Beam Phasing of Autooscillating Systems

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Abstract

A new method of phasing of autooscillating systems is suggested. The RF fields of linear accelerator sections, each powered by separate RF source operating in autooscillating regime, are phased due to beam interaction with accelerating structure and proper chosen feedback loop parameters.

1. INTRODUCTION

One of the problems arising in the process of constructing the CW accelerators with high average beam power is connected with a design of a simple and reliable RF power supply system. Because of heat deformations of the accelerator structure when operating at high level of RF losses in the structure walls (from 20 to 200 kW/m) the frequency shift of the operational mode can be several times higher then the half-width of the structure's resonant curve [1]. Taking into account, that the accelerators at a high beam current should be multi-section the presence of frequency shifts complicates the start-up and operation of the accelerator as a whole, because all sections must be phased and must operate at the similar frequencies. The second problem, even more essential, is connected with a non-linear behaviour of a resonant curve, resulting from the dependence of a resonant frequency on a level of RF losses in the walls. The operation of a multi-section accelerator in this conditions requires the frequency stabilisation for each section, that is not trivial at high levels of RF power.

Because of above reasons a self-excited mode of operation in a positive feedback loop klystron - accelerating section is the most reliable one. In this mode of operation the system oscillates at a section's resonant frequency, frequency changes being followed by a klystron automatically. Such system is stable in the conditions of high heat loading. One of the method of phasing the autooscillating systems by means of adding a part of a reference signal to a feedback was discussed elsewhere [2]. We investigate a new variant of RF power supply system for a powerful multi-section linac. This method is based on phasing of accelerating sections which operate in a self-excited mode, by the electron beam. The method is illustrated in Fig.1. Electron bunches after accelerating section S1 enter the second section S2, which operates in a positive feedback loop with RF amplifier (klystron, TVT) with a non-linear amplitude characteristic. The electromagnetic field induced by the beam enters the input of the amplifier through the feedback loop with regulated attenuation and phase shift. It is stated, that by appropriate choice of the system parameters, such as: section frequency detuning, beam loading, attenuation and phase in the feedback loop - it is possible to obtain the self-excited oscillations at the reference section's frequency, which are phased with the oscillations in the reference section and ensure the acceleration of the beam with high efficiency.

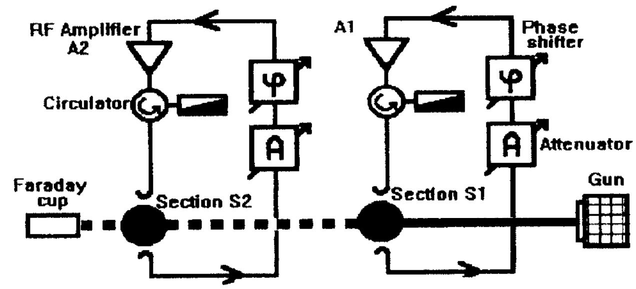

Fig.1 Block diagram, illustrating method

2. THEORY

Let us describe the accelerator structure in a coupled circuit model . We shall consider the accelerator structure consisting of a chain of coupled cavities as single cavity with equivalent values of shunt impedance R, intrinsic quality factor T. Equivalent diagram of this circuit is shown in Fig.2a.

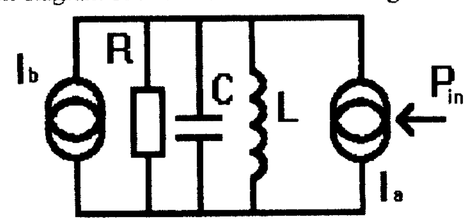

Fig.2a.Equivalent diagram of the external excitation.

The circuit is driven by two current generators: one, which describes the influence of beam current Ib, and the other, which describes the RF amplifier, Ia. We suppose that the bunches's frequency coincides with the RF frequency, and the generators are phased with each other. The results of the analysis of such system, when the amplifier is driven by the external RF signal, are well known. Specifically, a square of the absolute value of gap voltage and tangent of the voltage phase can be expressed in the following way:

$$|\dot{U}|^2 \Delta W = \frac{RTI_b}{(1+\beta)}\{\xi\cos(\varphi_a - \psi) - \cos\psi\}\cos\psi \tag{1}$$

$$tg\varphi_u = \frac{\xi\sin(\varphi_a - \psi) + \sin\psi}{\xi\cos(\varphi_a - \psi) - \cos\psi}, \tag{2}$$

$$\xi^2 = \frac{8P_a\beta}{RI_b^2}, \qquad \cos^2\psi = \frac{1}{1+Q_l^2\delta^2}, \qquad I_b = 2i_bMT. \tag{3}$$

$$M = \frac{\sin(\theta/2\beta)}{(\theta/2\beta)}, \quad \delta = \frac{2(\omega_a - \omega_0)}{\omega}, \quad Q_l = \frac{Q_0}{1+\beta}, \qquad (4)$$

where P_a - power of the signal at the amplifier output , I_b - amplitude of the first harmonic of beam current, i_b - average beam current, M -coefficient defined by the phase length of the bunch, φ_a -phase of RF signal at the resonator input, ψ - phase angle of the resonator detuning, ω_0 - resonant frequency, ω_a - RF frequency, θ - phase length of the bunch.

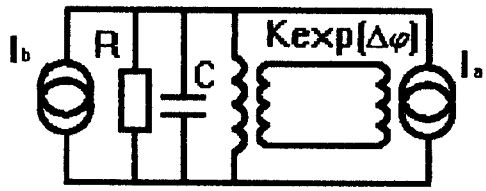

Fig.2b. Equivalent diagram of the autooscillations with beam loading.

When the feedback loop is closed, the equivalent diagram in Fig.2a transforms to the diagram schematically shown in Fig.2b. A signal with a power equal to a power of RF losses in the walls, attenuated by a factor of K , enters the input of the RF amplifier with a phase shift of $\Delta\varphi$. When the circuit is closed, phase correlation in the system are limited by the conditions:

$$\varphi_a = \varphi_u - \Delta\varphi \qquad (5)$$

Accounting for the expression for the phase of gap voltage (2), expression (5) is modified to the view:

$$\sin(\varphi_a + \psi - \Delta\varphi) = \xi\sin(\psi - \Delta\varphi) \qquad (6)$$

Equations (1) and (2) describing the absolute value of the voltage and its phase at the cavity gap , as well as the rest equations are still valid, but in this case P_a is a function of the gap voltage known either in a form of analytical expression, or as a dependence of the output power from the input power.

Before carrying out experimental investigation of the system it is important to estimate a range of system parameters, when the oscillations in the feedback loop have a frequency of electron bunches and the beam is being accelerated.

One of the conditions of existing the solution follows from equation (6):

$$\xi\sin(\psi - \Delta\varphi) > 0 \qquad (7)$$

This inequality is valid for $\xi < 1$, with the increase of ξ , the range of the value ($\psi - \Delta\varphi$) when the solution exists, becomes smaller. From the definition of the phase angle of detuning follows that ψ is in the interval $(-\pi/2, \pi/2)$.

From (1) follows:

$$\xi^2 + 1 - 2\xi\cos\varphi_a > 0 \qquad (8)$$

Changes of beam energy after passing through the structure:

$$\Delta W = \frac{RTI_b}{(1+\beta)}\{\xi\cos(\varphi_a - \psi) - \cos\psi\}\cos\psi \qquad (9)$$

Hence, for beam acceleration the following conditions should be valid:

$$\xi\cos(\varphi_a - \psi) - \cos\psi > 0 \qquad (10)$$

In order to define numerically the range of system parameters, where the solution exists, the system of non-linear equations (2),(6),must be solved using a real amplitude characteristics of the RF amplifier. The most essential, when planning the experiment, is a connection between beam current and RF power of the amplifier at the non-linear part of the characteristics. This connections depends on the parameter ξ . To estimate an order of magnitude let us suppose $\xi = 1$. From (3) follows:

$$i_b = \sqrt{\frac{4P_a\beta}{2RT^2M^2}} \qquad (11)$$

If we take as an example an on-axis coupled accelerator structure for the Moscow CW RTM [3] with the length of 1 m, effective shunt impedance of 75 MOhm/m, supposing RF power of the amplifier to be 20 kW and coupling constant =1, we can estimate the beam current to be i_b= 30-50 mA.

3. EXPERIMENTAL INVESTIGATIONS

The experimental stand on the basis of the equipment, designed in the framework of the Moscow CW RTM project, was constructed to carry out experimental investigations. A block diagram of the experimental layout is shown in Fig.1. The electron beam of the DC electron gun enters the capture section S1, which consists of 9 cells of the on-axis coupled accelerator structure with graded β. The capture section is connected with a CW klystron A1 through positive feedback loop. The klystron has a maximum power of 22 kW in the range of the frequency 2450 MHz. The feedback parameters are chosen to ensure the klystron operation at a power level of 9 kW. This power level enables the capturing of the electrons from the gun and their acceleration up to the energy of 600 keV. The resonant frequency of section S1 defines the frequency of electron bunches. Electron bunches, formed in the first section, enter the second section S2, which consists of 7 accelerator cells.

Beam current is monitored by a Faraday cup at the output of the second section. Maximum average beam current was limited a value of 1 mA. Taking into account the estimation by equation (12) we used as an RF amplifier for the second section a travelling wave tube (TWT) with maximum power of 1.3 W

The block-diagram of the RF system for section S2 is shown in Fig.3. The following parameters were controlled during the experiment: TWT power Pa, reflected power Pr, power of RF losses in the walls Pw, phase difference between sections S1 and S2, resonant frequencies of S1 and S2, beam current at Faraday cap. The parameters, which could be changed during the measurements, were: attenuation and phase shift of the feedback loop of S2, beam current and resonant frequency of section S2. Measurements showed, that starting from the beam current i_b>140-180 mkA in the wide ranges of detuning δ a coherent autooscillations become established in the second section with respect to the first one.

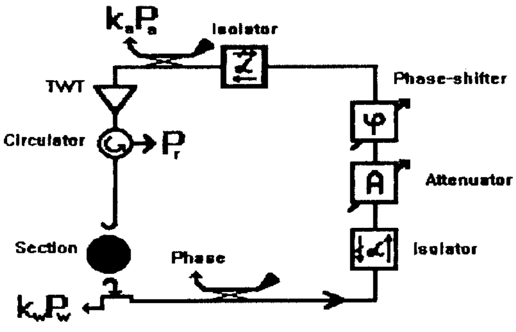

Fig.3. Block-diagram of the RF system

Fig.4 shows the dependence of RF power losses in the wall Pw, reflected power Pr, TWT output power Pa on the section frequency detuning for beam current i_b=600 mA.

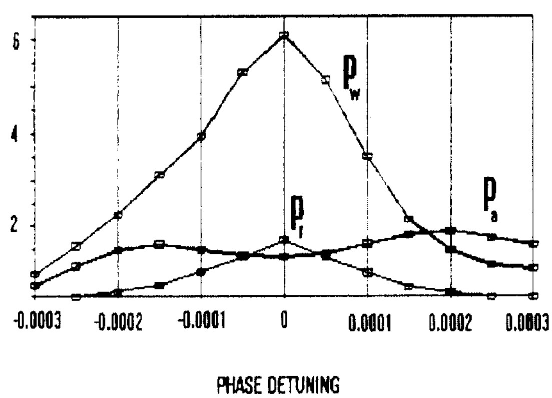

Fig.4. Balance of power in the system.

To use the effect of phasing by the beam the self-excited systems it is very important to find out the conditions of beam acceleration. The efficiency of transformation of RF power to beam power is also essential for practical purposes. In the present experiments changes of beam energy after passing through the second section S2 can not be measured because of low value of RF power (increase of beam energy is about several keV). But the fact, that the beam is accelerated can be registered and efficiency of RF to beam power transfer can be measured by analysing the power balance in the system. It is evident that the condition of accelerating the beam by TWT power is as follows:

$$P_a - P_w - P_r > 0 \qquad (13)$$

One can see from Fig.4 that the condition (13) is valid in the range δ >0.0002.

For detailed investigation of beam acceleration the values shown in Fig.4, were measured experimentally as a function of feedback attenuation, beam current and phase of the feedback loop.

Following conclusions can be made from the analysis of the obtained experimental data:

1) Accelerating section S2 operates in a self-excited mode at the frequency of the electron bunches in the wide range of frequency detuning between the resonant frequency of the section and the frequency of the electron bunches. The value of ξ parameter, when the effect can be observed, is ξ <2.9. For the standard accelerating section of the Moscow CW RTM the value of starting current is 10 mA.

2) The conditions of acceleration with high efficiency can be found by means of varying the system parameters: section detuning, beam current, phase and attenuation of the feedback loop.

For more detailed analysis of the experimental data we carried out numerical simulation of beam acceleration in phased self-excited systems. Comparison of calculated and experimental data showed that acceleration with high efficiency in the self-excited systems, phased with each other by the beam, is possible with a correct choice of system parameters.

4. SUMMARY

This variant is more perspective for very powerful CW accelerators. In this case the feedback between the accelerator structure and RF amplifier ensures a stable accelerator operation in the conditions of high heat loading, and phasing of the accelerator structures by the beam simplifies considerably the start-up of the accelerator and its operation.

We have modelled beam acceleration in the system with high power of RF amplifier. We considered the RF amplifier with output power in saturation of 1.7 MW. Accelerator structure was supposed to have a shunt impedance of 120 MOhm, which corresponds to the length of the structure 2.5 - 3.0 m in the frequency range of 2450 MHz. Intrinsic quality factor was 15000, coupling constant 1.9, frequency detuning of the structure in δ respect to bunches frequency δ =0.00018. Maximum energy gain and beam power are observed at the beam current of 290 mA and are, correspondingly, 4.12 MeV (about 1.5 MeV/m) and 0.84 MW. Power of RF losses in the walls is about 450 kW (150 kW/m), reflected power 5 kW, output power RF amplifier 1.34 MW. Efficiency of power transfer from RF to the beam is about 64%.

4. REFERENCES

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