SIMULATIONS OF TRANSIENT PHENOMENA IN THERMIONIC RF GUNS*.

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Abstract

The report is dedicated to simulation of transient phenomena in resonant systems of thermionic RF guns caused by beam loading effect. The technique of the PARMELA code usage for evaluation of a resonant system excitation by electron bunches is described. The results of transient phenomena simulation in some RF guns are given as examples.

1 INTRODUCTION

Termionic RF guns are known as sources of a high brightness electron beam. In the process of the gun development such a phenomenon as back bombardment of a cathode by electrons must be taken into consideration.

Back bombardment electrons with energies 10^3 – 10^5 eV heating the cathode cause both change of temperature of the cathode within the RF pulse duration and increase of its mean temperature. Beam characteristics in the RF gun exit are changed within the RF pulse duration because of the beam loading effect. Therefore, RF gun operation is essentially unsteady.

The report is devoted to the description of a numerical simulating technique of transients in RF guns caused by beam loading of a resonant system considering a space charge field and change of cathode emission with the back bombardment effect.

The technique consists of the solution of the self-consistent task of cavity excitation both by an electron beam and an external RF generator. The PARMELA program [1] was utilized for simulation of particle dynamics in a RF gun.

2 DESCRIPTION OF THE TECHNIQUE

Let's consider the technique in detail. The used approach is based on the theory of non-stationary excitation of resonators [2].

In the considered model we suggest that electron bunches pass through a resonator with a frequency ω that is equal to a frequency of a RF generator. This driving frequency is close to one of a resonator eigenfrequencie ω_r, and other eigenfrequencies are far enough from ω. In this case, vortex electrical and magnetic fields in a cavity can be presented in the form:

$$\begin{aligned}\vec E(t,\vec r) &\approx \mathrm{Re}\{C_r(t)\vec E_r(\vec r)e^{i\omega t}\}\\ \vec H(t,\vec r) &\approx \mathrm{Re}\{C_r(t)\vec H_r(\vec r)e^{i\omega t}\}\end{aligned} \quad (1)$$

where: $\vec E_r, \vec H_r$ - eigenfunctions of electrical and magnetic fields calculated with the SUPERFISH program [3].

The factor $C_r(t)$, being slowly varying function of time t, obeys to the following equation:

$$\begin{aligned}&\frac{dC_r}{dt} + i\left(\omega - \omega_r - i\frac{\omega_r}{2Q_r}\right)C_r = \\ &= -\frac{1}{N_r}\int_V \overline{\vec j_b(t,\vec r)\vec E_r(\vec r)e^{-i\omega t}}dV - \frac{1}{N_r}\int_V \overline{\vec j_g(t,\vec r)\vec E_r(\vec r)e^{-i\omega t}}dV\end{aligned}, \quad (2)$$

where: $\vec j_b(t,\vec r)$ and $\vec j_g(t,\vec r)$ - current density of a beam and current density in a coupling loop respectively (we consider that RF generator is coupled with a cavity through a loop); Q_r - unloaded quolity factor of a cavity on a selected oscillation mode; N_r - norm of this oscillation. The integration in a right partr of (2) is carried out on a cavity volume V. The superscript line in the excitation integrals means averaging on time [2].

In the PARMELA program a beam is modeled as a set of particles that are characterized by a charge q, velocity $\vec v_\alpha$ and a position vector $\vec r_\alpha$. Therefore, the excitation integral of a cavity by a beam can be expressed through velocities and coordinates of particles:

$$\int_V \overline{\vec j_b(t,\vec r)\vec E_r(\vec r)e^{-i\omega t}}dV = q\sum_\alpha \overline{\vec v_\alpha(t)\vec E_r(\vec r_\alpha(t))e^{i\omega t}}, \quad (3)$$

where α - a number of a particle that is located within the limits of a cavity.

The excitation integral of a cavity by the RF generator can be expressed through power of the generator $P^+(t)$ and a "cold" coupling coefficient of a cavity with the feeder β. Finaly equation (2) can be represented as:

$$\begin{aligned}&\frac{dC_r}{dt} + i\left[\omega - \omega_r\left(1 - \frac{\omega_r\beta}{2Q_r}\right) - i\frac{\omega_r}{2Q_r}(1+\beta)\right]C_r = \\ &= -\frac{qZ_{sh}\omega_r}{2Q_rE_0^2d}\sum_\alpha \overline{\vec v_\alpha(t)\vec E_r(\vec r_\alpha(t))e^{i\omega t}} + \\ &+ \frac{i\omega_r(1-i\gamma)}{Q_rE_0}\sqrt{\frac{Z_{sh}\beta ZP^+(t)}{(Z+R)(1+\gamma^2)d}}e^{i\phi_0}\end{aligned} \quad (4)$$

where: d – cavity length; E_0 – mean amplitude of an electric field strength on a cavity axis; Z_{sh} – shunt impedance of a unit length of a cavity; Z – impedance of the feeder; $\gamma = \omega L/(Z+R)$; L – inductance of a coupling loop, R – resistance of a coupling loop; f_0 – phase a wave of voltage going from a RF power source. The SUPERFISH program normalizes fields so, that E_0 = 1MV/m. At simulation of a cavity, coupled with the waveguide through the iris, L and R were set equal to zero.

A reflected RF power in a feeder line will be equal:

$$\begin{aligned}P^-(t) = \frac{1}{2Z}\Bigg|&\left(\frac{2R}{(Z+R)(1+i\gamma)} - 1\right)\sqrt{2ZP^+(t)}e^{i\phi_0} - \\ &- \frac{i2ZE_0d}{(Z+R)(1+i\gamma)}\sqrt{\beta\frac{2(Z+R)(1+\gamma^2)}{Z_{sh}d}}C_r(t)\Bigg|^2\end{aligned} \quad (5)$$

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The equation (4) was integrated numerically on the basis of both the Runge-Kutta method with automatic selection of a step and the Euler method. Both methods of integration yield close results. The PARMELA program was included in a loop of integration for evaluation of a cavity excitation integral by a beam.

In the process of simulation we consider the processes for which the most probable time interval of particle presence in a cavity is not more than that of integration step duration Δt. In this case, the excitation integral of a cavity by a beam for the given complex amplitude of a vortex field computed at the previous step $C_r(n\Delta t)$ can be represented as follows:

$$q \sum_{\alpha} \overline{\vec{v}_{\alpha}(t)\vec{E}_r(\vec{r}_{\alpha}(t))e^{i\omega t}} \approx \approx \frac{q}{2\pi M} \sum_{\alpha} \int_{\varphi_1}^{\varphi_2} \vec{v}_{\alpha}(\varphi)\vec{E}_r(\vec{r}_{\alpha}(\varphi))e^{i\varphi}\, d\varphi \tag{6}$$

here M - number of periods of injection of a beam into a cavity on each temporary step Δt, and $2\pi M < \omega\Delta t$; φ_1 - phase of injection of the first particle into a cavity on the given temporary step, φ_2 - phase, at which the last particle from all injected particles on the given integration step escapes a cavity. Phase φ_2 should not be more than $\varphi_1+\omega\Delta t$, so PARMELA stops running at this condition. Such method of averaging allows taking into account the particles, which go back, and also those that slip from period to period in a beam that is represented as a sequence of bunches following with a frequency equal to that of RF oscillations.

At the given stage, a RF pulse was represented as rectangle. The program allows entering delay between instants of RF pulse leading edge and that of beam injection. Prior to the beam injection the PARMELA program is not used. It allows conducting test simulation of cavity excitation by the RF generator.

After the beam injection at each integration step the input file of the PARMELA program changes according to current values of field strength and its phase in a cavity and input beam characteristics. The latter are determined according to the Richardson – Dushman law taking into account the Schottky effect.

As the emission of the cathode changes within RF period, it was broken into 10 slides to reproduce a temporary profile of an input bunch. Quantity of particles in slides was selected proportionally to product of a slide charge on the total amount of particles and in inverse proportion to the total charge of slides. The reference particle was placed in a head of a bunch. As the emission of the cathode depends on its temperature, cathode temperature increment ΔT_c at the integration step Δt was determined with the simple thermodynamic model:

$$\Delta T_c = \frac{P_{back} \cdot \Delta t}{l_r \cdot \pi \cdot r_c^2 \cdot \rho_c \cdot c_p} \tag{7}$$

where P_{back} - power of back bombardment electrons falling on the cathode, l_r - extrapolated electron track length in substance of the cathode, when the electron has energy equal to the mean energy of back bombardment electrons, r_c - a radius of the cathode, ρ_c - density of cathode substance, c_p - thermal capacity of cathode substance.

The power of back bombardment electrons falling on the cathode was determined with the analysis of coordinates and energies of lost particles.

The average characteristics of a beam (emittance, radius, phase and energy spreads, energy and phase of a barycentre of bunches) in outputs of the modeled device units at the given instants are evaluated by processing of the PARMELA output file *tape2*. It allows receiving the data on changes of the beam characteristics within the RF pulse duration.

The described technique also allows modeling transients in the systems consisting of a chain of uncoupled cavities excited by a beam.

3 RESUTS OF SIMULATION, COMPARISON WITH EXPERIMENT

The model was checked up on the basis of simulation of pillbox cavity excitation by short relativistic bunches. For this case it is possible to receive the analytical solution of an excitation equation. The results of simulation coincide very well the analytical results.

The described model allowed researching the transients in several thermion RF guns with different types of cathodes. It is necessary to note, that the emissive capacity of the cathode of a RF gun can vary in the cathode - to - cathode range. It can also change for a separate cathode during its operation, because the work function of the cathode depends on conditions of its manufacturing and maintenance. Therefore, the needed output current of a RF gun is usually set up by filament power adjusting. When simulation we fulfilled the same operations we changed reference temperature of the cathode for obtaining a desirable output current of a gun.

Figure 1 shows the results of simulation of a RF gun with the single-crystal lanthanum hexaboride cathode. The gun design is similar to that of the RF gun of the MARK III accelerator. Modifications of this gun are used in several free electron lasers [4,5,6].

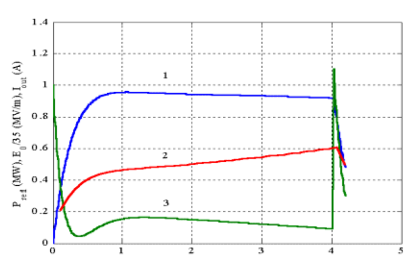

Figure 1: Time dependence of an on-axis field in a cavity (1), output current (2) and reflected power (3).

At simulation the following values were used: f = 2856 MHz; P^+ = 1 MW; $\beta = 3$; Q_r = 12350; Z_{sh} = 107 MOhm/m; f_r = 2855.6 MHz

The results of simulation and their comparisons with experimental data for a RF gun with the pressed Ba-Ni cathode are presented below. This gun is used as an injector in LIC accelerator [7]. The RF gun has a double-cavity resonant system. When simulating on the basis of the given technique only the "π" longitudinal mode was taken into account. The "0" mode of oscillations is excited by a beam ineffectively. Nevertheless, in further we will consider excitation of all longitudinal modes using a technique offered in [8]. The characteristics of RF power and the resonant system of the gun were the following: f = 2797.15 MHz; P^+ = 1.5 MW; β = 1; Q_r = 10600; Z_{sh} = 37 MOhm/m; f_r = 2796.85 MHz;

Some computational relations describing the operation of the LIC RF gun are shown in fig. 2 and 3, while the measured pulse signals are shown in the fig. 4 and 5 in comparison.

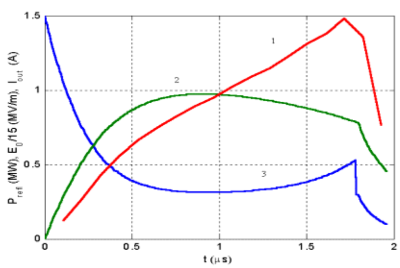

Figure 2: Time dependence of an output current (1), on-axis field of a gun cavity (2) and reflected power (3) for the LIC RF gun.

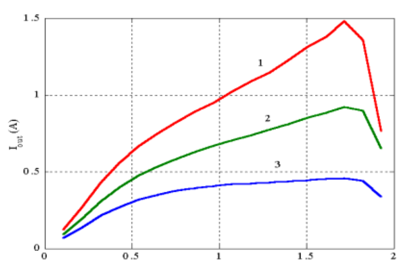

Figure 3: An output current of the gun at different reference temperatures of the cathode (1 - T_{ic} =1170°K, 2 - T_{ic} =1150°K, 3 - T_{ic} =1130°K).

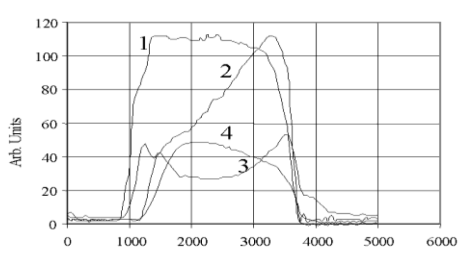

Figure 4: Measured current pulse on an exit of the LIC gun (2), envelopes of incident (1), reflected (3) power and field in a cavity (4).

As one can see from figures, the simulation describes adequately enough the processes in termionic RF guns. A back bombardment causes a ramp of cathode temperature and increases emission, respectively. The field in a cavity decreases because of beam loading at essential emission growth.

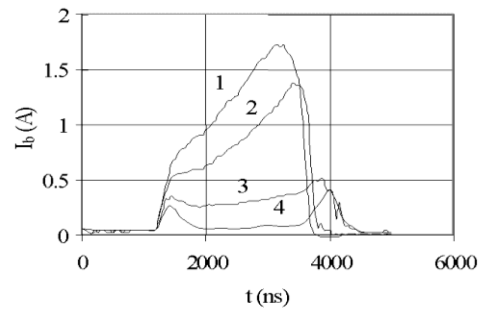

Figure. 5: Measured current pulses on an exit of the LIC RF gun at different filament currents I_f of the cathode (1 – I_f = 4.1 A, 2 – I_f = 3.99 And, 3 – I_f = 3.8 A)

Thus, relative quantity of the electrons that have reached an exit of a gun and, accordingly an output current of a gun can decrease. After a RF power pulse, the output current of a gun also decreases because of field diminishing in a cavity. The overshoots at the leading and trailing edges of curves 3 and 4 in figures 5, in our opinion, may be caused by a secondary emission reproduction of electrons, which was not taken into account at simulation.

4 SUMMARY

The designed technique of simulation of transients in thermionic RF guns allows receiving the data on the non-stationary characteristics of a beam. The carried out simulation of transients in several guns has shown, that the model describes adequately actual physical processes. The described technique can be also utilized for simulation of transients in injectors of resonance electron linacs and klystron amplifiers.

5 REFERENCES

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