Study on the production of the subpicosecond electron bunch

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Abstract

The production of the high brightness femtosecond electron bunch is now one of the hot research topics. This paper describes one electron linac facility used to produce the subpicosecond electron bunch. We analyze the main structure parameters, and study the beam dynamics of the facility. Finally, we discuss the application of this facility in Compton scattering.

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1 Introduction

During the past several years, the milestone progress has been made in the field of X-Ray free electron laser (XFEL)[1, 2]. Both LCLS at SLAC and SACLA at Spring-8 are successful to produce the hard X-Ray free electron laser. There arrives the new high peak time for XFEL research. Many new kinds of operation modes appear, such as echo, self seeding, etc. One of the key techniques for XFEL is the high brightness electron preinjector. Among the present research cases, the photocathode RF gun is the most successful[3, 4]. In case of S-band technique, the BNL type 1.6 cell photocathode RF gun is widely used in many laboratories. This paper does beam dynamics study on the subpicosecond bunch production facility at Tokyo University (shown is Figure 1)[5, 6, 7]. The linac is made of the photocathode RF gun, the $2856\,MHz$ accelerating structure, the solenoid, and the chicane.

Figure 1. The schematic figure for the linac facility

2 Bunch compressing

Bunch compressing technique[8] is widely used in linear collider and FEL driver linac to get the short high peak current bunch. Bunch compressing is usually referred to the magnetic compressing. The compressing section is made of the RF accelerating part and
its related following chicane. In the accelerating part, as the accelerating phase is not at the peak phase, the related correlated energy spread is produced as the bunch goes through the accelerating section. The bunch is compressed when the particles with the different energy at the bunch go through the chicane to form the distance difference. In the early development, $\alpha$ magnet is often used in the linac to compress the bunch to drive the low gain FEL oscillator. At present, we commonly use the chicane made of four equal bends to finish the bunch compressing.

3 Beam dynamics

The facility is made of the S-band photocathode RF gun, the 2856$MHz$ accelerating structure, and the chicane. The main parameters of the photocathode RF gun are shown in Table 1.

| Cathode radius | 1 mm |
|----------------|------|
| Quantum efficiency | $> 10^{-8}$ at 266 nm |
| Peak electric field on the cathode surface | 100 MV/m |
| Energy | 5 MeV |
| Charge | 100-1000 pC |
| Energy spread | $< 0.2\%$ |
| RF frequency | 2856 MHz |
| Rep. rate | 10 Hz |
| Microwave pulse length | 3 $\mu$s |
| Microwave peak power | 10 MW |
| Filling time | 0.55 $\mu$s |

The accelerating structure section is made of 61 cells, and works at $\frac{2\pi}{3}$ mode. The main parameters of the accelerating structure are shown in Table 2.

| RF frequency | 2856$MHz$ |
| Mode | $\frac{2\pi}{3}$ |
| Field distribution | constant gradient |
| length | 2.09$m$ |
| Number of cell | 61 |
| Quality factor | 11000 |
| Shunt impedance | 57$\Omega/m$ |
| Attenuation factor | 0.57$dB$ |
| Group velocity | 0.02 – 0.03$c$ |
| Filling time | 0.55 $\mu$s |

The accelerating structure matches the DC electron gun in the original design. Now the photocathode RF gun take place of the original DC gun, so there is mismatch between the RF gun and the accelerating structure. The first ten cells are the region of varing
phase velocity. The phase velocity of the first four cells are 0.77c, the phase velocity of the next three cells are 0.94c, and then the next three cells have the phase velocity of 0.99c. In addition to the varying phase velocity region, there are 51 cells with the constant light velocity. In RF linac, the wave impedance (the ratio of the transverse electric field to the transverse magnetic field) are often defined as

$$Z = \frac{60}{k} \frac{k_3}{k_2} \left( 1 - \frac{J_0(k_1a)}{J_1(k_1a)} \right), \tag{1}$$

where $k$ is the wave number in the free space, $k_3 = \frac{2\pi}{\beta_w \lambda}$, $k_1^2 + k_3^2 = k^2$, $\beta_w$ is the phase velocity. The wave impedance of the varying phase velocity region varies slowly. The structure design is reasonable. There exists the phase slippage motion in the region of the varying phase velocity due to the mismatch between the photocathode RF gun and the accelerating structure. The main parameters of the chicane are shown in Table 3.

Table 3. The main parameters for the chicane

|                       |          |
|-----------------------|----------|
| Energy                | 15.46MeV |
| Energy spread         | 8.8%     |
| Compressing ratio     | 10       |
| $R_{56}$              | -13mm    |
| Total length          | 1.04m    |
| Project distance      | 0.194m   |
| Project distance      | 0.19m    |
| Length of bend        | 0.116m   |
| Deflecting angle      | 10.4°    |

Before the chicane, there are four quadrupoles used for the match between the accelerating structure and the chicane.

We use PARMELA[9] to simulate the linac facility. PARMELA is a multiparticles PIC code which takes into account of the space charge effect and is widely used in accelerator community. The version we used does not include the coherent synchrotron radiation (CSR) effect. So the normalized emittance we get in the simulation is smaller than that in the experiment. We include the fringe field of the bends in the simulation. There are many choices for the cathode material, such as Cu, Mg, and Na$_2$KSb. When we use Cu or Mg, the main parameters of the laser are shown in Table 4.

Table 4. The typical laser parameters

|                |          |
|----------------|----------|
| Wavelength     | 266nm    |
| Waist          | 1mm      |
| Rep. rate      | 10Hz     |
| Pulse energy   | 20µJ     |
| Pulse length   | 10ps     |
| Rise time      | 0.7ps    |
| Longitudinal shape | uniform |

Figure 2 and Figure 3 give the beam longitudinal distribution before and after the compressing. It is obvious that the bunch is compressed from 10ps to less than 1ps. The normalized emittance dilutes about 0.1mmmmrad.
CSR is one of the research topics in the XFEL field. The radiation of the moving charged particle is a kind of retarded potential. In case of the electron bunch, due to the orbit arc, the radiation of the bunch tail will have effect on the bunch head. This kind of effect is called CSR wakefield. When the electron bunch with the energy spread induced by the CSR impedance goes through the dispersion region, the normalized emittance will dilute. The research of CSR effect is more complex. The present analytical study is only limited to one dimensional theory[10]. The high dimensional theory now rely only on the numerical method. Trafic4 is a better PIC code to simulate the CSR effect. The Trafic4 result shows that 100$pC$ bunch will have the normalized emittance dilution of 0.3$mmr$ad going through the chicane. While the PARMELA result is 0.1$mmr$ad.
5 Application in Compton scattering

In comparison with the FEL mechanism, Compton scattering is also an effective method to produce X-Ray radiation. Compton scattering is the scattering between the photon and the electron, the energy of the electron is not necessarily high. The coherence and the brightness of the scattering photon are weaker than that of the free electron laser. We use the following laser parameters (shown in Table 3) in the simulation.

Table 3. The laser parameters used for Compton scattering

| Parameter       | Value       |
|-----------------|-------------|
| Wavelength      | 3$\mu$m     |
| Rayleigh length | 32$\mu$m    |
| Rep. rate       | 10 Hz       |
| Peak power      | $6.75 \times 10^{14} W/cm^2$ |
| Length          | 30 ps       |

We use Cain by Yokoya[11] to simulate the Compton scattering photon spectrum. The peak value is at $1.5 keV$ or so.
6 Discussion

The low energy linac can also be used to produce X-Ray radiation. In this paper, we simulate the linac facility used to produce the subpicosecond electron bunch. The produced electron bunch can be applied both for the X-Ray generation and the inverse free electron laser acceleration. We simulate the Compton scattering numerically in the end.

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