The method of accelerating structure tuning and manufacturing quality control

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Abstract. For the multipactor discharge (MP) damping in the new CDS structure a method of forced excitation of high voltage oscillations in the coupling cell is proposed. It can be realized by application of an alternating frequency shift in the neighboring accelerating cells. For assured MP damping a control of both operating frequencies and the alternating frequency shift obtained is required. A method for determination of shifted frequencies in cells by the measurements in full setup (FS) and minimal setup (MS) of the structure was proposed. The substantiation of the technique arising from the equivalent circuits method and numerical simulations of the operating frequencies in FS and MS is presented.

1. Introduction
The CDS structure was proposed to replace the first cavity of the INR RAS linear proton accelerator. It has four sections, consisting of 18-21 periods of structure [1].

After manufacturing the structure cells some frequency dispersions of the accelerating and coupling modes can be expected. Their values depend on the chosen manufacturing tolerances. If the value of manufacturing tolerances is 30 μm the values of frequency dispersion are expected to be δf_a=±3σ_f_a=±0.675 MHz and δf_c=±3σ_f_c=±5.414 MHz, respectively [2].

The acceptable value of the stop bandwidth along the cavity is assumed to be 200 kHz. During the measurements in the cells it is necessary to control the mean stop bandwidth value for the full cavity section.

For the multipactor discharge (MP) damping an alternating frequency shift in the accelerating cells is applied. The value of the required frequency shift is estimated using the equivalent circuits method and amounts to ±800 kHz. The numerically calculated value of the required alternating frequency shift for neighboring cells appeared to be ±1.2 MHz. For cavity sections 1 and 4 which are distant from the feeding waveguide a control of alternating frequency shift for MP damping is also required [3].

A technique is proposed for determining the eigenfrequencies of the half cells that make up the cavity section. The application of the technique is illustrated on the example of the first cavity section, consisting of 18 periods of the CDS structure, which will be obtained from 36 half cells during production.

2. The half cells tuning devices
For tuning the frequency of the half cells accelerating mode it is proposed to introduce into the structure an additional ring of the trapezoidal cross-section. It is shown in Figure 1.
The coefficient of influence of the tuning ring length on the accelerating mode frequency is $k_{fa} = 1.160 \text{ MHz/mm}$. For the assurance of accelerating mode shift for MP damping in neighboring cells and with regard to frequencies dispersion the initial values of geometrical parameters are set to reach the accelerating mode frequency of 989.00 MHz. In this case the height of the tuning ring is selected to set the half-cell operating mode frequency to 993.000 MHz.

In order to provide the required alternating frequency shift the tuning ring is ground off until the operating frequency is 989.800 MHz for the odd-numbered cells and 992.200 MHz for the even-numbered cells. Thus a pair of half cells provides the required frequency shift of 1.200 MHz.

The tuning of the coupling mode frequency in the half cells is possible only by boring the coupling cell radius. For the cell radius the calculated value of the coefficient of influence on frequency is $k_{fc} = 14.270 \text{ MHz/mm}$. With regard to the coupling mode dispersion the initial radius of the coupling cell was set in such a way as to reach the coupling mode frequency of 997.000 MHz.

Due to nonlinear dependence of the coefficient of influence of the tuning ring length on the accelerating mode frequency, the adjustment of the half cells to the operating frequency value should be performed in several stages. At each stage, the frequencies of the section and half cells are measured to clarify the actual value of the tuning ring influence coefficient and its possible approximation.

3. Measurements in full section (Full Setup)

At the first stage of measurements it is supposed to find the values of the accelerating mode frequency, the stop bandwidth and the coupling mode frequency in full setup of the cavity section consisting of 36 half cells. The mean value of the accelerating mode frequency $f_a$ in full setup is measured directly [4].

For experimental definition of the stop bandwidth we can use a linear expression stipulating equal deviations of the modes from the operating frequency in the upper and lower branches of the Brillouine diagram (BD). For this purpose let us use the mode closest to the operating one:

$$\delta f = \Delta F_n = f^t_n + f^b_n - 2f_a$$

where $f^t_n$ and $f^b_n$ are the modes frequencies in the upper and lower branches of the BD, $f_a$ is the operating mode frequency. Thus in this case the calculated stop bandwidth amounts to $\delta f = 4.578 \text{ MHz}$ with a relative error of the stop bandwidth $(\delta f - \delta f_{calc})/\delta f = 13.5\%$. To increase the accuracy of determining $\delta f$ let’s proceed to expansion into a series in terms of $\xi = 0, 0$ for the linear zone of the BD:

$$f_{0}^{t,b}(\xi) = f_a + \frac{\delta f}{2} \pm \frac{\beta \varepsilon}{\pi \beta} + \frac{\partial^{2} f^t}{\partial \xi^{2}} \frac{\varepsilon^{2}}{2} \pm \frac{\partial^{3} f^t}{\partial \xi^{3}} \frac{\varepsilon^{3}}{6} + \frac{\partial^{4} f^t}{\partial \xi^{4}} \frac{\varepsilon^{4}}{24} \pm ... = \frac{\delta f}{2} + f_{0}^{t,b}(\xi)$$
where $\beta_g$ is a group velocity and $\beta$ is a phase velocity.

If we consider members up to the 3rd order the $\delta f$ is determined by two modes closest to the operating mode in the BD [5]:

$$\delta f = \frac{m^2 \Delta F_n - n^2 \Delta F_m}{m^2 - n^2}$$ (3)

where $n, m = 1, 2$ are the modes numbers closest to the operating mode, $\Delta F_{n,m}$ are the modes frequencies dispersions in the upper and lower BD branches calculated from (1). Thus in this case the calculated stop bandwidth amounts to $\delta f = 4.162$ MHz with a relative error of the stop bandwidth $(\delta f - \delta f_{\text{calc}})/\delta f = 3.2\%$. To increase the accuracy in $\delta f$ determination the members up to the 5th order can be considered in (2). Thus $\delta f$ is determined using three modes closest to the operating mode in the BD [6]:

$$\delta f = \frac{\Delta F_n m^2 j^2 (j^2 - m^2) + \Delta F_m n^2 j^2 (n^2 - j^2) + \Delta F_j n^2 m^2 (m^2 - n^2)}{n^2 m^2 (m^2 - n^2) + m^2 j^2 (j^2 - m^2) + n^2 j^2 (n^2 - j^2)}$$ (4)

where $n, m, j = 1, 2, 3$ are the modes numbers closest to the operating mode, $\Delta F_{n,m,j}$ are the modes frequencies dispersions in the upper and lower BD branches calculated from (1). Thus in this case the calculated stop bandwidth amounts to $\delta f = 4.041$ MHz with a relative error of the stop bandwidth $(\delta f - \delta f_{\text{calc}})/\delta f = 0.2\%$.

Thus the mean value of coupling mode frequency along the section could be determined as:

$$\bar{f}_{c} = \bar{f}_{a} + \delta f$$ (5)

The mean value of coupling mode frequency calculated using (4) and (5) amounted to $f_c = 997.092$ MHz. The section coupling coefficient amounted to $k_c = 15.576$ %.

In the first section of the cavity an alternating accelerating cavity frequency shift of $\pm 1.200$ MHz is applied for MP damping. Such a shift can cause perturbations of the field amplitude in the cavity section. In this case a field amplitude distribution measurement along the section is required.

4. Measurements in minimal setup

To control the obtained values of accelerating and coupling modes frequencies for individual half cells a set of eigenfrequencies measurements in the minimal setup (MS), consisting of two half cells, is proposed. The MS is shown in figure 2.

In such a setup, if some electrical shorting plates are implemented, three mode frequencies can be measured directly: the operating $\pi$-mode frequency and two 0-mode frequencies.
The coupling mode frequency is calculated from the equations introduced under the condition of frequency shift conservation with a constant coupling coefficient:

\[
\delta \tau_c + \delta \tau_a = \delta \tau_0^{(1)} + \delta \tau_0^{(2)}
\]  
(6)

\[
\delta \tau_c = \delta \tau_0^{(1)} + \delta \tau_0^{(2)} - \delta \tau_a
\]  
(7)

\[
f_c^{\pi} = f_c^{\pi} + \delta f_c^{\pi}
\]  
(8)

Thus, the coupling mode frequency in the MS is determined by calculating its deviation from the average value over the section which is determined in Paragraph 1.

To determine the accelerating mode frequencies in each half cell, a series of measurements using three half cells is necessary. The frequency of the accelerating mode in the MS is the average value of the frequencies of its constituent half cells. Therefore, if three MCs are composed of three half cells, we can construct a system of equations:

\[
\begin{align*}
\frac{f_a^{(1)} + f_a^{(2)}}{2} &= f_a^{(1,2)} \\
\frac{f_a^{(1)} + f_a^{(3)}}{2} &= f_a^{(1,3)} \\
\frac{f_a^{(2)} + f_a^{(3)}}{2} &= f_a^{(2,3)}
\end{align*}
\]  
(9)

where \(f_a^{(n)}\) is the frequency of the accelerating mode in the corresponding half-cell, \(f_a^{(n, m)}\) is the measured average frequency of the accelerating mode in the corresponding MS. Thus, solving system (9) we get the values of the frequencies in each of the half cells.

Thereafter, the found frequency value of the accelerating mode for the first half cell \(f_a^1\) can be used as a reference for determining the frequencies of the rest half cells of the section, forming a MS with them. Similarly, the values of the coupling mode frequency in the half cells are determined.

For the method checkout a numerical experiment was performed with a conducting ball implemented in the volume of one of the MS half cells. Its radius was chosen so that the MS frequency corresponded to a half cell frequency shift of \(\delta f = 3\sigma_a = 0.675\) MHz and amounted to 6.20 mm. The MS with a shifted half-cell is shown in figure 3.

**Figure 3.** MS with a shifted half cell

With the ball implemented the accelerating mode frequency of such a MS amounts to \(f_a = 992.670\) MHz. The frequency of MS without shift is \(f_a = 993.007\) MHz. The calculated with (9) value of the shifted half-cell accelerating mode frequency is \(f_{a_{sh}} = 992.333\) MHz.
If the ball is placed near the coupling window as is shown in figure 3 the coupling mode is also shifted. To determine the coupling mode frequency in the shifted MS a FS, including this MS, was composed. The mean value of the coupling mode frequency in this FS, according to (4) and (5), amounted to $f_c = 997.046$ MHz. The MS coupling mode frequency shift calculated with (7) and (8) was $\delta f_c = 0.229$ MHz, accordingly the coupling mode frequency itself was $f_c = 997.275$ MHz. The numerically determined coupling mode frequency amounted to $f_c = 997.257$ MHz.

So that is the way how the accelerating and coupling mode frequencies in the half-cells of the cavity section are found.

With the known influence coefficients for the tuning ring and coupling cell radius the half cells are tuned to the coupling mode frequency of 991.000 MHz, the odd-numbered half cells are tuned to the accelerating mode frequency of 989.800 MHz and the even-numbered half cells – to 992.200 MHz. In this case the mean value of the accelerating mode frequency along the section is 991.000 MHz and the stop bandwidth doesn’t exceed 200 kHz.

5. Conclusion
A method has been proposed that allows tuning the accelerating structure to the required values of operating frequencies while maintaining an acceptable level of field dispersion. The application of the method is considered for the new CDS structure of the first cavity of the main part of the INR linac. In the full section setup the mean value of the accelerating mode frequency is measured directly. The mean coupling mode frequency over the section is determined indirectly using the measured modes frequencies nearest to the operating frequency in the BD. The mean coupling mode frequency in the full setup of the cavity section is determined with a high precision using the expressions including members up to the 3rd or 5th order. To calculate the eigenfrequencies of the half cells that compose the cavity section, a series of measurements in the MS is performed. The mean value of the operating mode frequency in the MS is measured directly. The average coupling mode frequency is determined indirectly by its deviation from the mean value over the section.

A specific feature of the described method is that it allows one to adjust both the frequencies of the half cells and the section as a whole, and the alternating frequency shift of the neighboring accelerating cells for multipactor discharge damping.

6. References
[1] Rybakov I V, Feschenko A V, Kalinin Y Z, Kravchuk L V, Leontiev V N, Naboka A N, Paramonov V V and Serov V L 2016 Proc. 25th Russian Particle Accelerator Conf. pp 216-218
[2] Rybakov I V, Paramonov V V and Skasyrskaya A K 2016 Proc. 25th Russian Particle Accelerator Conf. pp 291-293
[3] Rybakov I V and Isaev I I 2016 Proc. 25th Russian Particle Accelerator Conf. pp 291-293
[4] Naboka A N, Paramonov V V, Floettmann K 2008 Problems of Atomic Science and Technology. Series Nuclear Physics Investigations №5 pp 35-39
[5] Paramonov V V, Kravchuk L V, Puntus V A 1998 Proc Linac Conf. ANL-98/28 p 579
[6] Paramonov V V 2001 The Annular Coupled Structure optimization for JAERY/KEK Joint Project. KEK report Japan 14