DEVELOPMENT OF AN INJECTOR TO GENERATE A VERY SHORT BUNCH FOR A SUPER COHERENT TERAHERZ LIGHT SOURCE PROJECT*

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Abstract

A project to develop a coherent Teraherz (THz) light source is in progress at Laboratory of Nuclear Science, Tohoku University. The coherent synchrotron light in the THz region is emitted from electron bunches with a very short bunch less than 100 fs (rms) generated by a thermionic RF gun and a sophisticated bunch compressor. As an injector for the linac, we have developed an independently tunable cells (ITC) RF gun and a magnetic bunch compressor which consists of a triple-bend achromat (TBA) lattice. As a result of simulation of the injector, we have obtained a very short bunch length of ~ 40 fs (rms). Results of low power tests of the ITC-RF gun and the tracking simulation of the bunch compressor will be presented in this proceeding.

INTRODUCTION

For a coherent Teraherz (THz) light source project employing an isochronous ring [1], a very short bunch less than 100 fs (rms) is required as an injected beam. A thermionic ITC-RF gun and a bunch compressor with a TBA lattice have been studied as the injector for the linac [2]. The thermionic RF gun can generate a macropulse with μs order which is an advantage for generating high average power of the radiation. Longitudinal phase space distribution can be manipulated in the ITC-RF gun so that the bunch length can be compressed effectively at the downstream of the gun. This gun can also generate a low emittance beam compared with a conventional dispenser cathode DC gun. Since the designed bunch compressor can vary R_{56} and the higher order term of the dispersion function, the bunch compression is able to be optimized even the initial longitudinal phase space distributions is changed.

GENERATION OF VERY SHORT BUNCH

Design of a thermionic RF gun

Taking the circumference of the isochronous ring (~ 150 ns) and the filling time of the gun assumed 0.3 μs into account, the macropulse duration of the injector has been chosen to be around 1.5 μs, which is possibly an advantage for avoiding back-bombardment effect [3]. The bunch charge should be as large as possible. The momentum deviation of the injected beam for the ring should be the order of 10^{-4} to have the beam turns the ring many times without bunch lengthening. Consequently the momentum acceptance of the injector part is required to be at least 10^{-2} because the beam is accelerated from 2 MeV to 200 MeV in the linac. Normalized rms emittance of the beam has to be very small less than 2 π mm mrad because the path length difference due to the betatron oscillation should be reduced. As a cathode material, a small single crystal of LaB_6 with a diameter 1.75 mm has been chosen. This cathode has a higher current density than that of conventional dispenser cathodes. The normalized emittance can achieve a small value because of the small area of the surface. According to a simulation study, the small cathode is also effective to reduce back-bombardment effect because the beam size of backstreaming electrons is larger than the area of the cathode [4]. To control an electron distribution in the longitudinal phase space, we employed independent two cells, which don't couple with each other. Parameters of the gun are listed in Table 1.

Table 1: Design parameters of ITC-RF gun

RF frequency	2,856 MHz (S-band)
Cathode material	LaB_6
Current density @ cathode	100 A/cm^2
Cathode diameter	1.75 mm
Number of cells	2
Feeding total power	~ 5 MW
E_{total} @ exit of gun	~ 2 MeV
Bunch length (rms)	~ 100 fs
Bunch charge	~ several tens pC
$\varepsilon_{norm,\ rms}$	< 2 π mm mrad
$\Delta p/p$	< 2 %
Macropulse duration	1.5 μs
Filling time	0.3 μs

Study of the beam dynamics in the ITC-RF gun has been done by using a 3D FDTD PIC code [4]. We had to find out an appropriate distance between the cells and the strength of the accelerating field in each cell, because the longitudinal phase space strongly depends on these parameters. A 2D code: SUPERFISH [5] has been used to determine the radius of cells so as to resonant frequencies become 2856 MHz. The iris radius between cells has been

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also determined by the code to make the coupling between cells negligible. The gun will be operated at the π-mode-like basically.

The gun has three degrees of freedom to control: the field strength of 1st cell E_1, the field strength of 2nd cell E_2 and relative phase between cells $\Delta\theta$. To compress a bunch length effectively by a magnetic bunch compressor located at the downstream of the gun, we have searched an optimum operating point of the gun to generate a beam with a linear distribution in the longitudinal phase space. As a result of optimization, E_1 was fixed around 25 MV/m because the head of emitted electrons from a cathode must arrive at the middle point of between cells on time of a half RF cycle. Using optimized parameters (E_1, E_2) = (25, 50) MV/m, longitudinal phase spaces at exit of this gun for different values of $\Delta\theta$ are shown in Fig. 1.

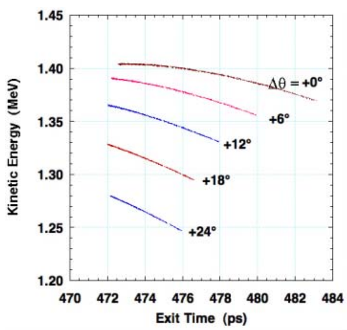

Fig. 1: longitudinal phase space. $\Delta\theta$ is a variable in this simulation. (E_1, E_2) = (25, 50) MV/m. $\Delta p/p_{max}$ = 2 %.

As shown in Fig. 1, a linearity of phase space distributions depends on the $\Delta\theta$, and then we can manipulate it.

The normalized rms emittances less than 1 π mm mrad obtained by the simulation satisfy the designed. The bunch charge of this beam with momentum width $\Delta p/p$ = 2 % is about 30 pC which almost satisfies the design value.

Measurement basic parameters of the ITC-RF gun

A prototype of the ITC-RF gun has been manufactured as shown in Fig. 2.

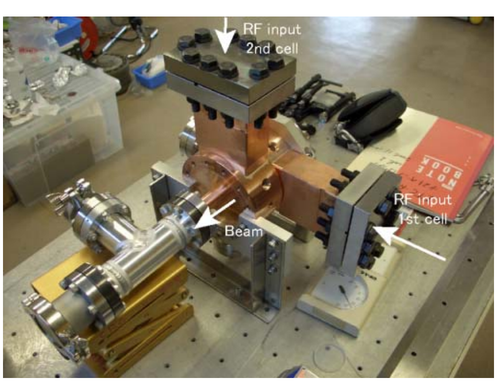

Fig. 2: An overview photo of the manufactured gun.

Some basic parameters of the gun has been measured by using a network analyzer (Agilent 8753ES). Resonant frequencies of both cells, two coupling coefficients β between RF input port and cell, and Q values have been measured at several conditions. The temperature around the gun has been kept at 21℃ within accuracy of 1℃ during the measurement. Measured resonant frequencies are (f_1, f_2) = (2810.8, 2821.3) MHz, where f_1 and f_2 represent frequencies of the 1st cell and the 2nd cell respectively. The measured frequencies are lower than a designed value of 2856 MHz. Calculating the resonant frequencies by 3D codes, an FDTD code or MW-STUDIO [6], it became clear that those are decreased by adding RF input ports and vacuum ports to. There are some methods to adjust resonant frequencies. Operating temperature of this gun changes the frequencies. Another way is changing inner wall shape by bolting down the outer wall. There are six holes to bolt down the outer wall for each cell. The first method is used to have the frequencies become down mainly by rising temperature from 21℃ to 50℃. Frequency change has been measured as a function of the temperature, which is summarized in Table. 2.

Table 2: Response rates of resonant frequencies to the temperature

df/dT	Measured value [kHz/K]	Calculated value [kHz/K]
1st cell: df_1/dT	-46.9	-37.9
2nd cell: df_2/dT	-45.9	-48.0

In SUPERFISH calculation in Table 2, it was assumed that the geometrical change caused is only the cavity diameter. The measured value of df_2/dT is in good agreement with the calculated value. The measured value of the 1st cell is different from the calculated value compared with the 2nd cell. Because the geometry of the 1st cell is not perfectly pill-box shape, the frequency response depends on not only the diameter but also the other geometrical lengths.

By using the second method, bolting down the outer wall of each cell, each resonant frequency can shift to 2815.5 MHz and 2825.3 MHz respectively. Both resonant frequencies were increased by 5 MHz higher than before. As a result, the adjustable range of frequency is from -1.5 MHz to +5.0 MHz around the target frequencies. It is important to estimate the amount of frequency shift by adding RF input ports and vacuum ports to axially symmetrical cavities. A measured strength of RF coupling between 1st cell and 2nd cell is negligible small. Measured parameters are summarized in Table 3.

From measured beta in Table 3, the filling times of each cell are 0.34 μs and 0.24 μs respectively. The acceptable macropulse duration for the THz ring is about 150 ns. Consequently macropulse duration of 1.5 μs is long enough to generate 150 ns flat top.

Table 3: Measured values in low power tests and calculated parameters using SUPERFISH

parameter	Measured value	Calculated value
f_1 [MHz]	2810.81	2856.0
f_2 [MHz]	2825.36	2856.0
β_1	2.3	—
β_2	3.4	—
Q_1	9984	13000
Q_2	9600	12500

Magnetic bunch compressor

Beam has to be compressed from several ps to less than 100 fs at the downstream of the gun by the magnetic bunch compressor. Magnetic bunch compression employs path difference for particles at different momenta in a dipole magnetic field. In case of the ITC-RF gun, momentum deviation makes a considerable difference of velocity for each particle because of the low beam energy around 2 MeV. As a magnetic compressor, a TBA transport has been adopted. In addition the bunch compressor can vary the higher order term of the dispersion function by using one family of sextupole magnet to manipulate nonlinear longitudinal phase space distribution. An element in the transport matrix R_{56} is varied by changing a dispersion function of the 2nd bending magnet. The designed optics is shown in Fig. 3.

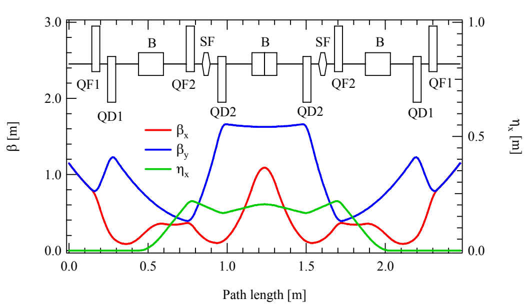

Fig. 3: TBA optics. Left axis is for beta functions. Right axis is for dispersion function.

Each bending angle is 60 degree. Total bending angle of the lattice is 180 degree. This lattice has four families of quadrupole as shown in Fig. 3 which are specified two purposes mainly. The dispersion function at the 2nd bending magnet is controlled by quadrupole magnets between bending magnets to change the R_{56}. The other quadrupole magnets are used for matching of horizontal and vertical Twiss parameters at exit and reducing the beta function in bending magnets. In order to estimate a bunch compression, a particle distribution of Fig. 1 ($\Delta\theta$ = 18 deg.) has been used. Designing of optics and tracking simulation have been done by using SAD code [7]. The results of the longitudinal phase spaces and the particle time distributions at a optimum operating point are shown in Fig. 4.

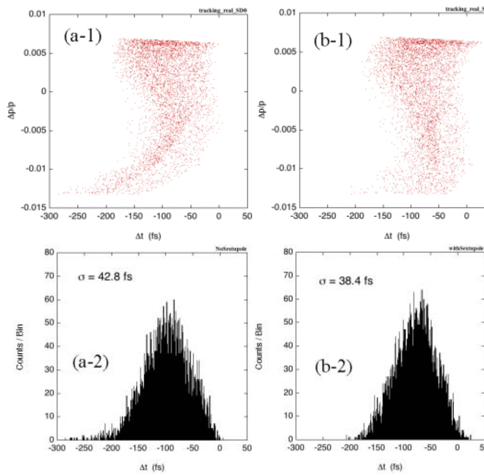

Fig. 4: longitudinal phase spaces of a compressed beam and its time distributions. (a-1) compressed beam with sextupole off, (b-1) compressed beam with sextupole on, (a-2) time distribution of (a-1), (b-2) time distribution of (b-1).

As shown in Fig. 4, the compressed bunch lengths are 42.8 fs (rms) with sextupole off and 38.4 (rms) fs with sextupole on. In the case of sextupole on, the higher order term of dispersion function can be compensated.

SUMMARY

A prototype of the ITC-RF gun has been manufactured, and some basic parameters were measured. The measured resonant frequencies of this gun are lower than the designed values. Therefore, it is important to estimate the amount of frequency shift caused by adding RF input ports and vacuum ports with using 3D code.

The bunch compressor has been designed to compress a beam from the gun. This transport has been designed as it can adjust the R_{56} and higher order of dispersion function to deal with various longitudinal phase space distributions. As a result of beam tracking, this transport can achieve a very short bunch length until 38.4 fs (rms) which is much shorter than the target value 100 fs (rms).

As an injector of the THz ring, the ITC-RF gun and the bunch compressor may have a possibility to generate a very short bunch.

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