Transient Effects in the Linear Accelerator for Free Electron Laser

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Abstract

This paper reports on the way accepted to calculate the fields, exited with an accelerated beam and UHF power source in a nonunifom cavity chain. Particle dynamics is treated in the self-consistent manner. Power and frequency instabilities and the beam intensity variation are taken into account. Influence of transient efects, arised after generator and e-beam turn on, upon the energy spectrum is discussed. Numerical data for the linear accelerator with the beam intensity up to 1 A, which uses RF gun and is designed for FEL, are given.

1. INTRODUCTION

Transient processes in linear high frequency pulsed accelerators are arised primarily owing to the power supply switch on/off and the beam injection. At a proper pulse delay their co-operative action may result in reducing or increasing the onset time of these processes. In addition, power and phase oscilations during the so-called flat part of the microwave pulse affect the beam spectrum. Just the same result my be obtained owing to the beam intensity and injection energy variation. The problems are analized elsewhere, see, for example, refs [1-2]. This paper reports on the results of computer study of the transient phenomena in the standing wave electron accelerator LUER-20M [3] and in the injection accelerating unit, designed for FEL. The computer code Transi [2] is used. Let's emphasize some features of the electrodynamic model and mathematical formulae used as similar ideas were considered in [5].

2. BASIC RELATIONSHIPS

2.1. Accelerating system

We consider a chain of L-cavities with a quality factor-Q_l, shunt impedanse-$R_{sh\,l}$ and own frequency- ω_l, having accelerating gaps-d_l and drift regions (fig. 1).

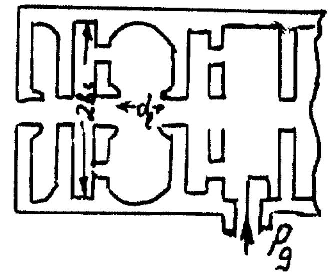

Fig.1. Accelerating structure.

The cavities are coupled by slots with the azimuth length-ϕ_l and height-Δ .

The system is driven by a microware voltage pulse:

$$V = |V^{+}(t)| \cos\left(\int_0^t \omega dt - \varphi_g\right)$$

The pulse is supplied to the m1-th cavity through a feeder at the moment t=0. The energy unused or not dissipated is removed from the m2-th cavity in a similar way. First electrons of the beam with current $I_b(t)$ are injected into the structure at the moment t_b .

2.2. Equations for field amplitudes

To find fields, induced in each cavity, we solve Maxwell equations in the Slater approach. It means, that the eigenfunctions of closed cavities are used. The current flow is represented as a system of large axially symmetrical particles of charge q_j entering the first cavity with the initial velocity v_{j0} at the moment t_{j0}. The particles travel with period T_0. Adiabathical variation of these parameters is assumed. The next step is representation of the time-dependent amplitude of the magnetic field, induced in the l-th cavity, in the form:

$$h_l = \frac{U_l + iV_l}{\sqrt{\delta_l}} \exp i(\bar{\omega}t - \varphi_g)$$

with $\delta_l = (1+\varepsilon_1^l)(1+\varepsilon_L^l)$.

As a result of time-averaging of the fast varying terms the 2L first order system of differential equations for the U (t) and V (t) envelopes is obtained:

$$U_\ell' + \tau_\ell^m U_\ell - \Omega_\ell V_\ell = \frac{\delta_\ell}{4}(k_{\ell,\ell+1}V_{\ell+1} + k_{\ell,\ell-1}V_{\ell-1}) + B_\ell \sum_j q_j S_{j\ell}\sin\psi_j^\ell + R_\ell^m \sin\psi_d;$$

$$V_\ell' + \tau_\ell^m V_\ell + \Omega_\ell U_\ell = -\frac{\delta_\ell}{4}(k_{\ell,\ell+1}U_{\ell+1} + k_{\ell,\ell-1}U_{\ell-1}) - B_\ell\sum_j q_j S_{j\ell}\cos\psi_j^\ell - R_\ell^m\cos\psi_d,$$

with

$$\psi_d = \int_0^t \omega\, dt - \bar\omega t;\quad \psi_j^\ell = (\omega_0-\bar\omega)t - \omega_0 t_{jc}^\ell + \varphi_j;$$

$$B_\ell = \frac{\sqrt{\delta_\ell}\, d_\ell}{2\bar\omega^2 T_0}\,\frac{\omega_\ell c}{1-a_\ell}A_\ell;\quad R_\ell^m = \frac{\alpha_{\ell 0}}{\bar\omega(1-a_\ell)}(1+\beta_m \mathcal{E}_\ell^m);$$

$$A_\ell = \frac{0{,}0322}{J_1(\nu_{0\ell})\, b_\ell \sqrt{\pi d_\ell}}\;\frac{1}{\sqrt{R_{sh\ell}\lambda/Q_\ell}};$$

$$\alpha_{\ell 0} = \frac{\omega_\ell}{2Q_\ell};\quad \Omega_\ell = \frac{\alpha_{\ell 0}}{\bar\omega(1-a_\ell)} + \frac{\bar\omega^2-\tilde\omega^2}{2\bar\omega^2};$$

$2\Theta_{\ell h}^\ell$ - is the transit angle;

t_{jc}^ℓ - is the time, when the j-th particle intersects the center of the l-th cavity

β_m - is cavity-feeder coupling;

$\tilde\omega_\ell$ - is the l-th cavity frequency, taking account of the coupling aperture influence. It can be determined according to the relation

$$\tilde\omega^2 = \omega_\ell^2/(1-a_\ell).$$

The term a_ℓ (the formulae is omitted) depends on the slot coupling integrals. Note, that the initial data can be given taking into account this correction. The cavity coupling depends on the slot geometry:

$$k_{\ell,\ell-1} \sim \left[kH_\ell - \sin kH_\ell - (1-\cos kH_\ell)\,\mathrm{tg}\frac{kH_\ell}{2}\right]\frac{\Delta N_s}{k^3},$$

where $H_\ell = R\Phi_\ell$, N_s - is the number of slots in a disc. Parameter $R_{sh}\lambda/Q_\ell$ is just the same and equals 968 Ohm for different cylindrical cavities; for Ω-shaped or any other cavities it's neccesary tocalculate Zeff.

2.3. Beam dynamics

Relativistic electron dynamics is dictated by the microware field, induced with an accelerated beam and power source, as has been previonsly discussed, as well as, by the external focusing field and coulomb forces:

$$\frac{d\vec{P}}{dt} = \vec{F}_i + \vec{F}_f + \vec{F}_c \qquad (2)$$

To calculate fields of the electrostatic nature we aproximated beam as a system of large particles of toroidal shape. Poisson equation was solved within the frame work of the coordinate system moving with the particle average velocity. The charge density was determined according to the cloud in cavity method. Fast F-transformation was used for Z-axis.

3. COMPUTER CODE

The relationships (1) and (2) are programmed in the code Transi, intended for the self-consistent computer study of the electron acceleration in a nonuniform cavity chain. Similar to ref. [5], they are integrated with the Runge-Kutta method. Power and frequensy variations are taken into the account, as well as the beam intensity and injection energy. To calculate beam dynamics for a long electron pulse the method of the successive injection is used. As a result of performed computations we obtain the numerical data for cavity field envelopes, the phase and the shape of the reflected signal and information about angular and phase-energy beam parameters.

4. COMPUTATIONAL RESULTS

4.1. Accelerator LUER-20M

Data on this accelerator, designed in NIIEFA for medical applications [3] in the energy range from 5 to 20 MeV for electrons and -rays, where used for test computations. Its accelerating system is a bi-periodical standing wave structure of $\pi/2$ -mode with the internal coupling. Number of cavities equals 56; the microware power source (P=4.5 MW, f=2450 MHz) feeds the cavity chain through the coupler in the 29-th cavity. The 41-th cavity, divided into too parts, both of which can be retuned, is designed for energy requlation.

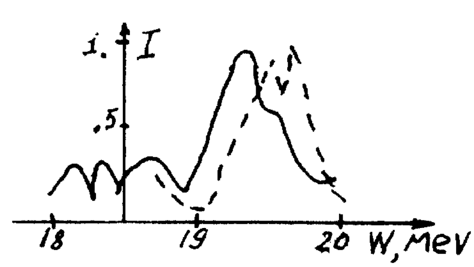

Fig.2. Energy spectrum of electrons, accelerated in the LUER-20M.

In fig.2 the energy spectrum curves for different electron injection delays are presented. A microware trapetium pulse has the length of $f\tau$=24000, and its rise time equals 5000 periods. The steady state injection current value is 54 mA at the injection energy of 20 keV. For this case 40% of electrons are captured.

4.2. RF electron injector

In some accelerators designed for FEL, for example [4], the RF gun is intended to be used as an injector. In this connection the transient effects in the accelerating system, like as shonn in fig.1, were analizied. The system has three coupled cavities of quality factor Q=20000. The thermocathode is placed on the left side of the first cavity.

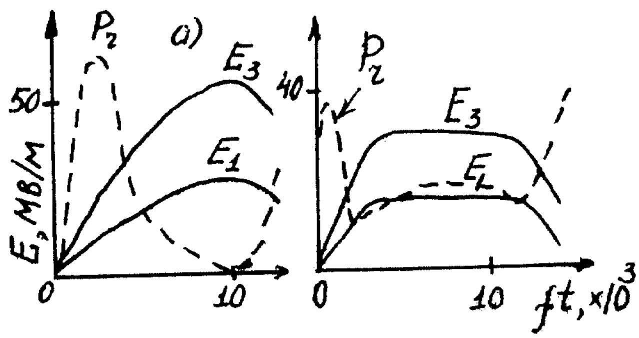

Fig.3. Field envelopes.

The electron current emitted out of the cathode is determined by the 3/2 low, howerer other equations can be also used. Field envelopes and reflected power pulse for β=1,2 and I_b (t)=0 aredisplayed in fig.3a.

The RF-power source (P=3,5 MW, f=1,3 GHz) feeds the third cavity. In the next picture (fig.3b) the curves coresponds to the case with the beam on. The beam increasing intensity of the beam is determined by the electric field strength for the first cavity E_1 (t). The steady state average pulse current equals 1 A. The generator-cavity coupling is β =4.
It's seen, that the beam loading decreases the rise time to the value of 2,4 sec.

5 REFERENCES

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