Beam dynamics design of an SP-FEL compact THz source

DAI Dongdong[1, 2] DAI Zhimin[1*]

[1] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

[2] *Graduate School, Chinese Academy of Sciences, Beijing 100049, China*

Abstract In recent years, people are looking for a new compact THz source with high emission power, one potential choice is to build small accelerator with Smith-Purcell radiation. The main difficulty is how to obtain high quality electron beam. In this paper, the beam dynamics design of a compact THz source is presented. The electron beam is produced by an electron gun and compressed by permanent magnets. The electron gun is similar to the Shanghai EBIT, but permanent magnets are used, instead of the superconducting magnets in Shanghai EBIT. With this design, we can reduce the size and cost of the whole device. Poisson/Pandira was employed to simulate and optimize the magnetic field. Egun was used to simulate the beam trajectories from the electron gun to the collector. Within 2 centimeters around the center of longitudinal magnetic field, the calculation showed that the beam satisfies to our design aim.

Key words THz source, Smith-Purcell radiation, Permanent ring magnet, NdFeB

1 Introduction

The frequency band between the microwave band and the far-infrared ray band is recognized as the Terahertz (THz) region, which corresponds to millimeter and sub-millimeter waves. THz band, as the final band to be exploited, will certainly be of benefit for progresses in new fields of research. THz applications cover a number of fields, such as imaging, biology, medicine, defense, communication and astronomy.

However, the development of THz science and technology has been hindered by the lack of compact, highly efficient and tunable THz sources. Smith-Purcell radiation, observed first by Smith S J and Purcell E M in 1953[1], can well be a solution to this problem. It is believed that a Smith-Purcell radiation emitter, a simple vacuum electron device, is an effective candidate for the broad band and tunable THz rays[2]. When high emission power is required, the device shall be designed under the same mechanism as a free electron laser to achieve greater energy conversion efficiency, hence the name of Smith -Purcell Free Electron Laser (SP-FEL).

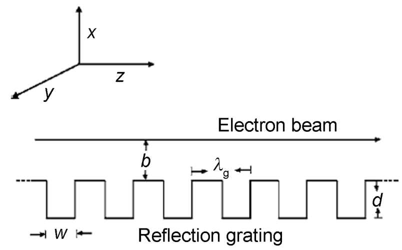

Fig.1 Schematic of the Smith-Purcell radiation.

Smith-Purcell radiation is generated when an electron passes the near-surface of a metal diffraction grating. Moving perpendicularly to the grating teeth, the electron induces radiation emitted from the grating (Fig.1). Theoretical analysis on SP-FEL by Andrews and Brau[3] shows that the dispersion and attenuation properties of the grating play an important role in performance of the SP-FEL. The predicted gain is proportional to cube root of the current. Dartmouth[4] observed superradiant SP emission on a device equipped with a scanning electron microscope. He also found that nonlinear phenomena would occur when the beam current exceeds certain threshold point.

In this paper, a compact THz source of the SP-FEL type is designed. The Possion/Pandira and Egun codes are adopted to simulate the magnetic field

* Corresponding author. *E-mail address:* daizhimin@sinap.ac.cn

Received date: 2009-12-20

of the source for studying dynamic characteristics of the electron beam. Proper shape of electrode structure is chosen, and the magnet parameters are optimized. The outcome of the simulation provides us with an electron beam of high current and small radius, which makes it possible to work as SP-FEL.

2 Structure optimization of the source

Fig.1(a) is schematic diagram of the compact THz source. The stainless steel vacuum chamber of less than 1 m in diameter is small enough to be placed on a desk. The electron gun, the Smith-Purcell radiation component, and the collector are arranged horizontally. A pair of NdFeB rings is used to focus the electron beam.

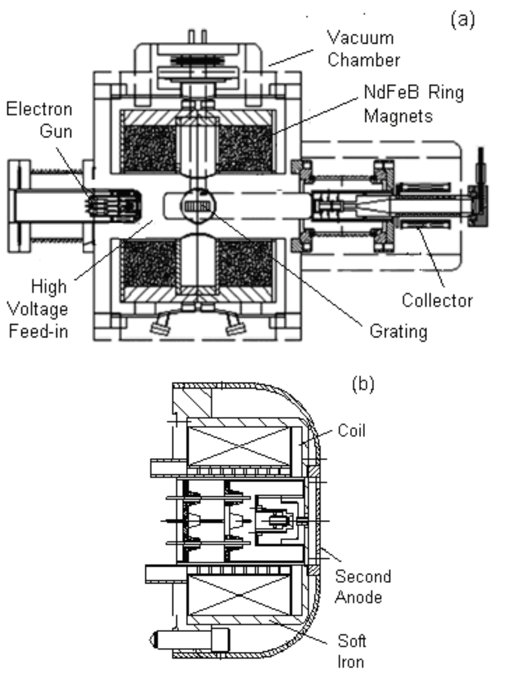

Fig.2 Schematic diagram of the compact THz source (a) and the electron gun (b).

The electron gun is of the same type as the one in the Shanghai EBIT(electron beam ion trap)[7,8]. As shown in Fig.2(b), it is a pierce type gun with a spherical-concave shaped dispenser type cathode of Φ3 mm. The cathode is a porous tungsten matrix diffused with BaO, CaO and Al_2O_3. In operation, the electron gun of Shanghai EBIT generates beams with an average current of up to 200 mA. The electron gun designed for the SP-FEL source has the same cathode, focus and anode electrodes as the electron gun of Shanghai EBIT, but it uses permanent ring magnets, rather than the superconducting magnets in the Shanghai EBIT.

According to Hermann theory[5], for an electron gun, achieving high compression of the electron beam requests reduction of the magnetic field as much as possible at the cathode. Gradient of the initial magnetic field is also essential for matching the electron beam trajectories to the axial magnetic field[6]. Thus, the electron gun is enveloped by soft iron as a magnetic shield. Inside the soft iron, several electromagnetic windings on the electron gun are used for performing slight adjustment of the magnetic field at the cathode.

The NdFeB rings to form the axial magnetic field for focusing the electron beam are positioned axial-symmetrically with the north pole on the inner face and the south pole innermost. Each ring consists of 23 magnetized wedges and one nonmagnetic wedge. The two nonmagnetic wedges are placed parallel to the ground plane, and one hole is incised on each for the THz radiation output coupling.

The interval between the two ring magnets is limited by the size of a pipe through which the Smith -Purcell radiation grating is pumped. To design and optimize the axial magnetic field, numerical model based on the Possion/Pandira code has been carried out. Volume of the ring magnets is minutely considered.

The position and structure of the soft iron in the electron gun will be discussed in detail. The optimized magnetic field along the longitudinal *z* axis is shown in Fig.3. The calculations were performed for the magnetic rings of an outer diameter of 300 mm, an inner diameter of 130 mm, a length of 100 mm, and the interval of 82 mm between two rings. The magnetic field at the center of radiation grating is approximately 0.70 T. The reduction of the magnetic field due to the nonmagnetic wedges is about 4% along the longitudinal axis, almost uniform between the cathode and the collector. Such a small variation causes no significant degradation to the beam quality. Therefore, the axial magnetic field is treated as cylindrically symmetric in the investigation of the electron beam dynamics.

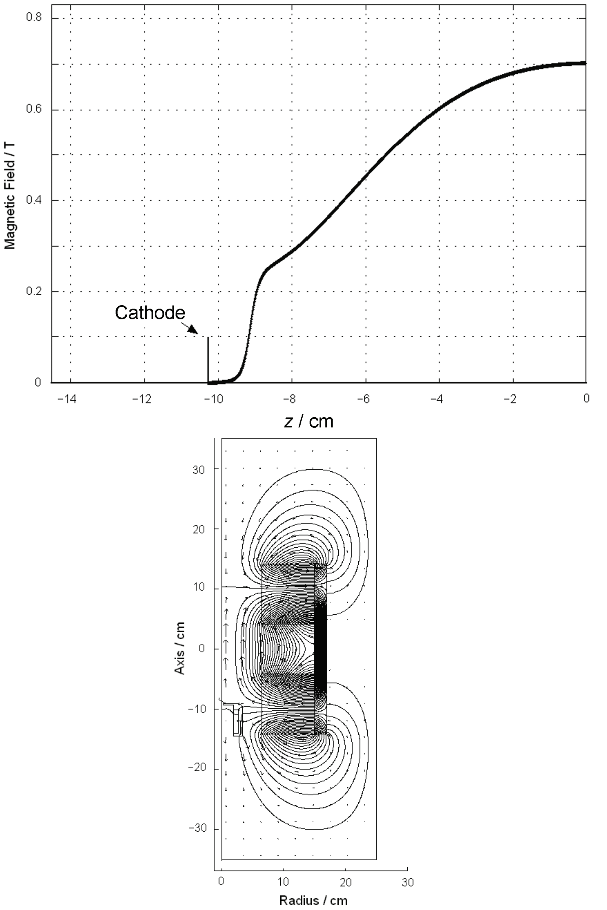

Fig.3 The axial magnetic field distribution along the electron beam.

3 Study of beam dynamics

The voltages applied to the electrodes have been numerically investigated to generate high quality electron beams. The optimized electron beam is shown in Fig.4, with the first anode at 6 kV, the second voltage at 10 kV, and the focus electrode voltage at −5 V.

According to Ref.[5], 80% of the electron beam of the electron gun is inside the Hermann radius, r_H,

$$r_H \approx 260(r_c/B)^{1/2}(kT_c)^{1/4} \quad (\mu m) \qquad (1),$$

where r_c (cm) is the cathode radius, B(T) is the magnetic field at the center, T_c is temperature (K) of the cathode, k is the Boltzmann constant, and kT_c is in eV. In our design, r_c= 0.15 cm, B= 0.7 T, kT_c = 0.1 eV, then the theoretical radius of 80% electron beam is about 67.7 μm from Eq.(1).

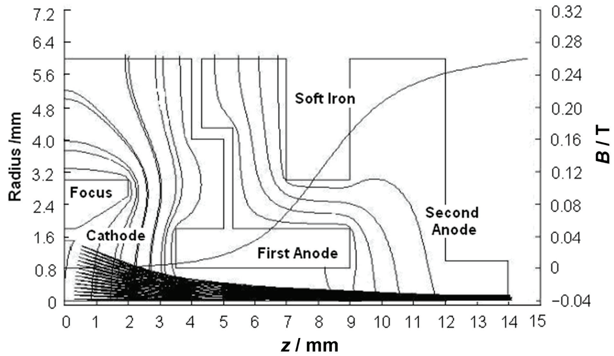

Fig.4 Beam trajectories of the electron gun. Voltages on the electrodes were optimized for 35 keV 200 mA beam.

With the optimal voltages applied to the electrodes, Fig.5a shows the electron beam enveloped by the cathode to the center of the radiation grating. The electron beam is focused perfectly, and the longitudinal position of the beam waist is the center of the grating where the axial magnetic field is the maximum 0.70 T. Fig.5b illustrates the radial distribution of the electron beam, and the result is consistent with the theoretical calculation.

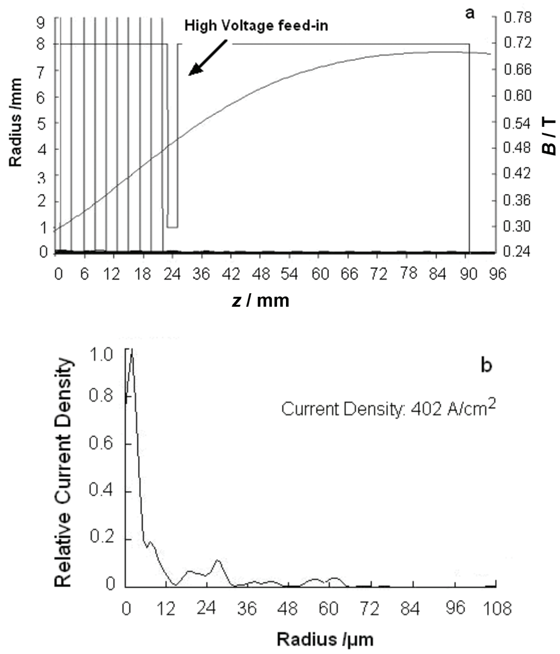

Fig.5 Dynamic characteristics for the electron beam. (a) is the electron beam envelope and (b) is the radial distribution(normalized current density) at the center of the radiation grating.

The THz radiation grating, 2 cm in length, is directly conjoint with the ground, with a water cooling system. The radial current density distributions are given in Fig.6, at different longitudinal positions with respect to the center of the grating. The current density peaks at large radiuses are caused by the trajectory oscillations of the outermost electrons. Electric field is disturbed at the aperture at the anode and the edge at the cathode, where trajectories of the outermost electrons are influenced strongly, resulting in oscillations finally. The inner part of the electron beam has a small oscillation in trajectories, too. Thus it leads to a ringed electron beam at a certain longitudinal position.

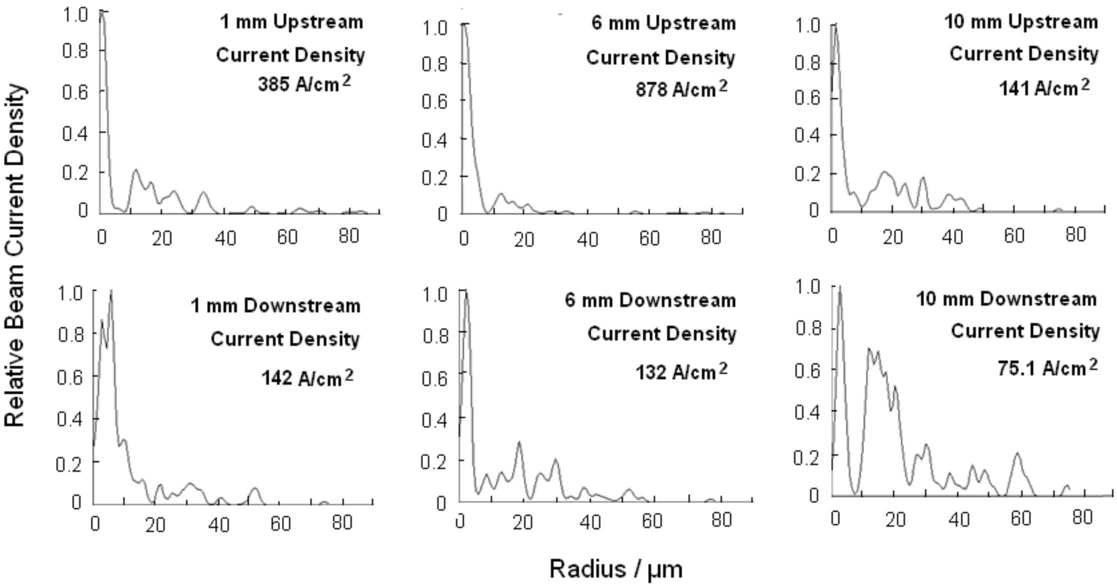

Fig.6 Radial current density distributions at 1, 6 and 10 mm from the grating center, with 35 keV 200 mA electron beam.

For a clearly understanding of the electron beam quality, the average radius, $\bar{r}$, and non-laminarity, $\bar{w}$, of the electron beam, are defined as follows,

$$\bar{r} = \sum_i r_{i,\mathrm{cath}} r_i \Big/ \sum_i r_{i,\mathrm{cath}} \quad (2),$$

$$\bar{w} = \sum_i r_{i,\mathrm{cath}} (r_{i,\max} - r_{i,\min}) \Big/ \sum_i r_{i,\mathrm{cath}} \quad (3),$$

where r_i, $r_{i,\max}$ and $r_{i,\min}$ are the average, maximum and minimum radius of the i^{th} electron in the grating region, respectively, $r_{i,\mathrm{cath}}$ is the radius of i^{th} electron at the cathode. After the optimization of the system, Table 1 lists the main parameters of the whole system. The average radius is 47 μm. The non-laminarity is 60 μm, which is a little larger than our expectation, but still good enough for a beam source for THz radiation.

Table 1. Characteristic of the whole system.

Electron beam energy / keV	35
Electron beam current / mA	200
Voltage on the cathode / kV	0
Voltage on the focus electrode / V	−5
Voltage on the first anode / kV	6
Voltage on the second anode / kV	10
$\bar{r}$ / μm	47
$\bar{w}$ / μm	60

Finally, we discuss the electrode where the electron beam is collected. The collector has a conical inner face. Since high voltage of −35kV applied on the collector, it will be cooled by oil. In the collector, several electrodes are utilized to control the electron beam and the secondary electrons emitted inside the collector. The shapes and the applied voltages of these electrodes are optimized. Fig. 7 illustrates the optimal voltages and the electron beam trajectories to the collector.

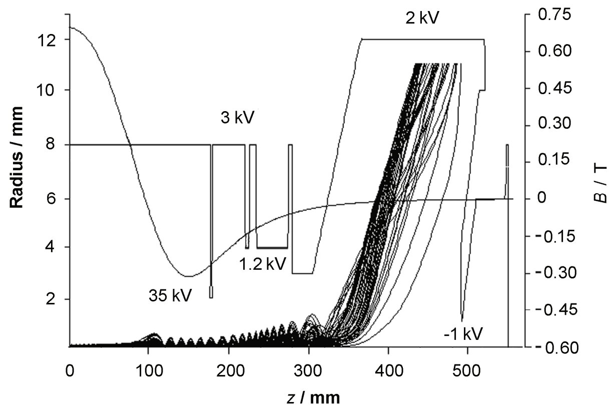

Fig.7 The optimal voltages and the electron beam trajectories to the collector.

4 Conclusions

We use similar basic elements of shanghai EBIT to achieve high brightness electron beam, only substitute the focusing superconductor magnets with the newly designed permanent magnets The electron beam can drive THz Smith-Purcell radiation with low cost. The pierce gun, focusing system and the collector of the electron beam are designed and optimized, based on the design of Shanghai EBIT facility. The beam dynamics of the electron beam are investigated. The results indicates that, an electron beam with energy of 35 keV, beam current of 200 mA and rms beam radius of 75 μm, can drive Smith-Purcell radiation with high intensity power.

In a size of less than 1 meter, our THz radiation source can be placed on a desktop. Miniaturization of the THz source will find wide applications in industries, fundamental research, medicine and other fields. Current work is preliminary, continuous optimizations on THz radiation properties are under way.

Acknowledgement

We are grateful to Dr. Sheng S G for his help on mechanics design. We also thank Dr. Bei H and Deng H X for their useful discussion on physics designs.

References

1 Smith S J, Purcell E M. Phys Rev, 1953, **92:** 1069–1069

2 Kim K J, Song S B, Nucl Instrum Meth Phys Res A, 2001, **475**: 158–163.

3 Andrews H L, Brau C A, Phys. Rev. ST Accel Beams, 2004, **7**: 070701–1-7.

4 Urata J, Goldstein M, Kimmitt M F *et al*. Phys Rev Lett, 1998, **80**: 516–519.

5 Gabriel Herrmann, Appl Phys, 1958, **29**: 127–129.

6 Brewer G R., in: A. Septier (Ed.), Focusing of Charged Particles, Vol. 2, Academic Press, New York, 1967, 73–77.

7 Zhu X K, Jiang D K, Guo P L *et al*, Shanghai Electron Beam Ion Trap: design and current status. Journal of Physics: Conference Series, 2004, **2**: 65–74.

8 QIAN L. Study on the performance of EBIT’s electron beam, in Nuclear Technology and Application. 2004, Shanghai Institute of Applied Physics: Shanghai.