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Numerical simulation of longitudinal and transversal electron dynamics in classical microtron

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Abstract. Numerical simulation of 3D electron dynamics in classical Lebedev institute microtron with energy 6-10 MeV is carried out. Special attention is paid to particles transversal motion investigation. A comparison of physical electric field distribution along cavity axis with that obtained by means numerical calculation is done. The obtained results are discussed.

1. Introduction

Microtron is the cyclic resonance relativistic accelerator with variable harmonic number. It is known that the mechanism of relativistic particle acceleration realized in the microtron was proposed by Veksler in 1944 [1]. Electrons dynamics in a microtron has a number of specific features that differ it from other circular accelerators and result in unique geometric and energy parameters of the accelerated beam [2]. Such electron accelerators are widely used as injectors for electron synchrotrons, as well as accelerator-drivers in experiments on generation of coherent terahertz electromagnetic radiation. In a number of experiments, a microtron is used as electron source in free-electron lasers of submillimeter band. It is important to know the parameters of the electron bunch at the microtron output to simulate the generation mode.

One of the urgent tasks of modern particle accelerators technology is a design and development of specialized synchrotron radiation sources of the fourth generation [3-11]. Such sources will become a unique tool for research tasks like ultra-small angle x-ray scattering, high resolution powder diffraction, coherent x-ray scattering, micro-macromolecular crystallography, material science, structural biology, biomedical imaging etc. Circular resonance electron accelerator, microtron, can be proposed as an injector for some of such sources.

2. Numerical simulation of electron dynamics

We investigated the three-dimensional electrons motion in 6.5 MeV microtron, that is the injector of 1.3 GeV “Pakhra” LPI synchrotron [12]. Accelerating the electrons occurs in the cylindrical cavity with operating frequency is equal to 2.856 GHz. Electron source is a thermionic cathode LaB₆ 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. The microtron is operated with the Russian first type of acceleration. Emitted electrons traverse the microtron cavity through the



special windows which original dimensions ($y \times x$) are 7.3×25 mm (input window) and 8.2×14.3 mm (output one).

RF electromagnetic field of the resonator partially penetrates beyond the special windows and it is ending on the outer side of the cavity walls and partly on the windows surfaces. It results in field vertical component appearance. A penetration of the field beyond cavity boundaries (for $x = 0$) is shown in the figure 2.

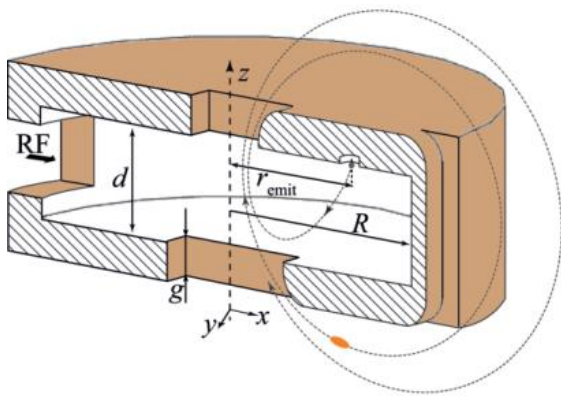


Figure 1. Cross-sectional view of RF cavity.

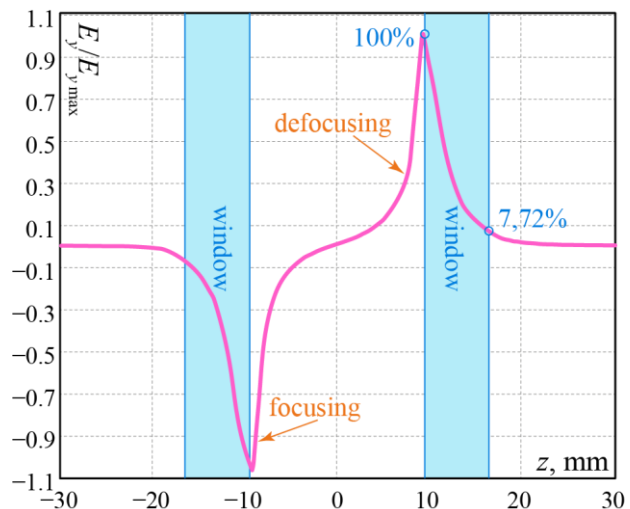


Figure 2. A penetration of the RF field beyond cavity boundaries through its windows.

One of the main requirements for electrons dynamics in a classical microtron is to provide vertical stability. Vertical stability is achieved by means of two counteracting factors: focusing and defocusing action of RF field in the area of special windows. Namely, phase shift between electric field vertical components oscillations in those areas is equal to π . It is equivalent to FODO focusing system or electrostatic focusing in cyclotron.

In order to investigate motion of electrons, and especially transverse one, numerically calculated three-dimensional distribution of the cavity RF field is used (TM_{010} mode), which coincides with the real distribution with high accuracy. The following microtron parameters are assumed: emitted electrons energy is equal to 5 eV (under Gaussian energy distribution), r_{emit} is equal to 75 cm, emitter spot diameter is equal to 4 mm, an amplitude of accelerating voltage is equal to 678 kV under equilibrium particle phase is equal to 15° , uniform magnetic field for circular motion is 0.12 T under magnet pole diameter is equal to 75 cm.

The influence of input window vertical size on particle transition was investigated as well. It was found, by means of numerous simulations, that optimal dimensions of input window are 12.5×25 mm. Minimum amount of particles die on the wall in that case.

Electron trajectories and electron bunch characteristics was calculated by means of numerical integration of the three-dimensional motion equation, in the approximation of non-interacting particles, as it was done in [13]. The average particle energy at the final microtron orbit (the 9th) is equal to 6.71 MeV. The calculated transverse and longitudinal dimensions of the beam, as well as the energy spread of the beam particles at the final microtron orbit are $\Delta z = 6.9$ mm, $\Delta y = 4.2$ mm, $\Delta x = 2.3$ mm and $\sigma_w = 0.67\%$ respectively.

Energy spectrum of electrons is shown in figure 3. One can see that it is close to the normal Gaussian distribution. A distribution of charge density in bunches on the 9th orbit in the median and vertical planes are shown in figure 4.

Vertical motion of electrons during the acceleration for a few initial orbits is shown in figure 5 where dashed rectangles indicates output cavity window. Note that the focusing and defocusing forces act alternately on the particles during each transition of electrons through the accelerating gap. The

first transition is specific. On the first orbit emitted electrons pass through only the one window, in which particle vertical momentum is increased significantly. It leads to significant particle losses at a few first orbits.

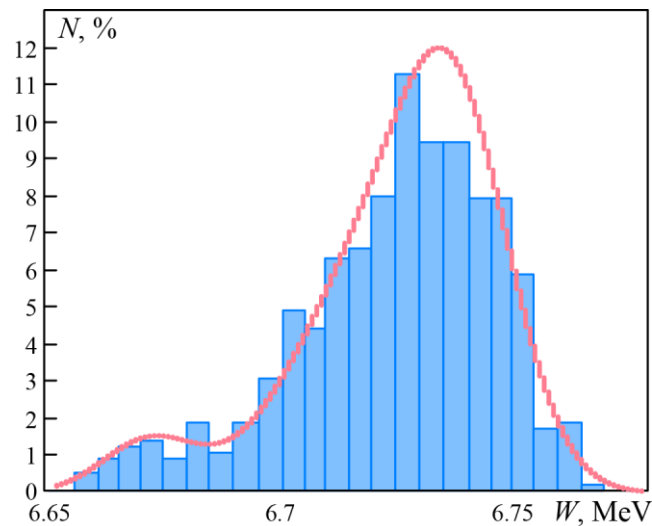


Figure 3. Particles energy spectrum.

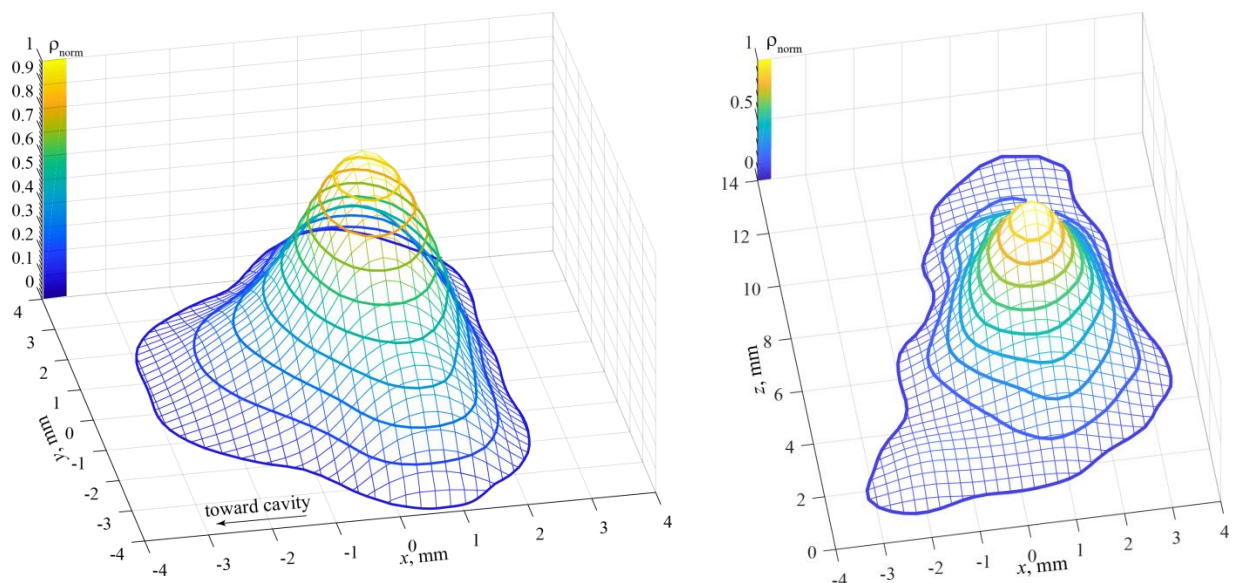


Figure 4. The distribution of charge density in bunch in vertical plane (left) and in median one (right).

Numerical simulation showed that 33% of particles were captured in stable acceleration mode, 26% of particles were lost on the inner cavity wall, 30% – on the outer cavity wall and 11% – on the other cavity parts for the RF field phase range from -90° to -50° under chosen microtron parameters. Figure 5 illustrates calculated transversal losses of electrons, which are injected in different RF field phases, on cavity walls (a – inner side of the cavity wall with output window, i.e. that one which with cathode; b – outer side of the wall with input window).

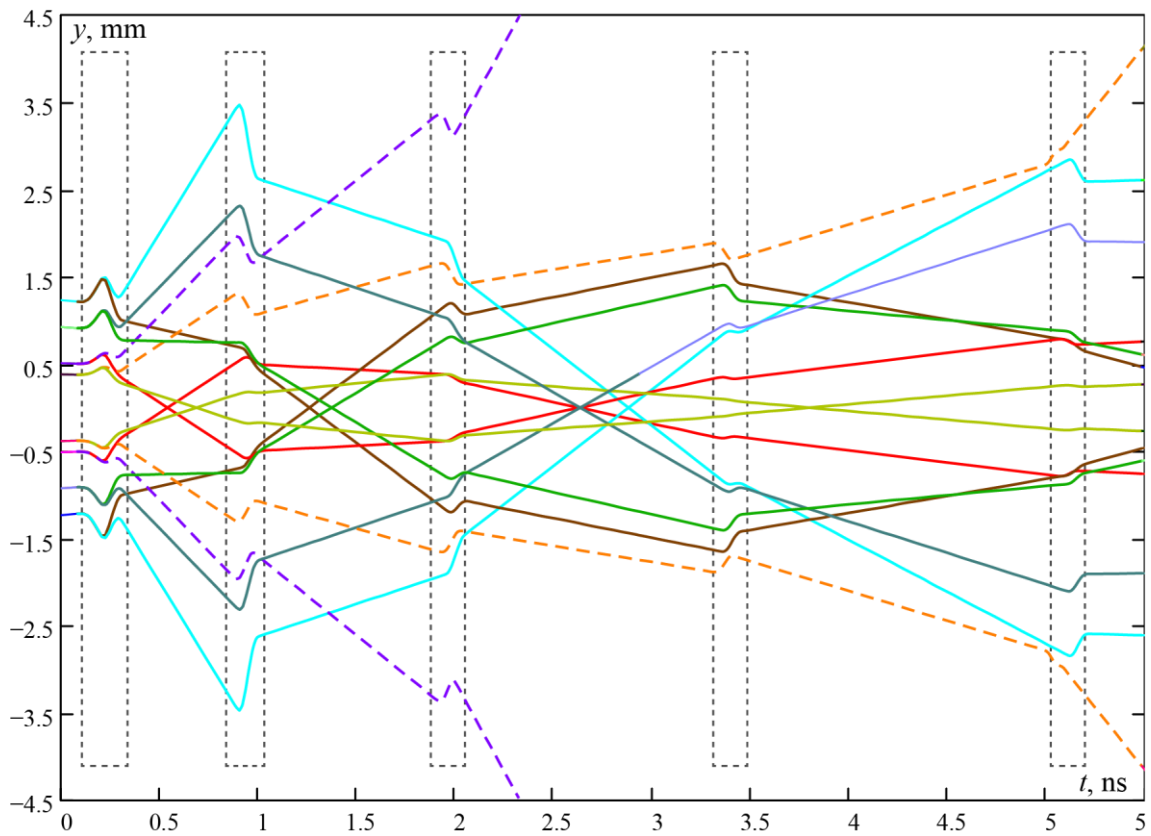


Figure 5. Vertical motion of electrons.

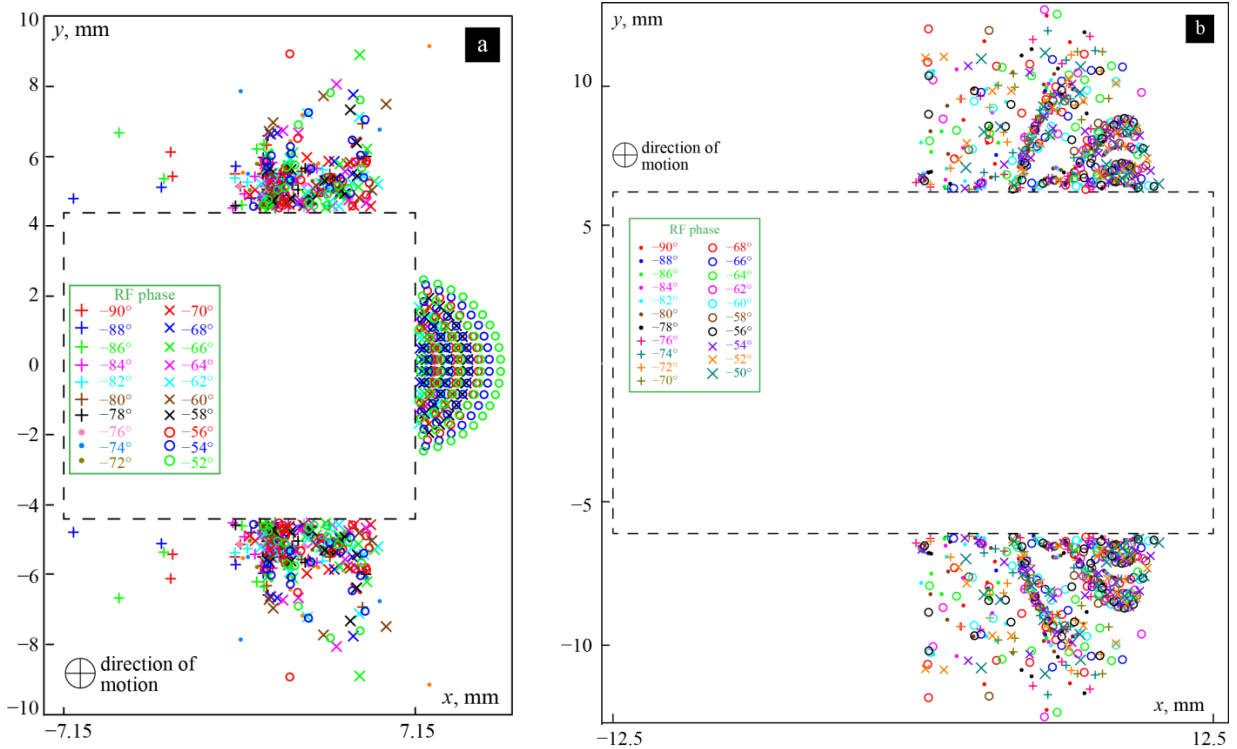


Figure 6. Electrons passing through cavity windows.

Note, that for a more efficient use of the microtron cavity it makes sense to consider using photocathode as electron source. In principle, it is possible to synchronize short laser pulses with the accelerating RF field, so that emitted particles will be accelerated effectively.

3. Conclusion

Transverse electrons dynamics in 6.5 MeV LPI microtron was investigated. It was shown that microtron cavity windows affect transverse particle motion strongly, mainly on a few first orbits, leading to defocusing of particles. The optimal parameters of electron injection from the thermionic cathode were found. Good beam quality was obtained on the final orbit under used microtron parameters.

Acknowledgments

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