RESEARCH OF THE ACCELERATOR RF SYSTEM WITH BIPERIODIC ACCELERATING STRUCTURE

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Abstract

In the report the characteristics of the accelerator radio frequency (RF) system with the biperiodic accelerating structure are examined. A structure feeding is carried out from magnetron. The generator insulation from high Q-factor load is provided with the help 3-dB directional coupler. Biperiodic structure specific feature is some resonant modes next with operational mode. These modes can render essential influence on work of the accelerator radio-frequency system. It is discussed definition technique of tolerances on characteristics tuning of RF-units and accelerating structure. Implementation of these tolerances at operational and next to it modes make generator work steady and stable in various regimes. The calculated results well coincide with experimental data received at several working accelerators.

1 INTRODUCTION

Linear electron accelerators with biperiodic accelerating structure are widely used for many applications. Biperiodic accelerating structure has some advantages with respect to other structures. Its shunt impedance is high enough and beam focusing may be carried out by edge fields on accelerating gaps. Microwave power feeding of the accelerator with small energy is fulfilled usually from magnetron. To get generator excitation at structure resonance frequency it is necessary to use insulators to eliminate large wave reflected from the section during transient process at the section. Usually ferrite circulators are used as the insulators. There is the other type of insulator, 3-dB directional coupler [1]. It has some advantages. There are no power losses in this insulator. Coupler has simple construction and can be included into accelerator vacuum volume that increases electrical strength of the accelerator channel.

The application of 3-dB directional coupler requires partition of the accelerating structure on two sections possessing close input admittance. It is the most important problem at creation of a microwave structure based on waveguuide coupler.

2 RESEARCH METHOD

For determination of operating parameters of insulator and structure, at which the steady and stable excitation of the magnetron on operational frequency will be realised, it is necessary to conduct the analysis of operational mode of the oscillatory system with the help of generator excitation equation [2]. This equation presents the balance of generator admittance and load admittance. At the simplest case it looks like:

$$B_{gen} + B_{in} = 0 \qquad (1)$$

Here B_{gen} - generator cavity reactive admittance, B_{in} - reactive admittance of the RF system.

The second characteristics can be got from the reflection coefficient of the RF system Γ_{in}. This characteristic has a kind (see Fig.1):

$$\Gamma_{in} = S_{12}^2 \Gamma_1 e^{j\varphi_1} + S_{14}^2 \Gamma_2 e^{i\varphi_2} \qquad (2)$$

Here Γ_1 and Γ_2 - complex reflection coefficients of the first and second section accordingly, φ_1 and φ_2 - phase shifts from the microwave channel input to the first and second section, S_{12} and S_{14} - scattering matrix elements of the directional coupler.

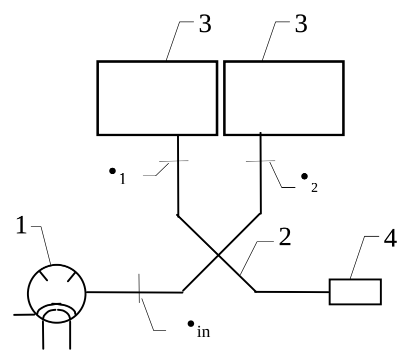

Figure 1: Accelerator RF system with 3-dB directional coupler: 1-magnetron, 2 -directional coupler,3 -biperiodic accelerating structure, 4 -damping load

These coefficients are described as follows:

$$\Gamma_1 = \frac{1-Y_1}{1+Y_1}, \ \Gamma_2 = \frac{1-Y_2}{1+Y_2} \qquad (3)$$

Here Y_1 and Y_2 - section input admittance of the sections, look like:

$$Y_1 = \frac{Q_{ex1}}{Q_{01}}\left[1 + jQ_{01}\frac{2(f - f_{01})}{f_{01}}\right]$$

$$Y_2 = \frac{Q_{ex2}}{Q_{02}}\left[1 + jQ_{02}\frac{2(f - f_{02})}{f_{02}}\right] \qquad (4)$$

Here f_{01}, f_{02} - resonant frequencies of the sections, Q_{01}, Q_{02}, Q_{ex1}, Q_{ex2} - own and external Q-factors of the sections.

The scattering matrix elements of the coupler look like:

$$S_{12}=\sqrt{1-k^2} \quad , \quad S_{14}=jk \qquad (5)$$

Here k - coupling coefficient of the coupler.

Reactive admittance of the RF system is the imaginary part of the RF system input admittance that can be got from expressions (1) - (5). It depends on the reflection coefficient phase at the channel input. The optimum phase of reflection coefficient on microwave system input is equal 2π. At manufacturing of channel elements the equality of geometric lengths from the generator up to both sections is always executed with good accuracy, therefore we shall consider $\varphi_1 = \varphi_2$.

When $k = k_0 = 1/\sqrt{2}$ (transitional attenuation 3 dB) and $Y_1=Y_2$ then $\Gamma_{in}=0$ and generator operates with adjusted load. Oscillation frequency can differ from section resonant frequency and accelerating field will be small. To get generator excitation on sections' frequency the coupler transitional attenuation can be made not equal to 3 dB. Generator excites on section frequency because of the generator parameter fixation by high-quality section. Generator excitation equation has single solution on sections' frequency (see Fig.2, curve 1).

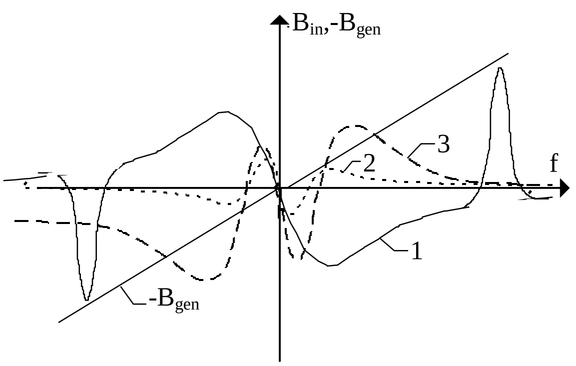

Figure 2: Generator reactive admittance B_{gen} and input reactive admittance B_{in} dependence versus frequency;
1 - $Q_{01}\approx Q_{02}$, $Q_{ex1}\approx Q_{ex2}$, long sections; 2- $Q_{01}\approx Q_{02}$, $Q_{ex1}\approx Q_{ex2}$, short sections; 3 - $Q_{01}\neq Q_{02}$, $Q_{ex1}\approx Q_{ex2}$, short sections.

Section input admittances do not equal to each other. Usually first section includes some bunching cells that have shape and sizes different with respect to accelerating cells. The Γ_1 and Γ_2 difference can arise because of difference of section resonant frequencies, section unequal own Q-factors and section coupling coefficients with a channel. The second and third reason of reflection coefficient difference in rather long sections, containing more than 6-8 cells, can be eliminated because of the parameters statistical average of separate cells. It gives possibility to have equal own Q-factors and coupling coefficients with a channel for both sections. Thus, the main reason of the section characteristic difference is the own frequencies' difference that can arise both at its manufacture and at maintenance during operation because of sections unbalanced thermal and beam load.

For short sections, containing 3-4 cells, sections own Q-factors can differ to each other due to bunching cells essential influence on the first section parameters. Generator excitation equation can have some solutions not at section frequency (see Fig.2, curve 3). To decrease parameters inequality the sections can be manufactured with different number of the cells. As analysis shows that it gives possibility to make section characteristics close to each other. Generator excites on section frequency (see Fig. 2, curve 2).

When generator excitation equation (1) has the single solution the frequency stabilisation factor S has a kind:

$$S = 1 + \frac{Q_{ex}}{Q_{exgen}} \frac{4\left|2\Delta k^2 - Q_{ex}\, 2\left(f_{01}-f_{02}\right)/\left(f_{01}+f_{02}\right)\right|}{\left(1+G\right)^2} \qquad (6)$$

Here Q_{exgen} - external Q-factor of the generator cavity, $\Delta k^2 = k^2 - k_0^2$, $G=Q_{ex}/Q_0$.

The analytical expression for the frequency band Δf_{0gen} at which there is steady generator excitation on the accelerating section frequency can be obtained only for identical sections ($\Gamma_1 = \Gamma_2$). It can be written as follows:

$$\Delta f_{0gen} = \frac{f_0}{Q_{ex}} \frac{[1+G+4\left|\Delta k^2\right|(1-G)]}{1-4\left|\Delta k^2\right|} \frac{\sqrt{F}(S+F)}{1+F} \qquad (7)$$

Here: $F = \dfrac{S-3+\sqrt{(S-1)(S-9)}}{2}$.

There is important feature of the biperiodic accelerating structures. It consists in the presence oscillation modes close to the main ($\pi/2$) mode. These neighbouring modes can influence on magnetron excitation. To receive analytical expressions permitting to calculate the tolerances on the section characteristics on neighbouring modes, we shall make a number of the simplifying suppositions. It is supposed that sections can differ only on resonant frequency at neighbouring modes, whereas their own Q-factors and coupling coefficients coincide. Besides we suppose, that the transitional attenuation of the directional coupler makes 3 dB sharp. The consideration of the coupler transitional attenuation real value complicates the expressions, but gives only a small correction to the tolerances on difference of sections' frequencies.

One can use the following designations for section parameters at neighbouring mode: Q_0' - own Q-factor, Q_{ex}' - external Q-factor, f_{01}', f_{02}' - sections' own frequencies. Besides it will be used designations: $G' = Q_{ex}'/Q_0'$, $\varepsilon_0' = 2\left(f_{01}' - f_{02}'\right)/\left(f_{01}' + f_{02}'\right)$.

The maximum module of the reflection coefficient from the microwave channel input on frequencies close to frequencies of a neighbouring mode is noted as follows, proceeding from expression (2):

$$\Gamma'_{\text{in max}} = \frac{2Q'_{ex}\left|\varepsilon'_0\right|}{\left(1+G'\right)^2 + \left(Q'_{ex}\varepsilon'_0\right)^2} \quad \text{at} \left|\varepsilon'_0\right| < 1/Q'_l \qquad (8)$$

$$\Gamma'_{\text{in max}} = \frac{1}{1+G'} \quad \text{at} \left|\varepsilon'_0\right| > 1/Q'_l \qquad (9)$$

Here Q'_l - loaded Q-factor of section on the neighbouring mode.

The obtained expressions should be used for the RF system reactive admittance calculation at neighbour mode. The maximum value of this admittance is compared with generator cavity reactance. One can get expression for the allowed frequency difference between generator and neighbour mode:

$$\frac{2\Gamma'_{\text{in max}}}{1-\left(\Gamma'_{\text{in max}}\right)^2} < Q_{\text{exgen}} \frac{2\left|f'_0 - f_{0\text{gen}}\right|}{f_{0\text{gen}}} \qquad (10)$$

It is necessary to note, that the expression (9) corresponds a large frequency difference between the sections at neighbouring mode. The determination of an allowed frequency interval between a main and neighbouring mode needs to be executed originally with use of this expression. If the frequency separation of the modes in the sections exceeds calculated value, it is sufficient indication that these modes do not influence on the generator excitation. Typical view of the reactive admittance of RF system with neighbouring modes is shown in Fig.2, curve 1.

3 RESEARCH RESULTS

There were carried out calculations for S-band accelerators. For typical section parameters (Q_0 ~15000 and Q_{ex} ~ 6000) frequency stabilisation factor S is about 15, generator frequency band Δf_{0gen} is some MHz. To get steady generator excitation on section frequency the difference between the Q-factors of the sections should be smaller than 10%.

In case of 10 accelerating cells in section the neighbouring modes will usually defend from main one at 7-8 MHz. At 6 accelerating cells this separation makes about 13-15 MHz. The calculation results have shown, that at frequency separation of neighbouring modes should not exceed 0.6 MHz for the section with 10 accelerating cells. For the section including 6 accelerating cells there is no influence of the neighbouring modes on the generator excitation. At calculation the coupling coefficient with the channel on neighbouring mode was supposed 2.5, the Q-factor 6000. It is approximately corresponds to sections' typical parameters.

4 CONCLUSION

The calculated results were tested at several working accelerators. Experimental researches showed that only fulfilling of the tolerances on the sections' parameters gives possibility to get steady and stable generator excitation on operational frequency.

REFERENCES

[1] V.A. Vaguine ″Standing wave high-gradient accelerator structure″, IEEE Transactions on Nuclear Science, v. NS-24, No 3, 1977, pp. 1084-1086

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