AN INDEPENDENTLY TUNABLE CELLS THERMIONIC RF GUN (ITC-RF GUN) FOR SUB-PICOSECOND SHORT PULSE

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Abstract

Recently a wavelength region shorter than mm but longer than 100 μm, so-called THz radiation, is paid attention and development of THz sources is rapidly developed, because the THz light is passing through semiconductors like Si but the water is not transparent. These specific characters are completely different from usual X-rays, so that many applications are considered worldwide.

The THz radiation is normally produced using conventional lasers via a non-linear crystal. In this case, the power is pretty low but a frequency resolution is better. The most promising high quality THz radiation may be coherent synchrotron radiation emitted from the extremely short electron bunch or Far-IR FEL.

Although photo injectors using RF guns are rapidly developed as high brilliant electron sources, meanwhile thermionic RF guns are still expected to have potential ability to create high-brightness and short-pulse beams [1]. In particular, whole system of the thermionic RF gun is simple, compact and low-cost than that of a photo-cathode RF gun.

In addition, a velocity-bunching like effect may be occurred in the gun, so that the short pulse beam from the thermionic RF gun is a better candidate to produce the coherent THz synchrotron radiation.

For creating such beams, thermionic RF gun has been designed and its characteristics have been studied by a 3-D simulation code developed based on an FDTD (Finite Difference Time Domain) method [2]. The gun is consists of two independent power feeding cavities, so that we call it " independently tunable cells (ITC)"-RF gun. The first cell is a cathode cell to extract the beam and the second one is an accelerating cell. The ITC gun can be operated at modes with different RF-power ratio and phase between two cavities. A similar way of operating RF gun has been already reported by Lewellen [3]. This paper describes the results of simulations for this thermionic RF gun.

INTRODUCTION

Conventional way to compress the bunch length from the thermionic RF gun is employing an α-magnet [4]. Though the α-magnet is apparently working skilful manipulation of longitudinal phase space, it would be a bit annoyance when the beam kinetic energy is higher.

Beside the problem of back-bombardment [5], there is a specific feature in the longitudinal dynamics in thermionic RF guns. At the beginning of the beam extraction, a head of the electrons from the cathode is followed immediately by the electrons just behind, which is extracted by the higher electric field than that at the head of the beam train. Thus later electrons would get kinetic momentum or velocity faster than the head of the electrons. Consequently the electrons are expected to be concentrated around the head of the beam train under certain conditions such as the gun geometry and the velocity gain. This velocity-bunching-like phenomenon has already known by developers of the thermionic RF guns [1]. According to our simulation study so far, this velocity-bunched peak on the head of the beam train might possibly reach to a pulse width of ~ 200 fs with a couple of tens pC.

If the velocity-bunching-like effect occurred at the beginning of rising up of the longitudinal electric field, is intentionally enhanced, the sub-picosecond beam would be obtained without any bunch compressors. In order to carefully design the ITC-RF gun, we have used the FDTD method that includes certain boundary condition and also space charge (wake-field) effect. The most significant disadvantage of this 3D simulation is the accuracy because a terribly large memory area is required if you want a general accuracy. However overall characteristics of the extracted beam can be predicted because of no obvious inconsistency in solving the Maxwell's equations.

A ring type coherent terahertz (THz) radiation source is our final target by producing very short bunches from the ITC-RF gun [6]. On Table 1, our target performance of the ITC-RF gun is listed.

Table 1: Target parameters of the ITC-RF gun

RF frequency	2,856 MHz (S-band)
Material of cathode	LaB_6
Emission current density	~100 A /cm^2
Cathode radius	2 ~ 4 mm
Number of cells	2
Feeding total power	~ 5 MW
Total energy gain	~ 1.5 MeV
Bunch length (rms)	~ 100 fs
Bunch charge	~ a several ten pC
$\varepsilon_{norm.\ rms}$	< 2 π mm mrad
Δp/p	< 1 %

STRUCTURE OF THE ITC-RF GUN

The ITC-RF Gun has been designed so as to vary the relative phase and the amplitudes of RF field in each cell, independently. So far, the simulation can optimise the gun geometry and other parameters, but there has been no confidence whether the gun has been actually working

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with same parameter as the simulation, because errors of the fabrication, the power feed and the mode purity are not difficult to be confirmed experimentally.

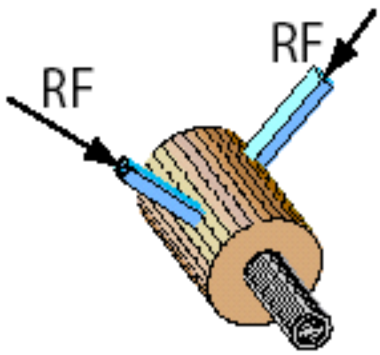

Figure 1: Schematics of the ITC-RF gun.

In Fig. 1, a schematic drawing of the ITC-gun is shown. The RF powers are fed separately into each cell. We performed a basic design of the ITC-RF gun by using a code SUPERFISH. The kinetic energy gain in the 1st cell has to be reduced to less than ~ 0.5 MeV to enhance the velocity-bunching effect at the entrance of the 2nd cell. Furthermore the length of the 1st cell (from the cathode to the end of 1st cell) is very important for the velocity-bunching. Finally we decided to separate the cells and control the power and phase of the RF for each cell independently to compensate fabrication errors and other error sources. In order to obtain, therefore, almost no RF coupling between two cells, a radius of the connection beam duct has become to be 4 mm.

Results of the calculation of the RF field for each cell using SUPERFISH are shown in Fig. 1.

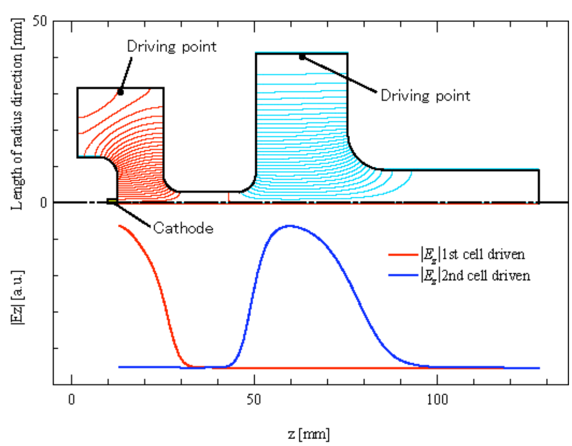

Figure 2: Calculated electric field lines and longitudinal electric field strengths along the beam axis are shown. The red line is results by excitation of the 1st cell, and the blue line indicates the case of the 2nd cell excitation.

THE FDTD SIMULATION

FDTD 3-D simulation

Dimensions for a 3-D cubic grid is shown in Fig. 3.

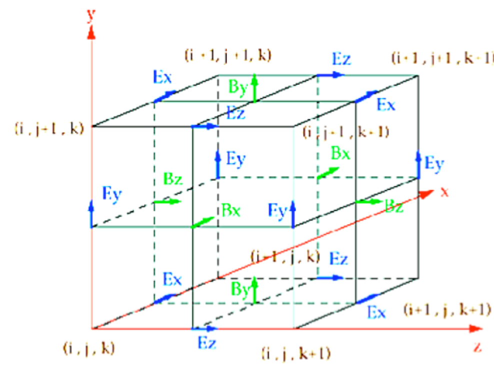

Figure 3: A 3-D cubic and locations of E and B representatives for the FDTD method. Symbols i, j and k are used to identify the grid number.

A leap-frog algorism gives a solution of the time dependent Maxwell's equation as (for example, a solution of E_x)

$$E_x^{n+1}\left(i+\frac{1}{2},j,k\right)=E_x^{n}\left(i+\frac{1}{2},j,k\right)+c^2\Delta t\left[\frac{B_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)-B_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},j-\frac{1}{2},k\right)}{\Delta y}-\frac{B_y^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)-B_y^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)}{\Delta z}\right]-\frac{\Delta t}{\varepsilon_0}J_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j,k\right), \tag{1}$$

where n is the step number, so that n+1/2 means the calculated result for the magnetic field at after 0.5 steps. The location indicated by i, j and k are indicated by Fig. 2. Time step Δt has to be satisfied followed relation to avoid solution instability,

$$(c\,\Delta t)^{-1} \geq \sqrt{\Delta x^{-2}+\Delta y^{-2}+\Delta z^{-2}}, \tag{2}$$

where c is the light velocity and Δx, Δy and Δz are the size of the 3-D cubic grid. If we choose 2 mm for the cubic size, step Δt has to be less than 3.85 ps, so that one can easily imagine huge cpu times and memories. The cubic size around 2 mm is still large, but it is rather realistic better size at the moment.

Results of the simulation for the ITC-RF gun

A snap shot of the beam acceleration in the gun shows in Fig. 4. In the simulation, the maximum strength of the electric field on the cathode is 25 MV/m, which was determined so as to the bunch head gets into the acceleration field of the 2nd cell just after 0.5 RF cycle passed.

Phase between two cells was decided to be π at the moment and the peak electric field in the 2nd cell has been ~ 45 MeV to obtain a linear dependence of the exit time on the gained energy in the gun.

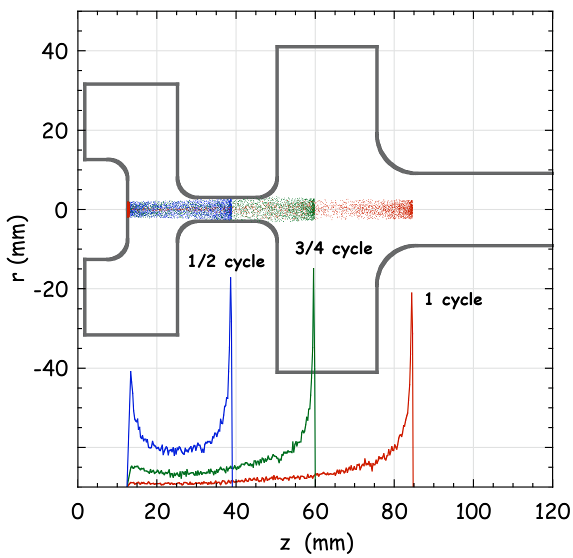

Figure 4: Three snap shots at after 0.5 rf-cycle, 0.75 rf-cycle and 1.0 rf-cycle. Longitudinal distributions for each identical time are also shown in lower part of the figure.

In order to clarify the velocity-bunching in the ITC-RF gun, the particle distributions along the axis during the acceleration are shown in Fig. 4.

Projected spectra on the time axis and the energy axis are shown in Fig. 5. Both have spike structure at the heads of the bunch. For the time spectrum, the shape peak FWHM is approximately 200 fs, and that for the energy spectrum peak is ~ 0.3 % and the mean energy of the peak is around 1.26 MeV. This energy would be thought to be still dangerous for the space charge force, but actually there is not much charge in the peak (~ 20 pC). It is a rather suitable energy to manipulate the longitudinal phase apace.

However we are not going to use α-magnet to get further shorter bunch because the energy spread grows. Consequently we use just the energy slit at the dispersive space placed just in front of the accelerating structure. In this case, the stability of the ITC-RF gun is very important because only the 0.3 % energy width from the top will be used. Since the mean energy of the peak structure is 1.26 MeV, if we want to reduce a energy fluctuation less than 1 %, the energy gain stability of ~ 40 eV is required.

TRANSVERSE EMITTANCE

Transverse emittance is also derived from the FDTD simulation for various emission-current density of the cathode. By using a following equation,

$$\varepsilon_x = \beta\gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x\, x' \rangle^2} \qquad (3)$$

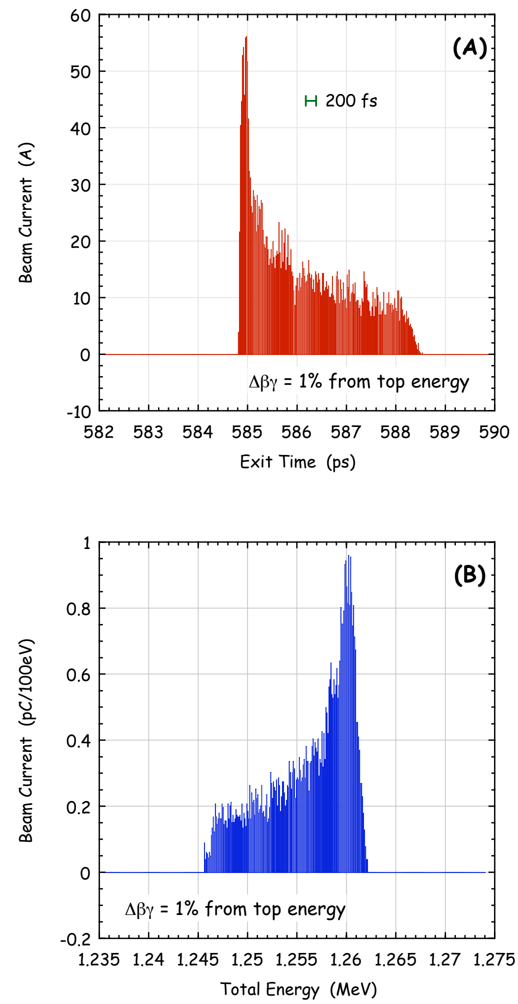

Figure 5: A final time distribution (A) and an energy spectrum (B). Both spectra were cut from 1 % energy width from the top energy. The acceleration field gradients are 25 MV/m on the cathode and 45 MV/m for the maximum in the 2nd cell.

The normalized emittance is estimated. Note the value is not elliptical area surrounding particles.

Figure 6 shows the final transverse phase spaces for three different cathode current densities as noted in the caption. Emittance is of course varying for which part of the extracted beam is selected in the time domain (sliced emittance). Here we cut the beam for the energy width of 1 % from the top energy, which is same condition indicated as Fig. 5.

It should be noted that the normalized emittance is not much changed as increasing the beam current. This may be because of relatively low charge inside the peak. After exiting the gun, beam will be transported in to the energy filter line consisted of two bending magnets and some quads. The length from the gun exit to a first accelerating structure will be 50 cm, so that actual emittance would be a bit spread. However the normalized emittance around 1 π mm mrad is pretty acceptable for out ring THz source project [7] .

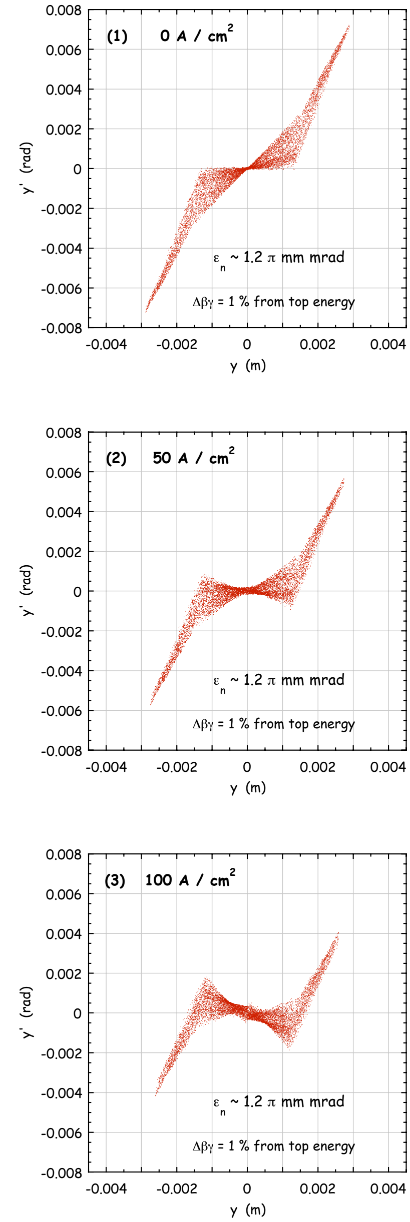

Figure 6: Transverse phase spaces for the cathode current density of 0 (1), 50 (2) and 100 (3) A / cm^2, respectively. There is no difference in normalized emittances derived from Eq. (3) in the text.

SUMMARY

Simulation study of an Independently-Tunable-Cells (ITC) RF gun using thermionic cathode is discussed. The present target benchmark of the beam properties of which the time duration is a couple of hundred fs with several ten pC charge may be possible.

The FDTD simulation, which has been developed by our group shows that a time duration of 1ps from the top of the bunch contains 30 pC and the FWHM (if we cut the tail part) might be ~ 300 fs will be obtained for a current density of 100 A / cm^2 cathode.

The biggest technical issue is probably the cathode assembly, because we are going to a single crystal of LaB_6 that requires a very high temperature for stable operation. In order to heat up the cathode, a heater electrode is normally used. However it is difficult to keep thermal contact with a heater and the crystal. A method of laser-assisted heating is one of promising techniques. Another issue maybe the energy filter to cut the bunch of only a part of 5 keV or less. Stability of the whole system and precise evaluation for designing the dispersive arc are necessary.

At the moment, we have not finished appropriate optimization for the designing the ITC-RF gun. Shape of the gun is possibly slightly changed. However we won't use a photo-cathode because it would be a very expensive system and not suitable for our THz project of which the multi-bunch beam is preferable and it may be satisfied by a relatively low charge in a bunch [7].

REFERENCES

[1] P. Kung, et al., Phys. Rev. Lett. 73 (1994) 967; S. Rimjaem, et al., Nucl. Instr. and Meth. A 533 (2004) 258.
[2] Hama, et al., Nucl. Instr. and Meth. A 528 (2004) 371..
[3] J.W. Lewellen, Proc. of the 2003 Particle Accelerator Conf., Portland, Oregon, pp. 2035.
[4] H.A. Enge, Rev. Sci. Instr. 34 (1963) 385; M. Borland, Ph.D. Thesis, Stanford University, 1991.
[5] C.B. McKee and J.M.J. Madey, Nucl. Instr. and Meth. A 296 (1990) 716.
[6] T. Tanaka, et al., will be published in Proc. of Particle Accelerator, Knoxville, TN (2005).
[7] H. Hama, "Dream of Isochronous Ring Again", in these proceedings.