# Optical Resonator Optimization of CAEP THz-FEL

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***Abstract*—The optical resonator of CAEP THz-FEL is optimized to ensure wavelength tunable in a wide range and high power operation. The FEL power strongly depends on the performance of the optical resonator including output efficiency, gain and round-trip loss. The optical resonator consists of metal-coated reflect mirror, the center-hole output mirror, waveguide. The influence of waveguide and Rayleigh length on the quality of optical cavity is evaluated by the 3D-OSIFEL code. The waveguide size, mirror curvature radius, output hole radius is optimized to different frequencies between 1 THz to 3 THz.**

## I. INTRODUCTION

THz radiation is being increasingly adopted in a wide variety of applications. Many of the applications utilize short pulse, broad-band THz sources based on conventional laser technology. The available output power in those systems remain low. But FEL systems can offer the tunability, high power and flexible picoseconds-pulse time structure of THz radiation[1-4]. A free-electron laser facility based on photocathode DC-gun and superconducting accelerator at China Academy of Engineering Physics (CAEP) in a radiation frequency range of 1~3 THz has been demonstrated[5-7]. The facility operates in the quasi CW mode and the average output power is about 10 W. To adapt a wide range of tunability over 1-3THz, optical resonator needs been optimized corresponding to different frequencies. In this paper, the parameters of the optical resonator, including mirror curvature radius, center-hole radius, waveguide are optimized for the CAEP THz-FEL corresponding to different frequencies through analysis and numerical simulation using our 3D-Osifel code[8].

## II. RESULTS

The cavity length is designed to be 276.9 cm long according to the repetition rate of the micro bunch is 54.17 MHz. The period length and period number of the wiggler are designed as 3.8 cm and 42. The electron beam current is 12.5 A and its pulse length is 8 ps. The main parameters of CAEP THz FEL are listed in Table 1.

Table 1 Main parameters of CAEP THz FEL

| **Electron beam** | | **Wiggler** | |
|---|---|---|---|
| Energy /MeV | 6~8 | Period /cm | 3.8 |
| Peak current /A | 12.5 | Peak field strength /kG | 2.5~5.0 |
| Micro bunch /ps | 8 | Number of periods | 42 |
| Emittance / π mm mrad | 10 | Cavity length /m | 2.769 |
| Energy spread /% | 0.75 | | |
| Repetition rate/MHz | 54.17 | | |

### A. INFLUENCE OF WAVEGUIDE

The large diffraction loss inherent in long wavelength radiation implies the use of waveguide in THz- FEL resonator, which can substantially improve the overlap between the optical and electron beams, and consequently the FEL gain as compared to open resonators.

The normalized radiation vector potential in the x direction is given by

$$A_x(x,y,z)=\sum_n -\frac{i}{2}A_n(x,z)A_{yn}(y)e^{ik_{zn}z-i\omega t}+c.c \quad (1)$$

$$A_{yn}(y)=\begin{cases}\cos(k_{yn}y), & n=odd\\ \sin(k_{yn}y), & n=even\end{cases} \quad (2)$$

Where Kyn=n π /b, ω is the radiation frequency, b is the gap of waveguide, An is the slowly varying function of z. Using our the 3D-OSIFEL code, Simulations of the waveguide in the whole optical cavity of CAEP high power THz-FEL device are achieved. In the simulations, the distribution functions of transverse position and velocity and energy of the electrons are assumed to be Gaussian. The corresponding initial values of sample electrons are determined by a Monte Carlo method, and the initial phases are loaded according to the 'quiet start' scheme to eliminate numerical noise. The energy spread and emittance are specified as FWHM and RMS, respectively.

The influence of different waveguide size is compared according to different frequency of 1-3THz by simulations. Fig 1. Shows that output power as a function of the optical pass to different waveguide gap when the radiation frequency is 2THz. It can been seen that the output power is higher when waveguide gap is 10mm and 14mm than the waveguide gap is 22mm and 28mm.

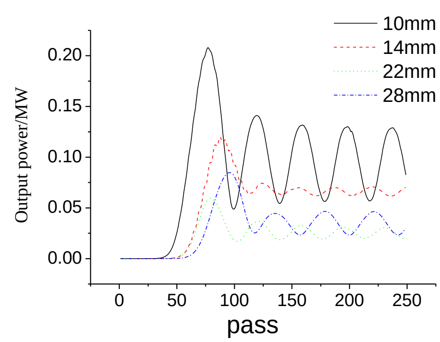


Fig 1. Output power as a function of the optical pass to different waveguide gap when the radiation frequency is 2THz.

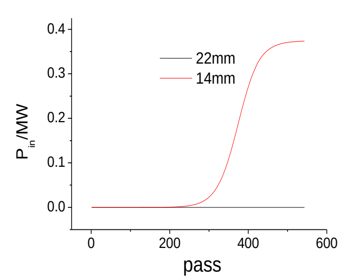


Fig 2. Resonator power as a function of the optical pass to waveguide gap 14mm and 22mm when the radiation frequency is 1THz.

Two waveguide gap that is 14mm and 22mm is chosen. Fig 2 shows that resonator power as a function of the optical pass to waveguide gap 14mm and 22mm in the frequency 1THz. From Fig 1, it can be seen that when the gap of waveguide is 22mm, the resonator will not start up. So when the radiation is about 1THz, the gap of waveguide must be 14mm to make the facility can work. The shape of the waveguide is adopted a rectangle (28mm×14mm). When the facility is testing above 2 THz, the waveguide gap can be adjusted to 22mm in order to ensure security.

### B. RAYLEIGH LENGTH

The Rayleigh length is decided by the mirrors curvature radii. The optical waist radius on the middle of resonator and the optical radius on mirror are closely related to the Rayleigh length, the mini-extremum of optical waist radius exists when changing the Rayleigh length. Rayleigh length influences on the FEL interaction and single-pass extraction, that is, on resonator loss and gain. A more accurate determination of optimum value is obtained to different frequencies by simulations. The resonator loss $\eta_{loss}$ and gain $G_{net}$ and output peak power $P_{peak}$ are calculated corresponding different Rayleigh length when radiation frequencies is 2 THz. The results are shown in table 2. From the table, it can be seen that when mirror curvature radius is 185cm, the gain of wiggler is largest and when mirror curvature radius is 320cm the resonator loss is smallest. The optimum mirror curvature radius is 221cm for higher outpower in 2THz.

Table 2 Characteristics of the resonator for various mirror curvature radii.

| $R_{curv}$/cm | $P_{peak}$/kW | $G_{net}$/% | $\eta_{loss}$/% |
|---|---|---|---|
| 185 | 114.5 | 27.4 | 4.9 |
| 196 | 124.9 | 25.6 | 5.2 |
| 221 | 139.2 | 23.3 | 5.0 |
| 320 | 166.6 | 16.6 | 4.8 |

### C. OUTPUT COUPLING-HOLE

For the CAEP THz FEL, the facular image on the mirror is an ellipse due to a waveguide is needed to reduce the diffraction loss due to longer wavelengths. To increase the output power and resonator quality, the scheme of elliptical hole-coupling optical resonator is proposed instead of circular hole-coupling resonator which is used in facility. The size of coupling-hole is optimized to different frequencies between 1 THz to 3 THz. The results show that the optimum size of elliptical hole is 1.6mm×0.8mm in 1 THz and 2.2mm×1.1mm in 2-3THz. the optimum size of round-hole will be 0.9mm in 1THz and 3 THz and 1.2mm in about 1.6THz and 2.6 THz.

Table 3 Characteristics of the round hole-coupled resonator in different radiation frequency.

| $f$ /THz | $R_{round}$/mm | $G_{net}$/% | $P_{average}$/W |
|---|---|---|---|
| 1 | 0.9 | 33.6 | 48.8 |
| 1.6 | 1.2 | 21.7 | 141.7 |
| 2.6 | 1.2 | 20.4 | 181.4 |
| 3 | 0.9 | 17.6 | 121.3 |

Characteristics of the round hole-coupled and elliptical hole-coupled resonator in different radiation frequency are simulated. The results show in Table 3 and Table 4, Where $f$ is the radiation frequency, $R_{round}$ is the output round hole radius, $R_{elliptical}$ is the elliptical hole size, $P_{average}$ is the average output power. From Table 3, it can been seen that when the radiation frequency is 1 THz, the average output power is about 48 W and it is lower than the other radiation frequency. It is due to the large diffraction loss in 1 THz. From Table 4, it can been seen that using elliptical hole-coupling the average output power is about 69W in frequency 1 THz, it can be increased by about 40% than the case of the round hole-coupled. Compared with the case of round-hole coupling, the output power and coupling efficiency of elliptical-hole coupling are higher.

Table 4 Characteristics of the elliptical hole-coupled resonator in different radiation frequency.

| $f$ /THz | $R_{elliptical}$/mm | $G_{net}$/% | $P_{average}$/W |
|---|---|---|---|
| 1 | 1.6*0.8 | 32.8 | 69.9 |
| 1.6 | 2.2*1.1 | 18.0 | 156.0 |
| 2.6 | 2.2*1.1 | 14.1 | 210.2 |

## III. SUMMARY

In conclusion, parameters of the optical resonator is optimized corresponding to different frequencies between 1 THz to 3 THz.The influence of waveguide and Rayleigh length on the quality of optical cavity is evaluated by the 3D-OSIFEL code. The waveguide size, mirror curvature radius, output hole radius is optimized to different frequencies between 1 THz to 3 THz. To increase the output power and resonator quality, the scheme of elliptical hole-coupling optical resonator is proposed. Compared with the case of round-hole coupling, the output power and coupling efficiency of elliptical-hole coupling are higher.


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