RF SELF–CONSISTENT ELECTRON BEAM DYNAMICS SIMULATION IN THZ GENERATOR BASED ON PHOTOINJECTOR AND CHERENKOV DECELERATING SYSTEM

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Abstract

The generator of high intensity monochromatic radiation in sub-mm range is currently under R&D at the Department of Electrophysical Facilities of MEPhI. This generator is based on photoinjector and irradiating Cherenkov capillary. It is necessary to have high brightness electron beam for generation of monochromatic radiation in this type of structure. Such beam can be produced by photocathode and accelerated to energy of several MeV using short structure with high acceleration efficiency. Irradiating capillary represents as metal tube with inner radius of the radiation wavelength order and covered with dielectric layer or made of corrugated waveguide. It is important to study the self-consistent dynamics of the beam during the acceleration as the current pulse is equal to several A, i.e. the beam dynamics should be studied considering both RF (radiation) and Coulomb components of self-field of beam. Another problem is to study the electron beam dynamics and fields irradiated by it in decelerating structure in the absence of external fields. The scheme of irradiating facility, its operation mode and high-current beam dynamics simulation results in accelerating structures are presented.

INTRODUCTION

The generators of high intensity monochromatic radiation in sub-mm range are highly demanded nowadays and developed for a number of research centers and applied tasks. One of the applications is cargo inspection system that demands high power THz radiation and working mode with repetition rate about tens of Hz.

High radiation power can be generated using large accelerator (linear or synchrotron) and free electron laser (FEL) but such facilities are not compact. Traditional vacuum (e.g. traveling wave tubes) and solid state (OLED, resonant tunnel diodes) generators doesn't provide the power level higher than 1 W.

THz radiation generation can be obtained using Cherenkov or Smith-Purcell radiation capillary channels and photoinjector accelerating system [1].

The important problem is investigation of self-consistent beam dynamics, mathematical model development and high current relativistic beam dynamics simulation during the acceleration and going through the irradiating structure.

In common case it is necessary to solve the motion equation together with Maxwell's equations. But sometimes we can replace the solution of Maxwell's equations (this is a quite complicated task) by the solution of Poisson's equation (for example, if we are looking for the solution of motion equation for intensive non-relativistic ion beams) or excitation equation (in case of ultrarelativistic beams, when we can neglect the Coulomb component of self-field of the beam). But for some tasks we have to consider both quasi static Coulomb component of self-field and RF radiation field of the beam.

The developed model considers full self-consistent field (both Coulomb component and radiation field), induced by beam in structure.

The key feature of the model is external field absence in irradiating structure.

FACILITY SCHEME

The coherent Cherenkov radiation can be generated using short and well collimated electron bunches with ps or sub-ps duration and 100-200 μm transverse size. Such bunch can be formed using a photocathode and compact accelerating system providing high accelerating gradient. The laser system in photogun is proposed to generate a series of short laser pulses which irradiate photocathode placed in the sidewall of an accelerating system. It was proposed to separate the accelerating structure into two sections (Fig. 1).

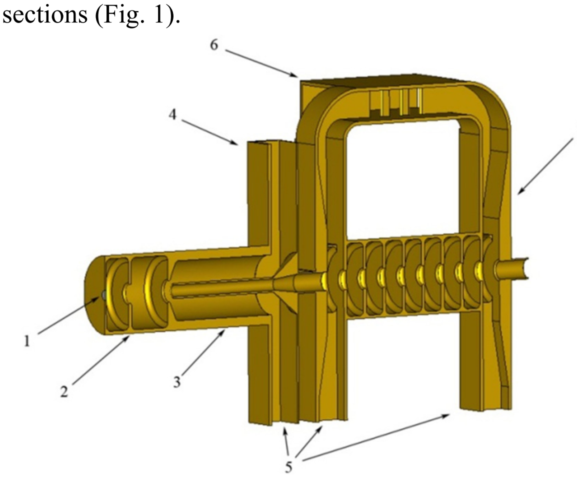

Figure 1: Accelerating system: 1 – photocathode, 2 – 1.6 cell structure, 3 – coaxial wavetype transformer, 4 – power input, 5 – vacuum ports, 6 – directional coupler, 7 – travelling wave resonator structure.

The first accelerating system is based on 1.6-cell disk loaded waveguide (DLW) and provides maximum accelerating fields on the cathode surface. After that the bunch (or bunch packet) should be accelerated in the

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second structure to the energy of several MeV. Second accelerating structure is traveling wave structure based on traveling wave resonator principle (TWR) [2]. After acceleration bunch should be injected into special irradiating capillary channel where electromagnetic radiation will be induced under the Cherenkov principle.

Two types of capillary channel can be used in the proposed generator. First one is conducting (copper) capillary tube coated inside by dielectric. The slow-wave structure can also be made as a metal corrugated channel or a grating surface. Both decelerating systems have transverse sizes compared with the wavelength of generated radiation (0.1-1 mm) and a length of several cm.

HIGH CURRENT BEAM DYNAMICS

Space Charge Field

Space charge field (Coulomb component of self-field of beam) calculation is proposed to be carried out using "large particles" method [3]. The main point of this method is the following. During bunching or emission processes beam is formed into separate bunches which follow each other with some period. We consider the area with length of few periods (usually 1-3). Into the bunch area we involve spatial grid. Bunch represents as a large number (N>>1) of particles with limited size. According to three dimensional model particles are divided into rectangular parallelepipeds of the same size.

If we know beam current density and size of large particle, we can find its charge. Then the solution is reduced to three tasks. The first one is to find charge density distribution on the grid. Then the Poisson equation

$$\bar{U}_c = -\bar{\rho}_c / \varepsilon_0$$

is solved using Fast Fourier Transformations (FFT) and, finally, the components of electric self field of the beam are defined by potential differentiation.

Large particle method has few varieties, which differ from each other by charge distribution way in cells of spatial grid. For modeling beam dynamics CIC (Clouds in Cells) method was used. Here charge of each particle is spread to the nearest nodes of grid with corresponding "weight coefficients".

Beam Loading Simulation

In this фкешсду based on electro dynamical theory excitation simulations were carried out for accelerating structures on standing and traveling waves in case when the duration of current pulse is many times smaller than filling time of structure with RF power (short electron pulse from photocathode case).

More details about excitation calculation theory can be found in book of Prof. E. S. Masunov [4].

Beam Dynamics Simulation In 1st Accelerating Section Considering Beam Loading

After formation beam is accelerated in 1st accelerating section represented as 1.6 cell structure and accelerates beam on standing wave on π mode.

Main electro dynamical parameters for 1st accelerating section are shown in Table 1.

Table 1: Main electrodynamics parameters for 1st accelerating section.

Section length (m)	0,072
β_v	0,9
Wave length (m)	0,1
Efficient shunt impedance (MΩ/m)	50
Q factor	13000

Initial particles phases during injection into the 1st section are chosen from the point of max efficiency of acceleration. Main parameters used in the simulation are shown in Table 2:

Table 2: Main parameters used in the simulation.

Wave length (m)	0,1
Section length (m)	0,072
Attenuation parameter *w*	0
Initial phase duration of current pulse	0,02
Initial dimensionless amplitude of electric field	2,544

Motion equations were used to simulate beam dynamics considering beam loading in 1st section are the following:

$$\frac{dA}{d\xi} = A\left(\frac{d}{2d\xi}(lnR_n) - w\right) - \frac{2B}{N}\sum_{n=1}^{N} I_0\left(\frac{2\pi}{\beta_v}\sqrt{1-\beta_v^2}\eta_n\right)cos\psi_n$$

$$\frac{d\psi_i}{d\xi} = 2\pi\left(\frac{1}{\beta_v} - \frac{1}{\beta_{\xi,i}}\right) + \frac{2B}{AN}\sum_{n=1}^{N} I_0\left(\frac{2\pi}{\beta_v}\sqrt{1-\beta_v^2}\eta_n\right)sin\psi_n$$

$$\frac{d\gamma_i}{d\xi} = Acos\psi_i$$

where B characterizes beam-structure coupling,

$$B = \frac{eJ_0\omega R_{sh}\lambda^2}{4W_0 QLV_{gr}}$$

N – number of particles in bunch, $\xi = z/\lambda$ - dimensionless longitudinal coordinate, $\tau = \omega t$

$$A_z = (e\lambda / m_0 c^2)E_z$$

As a result of beam dynamics simulation in 1st section the dependence of average energy of all particles as a

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function of longitudinal coordinate is presented at Figure 2.

Preliminary studies shows that pulse beam current equal to 1 A is necessary for THz generator operation. According to Fig. 2 beam with beam current equal 1 A is accelerated to the energy of 1.33 MeV. We assume this energy as injection energy for 2nd accelerating structure. Output phase duration of current pulse after 1st accelerating structure equals 0.0016.

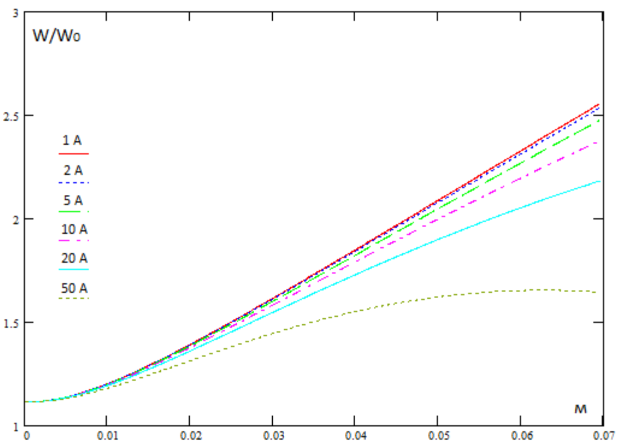

Figure 2: Average energy of all particles as a function of longitudinal coordinate with different beam currents.

Beam Dynamics Simulation In 2nd Accelerating Section Considering Beam Loading

After 1st accelerating section beam is moving to the 2nd accelerating section is presented as an 8 cell structure and accelerates beam on traveling wave with negative dispersion on π/2 mode.

Table 3: Main electrodynamics parameters for 2st accelerating section.

Section length (m)	0,2
β_v	1
Wave length (m)	0,1
Series impedance (MΩ/m)	70

Motion equations used to simulate beam dynamics considering beam loading in 2st section are:

$$\frac{dA}{d\xi} = A\left(\frac{d}{2d\xi}(lnR_n) - w\right) - \frac{2B}{N}\sum_{n=1}^{N} I_0\left(\frac{2\pi}{\beta_v}\sqrt{1-\beta_v^2}\,\eta_n\right)cos\psi_n$$

$$\frac{d\psi_i}{d\xi} = 2\pi\left(\frac{1}{\beta_v} - \frac{1}{\beta_{\xi.i}}\right) + \frac{2B}{AN}\sum_{n=1}^{N} I_0\left(\frac{2\pi}{\beta_v}\sqrt{1-\beta_v^2}\,\eta_n\right)sin\psi_n$$

$$\frac{d\gamma_i}{d\xi} = Acos\psi_i + Acos\left(\frac{\xi}{\beta_{ph}} + \tau\right)$$

$$\frac{d\tau}{d\xi} = \frac{1}{\beta_{ph}}$$

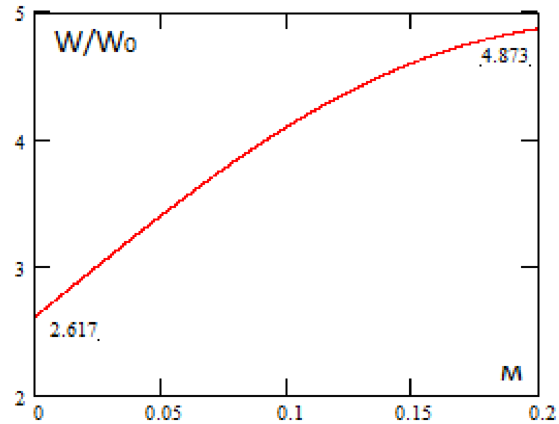

Figure 3: Lorenz factor value as a function of coordinate in 2nd accelerating structure for beam current value of 1 A

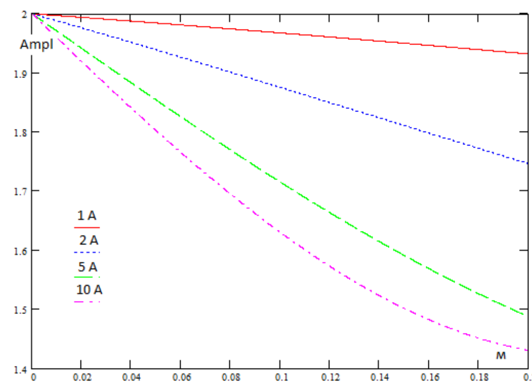

Figure 4: Accelerating field amplitude as a function of coordinate considering different beam current during the acceleration in 2nd accelerating structure.

SUMMARY

The generator of high intensity monochromatic radiation in sub-mm range was discussed with an emphasis on beam dynamics investigation in accelerating sections considering full self-field of the beam.

Mathematical model for high current beam dynamics calculation considering both Coulomb and radiation field was developed.

Beam loading simulation was carried out in 1st and 2nd accelerating sections. Figure 2 shows output beam energy after 1st accelerating section for different beam current values. As a working beam current we choose 1 A. Output energy after 1st accelerating section is equal to 1.33 MeV. According to Figure 3 the output energy after 2nd accelerating section is equal to 2.44 MeV.

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