EFFECTS OF METAL MIRRORS REFLECTIVITY AND ABERRATIONS ON THZ FEL RADIATION PERFORMANCE

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Abstract

The primary design study of a terahertz free-electron laser (FEL) is presented in this paper. The effects of optical cavity parameter, metal mirrors reflectivity and aberrations on the THz FEL radiation performance have been explored. The reflectivity characteristics of copper, silver and gold are tested in terahertz region. The effects of metal mirrors reflectivity and aberrations on the THz FEL radiation performance are studied by numerical simulation.

INTRODUCTION

An RF-linac based terahertz FEL oscillator is proposed by Huazhong University of Science and Technology, which is considered to produce 60-150μm terahertz radiation. It is necessary to optimize the strength of the fundamental FEL coupling by choosing basic parameters to maximize the small signal gain parameter. And other parameters should be optimized to minimise the gain degradation. The electron beam quality and undulator properties needed for a THz FEL oscillator have been explored in references [1, 2]. The effects of optical cavity parameter, metal mirrors reflectivity and aberrations on the THz FEL radiation performance are focused in this paper. The main design parameters are listed in Table 1.

Table 1: Design Parameters of the THz-FEL Oscillator

Parameters	Value
Beam Energy	6-10MeV
RF frequency	2856MHz
Macro pulse width	4-6μs
RMS Energy spread	0.3%
Normalized Emittance	10π mm·mrad
Bunch Charge per pulse	300pC
Bunch length	10ps
Undulator Period Lu	32mm
Number of periods Nu	25
Undulator parameter K	1
Radiation Wavelength λ	60-150μm
Resonator length L_{cav}	2.89m
ROC of mirrors	1.48

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OPTICAL CAVITY DESIGN

The choice of parameters for the high-Q cavity is crucial to the performance of a low gain FEL oscillator. It is necessary to optimise the strength of coupling between electron bunch and FEL pulse and also to allow a stable optical mode be amplified over many pass without being oversensitive to mirror misalignment or distortion. Thus the design of an FEL optical cavity involves a compromise between performance and stability [3].

The optical cavity consists of two focusing mirror located on the undulator axis facing each other and the undulator is located in its centre. The distance between the two mirrors (cavity length) L_{cav}=2.89 is determined by the repetition rate of the electron pulses to ensure that the optical pulses in the cavity overlap with the electron pulses at the undulator entrance and ensure the space required for undulator, dipoles and quads. A small cavity length detuning in the order of the radiation wavelength may increase the final power of the laser pulses.

For a given wavelength and cavity length, the radius of curvature (ROC) of the mirrors defines both the Rayleigh length and the mode profile along the whole resonator. However, only certain combination of cavity length and ROC are stable. Resonator stability condition for a symmetric cavity:

$$0 < g^2 < 1, \text{ where } g = 1 - \frac{L_{cav}}{ROC} \quad (1)$$

The stability parameter g^2 changes with the ROC is presented in Fig. 1. The radius of curvature ROC=1.48 has been chosen so that the stability parameter $g^2 \approx 0.9$ giving a near-optimal filling factor while not pushing the cavity too close to an unstable configuration.

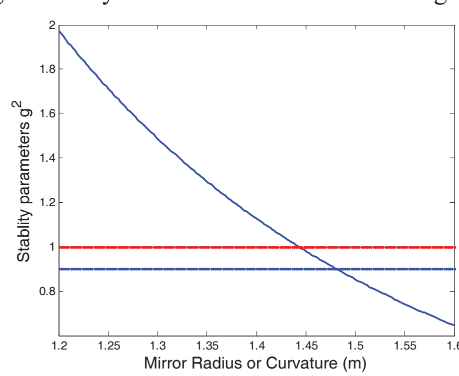

Figure 1: The stability parameter changes with the mirror radius of curvature (ROC).

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The FEL interaction does not occur at a single point but along the whole length of the undulator so the filling factor F_f is average along the undulator length, which is defined as

$$F_f = \frac{1}{1 + w_{av}^2 / 4r_b^2} \quad (2)$$

Where w_{av} is the mean optical model size, and r_b is the RMS electron beam radius.

With the parameters listed in the Table 1, the filling factor vs. the Zr is shown in the Fig. 2, where the radiation wavelength is 100μm, and r_b is1.5m.

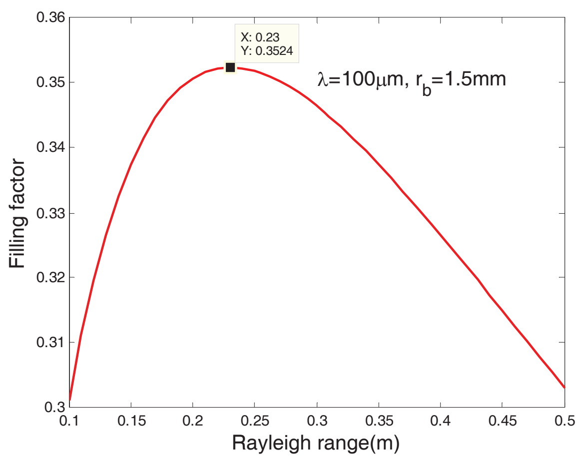

Figure 2: The filling factor vs. Rayleigh range, with the radiation wavelength λ=100μm and r_b =1.5m.

If the Rayleigh length is too short then, although the waist size is small, the diffraction of the optical beam is very strong and the filling factor is small. If the Rayleigh length is too long then, although diffraction is minimized the averaged optical cavity beam size is large, again giving a small filling factor. The averaged filling factor is maximized if the Rayleigh length is about 0.23m which is approximately $1/\sqrt{12}$ of the undulator length.

Due to the small gap distance of the undulator and large diffraction of the terahertz radiation, waveguide system needs to be considered and placed inside the optical resonator to minimise the losses in the cavity. So the inner surface of the vacuum channel is finely polished such that it works as a waveguide of terahertz radiation.

The absorption loss of mirror is a part of losses in the cavity, and may result in the aberrations of the mirrors in high power FEL THz sources. Deformation of mirrors in the optical cavity may cause the changes of mirror ROC. As the mirror curvature increases or decreases, the stability parameter changes with the ROC as shown in Fig. 1. When the mirror ROC decreases close to1.44, the cavity is unstable. The normalized radiation power evolutions at 100μm wavelength with different ROC are studied by numerical simulation with FELO code [4], and presented in Fig. 3. It seems that the cavity is stable if the change of mirror ROC is less than 2% and saturation time is less than 2μs.

Therefore the reflectivity of metal mirrors at frequencies is an important issue in optimizing system performance and reducing losses.

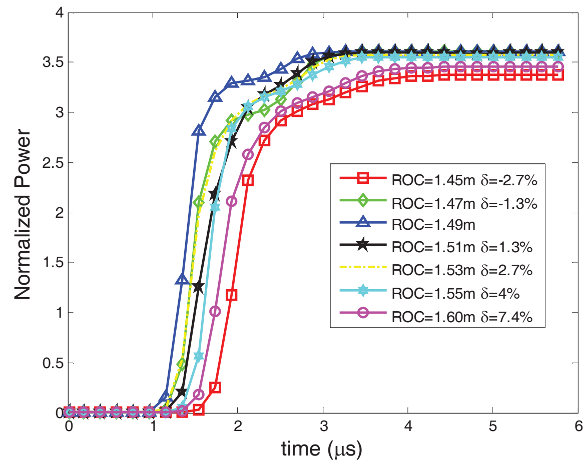

Figure 3: Evolution of normalized output power vs. time with different mirror ROC simulated by FELO code.

REFLECTIVIY MEASUREMENT OF METALL MIRRORS

Two issues arise in selecting a THz mirror: the metal coating and the mirror substrate. Metals are commonly used in terahertz mirror fabrication: aluminium, silver, copper and gold. Optical mirror manufacturers routinely publish reflectivity values up to 10μm (30 THz), but there is a severe paucity of similar data in the THz band at 0.1–10THz [5]. The reflectivity characteristics of copper, silver, aluminium and gold are therefore tested in terahertz region by our group. Five special metallic plane mirror samples B1-B5 are prepared, and their properties are listed in Table 2. The metal mirror coatings were deposited by high-vacuum evaporation.

The mirror reflectivity was measured using a standard THz time-domain spectrometer (Bruker IFS 66v/s) with a removable reflectance module and home-made mirror mount (see in Fig. 4). Fig. 5 is a schematic drawing of the THz beam path for reflectivity measurements. The angle of incidence at the plane mirror is 22º. The relative values of the reflectivity of these mirrors were measured from 50 cm^{-1} to 700cm^{-1}.

Table 2: Properties of mirrors tested

Symbol	Substrate	Coating	Surface finish
Standard	Silicon	Gold	--
B1	Copper	--	0.04μm
B2	Copper	Silver(200nm)	0.057μm
B3	Copper	Gold (200nm)	0.03μm
B4	Copper	Gold (100nm)	0.027μm
B5	Aluminium	---	0.06μm

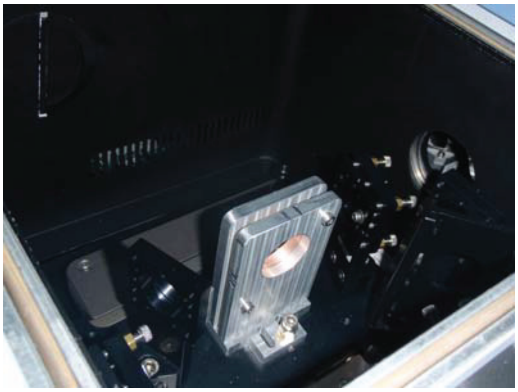

Figure 4: The removable reflectance module and home-made mirror mount.

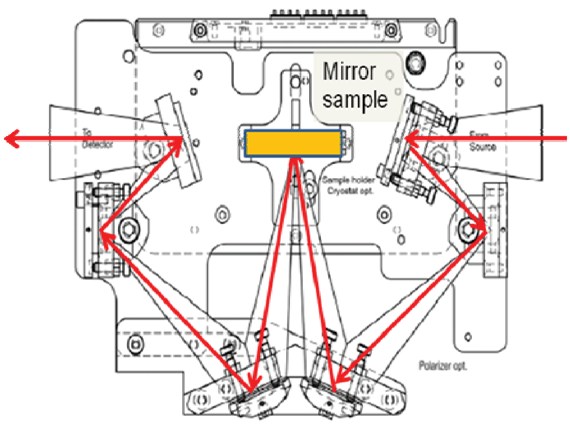

Figure 5: Schematic drawing of the THz beam path for reflectivity measurements.

Reflectivity was evaluated by measuring the THz signal obtained by placing the mirror in the sample mount (see Fig. 4). In the absence of a traceable reflectivity standard at these frequencies, the reflected amplitudes cannot be translated into absolute reflectance values and can only be interpreted as relative reflectivity. The reflectivity of 100% was defined by using a commercial gold-coated silicon plate mirror as a reference.

Fig. 6 presents relative reflection amplitudes from the mirrors test in the range of 50cm^{-1} to 700cm^{-1}. It is shown that all of these metal mirrors have high reflectivity. Among Ag, Au, Cu and Al, differences in reflectivity at THz region are not significant.

The thickness of the metal coating is an important concern. Metal conductivities and skin effects in THz region should be considered. A somewhat thicker layer is required for high reflectivity. As shown in Fig. 6, the reflective of mirror B3 with 200nm coating is better than that of the mirror B4 with 100nm coating. In order to achieve maximum reflectivity for a given metal, the thickness of the metal layer must be at least two skin depths at the frequency of the incident beam.

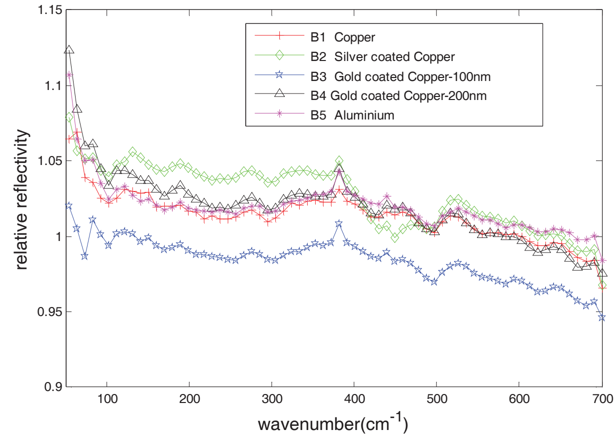

Figure 6: Measured relative reflectivity of the metal mirror samples B1-B5 from 50cm^{-1} to 700cm^{-1}

CONCLUSIONS

The effects of optical cavity parameter, metal mirrors reflectivity and aberrations on the THz FEL radiation performance are focused in this paper. High reflectivity mirrors are required. Then a variety of optical mirrors with silver, gold copper and aluminium were tested for reflectivity at THz frequencies. No significant different in performance were found. Gold coatings copper mirror with high reflectivity can be used at THz frequencies. In order to achieve maximum reflectivity for a given metal, a somewhat thickness of the metal layer is required. It is suggested that the thickness should be at least two skin depths at the frequency of the incident beam.

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