INVESTIGATION OF OVER VOLTAGES IN THE ANODE-GRID CAVITY OF THE 200 MHZ PULSE POWER AMPLIFIER OF THE MMF

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Abstract

RF system of the Moscow Meson Factory DTL consists of the 198,2 MHz four stage amplifier with the last one (PA) connected to the high quality tank ($Q_T \sim 10^5$) by a long coaxial transmitting line (CTL). During of the PA tuning it is need not only to reach a demanded level of the accelerating field in the tank but to decrease cross coupling links between the two fast feedback control systems, stabilizing an amplitude and phase of the RF accelerating voltage in the tank, and to obtain the necessary RF pulse shape. As a rule the best PA efficiency is achieved by tuning of the PA anode-grid cavity and adjusting of the coupling with CTL usually matched with the tank input impedance. The changing of the CTL length could allow to decide the next two tasks but for over voltages in the PA anode-grid cavity, caused by discharging of the RF energy, stored in the tank. They may achieve a value a few times higher than a steady state one and cause breakdowns in the anode-grid cavity. That is why a particular attention should be paid to a study of transients which take place at a RF pulse trailing edge. An analysis of over voltages in the paper is based on knowledge of free oscillation frequencies (FOF) of the tank and of the PA anode-grid cavity, which values depend on CTL length. It is estimated the influence of the output PA vacuum tube, installed in the anode-grid cavity, on transients in this one

1 INTRODUCTION

A general view of a scheme analyzed in this paper is shown in Fig.1

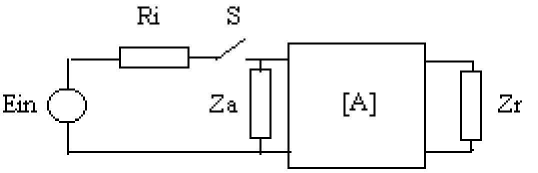

Fig.1 General view of a RF power output amplifier connected to a tank

A closed function switch S corresponds to a case of transmitting RF power during RF pulse from a RF voltage source E_{in} with inner impedance R_i to a load Z_r via a four-pole network described by a matrix [A]. Let's assume that the network between the RF source and the load consists of reactances, including coupling loops of the PA cavity and the tank, and a long coaxial transmitting line without losses. In this case $\left[A\right]=\begin{bmatrix} a_{11} & ja_{12} \\ ja_{21} & a_{22} \end{bmatrix}$ and it is true the condition $a_{11}a_{22}+a_{12}a_{21}=1$ (1)

In a steady state complex impedances Z_a of the PA cavity and Z_r of the DTL tank may be described in the following way: $Z_a = R_a/(1+j2Q_a x)$, $Z_r = R_r/(1+j2Q_r x)$, (2)
where $x=\Delta\omega/\omega_0, \Delta\omega=\omega-\omega_0$, x<<1 and ω_0 is a master oscillator (MO) frequency, R_a and R_r are shunt resistances of the PA cavity and the tank, Q_a and Q_r are quality factors of the cavity and the tank.

2 PROCESSES DURING RF PULSE

At that the function switch S is closed and the cavity and the tank are tuned at MO frequency. Moreover due to very high efficiency of the anode-grid cavity (η_a) R_a value isn't taken into account. Transforming RF source to the tank impedance it is not difficult to get the scheme presented in Fig.2. At the scheme $\bar{I}_g = \dfrac{E_{in}}{a_{22}R_i + ja_{12}}$ (3)

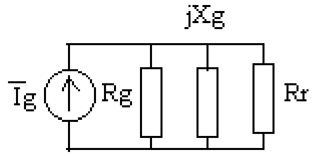

Fig.2 The simplified scheme of a RF system

$$X_g = \frac{(a_{22}R_i)^2 + a_{12}}{a_{11}a_{12} - a_{21}a_{22}R_i^2}, \ R_g = \frac{(a_{22}R_i)^2 + a_{12}}{R_i} \qquad (4)$$

The reactance Xg displaces the tank resonance frequency at the value: $\Delta\omega_g = -\omega_0 R_r / 2Q_r X_g$. In one's turn the resistance R_g shunts R_r decreasing the tank time constant. Taking into account expressions (4) we can estimate values of resonance frequency and a tank time constant deviations caused by connecting the tank to the RF power amplifier:

$$\Delta\omega_g = -\frac{R_r(a_{11}a_{12} - a_{21}a_{22}R_i^2)}{T_r(a_{12}^2 + (a_{22}R_i)^2)} \qquad (5)$$

$$T_g = T_r(1 - \frac{R_i R_r}{R_i R_r + a_{12}^2 + (a_{22}R_i)^2}), \qquad (6)$$

where $T_r = 2Q_r/\omega_0$. Except condition (1) there are two additional conditions coupling PA (R_i) and the tank (Rr) parameters with matrix components a_{ij} :

$$R_r = \sqrt{a_{12}a_{22}(a_{11}a_{21})^{-1}}, R_i = \sqrt{a_{11}a_{12}(a_{22}a_{21})^{-1}} \qquad (7)$$

The first one corresponds to matching of input impedance of the tank with characteristic impedance of the four-pole network, the second condition corresponds to equality of the inner impedance R_i and the characteristic impedance. At that a maximum value of RF power in a load takes place and in a steady state value of RF voltage in the tank is: $U_{r0} = 0.5E_{in}\sqrt{a_{22}a_{11}^{-1}}$.

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A high value of the DTL tank quality factor allows analyzing transients in the tank, considering steady state in networks between the PA and the tank and in the loaded PA cavity. With these admissions transients in the DTL tank are described by the simple differential equation of the first order [1]:

$$T_g \frac{d\overline{U}_r}{dt} + [1 + j(\Delta\omega_g + \Delta\omega_r)T_g]\overline{U}_r = \overline{I}_g R_r \frac{T_g}{T_r} \quad , \qquad (8)$$

where $\Delta\omega_r$ is an own tank detuning frequency. It is well known that the tank detuning frequency is the main reason of cross coupling links between both fast control loops stabilizing RF amplitude and phase in a tank. The cross coupling links as a rule decrease loops gains and worsen their qualities. For eliminating cross coupling links it is necessary to carry out one from two conditions:

$\Delta\omega_g + \Delta\omega_r = 0$, if $\Delta\omega_r \neq 0$ or $\Delta\omega_g = 0$, if $\Delta\omega_r = 0$.

In practice the first one is easily realized by controlling of the tank detuning until phase transients along the RF pulse will be eliminated. But the own tank detuning may be a reason of over voltages and additional losses in CTL. Hence, preferable method is the second one, when the tank is tuned and the PA operates at the matched load. From (5) and (7) it follows that condition $\Delta\omega_g=0$ can be carried out only if both expressions (7) are true.

3 PROCESSES AFTER RF PULSE

At that the function switch S is opened (anode supply of the PA and driver tubes is switched off) and the reverse processes take place: RF energy stored in the tank goes from it into the CTL and the anode-grid cavity, causing under certain circumstances over voltage in it, breakdowns and accelerator emergency stop. Over voltages appear at the travelling edge of a RF pulse and are accompanied by amplitude modulation with frequency, varying from a few hundred to a few tens kHz, as value of over voltage grows. It points at the difference between free oscillation frequencies (FOF) of the tank and the PA cavity. The investigation of amplitude-frequency response of the MMF DTL RF system output power amplifier at low level of RF power showed a possibility to determine the tuning of the PA and intermediate network between the PA and the tank, excluding an appearance of over voltage in the PA cavity. For determination of FOF values it follows to transform the tank complex impedance (2) to the PA cavity impedance and compare to zero the imaginary part of the resulting impedance. The obtained transcendental equation determines the x_a value of deviation of the PA cavity FOF (so-called transmission line resonance [2]) from the MO frequency ω_0.

$$\begin{aligned} &F(x_a)[a_{12}(x_a)(1+(2Q_r x_a)^2) - 2a_{11}(x_a)Q_r R_r x_a] \\ &- a_{11}R_r^2 G(x_a) + 2Q_r x_a R_a R_r = 0 \end{aligned} \qquad (9)$$

where $F(x_a) = a_{22}(x_a)R_a - 2a_{12}(x_a)Q_a x_a$,

and $G(x_a) = a_{21}(x_a)R_a + 2a_{11}(x_a)Q_a x_a$ (10)

In carrying out condition (9) the resulting shunt resistance of the PA cavity may be represented as follows:

$$R_{ar}(x_a) = \frac{a_{11}(x_a)R_r - 2a_{12}(x_a)Q_r x_a}{a_{22}(x_a)R_a + a_{11}(x_a)R_r - 2a_{12}(x_a)(Q_a + Q_r)x_a} \qquad (11)$$

It is necessary to have in view that $x_a=0$ is also a decision of equation (9) provided that the first condition (7) is true. A similar equations might be obtained for calculating of the relative detuning frequency x_r and the shunt resistance of the tank $R_{ra}(x_r)$ in result of changing in expressions (9) - (11) subscript a on r, a_{11} on a_{22} and vice versa. As an example let's consider a generally used scheme with two ideal transformers at the output of PA (n_a:1) and at the input of tank (1:n_r) and the coaxial transmission line without losses between both transformers.

$$a_{11} = n_a n_r^{-1}\cos(2\pi(1+x)l/\lambda_0), a_{21} = (Wn_a n_r)^{-1}\sin(2\pi(1+x)l/\lambda_0) ,$$

$$a_{12} = Wn_a n_r \sin(2\pi(1+x)l/\lambda_0), a_{22} = n_r n_a^{-1}\cos(2\pi(1+x)l/\lambda_0) \quad (12)$$

where l and W are length and characteristic impedance of the CTL. Substituting (12) in (10) and solving the obtained transcendental equation for desired parameters of the scheme one can determine dependence of the x_a value from the CTL length. In Fig.3 the calculated dependencies of the nearest to the MO frequency (zero line) FOF are shown for the next parameters of the RF system:

$Q_a = 8*10^3$, $Q_r = 5*10^4$, f_0 =198.2MHz, l/λ=20-20.5,

R_a = 64kΩ, R_i = 1kΩ, R_r = W n_r^2 , R_i = W n_a^2 , that are close to the real parameters, measured at the fourth RF channel of the MMF DTL RF system. Apparently the foregoing parameters answer demands of conditions (7). For comparison in Fig.4 experimental dependences of the PA detuning frequencies from a length of the power phase regulator (PR) installed in the CTL are shown. A good coincidence of dependences, presented in Fig.3 and 4, indicates that the scheme with ideal transformers and CTL quite good describes real processes in the PA cavity and the tank in a steady state. A similar situation takes place with calculated and measured values of the tank detuning frequency x_r. In Fig.5 the experimental dependences of the tank FOF deviation from MO frequency are presented. A jump of the tank FOF takes place near the PR length

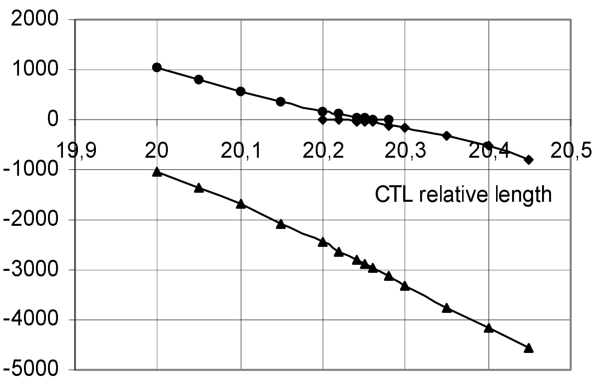

Fig.3 Calculated dependencies of the PA cavity detuning frequency, kHz

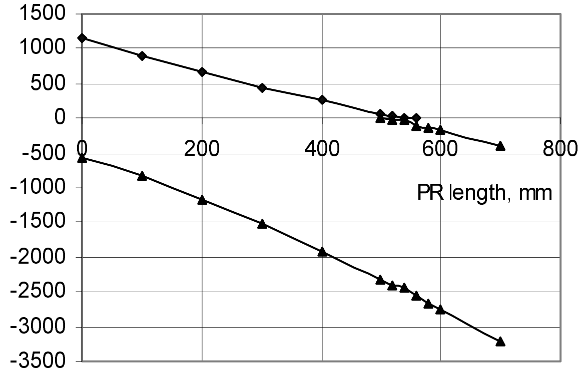

Fig.4 Experimental dependencies of the PA cavity frequencies for tank # 4

position of coinciding both the tank and the PA cavity free oscillation frequencies. This point is also characterized by the lowest value of the load tank Q-factor (R_{ra}) and, hence, by the shortest trailing edge duration of RF pulse in the tank. Namely in this point the over voltage value at the trailing edge of RF pulse in the PA cavity achieves its highest possible significance. Displacement at a quarter wave length from this PR position assures the absence of over voltages in the PA cavity and is also characterized by symmetric disposition of two nearest FOF. The similar situation has been considered in [2] with point of view PA dc operation stability. Observed processes at the trailing edge of RF pulse in the cavity show that transients in the main consist of two components. The first one is a fast (a few μs) process of exciting of the low quality cavity ($Q_a \sim 100$), tuned at MO frequency and loaded at matched input tank impedance. The second one is a result of exciting of the high quality unloaded cavity ($Q_a \sim 8*10^3$) resonance, frequency of which is far from the tank FOF (see Fig.3,4), and which is accompanied by damped oscillations with difference frequency between the tank and the PA cavity FOF. And total process (vector sum) damps with time constant of the loaded tank. Approximate estimations of transients may be fulfilled by using the equation (8) for the PA cavity. A more accurate decision is possible with regard of influence of “hot” tube in the PA cavity and transients in transmitting line. Frameworks of this paper don’t allow discussing over voltage transients in detail.

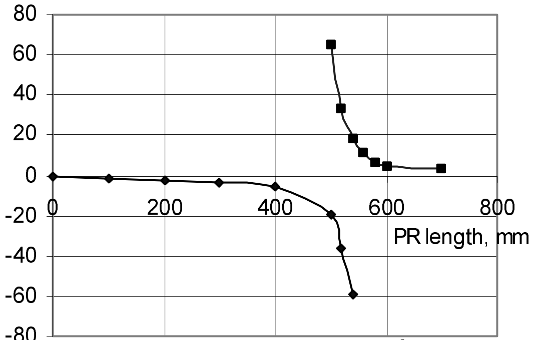

Fig.5 Experemental dependencies of tank #4 detuning frequencies, kHz

4 INFLUENCE OF PA VACUUM TUBE

So far an influence of “hot” vacuum tube at a value of over voltage in the PA cavity didn’t take into consideration. As a matter of fact appearance of RF voltage in the PA cavity causes a current via a tube. The first harmonic of the current loads the PA cavity and decreases its Q-factor while dc component re-charges the capacity in the anode of vacuum tube and increases anode-cathode voltage of closed modulator output tube. Installation of diodes in parallel to PA tube allows to eliminate a negative pulse, achieving 30-50% from the amplitude of positive modulator pulse. In estimating of tube current it’s necessary to take into account anode-grid and cathode-grid voltages being in-phase as well as nonlinearity of initial part of anode-grid characteristics and such peculiarities as fanning anode-grid characteristics. Approximate estimations show that when RF voltage in the PA cavity achieves 15-20kV an internal RF resistance of the PA tube GI-54A decreases in a few times Q-factor of the PA cavity. Strengthening of this useful effect would be possible by lengthening of modulator pulse at the PA tube plate relatively to the RF driver pulse at 5-10%, if the PA tube allowed to operate at the last part of RF pulse without RF excitation. Unfortunately, powerful generator triodes, such as GI-54A, don’t “like” to operate with plate voltage but without RF excitation and this method may be used at comparatively low plate voltage -up to 10-12 kV for tube GI-54A.

5 CONCLUSION

Examined in this paper well known phenomena is quite good explained by putting into consideration free oscillation frequencies of the output RF power amplifier anode-grid cavity and the high quality DTL tank. Namely in result of coinciding both free oscillating frequencies over voltages appear at the trailing edge of RF pulses in the PA cavity. A good correlation between PA amplitude-frequency response at low level of RF power and value of over voltage in the PA cavity at high level of RF power simplifies a procedure of tuning both the PA and the network between the PA and the cavity which excludes danger of breakdowns in the PA cavity.

6 REFERENCES

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