Study on the characteristics of linac based THz light source

ZHU Xiong-Wei(朱雄伟)[1)] WANG Shu-Hong(王书鸿) CHEN Sen-Yu(陈森玉)

(Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China)

Abstract There are many methods based on linac for THz radiation production. As one of the options for the Beijing Advanced Light, an ERL test facility is proposed for THz radiation. In this test facility, there are 4 kinds of methods to produce THz radiation: coherent synchrotron radiation (CSR), synchrotron radiation (SR), low gain FEL oscillator, and high gain SASE FEL. In this paper, we study the characteristics of the 4 kinds of THz light sources.

Key words photon, linac, THz, light source

PACS 29.20.Ej, 41.60.Ap, 41.60.Cr

1 Introduction

Photon science is now one of the hottest topics in physics world[1]. THz radiation is very important and useful due to its special position in the electromagnetic spectrum[2]. It can be used in communication, condensed matters, etc. The linac based THz radiation has the advantage of high power in comparison with solid and quantum devices.

Energy recovery linac[3] (ERL) is one of the compact candidates for the 4th generation light source. The main advantage of ERL is that it can recover the energy at the efficiency of 99.9%. ERL meets the requirement of modern society which uses the earth source economically, and it will be a big revolution in the world's light source research. As one of the options for the Beijing Advanced Light, an ERL test facility is proposed for THz radiation, as shown in Fig. 1.

In this test facility, there are 4 kinds of methods to produce THz radiation: coherent synchrotron radiation (CSR), synchrotron radiation (SR), low gain FEL oscillator, and high gain SASE FEL. In this paper, we study the characteristics of the 4 kinds of THz light sources in the test facility.

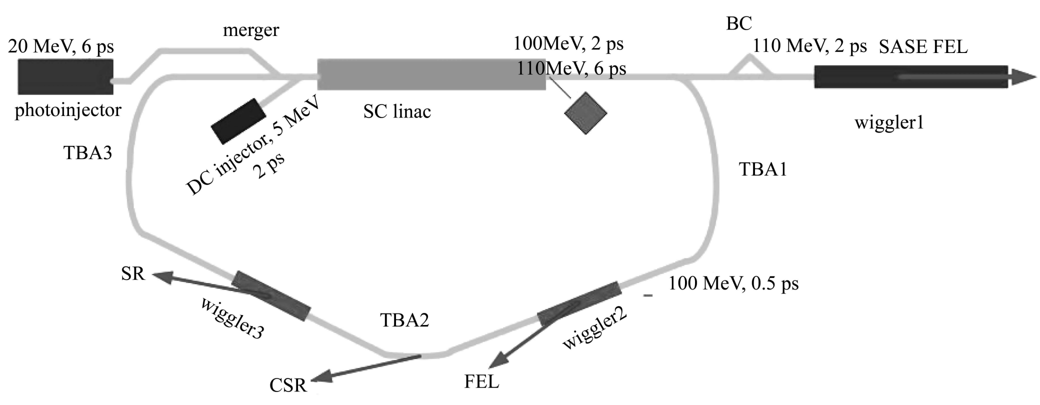

Fig. 1. The schematic setup of Beijing ERL test facility.

Received 29 December 2008

1) E-mail: zhuxw@mail.ihep.ac.cn

2 Characteristics of THz light source

The test facility mainly consists of one L-band photocathode RF injector, one L-band photocathode DC injector, merger, L-band supercondcting main linac, return loop, separator, and undulators. The ERL return loop consists of three TBAs, the loop will include two straight sections. As for the SASE FEL, after the separator, the bunch goes through a chicane to be compressed to enter the long undulator section. The main parameters of the test facility are from the preliminary start-to-end simulation of the test facility and are summaried in Table 1. We use the parameters of the 9-cell superconducting cavity from TESLA for the main linac. Our simulation takes into account the wakefield effect. Specially, the bunch compressor before the undulator needs the beam energy spread to compress the beam, the energy spread is about 1%. While the pierce parameter for SASE-FEL (THz band) is a few percent which is bigger than the beam energy spread, the beam still satisfies the coherent condition for FEL.

Table 1. The main parameters of test facility.

parameters	ERL	SASE-FEL
energy/MeV	100	110
average current/mA	10	1.3×10^{-5}
injector energy/MeV	5	20
bunch repetition rate/(MHz/Hz)	130	13
gradient/(MV/m)	23	23
phase (degree)	5	−15
bunch charge/(pC/nC)	77	1
normalized emittance/ (mm·mrad)	3	3
energy spread (%)	0.3	1

In the test facility, there will be three kinds of THz radiation sources from the ERL loop: CSR from the bend in the middle TBA, SR from the wiggler in one straight section of the loop, low gain FEL oscillator in another straight section of the loop. The fourth THz light source is the high gain SASE FEL from the long undulator added to the main linac. The main parameters of the electron bunch for the light sources are summarized in Table 2.

Table 2. The main parameters of the electron bunch for light sources.

	CSR	SR	FEL oscillator	SASE FEL
energy/MeV	100	100	100	110
normalized emittance/ (mm·mrad)	3	3	3	3
energy spread(%)	0.3	0.3	0.3	1
bunch length/ps	0.5	0.5	0.5	2
Rep. rate/Hz	1.3×10^{8}	1.3×10^{8}	1.3×10^{8}	13
average current/mA	10	10	10	1.3×10^{-5}

The power emitted by an electron bunch as a function of frequency and solid angle, is derived by extending the classical electrodynamics theory[4] for a single electron, to a system of N electrons, thus

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega\mathrm{d}\Omega} = [N+(N^2-1)f(\omega)]\cdot\frac{e^2\omega^2}{4p^2c}\cdot \left(\int_{-\infty}^{\infty}\widehat{n}\times(\boldsymbol{\beta}\times\widehat{n})\exp(\mathrm{i}\omega(t-\widehat{n}\cdot\boldsymbol{r}(t)/c)\mathrm{d}t\right)$$

where e is the charge of the electron, $\boldsymbol{\beta}$ is the ratio of the velocity of the particle bunch to the velocity of light, $\widehat{n}$ is a unit vector, $\boldsymbol{r}(t)$ is the position of the center of the electron bunch, N is the number of particles in the bunch, and $f(\omega)$ is the longitudinal particle distribution within the bunch. The second term in RHS is due to the coherence in time, the total emitted power is just a simple sum of single electron radiation power without the second term. When the bunch length is in the level of the wavelength, the contribution from the second term is very big. So the emitted power can be enhanced very much. This phenomenon is the so-called CSR effect.

The bend radius for CSR is 1 m. We use SPECTRA to calculate the photon flux through a pinhole (2 mm × 1 mm) located at the position of 30 m from the source. The flux spectrum is shown in Fig. 2. The wavelength range is from 8 μm to 10000 μm. We can observe the coherent enhancement over SR obviously (6—7 orders). The total emitted power is roughly estimated to be 100 kW which is far higher than the solid and quantum devices.

The parameters of the wiggler for SR are the gap of 1 cm, the period of 6 cm and the period numbers of 40. We also calculate the photon flux through a pinhole (2 mm × 1 mm) located at the position of 30 m away from the source. The flux spectrum is shown in Fig. 3. The wavelength range is from 30 μm to 500 nm. The SR spectrum is weak.

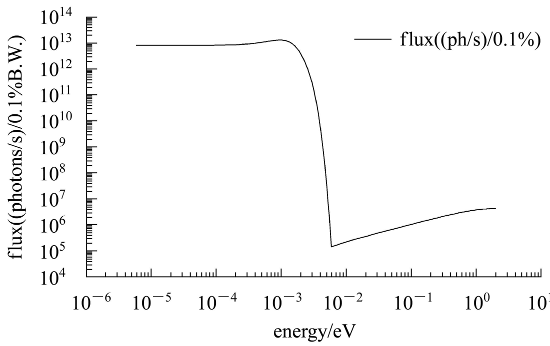

Fig. 2. The CSR flux spectrum of 0.5 ps, 77 pC ERL bunch through a rectangular area (2 mm × 1 mm) located at the position of 30 m away from the source.

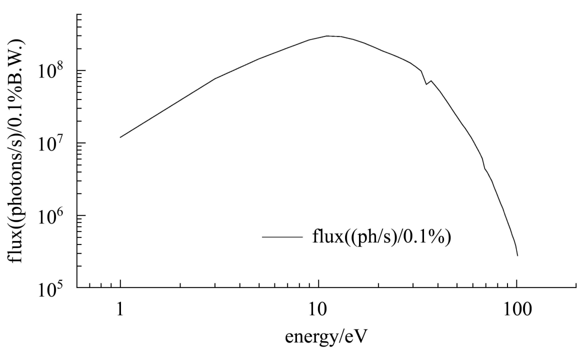

Fig. 3. The SR flux spectrum of 0.5 ps, 77 pC ERL bunch through a rectangular area (2 mm × 1 mm) located at the postion of 30 m away from the source.

The dispersion relation of photon is $\omega = kc$ (the rest mass of photon is just zero), while the dispersion relation (De Broglie wave) of the electron is $E^2 = m_0^2c^4 + p^2c^2$, $E = h\omega/2\pi$, $p = hk/2\pi$, where m_0 is the rest mass of the electron, c is the light velocity, and h is the Planck constant. In the plane of $\omega - k$, there is no intersection between the two dispersion relations. We should change the dispersion relation for the interaction. This is the basic principle for fast wave devices such as FEL, Gyrotron, etc. In FEL, we can use wiggler or undulator to complete this task.

The parameters of the wiggler for FEL oscillator are the gap of 1—2 cm, the period of 6 cm, the length of 2.4 m, and the span distance of mirrors of 4.615 m. The radius of the mirrors is adjusted to change the reflectivity in our calculation. We have simulated the low gain FEL oscillator, the stable output power is less than 20 MW (as shown in Fig. 4). The optical cavity detuning length is in the level of 20 μm, and the beam time jitter is in the level of 10 fs. Table 3 shows the main parameters of the FEL oscillator.

Table 3. The parameters of low gain FEL oscillator.

photon output	
wavelength range/μm	7—30
peak power/MW	< 20
pulse length/ps	0.5
Rep. frequency/Hz	1.3×10^8
wiggler parameter	
period/cm	6
Gap/cm	1—2
length/m	2.4
focusing	natural
optical cavity parameter	
cavity length/m	4.615
mirror radius/mm	50—90
rayleigh length/m	0.5—1.2

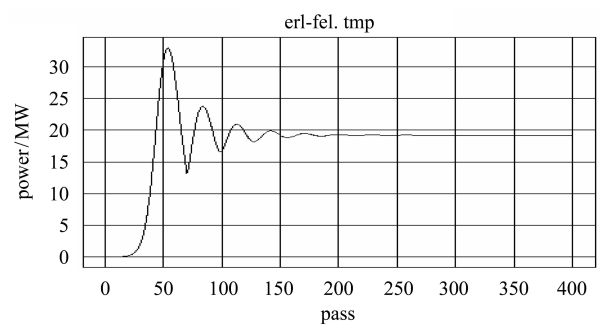

Fig. 4. The output power of the FEL oscillator.

The parameters of the linac SASE FEL is summaried in Table 4. We use Xie Ming's formula[5] to calculate the SASE FEL parameters which is in good agreement with the simulation result taking into account the lattice details (including the external focusing quadrupoles).

Table 4. The parameters of SASE FEL.

photon output	
wavelength range/μm	24—70
peak power/MW	80
pulse length/ps	2
Rep. frequency/Hz	13
pierce parameter(%)	2.6
peak brilliance	2×10^{23} (photons/s)·(mm^2· mrad^2 · 0.1%B.W.)
wiggler parameter	
period/cm	15
gap/cm	5.5—7.7
length/m	18
focusing	natural

3 Discussion

In this paper, we have studied the characteristics of the four kinds of radiation sources (THz band) based on the ERL test facility. The result shows that the peak power of SASE is the highest (FEL oscillator is the next), while the band of SR and CSR is broader than that of FEL. In general, the output power of the THz radiation sources based on linac is much higher in comparison with the solid and quantum devices, and can be used in the case of high power. The advantage of solid and quantum devices is their miniaturization.

The radiation of moving free electron is of diversity. The spontaneous radiation in the bend is the basic form. CSR is the enhanced form over SR. While FEL is the form of stimulated radiation, and the quality of the emitted light is much better than CSR and SR. There are many kinds of FEL operation modes (SASE, HGHG, etc). Recently, there are also many kinds of upgrade operation modes (EHGHG, ESASE, ECHO[6]) which increase the bunching factor. Actually, the concept of ECHO comes from the plasma physics using the memory function of the plasma. As for the endless march to hard X-ray source, SASE is the most successful operation mode up to now, and the FEL oscillator is also hopeful[7]. Therefore, in our test facility, we choose these two modes. The field of new radiation source is so wonderful that it needs more attention to be paid.

Thanks go to Prof. Alex Chao and Dr. Huang Zhirong from SLAC for the useful discussions.

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