW}{m}$. Due to the high heat loading an operating mode frequency shift is significant during operation. In this paper conditions for field distribution stability against small deviations in time of individual cell frequencies are considered. For $\frac{\pi}{2}$ structures these conditions were formulated by L. Young and Y. Yamazaki. General case of 0, $\frac{\pi}{2}$ and π operating modes is considered with common approach.

INTRODUCTION

In projects of modern particle accelerators NC structures are consideration for application with the strong heat loading due to high average RF power dissipation. It can be the sequence of a high accelerating gradient E_0T, or long RF pulse, or high RF pulse repetition rate or combinations of these factors. Together with bi-periodical (or compensated) structures, simple periodical structures with 0 or π operating modes are under consideration too due to a simpler design and construction. As it is known well, simple 0 or π mode structures are sensitive in electric field distribution to small deviations of cells frequencies. To ensure required accelerating field homogeneity, not so large number of simple structure periods $N_p \sim 5 \div 10$ should be in the cavity and coupling coefficient should be so high, as reasonable.

Nevertheless, let us suppose the cavity with the simple periodic or bi-periodic structure is tuned for required field distribution and another parameters. But during a high RF power operation a question of thermal stability arises.

THERMAL STABILITY

During a high RF power operation the temperature of the cavity increases and own cavity frequency f_0 decreases due to cavity expansion. For the fixed cooling conditions the cavity frequency shift is linearly proportional to the average dissipated RF power. For a heat loading of $\geq 20\frac{kW}{m}$ the cavity frequency shift df can be of $df \geq 2.0\cdot 10^{-4}f_0$. The cavity frequency for high RF power operation should be adjusted by the change of cooling water temperature.

Suppose we have a steady-state high RF power operation with a reference field distribution in the cavity. Let us suppose, that in one moment the cell with the number j got a small frequency deviation Δf_j due to some random reasons. Mostly possible reason is a fluctuation of a turbulent flow in cooling channels, because the turbulent flow is stable in average. For distinctness we will suppose $\Delta f_j < 0$, assuming cooling ability reduction. The small frequency change of the $j-th$ cell immediately will results in the change of the field distribution along the cavity and the change of relative field balance between cells. Depending on the structure dispersion properties, two options are possible.

In the first case the field in the $j-th$ cell relatively decreases. RF power dissipation in this cell decreases, the cell temperature decreases, the cell frequency increases, canceling initial cell frequency deviation. After some time the structure returns to operation with the reference field distribution. Such structures are thermally stable.

In the second case the field in the $j-th$ cell relatively increases. RF power dissipation in this cell also increases, the cell temperature increases, the cell frequency decreases, amplifying initial cell frequency deviation. Self-amplifying process starts. At least, such process can lead to the change in the filed distribution, because the cooling and control systems operate for the cavity as a whole. Such structures are thermally unstable.

Field distribution description

Suppose we know the total set of modes in the reference unperturbed cavity - frequencies f_ν and field distributions E_ν, H_ν, normalized as:

$$\int_V Z_0^2 H_n H_\nu^* dV = \int_V E_n E_\nu^* dV = \delta_{n\nu} W_0, \quad (1)$$

where $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$ and V is the cavity volume. The field distribution in the cavity with a small dimension deviation ΔV can be describe as [1]:

$$E = E_n + \sum_{\nu\neq n} E_\nu \frac{f_\nu^2}{f_n^2 - f_\nu^2}\frac{1}{W_0}\int_{\Delta V}(Z_0^2 H_n H_\nu^* - E_n E_\nu^*)dV. \quad (2)$$

In all periodical accelerating structures the field distribution along the axis can be described as:

$$E_{m\nu} = E_{\nu 0} cos(m\nu\pi), \quad (3)$$

where $E_{m\nu}$ is the field amplitude in the m-th cell, $\nu\pi$ is the phase shift per structure period. Here we assume the phase

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shift for operating mode $n\pi, n = 0, 1$. Transforming (2) with using perturbation theorem, one can get, remembering frequency detuning only in the j-th cell:

$$E = E_n + \sum_{\nu \neq n} 2E_\nu a_\nu \frac{\Delta f_j}{f_j} cos(jn\pi)cos(j\nu\pi), \quad (4)$$

where $a_\nu = \frac{f_\nu^2}{f_n^2 - f_\nu^2}$. The similar relation for descriprion of a field perturbation in the chain of coupled cavities is given in [2] with a matrix form.

Simple structures

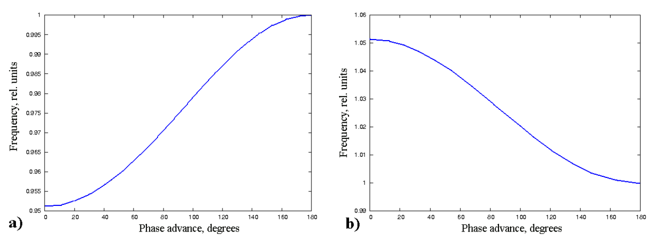

Figure 1: Dispersion curves for simple structures with positive (a) and negative (b) dispersion.

Dispersion curve for a simple periodical chain of coupled cells can be described by the equation:

$$f_\nu = \frac{f_c}{\sqrt{1 + k_c cos(\nu\pi)}}, \quad (5)$$

where f_c is the own cell frequency and k_c is the coupling coefficient. Depending of k_c sign, the chain can have a positive dispersion, $k_c > 0$, $\frac{\partial f_\nu}{\partial \nu} > 0$, Fig. 1a, or a negative one, $k_c < 0$, $\frac{\partial f_\nu}{\partial \nu} < 0$, Fig. 1b.

Examples of simple structures are shown in Fig. 2. The

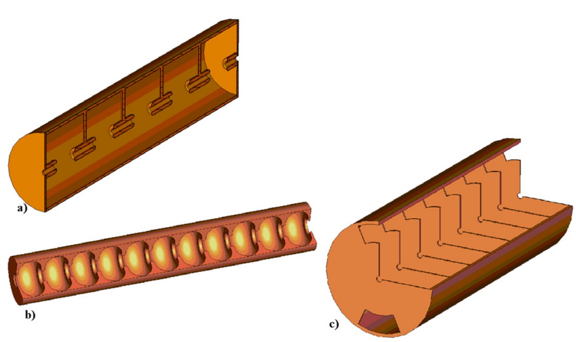

Figure 2: Examples of simple structures.

separated DTL structure [3] with operating 0 mode and positive dispersion is shown in Fig. 2a. Also positive dispersion has the structure with coupling through bore hole and operating π mode, [4], Fig. 2b. Negative dispersion has a structure with coupling slots and π operating mode, Fig. 2c.

For thermal stability of the structure coefficients a_ν in (4)

Table 1: Thermal stability of simple structures

Operating mode	**Dispersion**	**Thermal stabiliuty**
0 (2π)	positive	No
0 (2π)	negative	Yes
π	positive	Yes
π	negative	No

should be positive. With the negative $j - th$ cell detuning and positive a_ν value the perturbed field value in j-th cell will be decreased. One can check it by calculations in (2). It means for operating 0 mode the negative dispersion and for operating π mode the positive dispersion. Results of thermal stability definition for all combinations of operating mode type and dispersion sign are summarized in the Table 1.

To confirm this conclusion, direct numerical simulations of the field distribution in π mode structures with negative (slot coupled, Fig. 2c) and positive (bore hole coupled, Fig. 2b) dispersion and detuned first cell. Parameters of the structures are - $k_c = -5.0 \cdot 10^{-2}, N_p = 7, \frac{\Delta f}{f} = -5.2 \cdot 10^{-4}$ for slot coupled structure and $k_c = 1.25 \cdot 10^{-2}, N_p = 11, \frac{\Delta f}{f} = -4.4 \cdot 10^{-4}$ for bore hole couples one, where N_p is the number of periods (number of accelerating gaps). Large detuning value, due to conducting cylinder at the cell axis, is chosen to do effect evident. In Fig. 3 the calculated E_z distribution is for the perturbed operating mode are shown. One can see clear filed tilt in the filed distribution. For the π mode structure with negative dispersion the field in the detuned cell is larger, Fig. 3a, and this structure is thermally unstable. For the π - mode structure with positive dispersion we see the lower field in the detuned cell, Fig. 3b.

Important value is a rate of amplification $\frac{\partial E_j}{\partial(\Delta f_j)}$, which

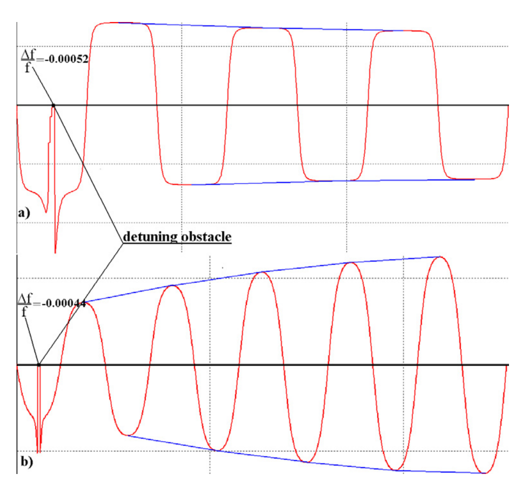

Figure 3: Calculated field distribution in π-mode structures with negative (a) and positive (b) dispersion with the detuned first cell.

is proportional to a_ν. The main contribution in the field perturbation provides the nearest mode with a_1 coefficient. Supposing dispersion curve is described by (5), $a_1 \sim \frac{2N_p^2}{\pi^2 k_c}$. For π mode structures, considered for Fig. 1, $a_1 = -1.57 \cdot 10^2$ and $a_1 = 1.62 \cdot 10^3$, respectively. Dispersion curve of the separated DTL, Fig. 2a, due to strong coupling is not described well by the relation (5). With direct simulations one can get $a_1 = 1.67$ for $\beta = 0.314$ and $a_1 = 3.75$ for $\beta = 0.553$ - rather small value.

Compensated structures

Let us remember, that a 'compensated' is named a structure in which at operating frequency coincide frequencies of two modes (accelerating f_a, E_a and coupling f_c, E_c modes) with different parities of field distribution with respect to symmetry plane [5]. Examples are well known structures, Side Coupled, Annular Coupled, On-axis Coupled, Disk and Washer, DTL with posts and so on. Dispersion curve of the compensated structure is shown in Fig. 1a, assuming operating π mode, and consists from two branches. In practice frequencies of accelerating and coupling modes do not coincide perfectly and between branches there is a stop band with the width $\delta f = f_c - f_a$. The relations for description of dispersion curve (Fig. 4b)

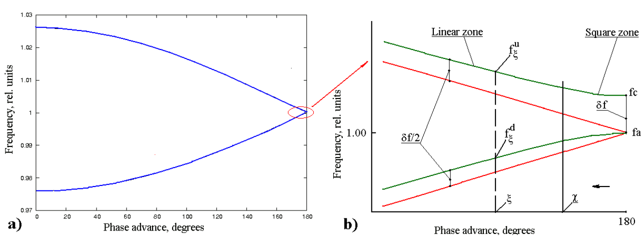

Figure 4: Dispersion curve for compensated structure (a) and behavior in the vicinity of operating point (b).

and field distributions of modes in the vicinity of operating point are given in [6] both for closed $\delta f = 0$ and open $\delta f \neq 0$ stop band.
For $\delta f \neq 0$ in the nearest vicinity of operating point $\xi \leq \chi$, 'square zone', where $\xi = \pi - \nu, \chi = \frac{2\delta f}{k_c f_a}$, [6], the field distributions for modes at upper f_ξ^u and bottom f_ξ^b branches of dispersion curve strongly differ and should not be modes in this region, $\nu_m = \frac{m\pi}{N_p}, \xi_m = \pi - \nu_m, \xi_m > \chi$. On the contrary, the structure has no properties of compensated one. It should be done in structure tuning by appropriate stop band width δf decreasing.
In the 'linear zone' $\xi \geq \chi$ the behavior of the upper f_ξ^u and the bottom f_ξ^b curve branches is approximated as [6]:

$$f_\xi^{u,b} \approx f_a + \frac{\delta f}{2} \pm \frac{f_a k_c \xi}{4} - \frac{f_a k_c^2 \xi^2}{8}, \qquad (6)$$

In this zone the branches of the dispersion curve are shifted at $\delta f/2$ value, but come parallel with respect to the branches for an ideal case $\delta f = 0$. The field distributions for modes at upper and bottom branches of dispersio curve are similar. We have to consider a simultaneous contribution of modes $\xi_m = \pi - \nu_m$ type in the field perturbation (4):

$$a_{\xi_m} = a^u_{\xi_m} + a^b_{\xi_m} = \frac{(f^u_{\xi_m})^2}{f_a^2 - (f^u_{\xi_m})^2} + \frac{(f^b_{\xi_m})^2}{f_a^2 - (f^b_{\xi_m})^2}. \qquad (7)$$

Taking into account (7) and (6), considering the main part of the field perturbation due to nearest modes $m = 1, 2, 3...$ in the linear zone, and neglecting second order terms in ξ_m and $\frac{\delta f}{f_a}$, one can get for perturbed field distribution (4):

$$E = E_a\left(1 + \sum_m \frac{64 \delta f \Delta f_a N_p \cos j\theta_m \cos i\theta_m}{f_a^2 m^2 k_c^2}\right) \qquad (8)$$

These contributions of nearest modes are partially compensated and a residual is proportional to the δf value. As one can see from (8), for thermal stability of the structure should be $\delta f \geq 0$. For compensated structures this conclusion has been done before, [7], [8] basing on coupled circuits approach [2].
Estimating coefficient a_1 of contribution for nearest modes into perturbed field distribution, for $k_c = 0.05, N_p = 50, \frac{\delta f}{f_a} = 10^{-4}$ one gets $a_1 = 32$ - a smaller value as for simple π mode structures with the same coupling coefficient but of order smaller number of periods.

SUMMARY

For compensated, or bi-periodical structures, thermal stable operation all time can be achieved by appropriate structure RF tuning. In simple periodical structures existence or absence of thermal stability is the property of the structure. Thermal run away probability depends on the amplification rate value for field perturbation.

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