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DETERMINATION OF REQUIRED TOLERANCES AND STOP BAND WIDTH FOR CELLS MANUFACTURING AND TUNING IN COMPENSATED HIGH ENERGY ACCELERATING STRUCTURES

I. V. Rybakov†, V. V. Paramonov
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

Abstract

The required value of the spread for accelerating field distribution comes from the beam dynamics conditions and for cavities in high energy hadron linacs is 1%. The standard deviation of the accelerating field distribution depends on the spread in frequencies of accelerating and coupling cells, stop band width and deviations in coupling coefficients. The deviations in frequencies for accelerating, coupling cells, coupling coefficients, are directly related with tolerances manufacturing tolerances for cells. The stop band width should be adjusted with cells tuning. Relations between standard deviation of field distribution and deviations in cells parameters, [1], are known. Together with relation between deviations in cells dimensions and cells parameters, [2], recommendations for cells manufacturing tolerances could be obtained. In relation to coupling coefficient of compensated accelerating structures (ACS [3], SCS [4], CDS [5], DAW [6]) for high energy parts of linacs some recommendations for determination of optimal manufacturing tolerances and acceptable stop band are presented.

INTRODUCTION

One of the complicated and critical stages of the new accelerating cavity for high intensity hadron linacs development is determination of optimal manufacturing tolerances and acceptable stop band.

As an example, we will consider the recommendations for selecting tolerances and stop band width in the sketch project of an accelerating cavity for β ~ 0.43, for which the CDS structure was considered in comparison with the structures, proven in acting installations, as shown in Fig. 1.

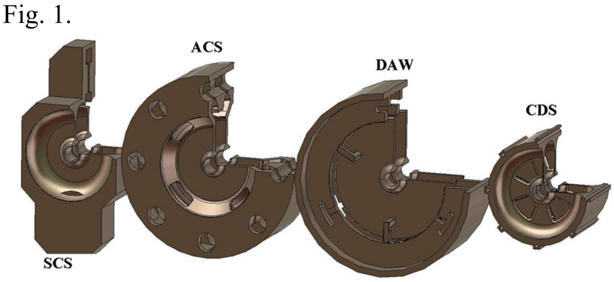

Figure 1: Comparison of accelerating structures for hadron linacs (tuned to identical operating mode frequency).

METHODICAL BASEMENT

To determine the optimal manufacturing tolerances of the cavity, it is necessary to calculate the influence of the deviations introduced into the accelerating field of the structure by deviations in geometric parameters. This effect is determined by the spread of the accelerating field distribution value:

$$\sigma_E^2 = \frac{\sum_{i=1}^{N}(E_i-\bar{E})^2}{N_p}, \tag{1}$$

where *Np* is the number of accelerating gaps, *Ei* is the field strength in i-th gap. As a relative estimation of the the accelerating field distribution spread, one can use the expression [7]:

$$\sigma_E^2 = \sigma_{E_f}^2 + \sigma_{E_k}^2, \tag{2}$$

where σ_{Ef}^2 is the dispersion caused by frequencies spread of accelerating and coupling modes, σ_{Ek}^2 is the dispersion caused by coupling coefficient spread. The analytical expressions for the sensitivity of frequencies and coupling coefficient to surface displacement for bi-periodic structures such as CDS were described in [1, 7]:

$$\frac{\Delta f_{a,c}}{f_{a,c}\Delta x_i} = \frac{\int_{S_i}(\varepsilon_0\vec{E}^2_{a,c}-\mu_0\vec{H}^2_{a,c})d\vec{S}}{4W_{a,c}}, \tag{3}$$

$$\Delta K_c = \frac{\int_{S_i}(\varepsilon_0\vec{E}_a\vec{E}_c-\mu_0\vec{H}_a\vec{H}_c)d\vec{S}_i\Delta x_i}{\sqrt{2W_aW_c}}, \tag{4}$$

where Δx_i is the tolerance (displacement) for geometrical parameters, $W_{a,c}$ is the stored energy in accelerating and coupling modes. To determine the manufacturing tolerances of the cavity sections, the technique using the ANSYS numerical simulations package [8] is proposed. Using the internal procedures of the package, the frequencies, the field distribution for the accelerating mode and the coupling mode of the operating π-wave are calculated. The inner surface of the structure is divided into numbered surfaces according to the internal ANSYS algorithm, corresponding to the geometric parameters of the structure, as shown in Fig. 2.

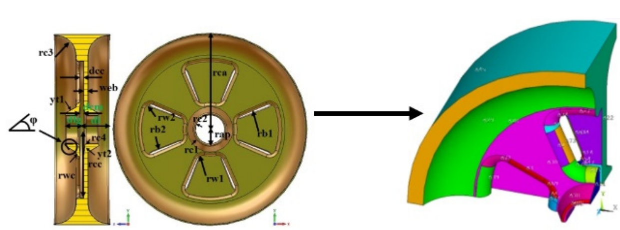

Figure 2: The CDS structure surface divided by numbered surfaces in ANSYS.

† irybakov@inr.ru

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Using the ANSYS macros the distributions of the mode's fields are compared and the values of the frequency shifts and coupling coefficient shifts for each of the surfaces are calculated using Eqs. (3) and (4). In the calculation a conditional $\Delta x_I = 1$ mm was used. In addition, several macros can be used to visualize the deviation introduced into the field as shown at Fig. 3.

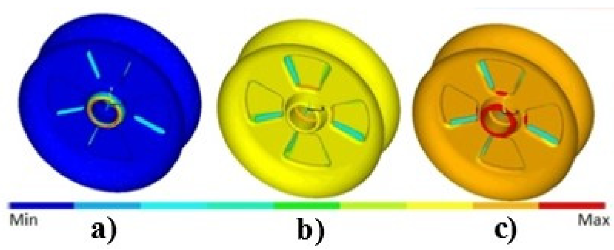

Figure 3: Density distributions for the sensitivity of the accelerating mode (a), the coupling mode (b), and the coupling coefficient (c) of the structure to the displacement of surfaces.

Such distributions clearly show the parts of the structure surface that have the largest influence on the dispersions.

NUMERICAL SIMULATIONS FOR CDS

Using the technique, the frequencies and coupling coefficient shift values were obtained for CDS structure geometrical parameters shown at Fig. 2. These values are presented in Table 1.

Table 1: The Influence of Geometric Parameters on the Values of Relative Deviations

Param. x_i, mm	$(1/f_a)*\Delta f_a/\Delta x_i$ 1/mm	$(1/f_c)*\Delta f_c/\delta x_i$ 1/mm	$\Delta K_c/\Delta x_i$, 1/mm
dcc = 2.00	-0.48	-3.31	13.12
dcm = 2.50	-0.10	104.94	0.00
rap = 17.00	1.45	1.21	0.00
rb1 = 8.00	-1.35	-19.92	5.19
rb2 = 2.00	-0.27	-16.26	0.00
rc1 = 1.50	7.64	0.02	0.01
rc2 = 2.00	9.09	0.03	0.00
rcc = 76.66	-0.15	-3.50	0.00
rw2 = 74.7	-1.00	-6.67	4.46
rwc = 7.00	-0.60	-6.98	-1.77
web = 12.0	-2.63	-0.58	-0.01
rca = 112.8	-12.72	-0.10	0.00

The value of the frequency shift of the accelerating mode is most affected by the parameters associated with the radius of the accelerating cell, the rounding radius of the drift tube and the coupling windows, the shift of the coupling mode - with the radius of the coupling cell, the length of the coupling cell, and the rounding radius of the coupling window. The shift of the coupling coefficient is most affected by the length of the coupling cell, the parameters of the drift tube and the coupling windows.

For the manufacturing tolerance of 50 μm, which is easily implemented on modern equipment with digital control, the value of the stop band based only on the condition of field uniformity is ~ 2.5 MHz. In reality, it is limited to other effects. For the RF power distribution along the cavity without phase distortion, it is essential to overlap the resonant curves of the operating mode and the coupling mode at a level not lower than $1/\sqrt{2}$ [9]. To determine the relative stop band width $\delta f/f_a$, where f_a is operating mode frequency, for RF power transmission one can use the expression, which associates acceptable $\delta f/f_a$ with quality factors:

$$\frac{\delta f}{f_a} < \frac{Q_a + 2Q_c}{Q_a Q_c}, \tag{5}$$

where $Q_{a,c}$ are the quality factors for accelerating and coupling modes.

Tuned to the same operating frequency the DAW structure and CDS gets the upper limit $\delta f/f_a = 1.6*10^{-4}$ and $\delta f/f_a = 5.1*10^{-4}$, respectively. Thus, the structure with higher Q has stronger limitation to the stop band and in this regard smaller manufacturing tolerance condition.

The dependencies between the frequencies, coupling coefficient dispersions and accelerating field distribution spread and the coupling coefficient (K_c) at the realistic $\delta f/f_a = 4.0*10^{-4}$ are shown at Fig. 4.

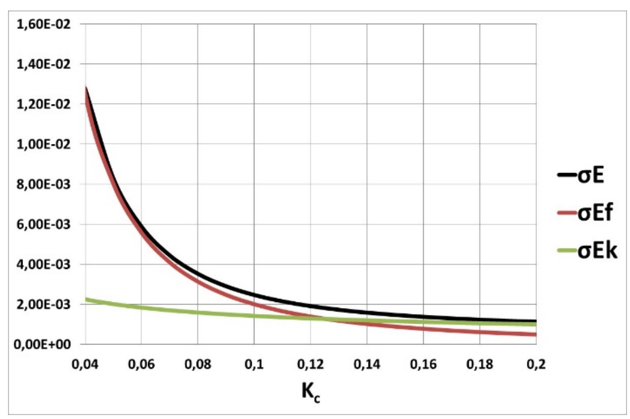

Figure 4: The dependence of the field dispersion on the frequency shift, the field dispersion on the coupling coefficient shift, the acceleration field distribution spread on the coupling coefficient K_c, $\delta f/f_a = 4.0*10^{-4}$.

At the $K_c < 0.12$ largest influence on the dispersion of the accelerating field is made by the frequency dispersion of the operating mode and coupling mode. With $K_c > 0.12$

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in the dispersion of accelerating field the coupling coefficient dispersion is more prevalent.

At the same time, when the coupling coefficient decreases below 0.1, the dispersion of the accelerating field increases by an order. If the coupling coefficient is less than 0.05, the accelerating field distribution spread exceeds 1% with an acceptable $\delta f/f_a = 4.0*10^{-4}$. This justifies the importance of a high coupling coefficient of more than 0.1 in relation to biperiodic accelerating structures for high intensity hadron linacs and the reasonableness of the $K_c \approx 0.16$ implemented in the CDS structure. At the same time $K_c \approx 0.40$ realized in DAW structure is excessive.

CONCLUSION

The development of new accelerating cavities for the main parts of hadron linacs is still a topical task associated with numerous technical difficulties. Determination of the acceptable and optimal manufacturing tolerances and stop band is a development step that affects both the complexity and cost of manufacturing the structure, as well as the further tuning and stability of operating regime. The simplification of this problem is considered by the example of the development of a sketch project of the low beta accelerating cavity. A technique for estimating the effect of shifts in geometric parameters on the frequency characteristics of a structure based on previously obtained analytical expressions for biperiodic accelerating structures is proposed and program implemented on the basis of the ANSYS package. The advantage of this technique is the necessity of performing only three numerical calculations of the eigenfrequencies of the structure. With the proposed technique, the optimal manufacturing tolerances of the new CDS cavity are justified with the acceptable stop band value. These tolerances are easily implemented on modern digitally controlled equipment.

By the comparison of DAW structure and CDS in upper limit of relative stop band width for RF power transmission it is shown that structures with high Q-factors on accelerating and coupling modes has stronger limitation to the acceptable stop band and in this regard smaller manufacturing tolerance condition.

The influence of the coupling coefficient on the accelerating field distribution spread is considered. It is shown that at a coupling coefficient less than 0.05, the accelerating field distribution spread exceeds 1% with $\delta f/f_a = 4.0*10^{-4}$. The conclusion is made about the importance of a high coupling coefficient value in accelerating structures for high intensity hadron linacs and the reasonability of the coupling coefficient implemented in the CDS structure, which reaches 0.16 as opposed to low coupling coefficient in ACS and SCS, and excessive in DAW.

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