SIMULATION OF A PHOTOCATHODE-BASED MICROTRON USING A PIC CODE

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Abstract

Korea Atomic Energy Research Institute (KAERI) has used a microtron accelerator based on a thermionic cathode for operating a compact terahertz (THz) free-electron laser (FEL). We would like to develop a photo-cathode-based microtron for generating high-peak (~ 100 A) and ultrashort (~ 1 ps) as an electron source for generating intense and ultrashort THz pulses. It is necessary to analyze precisely the electron beam dynamics in a microtron, especially, the relation between the RF phase in a microtron cavity and laser input time for adapting the photocathode to a microtron. Hence, we conduct computer simulation with a 3D PIC-code to find those optimized conditions for the photocathode-based microtron with the beam energy of ~7 MeV and bunch charge of ~ 100 pC with a bunch duration of 1 ps.

INTRODUCTION

Terahertz (THz) rays have been drawing attention because of their peculiarities which are different from visible ray or x-ray. Most interesting characteristic is that they can penetrate various substances but they are much less harmful than X-rays. And THz is known as a fingerprint spectral range for identifying molecules. So THz technology is promising for medical imaging and security inspection. However, this range is known as 'terahertz gap' because it is difficult to generate broadband THz ray with high power [1]. Recently, Nikolay Vinokurov proposed an efficient way of generating ultrashort THz pulses by sub-picosecond relativistic electron bunches passing through a multi-foil cone radiator [2]. The multi-foil cone radiator can improve the generation efficiency proportional to the number of foils than usual single-foil coherent transition radiation source. These THz-rays can be achieved by using multi-foil cone radiator which the coherent transition radiation is generated when sub-picosecond bunches are passing through the thin multi-foil. Microtron can accelerate the electron beam to get those ranges of energy. The microtron is the device that accelerates electrons with circular orbit due to Lorentz force under a constant magnetic field. The electrons are accelerated in the RF cavity, so the arrival time of electron beam and the RF field for accelerating in the RF cavity should be synchronized. It has not only relatively low cost but also quite small size for accelerating the electrons so it is suitable for compact THz Radiator [3, 4, 5].

SYNCHRONICITY AND PHASE STABILITY CONDITIONS

In the microtron, the electrons must have exactly same phase of electric field for acceleration that supplied from magnetron to gain the energy. For the start, the period of first orbit should be an integer multiple of period of RF to inject the acceleration phase. Also, the electrons which energy is increased at the acceleration field have larger orbit and the arriving time for the acceleration is longer than previous one. Therefore to inject appropriate phase of acceleration the gap between the two orbits must be an integer multiple of period of RF. This is called as synchronization condition and according to those conditions the orbit of first period (T_1) is given by $T_1 = 2\pi m_0\gamma_1 /eB$ and the difference between two periods of each orbit (ΔT) are given as $\Delta T = T_{n+1} - T_n = 2\pi m_0 \Delta\gamma_g /eB$, where B is strength of magnetic field, γ_1 is energy of electrons at the first orbit and $\Delta\gamma_g$ is energy gain at the RF cavity.

The more energy electrons get the period last longer, and then the range of stable phase of RF voltage is under the native slope. We can find the range of stable phase for acceleration of the electron beam by calculating the transfer matrix. At the accelerating cavity, the phase of the electrons is not changed because the velocity of them is close to the velocity of light, but the energy of the electrons is changed due to the RF. On the other hand, the energy of electrons is same at anywhere except RF cavity since there is no electric field but a uniform magnetic field. Then the transfer matrix can be calculated as shown below by applying those relations.

$$R = \begin{bmatrix} 1 & -\dfrac{2\pi l}{\Delta E} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\Delta E\ \tan\phi_s & 1 \end{bmatrix} = \begin{bmatrix} 1+2\pi l/\tan\phi_s & -\dfrac{2\pi l}{\Delta E} \\ -\Delta E\ \tan\phi_s & 1 \end{bmatrix}$$

To find the stable condition of the trajectory of electrons beam, eigenvalue and determinant of transfer matrix should be used. According to those qualifications, the stable condition is -2< Trace R <2, in other words the condition can be written as $-2 < \pi\ell \tan\phi_s < 0$. At this time the RF acceleration phase for stability is –tan-1(2/ $\pi\ell$) < ϕ_s < 0, then we can find the stable region of RF phase of fundamental mode, $-32.5 < \phi_s < 0$. It is natural that the phase oscillations are bigger when the ϕ_s approaches the boundary of the stable region. Therefore, the

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amplitude of oscillations is smallest near the middle of interval of whole range, where Trace R is 0. The phase which is correspond to the Trace R = 0 is $\phi_s = -\tan^{-1}(1/\pi) = -18$ degree [6, 7].

LONGITUDINAL PHASE FOCUSING

For electrons to be produced, an electron source is needed for every free electron. Cathode is a device that emits the electrons by various methods. Generally, the thermionic cathode and the photocathode are used for FEL. When using thermionic cathode for the emission of electron, the electrons always emit when the RF field is appropriate for the emission condition. So the several bunches of electrons with different radius are accelerated at the same time. Unlike thermionic cathode photocathode can emit the electrons when the laser hit the photocathode so heater or other devices are not needed for the emission. Therefore, in the photocathode based microtron, only laser makes the electrons emit therefore just one bunch with high peak current is accelerating in the microtron. In this case, however, the electrons should be injected at the accurate phase for the accelerating which is in the region as calculated above. That is to say the laser injection time is critical at the microtron combined with photocathode [8].

During the beam motion in the microtron, phase focusing is occurred in the longitudinal direction as shown in figure 1.

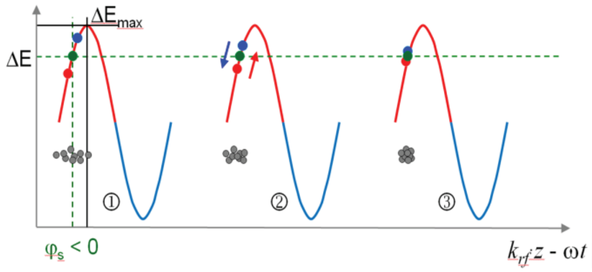

Figure 1: Principle of the longitudinal phase focusing during the electron beam trajectory. The head region of electron beam has higher energy than the tail region of that. So the path of head part is longer that tail part therefore during the trajectory, the head part and tail part can be closer due to the energy differences.

For longitudinal phase focusing, electron beam energies of the tail region should be higher than reference particle and electron beam energies of the head part should be lower than reference particle. In this case, the energy difference makes the electrons at the tail part can travel faster than the electrons at the head part. The electron beam with higher energy has longer path and takes more time while lower energy particle travels shorter path and takes less time than reference particle. Therefore higher energy particle which has longer path length arrives later than the reference particle while lower energy particle which has shorter path length arrives earlier so the electrons can be closer to the reference particle. This is the reason that the injection time of electrons at the RF phase is important for the acceleration at the microtron with photocathode. If the electrons are injected at incorrect phase, the electron beam will be debunched [9, 10].

SIMULATION AND RESULTS

The structure of THz generator using multi-foil is depicted in figure 2. The gaps between the foil are filled with vacuum or dielectric. When electron bunches pass through those foil, the coherent transition radiations are emitted between the gaps of foil. And then, the radiation pulses propagate radially outward. At the outer surface of the cone we can generate the radiation field of THz [2].

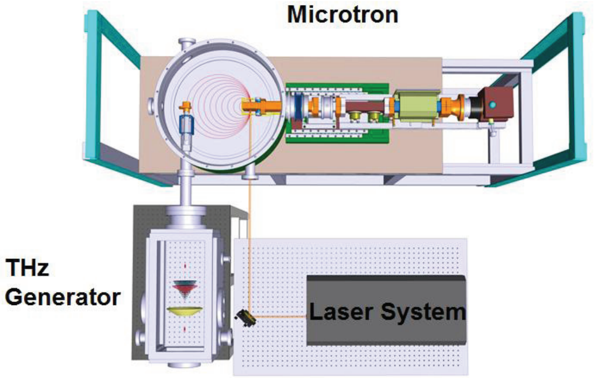

Figure 2: The structure of THz pulses with a multi-foil generator. Electrons are accelerated in the microtron which make the beam energy at 7.2 MeV and emits the THz ray after the multi-foil.

The microtron is feed by pulsed high-power RF generators, magnetron. When the RF is coupled to the resonator of the microtron, electron beam can get the kinetic energy. These electrons have sinusoidal motion in the undulator and then emit THz ray by changing the kinetic energy to light energy. For the electron emission, the cathode is located at the center of RF cavity in the microtron. KAERI has used thermionic cathode for emission to operate the THz FEL. The microtron combined with thermionic cathode has quite great beam parameters of the electron beam, low energy spread, low emittance. And the electrons are emitted when the RF is larger than threshold energy for the emission and that electrons, which are remained at the stable region are accelerated automatically with circular orbit, so the average current is such high but the peak current is quite low. But to generate ultrashort and high peak current beam, the thermionic cathode should be replaced with a photocathode. The electron beam behavior in the microtron combined with photocathode is simulated by using the CST 3D code [11]. The schematic of microtron is shown at figure 3. The radius of cylindrical cavity for the acceleration is 40.8 mm and the height is 17.8 mm. The waveguide for the microtron is 200 mm × 34 mm and the coupling gab is 13mm for the frequency stability. And the magnetic field for the circular motion which is 0.11 T.

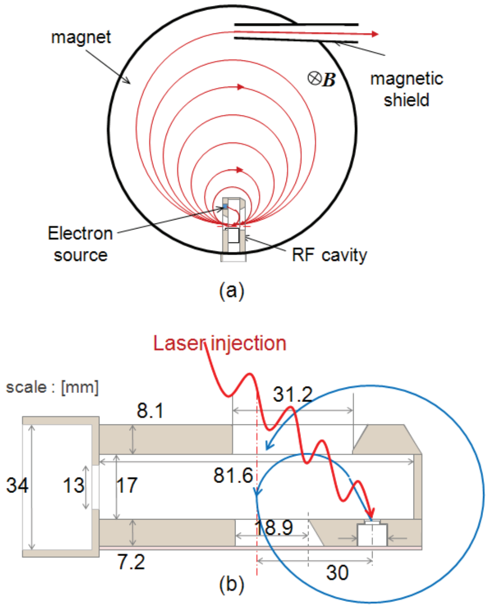

Figure 3: Schematics of the microtron (a) and design parameter of the microtron (b). Laser enters by the upper hole for the beam trajectory and strikes the photocathode. After that electrons come out for the acceleration.

At first we use the long pulse which length is about 10 ps to find the appropriate RF power. The number of particles is same at the emission, but the remained particles after the acceleration are different according to the RF power. As the results, the required RF power is 1.95 MW for the acceleration (Figure 4).

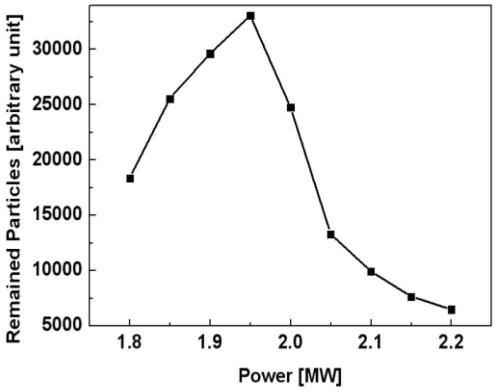

Figure 4: Required RF power for the microtron. The most particles emitted length is half period of RF wave are alive after the acceleration

And also we changed the laser spot size to choose the capable electron beam size for acceleration in the microtron. We can find out that the most number of particles are remained after the acceleration when the bunch size is being smaller and at this case we choose the 0.2 mm of bunch size for the simulation (Figure 5).

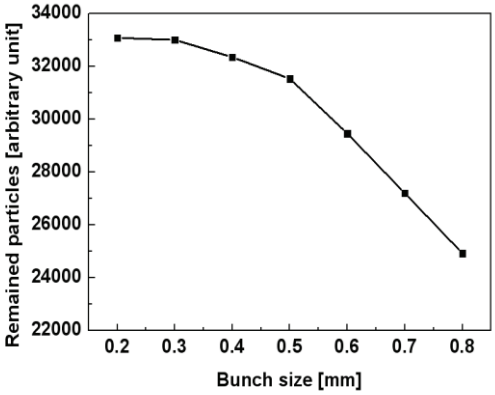

Figure 5: Alive particles ratio compared to the emission particles after the acceleration when emission bunch length is about 10 ps long. The smaller bunch size they have, the more particles are remained.

By using those conditions, the phase of laser injection can be found. Figure 6 shows that the relations between the laser injection time and behavior of the electron beam in the photocathode based microtron.

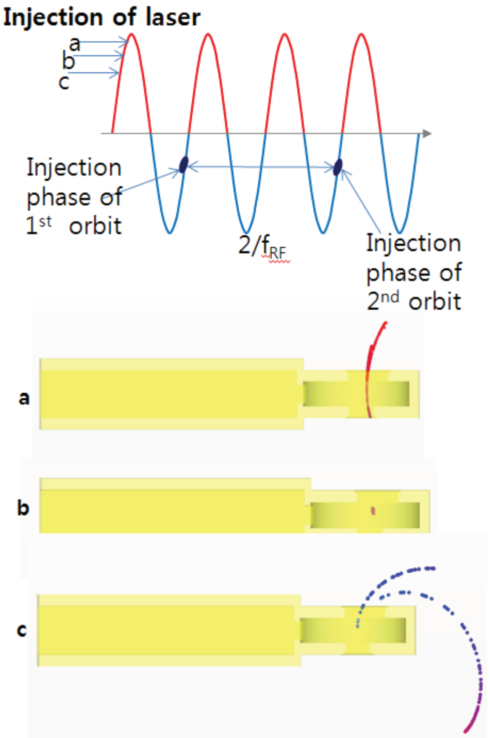

Figure 6: Behavior of electron beam in the microtron according to the injection time of laser. If the laser injection time is appropriate for entering accelerating field, the beam would accelerate with stable motion while other cases make the beam motion spread out.

If the injection time of laser is not appropriate for the emission time of electron at the cathode, it is needless to say that the electrons will be injected at the wrong phase for the acceleration. So as a result, the electron beam will be spread as explained above. The electrons which are

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emitted at the accurate phase of emission time will be injected the stable region for the acceleration, therefore the electrons have more stable motion compared with the previous cases. We have simulated to find the proper phase for laser injection without the space charge effect. As explained above, the particles are spread out if the phase for entering accelerating field is incorrect. In this case, particles emitted at the wrong phase are disappeared after bump into the cavity. Figure 7 shows that the phases all particles are remained after the acceleration.

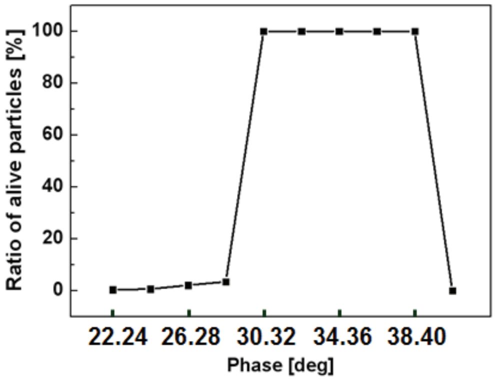

Figure 7: Ratio of remained number of particles after the acceleration to the number of emission according to the phase of laser injection. All particles are alive when the laser injection phases are in the range of 28.30 degree to 38.40 degree.

We should choose the one of laser injection phase for the acceleration in those ranges. For source of intense and ultrashort terahertz generation, we need the high peak and ultrashort pulses. So we compared the bunch length after the acceleration to select the shortest bunch length. In the result, the bunch has the shortest length when the laser injection phase is 34.36 degree.

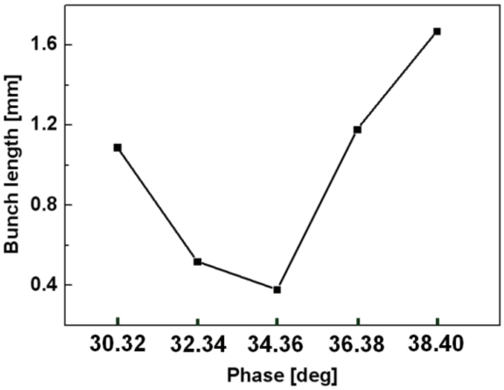

Figure 8: Bunch length after the acceleration according to the laser injection phase. For intense and ultrashort THz generation, the bunch length should be ultrashort. When the laser injection phase is 34.36 degree the bunch length is the shortest when we neglect the space charge effect.

In the simulation, the best phase of the laser injection is about 34.36 degree as shown in the figure 7 and figure 8. We can also check the phase of injection to 1st orbit is about -19 degree. These results check out with the theory of the most stable region as mentioned above. According to these results, the laser injection time sensitive for adjusting with stable behavior of electron beam.

CONCLUSION

In summary, we have presented the importance of laser injection time in the microtron combined with photocathode. For getting exact time of laser injection, CST 3D code is feasible to simulate the behavior of electron beam in the microtron. These results show that if the electron beam is passed slightly by the accelerating phase the electron beam motion would be unstable. The electron beam with ultrashrot and high peak current should be considered the space charge effect. Based on these results, the beam for multi-foil cone generator can be studied.

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