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

Thermionic 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 10³ – 10⁷ 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 ω₀ that is equal to a frequency of a RF generator. This driving frequency is close to one of a resonator eigenfrequency ωᵣ and other eigenfrequencies are far enough from ω₀. In this case, vortex electrical and magnetic fields in a cavity can be presented in the form:

\[ E(t, r) = \text{Re}[C_r(t) E_r(r) e^{i\omega t}] \]
\[ H(t, r) = \text{Re}[C_r(t) H_r(r) e^{i\omega t}] \]

where: \( E_r, H_r \) - 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:

\[
\frac{dC_r}{dt} + i \left( \alpha_0 - \omega - i \frac{\alpha_0}{2Q_0} \right) C_r = - \frac{1}{N_0} \int j_b(t, r) E_r(r) e^{i\omega t} dV - \frac{1}{N_0} \int j_s(t, r) E_r(r) e^{i\omega t} dV
\]

where: \( j_b(t, r) \) and \( j_s(t, r) \) - 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); \( Q_0 \) - unloaded quality factor of a cavity on a selected oscillation mode; \( N_0 \) - norm of this oscillation. The integration in a right part (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 \( \vec{v}_p \) and a position vector \( \vec{r}_p \). Therefore, the excitation integral of a cavity by a beam can be expressed through velocities and coordinates of particles:

\[
\int j_b(t, r) E_r(r) e^{i\omega t} dV = q \sum \vec{v}_a(\gamma) E_r(\vec{r}_a(\gamma)) e^{i\omega t},
\]

where \( \alpha \) - 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 \( P^r(t) \) and a “cold” coupling coefficient of a cavity with the feeder β. Finaly equation (2) can be represented as:

\[
\frac{dC_r}{dt} + i \left( \omega - \omega_0 - \frac{\alpha_0}{2Q_0} \left( 1 + \beta \right) \right) C_r = - \frac{qZ_{\alpha}}{2Q_0 E_0 d} \sum \vec{v}_a(\gamma) E_r(\vec{r}_a(\gamma)) e^{i\omega t} + \frac{i \omega_0}{Q_0 E_0} \sum \frac{Z_{\alpha}}{(Z + R)(1 + i\gamma)} e^{i\theta_0}.
\]

where: \( d \) - cavity length; \( E_0 \) - mean amplitude of an electric field strength on a cavity axis; \( Z_{\alpha} \) - shunt impedance of a unit length of a cavity; \( Z \) - impedance of voltage going from a RF power source. The SUPERFISH program normalizes fields so, that \( E_0 = 1 \)MV/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:

\[
P^r(t) = \frac{1}{2Z} \left( \frac{2R}{(Z + R)(1 + i\gamma)} - 1 \right) \frac{1}{2Z} e^{i\theta_0} - \frac{i2ZE_0 d}{(Z + R)(1 + i\gamma)} \sum \frac{\beta}{Z_{\alpha} d} \sum \frac{2(Z + R)(1 + i\gamma)}{Z_{\alpha} d} C_r(\gamma)
\]

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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 $\Delta t$. 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 $C_i(n \Delta t)$ can be represented as follows:

$$ q \sum_a v_a(t) E_r (v_a(t)) e^{i \omega t} = \frac{q}{2 \pi M} \sum_a \int_{\phi_1}^{\phi_2} v_a(\phi) E_r(r_c(\phi)) e^{i \omega t} d\phi $$

here $M$ - number of periods of injection of a beam into a cavity on each temporary step $\Delta t$, and $2\pi M < \omega \Delta t$; $\phi_1$ - phase of injection of the first particle into a cavity on the given temporary step, $\phi_2$ - phase, at which the last particle from all injected particles on the given integration step escapes a cavity. Phase $\phi_2$ should not be more than $\phi_1 + \omega \Delta t$, 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 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](image.png)

**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; $P^r = 1$ MW; $\beta = 3$; $Q_r = 12350$; $Z_{sh} = 107$ MOhm/m; $f_s = 2855.6$ 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: \( f = 2797.15 \text{ MHz} \); \( P^* = 1.5 \text{ MW} \); \( \beta = 1 \); \( Q_r = 10600 \); \( Z_{sh} = 37 \text{ MOhm/m} \); \( f_c = 2796.85 \text{ MHz} \).

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](image2)

**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](image3)

**Figure 3**: An output current of the gun at different reference temperatures of the cathode (1 – \( T_{ic} = 1170^\circ \text{ K} \), 2 – \( T_{ic} = 1150^\circ \text{ K} \), 3 – \( T_{ic} = 1130^\circ \text{ K} \)).

![Figure 4](image4)

**Figure 4**: Measured current pulse on an exit of the LIC RF 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 thermionic 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](image5)

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

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