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Numerical simulation of electrons dynamics in a microtron on 6 – 10 MeV

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Abstract. Electron dynamics in 6.5 MeV classic microtron of the Lebedev Physics Institute (LPI) is investigated by means of numerical methods. Particular emphasis is placed on the formation mechanism of electron bunches at the first circular orbits. An effect of microtron main parameters such as accelerating RF field amplitude, DC magnetic field, as well as a geometry and a position of a thermal emitter on characteristics of electron beam extracted from the microtron are studied. In the space of mentioned parameters a region corresponding an optimal microtron operation mode is found. It is noted that the unique geometric and energy characteristics of accelerated beam makes use of microtron attractive not only as injector into a synchrotron, but also as a driver in experiments on generation of coherent terahertz electromagnetic radiation.

1. Introduction

V.I. Veksler proposed two methods of relativistic particles acceleration in 1944 [1]. One of those was implemented in synchrotrons and the other one in the microtrons. In LPI microtron electrons are accelerated in RF cavity located inside the magnet that forms a uniform time-constant field. Electrons, captured in synchronous acceleration mode, move in circles with stepwise increasing radii. Note all these circles theoretically have a common point located inside the cavity [2]. The main advantages of the microtron are extremely narrow energy spectrum and small sizes of accelerated beams [2,3]. Additionally, the microtron has relatively simple design and low cost of operation. Classical microtrons are used in variety application of science (e.g. nuclear physics research), industry (e.g. industrial inspection, sterilization) and medicine (e.g. radioisotopes production, radiotherapy). Thus, microtron is used as injector for electron synchrotrons with average energy is equal to (0.250 – 1.5) GeV [4]. It can be an effective source of high energy photon radiation in photon and neutron activation analysis. Microtrons can be used for photonuclear reaction production [5], as well as for neutron production for pulsed fast neutron reactor [6]. The 6.5 MeV LPI microtron is used to study bremsstrahlung characteristics of relativistic electrons in complex structures. Also it is an injector of 1.3 GeV "Pakhra" LPI synchrotron [7].

2. LPI microtron cavity design

Acceleration of the electrons occurs in the cylindrical cavity with operating frequency is equal to 2.856 GHz. Electron source is a thermionic cathode LaB_6 placed inside the accelerating cavity. The cavity cross section in microtron median plane is shown in figure 1. There are basic geometric dimensions of the cavity in figure: radius (R), cavity length (d), distance between center of thermal emitter and the resonator axis (r_{emit}). We consider that cavity length d was equal to 19 mm, g and R were equal to 7 mm and 40.3 mm correspondingly. TM_{010} mode is the main one because ratio $d/R < 2.03$. The microtron is operated with the Russian first type of acceleration. It means that the first orbit of particles places inside cavity. Furthermore, cavity geometry has a deviation from axially symmetric because of electron dynamics feature at the first turns. On the one hand magnetic component of RF cavity field as well as output cavity window cause defocusing the particles. On the other hand particle losses can be reduced by proper choosing the input cavity window geometry.

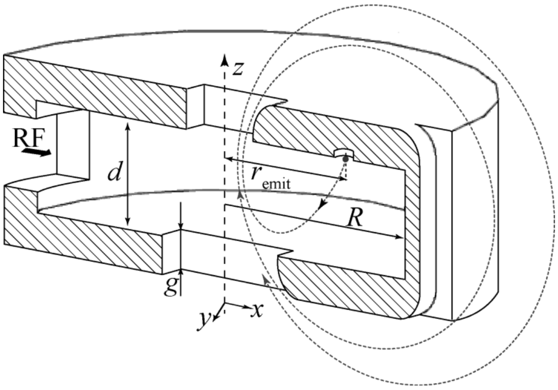

Figure 1. Cross-sectional view of RF cavity.

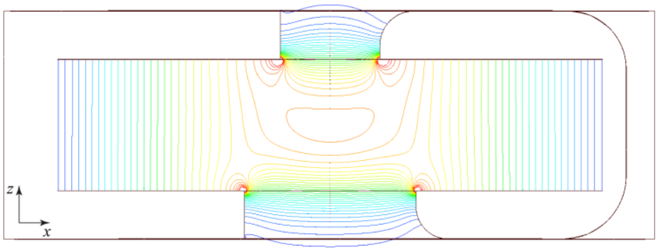

Figure 2. Typical spatial distribution of absolute electric field value in median plane.

3D distribution of RF electromagnetic field (electric and magnetic components) in microtron cavity was found numerically with the use of specialized code [8]. Calculated field distribution in described cavity is shown in figure 2. One can see that obtained field topology differs from that one in usual cylindrical cavity. A penetration of the field beyond cavity boundaries through its windows shown in the figure 3 for $x = 0$. There are accelerating component of the cavity field as a function of longitudinal and transversal coordinates in figure 4 and figure 5 correspondingly. There are two curves in the last figure: one of that is numerically obtained curve (solid) and another one is plotted in accordance with formulae for usual cylindrical cavity (dashed).

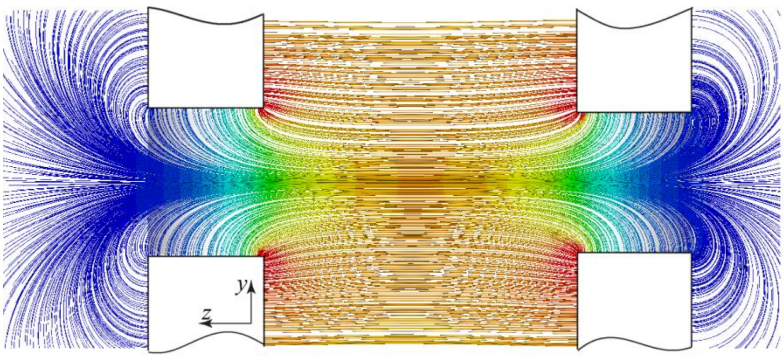

Figure 3. A penetration of the RF field beyond cavity boundaries through its windows.

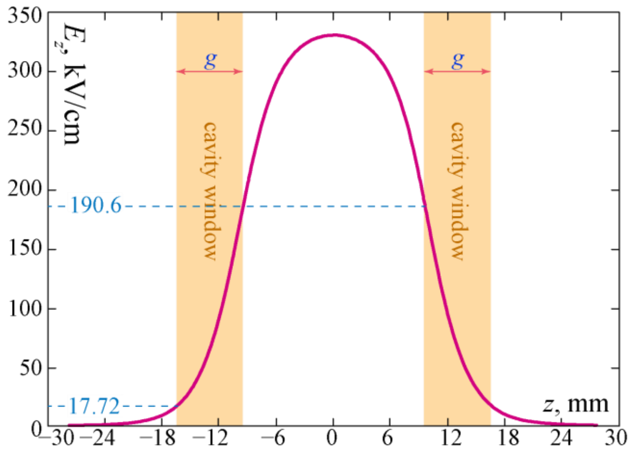

Figure 4. E_z vs z for $y = x = 0$.

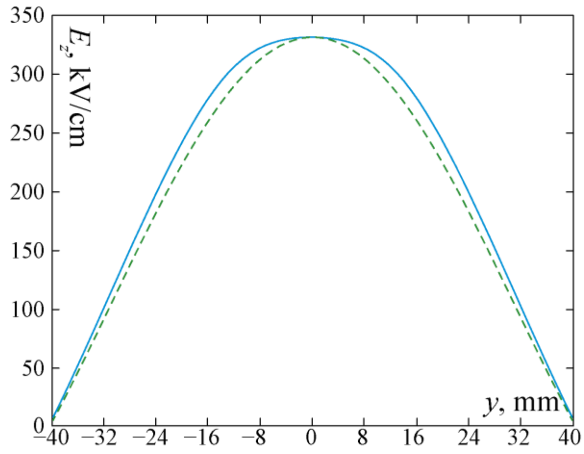

Figure 5. E_z vs y for $z = x = 0$.

3. Simulation of electron dynamics

Dependence of output beam parameters on microtron operation mode, namely on amplitude of accelerating voltage, was investigated. In the first step a special MICRO code was written [9] that allowed us to carry out a two-dimensional one particle electron dynamics simulation in the field, calculated above, in microtron median plane. The energy of the emitted electrons was equal to 5 eV and r_{emit} was equal to 27 mm (shifted-emitter microtron). On simulating the electron dynamics we found that uniform magnetic field for circular motion is 0.12 T under magnet pole diameter is equal to 75 cm. Energy gain for one period is defined as follows

$$\Delta W_s = eU_0 T \cos\varphi_s ,$$

where U_0 is an accelerating voltage amplitude:

$$U_0 = \int_{-\infty}^{\infty} E_z(0,0,z)dz$$

and transit-time factor is

$$T = 2\sin(\theta/2)/\theta, \quad \theta = \pi d/\lambda .$$

Thus, it was obtained that an amplitude of accelerating voltage should be equal to 678 kV under equilibrium particle phase φ_s is equal to 15° in order to satisfy resonant acceleration condition.

There are several electron trajectories in figure 6. Each of them corresponds to different moments of electron emission from the thermionic cathode in the cavity field. One can see that a significant part of the electrons fall on the inner cavity wall and some part are lost on the outer cavity side. It was found that the maximal energy value is typical for particles that were emitted in phases of the RF field in the range approximately from −90° to −70° (for cosine voltage variation). This is because the time of field-particle interaction inside cavity for RF field phase range at first orbit before RF field changes direction is enough to ensure that electrons obtain the required energy to skirt cavity wall.

Further 3D electron dynamics simulation in LPI microtron assuming continuous emission from thermionic cathode was carried out. Emitter spot diameter was presumed to be equal to 4 mm. It should be noted that the emitter was assumed to be a point in [9].

Calculated longitudinal beam size is equal to 15 mm, vertical and radial beam sizes are equal to 2.2 mm and 0.6 mm correspondingly for the 9th orbit. The beam particles energy spectrum on the 9th orbit is shown in figure 7. There is a typical view of forming the electron bunches in figure 8.

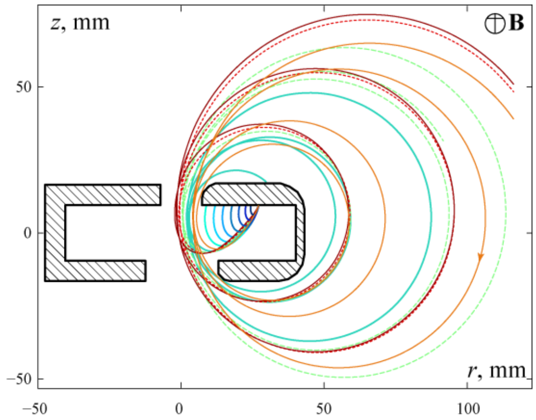

Figure 6. Typical trajectories of electrons in microtron.

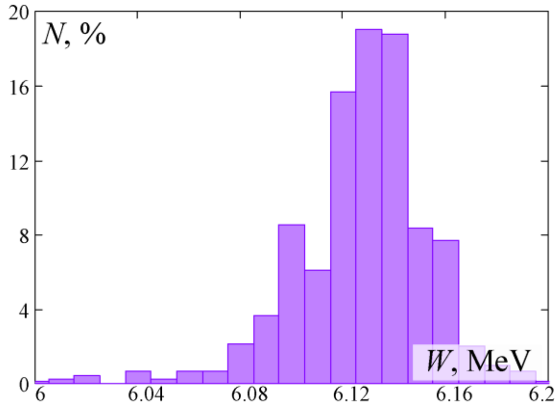

Figure 7. Particles energy spectrum on the 9th orbit.

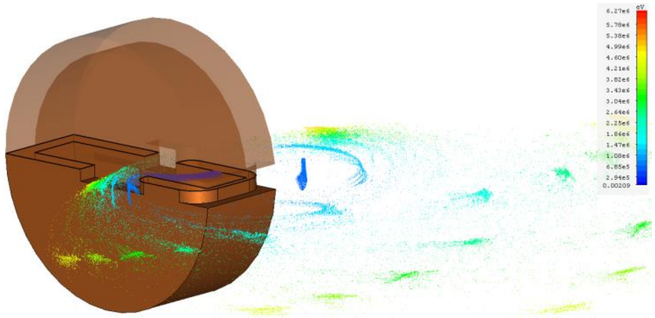

Figure 8. Typical view of forming the electron bunches in 3D space.

Note also that approximately 65% of emitted particles hits the internal cavity wall during one period of RF field and only 20% are accelerated up to final energy.

4. Conclusion

3D cavity model was developed and electromagnetic field distribution was simulated. Dynamics of electrons in LPI microtron was studied. Dependence of output beam parameters on microtron operation mode was investigated. Optimal values of microtron parameters were found.

Acknowledgments

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