COHERENT THZ LIGHT SOURCE USING VERY SHORT ELECTRON BUNCHES FROM A THERMIONIC RF GUN

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Abstract

We have planned to establish intense terahertz light source using coherent radiation from undulator. In order to emit coherent radiation, it is important to generate very short electron beam with a bunch length around 100fs. Now we have developed an injector to generate such short bunch beam. The injector consists of an Independent Tunable Cells thermionic rf gun (ITC rf gun) and a magnetic bunch compressor. Longitudinal and transverse phase space distribution can be controlled by changing input power of each cells and phase difference between cells in this gun. The compressor can change compression rate R_{56} and 2^{nd} order dispersion effect by 2 sets of quadrupoles and a set of sextupoles, respectively. Test model of ITC rf gun was manufactured and basic parameters were measured. From tracking simulation, it has been turned out the bunch compressor can reduce to bunch length less than 100fs. In this paper, we show overview of the coherent terahertz light source and the detail of the ITC rf gun and the bunch compressor.

INTRODUCTION

Intense coherent radiation at the terahertz region (λ ~ 300μm) will be powerful probe for bio-medical science, solid state physics and other many scientific fields. There was not such intense terahertz light source so far. There are two type of terahertz source, or laser based and accelerator based. We have developed accelerator based terahertz light source using intense coherent radiation [1]. Now a coherent terahertz source using undulator radiation has been planed.

In order to get coherent terahertz light, electron beam with very short bunch length σ_t < 100fs must be produced. Therefore an injector, which consists of Independent Tunable Cells rf gun (ITC rf gun) and magnetic bunch compressor, has been developed.

In this paper, the project of undulator coherent terahertz light source and the detail of the ultra short bunch injector are presented.

UNDULATOR COHERENT TERAHERTZ LIGHT SOURCE

A light source consists of an injector, an accelerating structure and an undulator. The schematic design is shown in Fig.1. The injector which consists of the ITC rf gun and magnetic bunch compressor generates electron beam with energy E ~2MeV, normalized emittance ε_n < 1πmmmrad and bunch length ~100fs. By the accelerating structure, beam energy goes up to 12 MeV. The ultra short bunch beam is passing through the undulator, then coherent terahertz light is emitted.

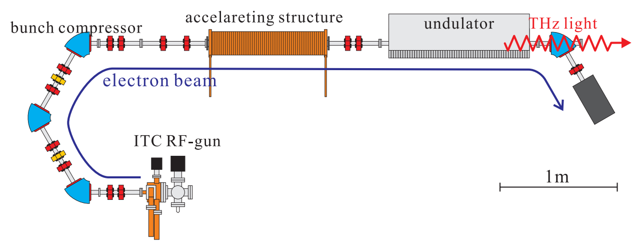

Figure 1: The schematic design of undulator coherent terahertz light source

The parameter of coherent terahertz light source is listed in Table 1.

Table 1: Parameters of coherent terahertz source

Energy ***E***	12MeV
Normalized emittance ε_n	< 1 πmm mrad
Bunch length σ_t	~100fs
Bunch charge I_e	~20pC
Undulator	
period length λ_p	8 cm
# of periods	15
Peak magnetic field B_{ymax}	0.3 T

Calculated terahertz spectrum from the undulator was shown in Fig.2 and Fig.3, where bunch length σ_t=100fs, number of electrons N_e = 1.25 x10^8 electrons /bunch (bunch charge is 20pC).

The fundamental wavelength λ_1 and its harmonics λ_i is

$$\lambda_i = \frac{\lambda_p}{2\gamma^2 i}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right), \quad (1)$$

where i is harmonic number, K=93.4 B_{ymax}[T] λ_p[m] is the strength parameter, γ is Lorentz factor, θ is the observation angle with respect to the axis[2]. In this case, the fundamental wavelength λ_1 is 257μm. Since bunch length σ_t=100fs ~ 30μm, only the radiation with fundamental wavelength is coherent, so proportional to N^2 ~ 10^{16}. Therefore, compared with the fundamental radiation, higherharmonics is suppressed (See Fig.2 and 3).

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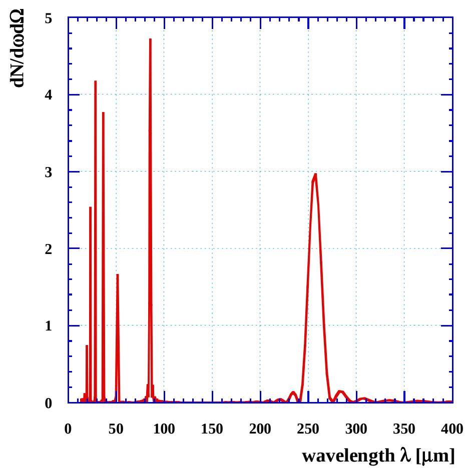

Figure 2: Spectrum of undulator radiation from single electron (θ=0)

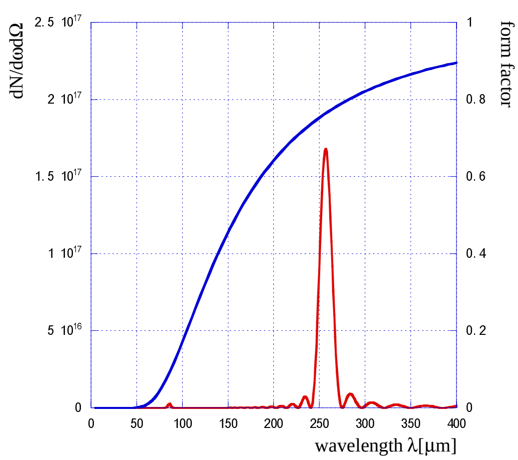

Figure 3: Spectrum of coherent undulator radiation at $Ne=1.25x10^8$ electrons/bunch, σ_t=100fs, θ=0 (red) and bunch form factor σ_t=100fs(blue)

AN INJECTOR FOR VERY SHORT BUNCH

ITC RF Gun

The ITC rf gun has two cells with a very low coupling, or independent cells as its name indicates. There are two rf input ports at each cells to feed the rf power from a klystron. By changing each input power of two cells and phase difference between cells, longitudinal and transverse phase space distributions at the gun exit can be controlled.

In order to generate low emittance beam with sufficient beam current, the cathode should have small radius and can produce high beam current. Consequently a single crystal LaB_6 cathode with the diameter ϕ1.75mm has been chosen.

By using a self-developed 3-dimensional Finite Difference Time Domain (FDTD) simulation code[3], operating parameters of ITC rf gun was optimized [1]. Table 2 shows optimized operating parameter and generated beam parameter under that condition. Simulation result of longitudinal phase space distribution is shown in Fig.4. The momentum spread Δp/p of the beam from the gun is ranging from maximum momentum P_{max} =1.77MeV/c to almost 0MeV/c. By using momentum slit put on the downstream of the gun, Δp/p will be selected to be less than 2%. From Fig.4, one can see the beam extracted from the gun has bunch length ~ 5ps (full width) within momentum spread Δp/p=2%.

Table 2: Parameters of the rf gun and the extracted beam for simulation

rf gun	
Max electric field of 1st cell E_{1st}	25 MV/m
Max electric field of 2nd cell E_{2nd}	50 MV/m
phase difference between cells	18 deg
current density at cathode(ϕ1.75)	50 A/cm^2
electron beam at the rf gun exit	
maximum momentum P_{max}	1.77 MeV/c
energy spread Δp/p(full width)	2%
normalized emittance ε_n	0.77πmmmrad
Twiss parameter (β,α,γ)	(1.11,1.21,2.22)

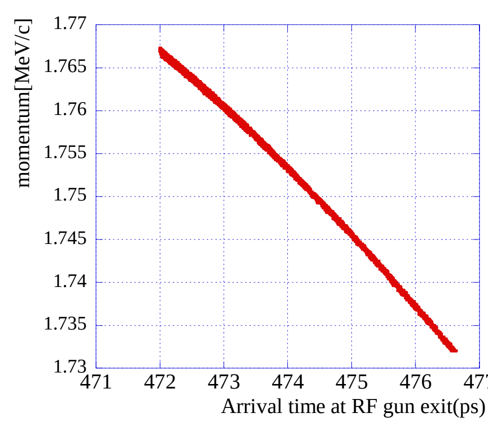

Figure 4: Longitudinal phase space distribution (FDTD simulation)

Magnetic Bunch Compressor

As shown in Fig.4, the relationship between momentum and time (=longitudinal position) is almost linear. Usually an α-magnet is used to bunch compression for a thermionic rf gun injector [4]. For our gun, a bunch compressor with the Triple-Bend-Achromat (TBA) like lattice has been designed. In addition, a set of sextupole magnets is installed in this bunch compressor. Consequently, this bunch compressor has properties 1) By two sets of quadruple magnets between bends, transfer matrix R_{56} can be changed to fit various (Δp/p)/Δt, 2) By a set of sextupoles, 2nd order dispersion function can be controlled. Especially it is difficult to obtain latter feature for α-magnet.

By the accelerator design code SAD[5], the optics of the bunch compressor is designed and shown in Fig.5.

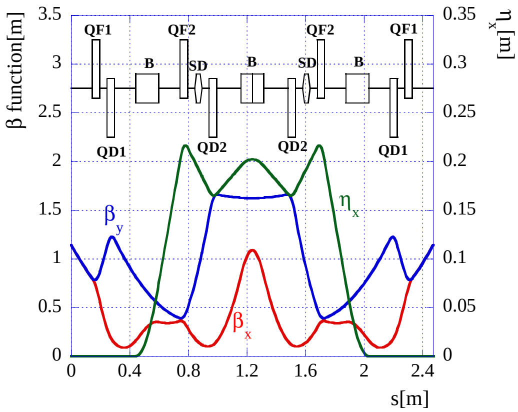

Figure 5: the optics design of bunch compressor

Using the result of FDTD simulation, tracking simulation in the bunch compressor was done by SAD. In this tracking, the space charge effect is not considered. The tracking result of longitudinal phase space distribution with/without sextupoles is shown in Fig.6, 7 respectively. From tracking results, bunch lengths σ_t were obtained 43fs, 38fs respectively. One can also see the 2nd order dependence can be compensated by sextupoles. It was confirmed that this injector can generate very short bunch less than 100fs.

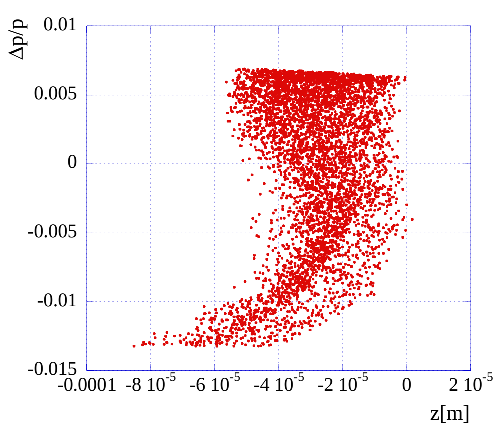

Figure 6: Longitudinal phase space distribution after bunch compressor without sextupole magnets

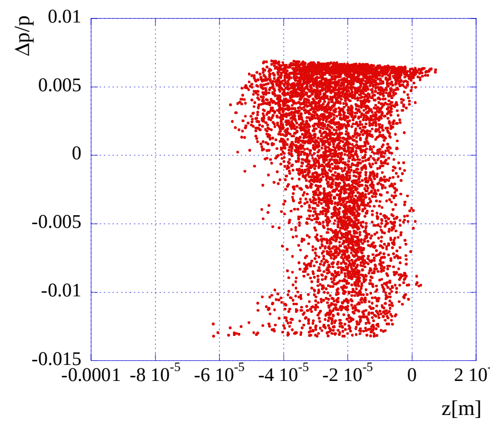

Figure 7: Longitudinal phase space distribution after bunch compressor with sextupole magnet

PERFORMANCE MEASUREMENT OF ITC RF GUN PROTOTYPE

The prototype of ITC RF-gun had been manufactured and basic parameters of rf cavities were measured. Results are shown in Table 3.

Table 3: Cavity parameters of ITC RF-gun prototype

resonant freq.(f_1, f_2)	(2810.81, 2825.36)GHz
coupling(β_1, β_2)	(2.3, 3.4)
Unloaded Q (Q_1 , Q_2)	(9984, 9600)
(R/Q_1, R/Q_2)	(117, 129)Ω

As shown in Table 3, resonant frequencies of each cells is different from design frequency 2856MHz. From the 3-dimentional electromagnetic field calculation code Microwave-Studio[6], it was found that this frequency shift is caused by the effect of the coupling port between waveguide and cavity. The amount of shift is consistent with the Microwave-Studio’s prediction.

Using a bead perturbation method, electric field distribution along the beam axis was measured. In Fig.8, a measured result is shown. The electric field distribution calculated by SUPERFISH is also shown.

A result of the electric field distribution is consistent with SUPERFISH calculation. R/Qs in Table 3 are calculated using measured data shown in Fig.8. From SUPERFISH, R/Qs are predicted to be 98.2Ω, 114.6Ω respectively and consistent with measurements.

In these measurements for the prototype, we confirmed that basic parameters of the rf gun are consistent with SUPERFISH’s prediction except for resonant frequencies. The resonant frequencies can be predicted by 3-D electromagnetic field calculation including rf coupling ports. Now we have designed a modified ITC RF-gun.

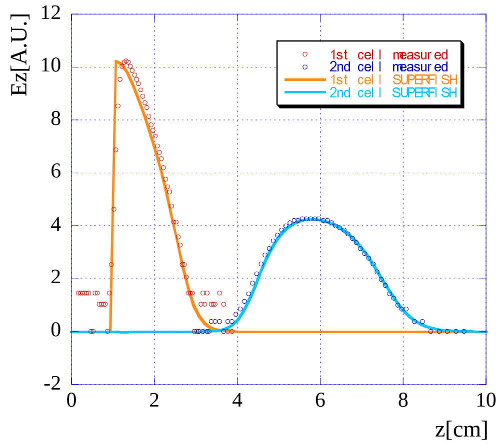

Figure 8: The electric field distribution (circle: results of bead perturbation methods. line: SUPERFISH calculation)

SUMMARY

An intense coherent terahertz light source using undulator radiation has been designed. In order to obtain coherent terahertz radiation, it is important to generate electron beam with very short bunch σ_t < 100fs. To realize such a short electron beam, the injector which consists of the ITC rf gun and the magnetic bunch compressor has been developed. From numerical calculation, it has been turned out that the injector can generate electron beam with very short bunch length σ_t around 50fs. Since it is difficult the beam simulation including space charge effects in low energy region such as the inside of gun, an initial small fluctuation affects results of beam parameters. The design of bunch compressor strongly depends on input beam parameters. We will compare with our simulation code and other commercial codes such as General Particle Tracer (GPT) [7]. At the present, the tracking simulation in the bunch compressor is not included space charge effects. We will investigate whether that space charge effects don't affect to the beam in the bunch compressor.

Additional optimization of the bunch compressor is needed to have wide capability to fit various input beam parameters.

The prototype ITC rf gun has been manufactured and parameters of the cavity also has been measured. From measurements for rf properties, cavity performance can be predicted by using calculation code. We have been designing the modified ITC rf gun.

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