Nuclear Instruments and Methods in Physics Research A 837 (2016) 58–62

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Optical alignment and tuning system for the HUST THz-FEL

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ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form
15 August 2016
Accepted 22 August 2016
Available online 24 August 2016

Keywords:
Free electron laser
Optical cavity
Alignment
Transverse
Longitudinal

ABSTRACT

A compact FEL oscillator with a radiation wavelength of 30–100 μm is proposed by HUST and NSRL. The optical cavity is very sensitive to misalignment errors of the mirror, due to its near-concentric and symmetric structure. The magnetic axis of the undulator, the optical axis of the resonator, and the electron beam propagation axis must all be aligned with high precision for achieving saturated lasing. This paper introduces a high-precision, multi-degree-of-freedom controlled optical alignment system, which has the ability to align in the transverse and longitudinal directions. The alignment tolerances are given by theoretical analysis and numerical simulations with three-dimensional FEL code GENESIS and optical propagation code (OPC). To accomplish optical alignment, two auxiliary HeNe laser systems were introduced. By adjusting the HeNe laser beam spot on the wedge, the optical axis can be aligned to the magnetic axis, and the estimated errors meet the tolerances. Finally, the electron beam will be guided through the hole in the central wedge to complete the transverse alignment. The longitudinal alignment and tuning methods are also described.

1. Introduction

Terahertz (THz) radiation, defined as the region of the electromagnetic spectrum that lies between 0.1 THz and 10 THz, exists between infrared radiation and microwave radiation, and shares some of their properties of the unique properties of THz waves (such as transience, coherence and broadband properties), terahertz radiation has wide applications including those in public security, imaging, biology and materials physics. Terahertz radiation sources based on low-gain FEL oscillators have great advantages of high average power, continuous tunability over a wide range, and good beam quality. A compact terahertz FEL oscillator for prototype study was proposed by Huazhong University of Science and Technology (HUST) and National Synchrotron Radiation Laboratory (NSRL/USTC). This oscillator is designed to generate 30–100 μm terahertz radiation [1]. The conceptual design of the compact THz-FEL oscillator is composed of an injector, a linac booster, a planar undulator, and a near-concentric waveguide optical cavity. An overview of the THz-FEL oscillator is shown in Fig. 1; its main parameters are listed in Table 1. Instead of the RF photo-cathode gun with an alpha magnet and a laser system, we chose an independently tunable cell (ITC) thermionic RF gun as an injector for its simple and compact structure. The electrons are further accelerated in an S-band room-temperature linac accelerator to energies of 8–14 MeV. When accelerated by the linac, the electron beam can be bent into the undulator. A planar undulator consists of two rows of permanent magnets forming 30 field periods of 32 mm in length; it generates a linearly polarized transverse magnetic field, which forces the electrons to move along sinusoidal trajectories and spontaneously radiate [2]. The gap between two rows can be varied to change the K-value of the undulator, allowing it to scan the radiation wavelength. After passing through the undulator, the electrons are bent into the beam-dump.

The optical cavity is one of the major components of an FEL system; in this case, it consists of two gold-coated copper spherical mirrors facing each other. The two mirrors have a diameter of 60 mm. The downstream mirror has a 1-mm-diameter hole for power out-coupling. Due to the large diffraction losses inherent in the THz spectral region [3], a waveguide optical cavity is employed to reduce diffraction losses. The transverse dimension of the rectangle undulator pipe is 10 mm × 40 mm, and the waveguide effect can be neglected for 30–50 μm wavelength. The cavity geometry is symmetrical and nearly concentric for minimizing heat damage on the mirrors. Compared with concentric structure, the density of heat load on the mirror for the confocal structure of the cavity will be hundreds of times more than the concentric cavity.

This paper combines theoretical analysis with actual experimental devices and focuses on a detailed description of the high-precision alignment scheme to realize optimal performance of the

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http://dx.doi.org/10.1016/j.nima.2016.08.043
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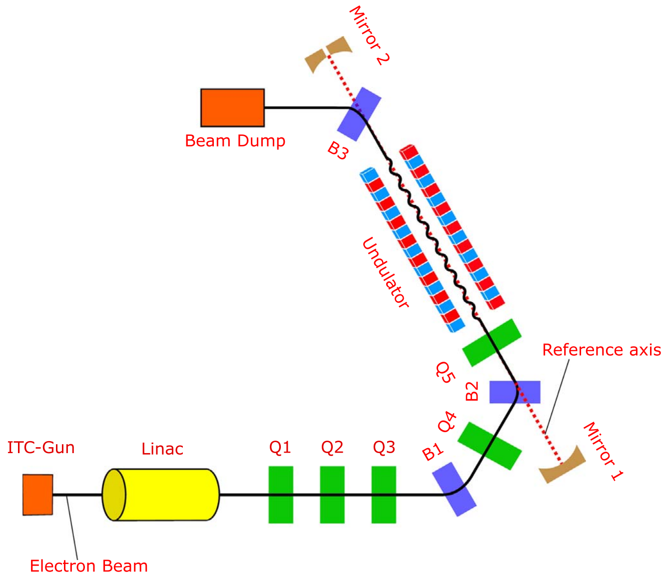

Fig. 1. Overview of THz-FEL system.

Table 1
main parameters of HUST THz-FEL oscillator.

Parameter	Value
Beam energy	8–14 MeV
Radiation wavelength, λ_s	30–100 μm
Bunch charge	≥200 pC
Bunch length(FWHM), σ_s	5–10 ps
Energy spread	0.3%
Normalized emittance	15 πmm mrad
Macro pulse length	1–4 μs
Undulator parameter	1.0–1.25
Undulator period number, N_u	30
Undulator period, λ_u	32 mm
Optical cavity length, L	2.992 m
ROC of mirrors, R	1.548 m
Peak power	0.5–1 MW

optical cavity. The structure of this paper is as follows: After a brief introduction of the THz-FEL oscillator in Sections 1 and 2 analyzes the effects of misalignment for the optical cavity and finds the misalignment tolerances. Section 3 describes the optical alignment system in detail, including transverse and longitudinal alignment, and discusses the experimental results.

2. Considerations of alignment tolerance

The near-concentric resonator can produce large spot sizes at both-mirrors and a small spot size at the waist, facilitating high optical gain and reducing the intensity at the mirror. Misalignments of the cavity mirror will degrade the transverse overlap between the electrons and THz radiation, increasing the cavity losses and decreasing the out-coupling efficiency. Consequently, precise alignment of the optical cavity is critical for good FEL performance. Here, we select 10 THz ($\lambda_s = 30$ μm) as the typical radiation wavelength, because of its more stringent requirements for misalignment, and study the effects of the offset and tilt of two mirrors on optimal output power. This work was carried out by using GENESIS 1.3 [6–8]and OPC code in the steady-state mode.

2.1. Tilt of the two mirrors

The essential structure of the optical cavity consists of two

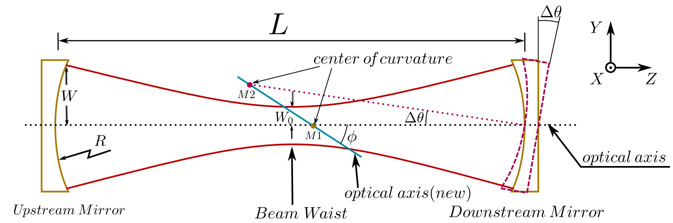

Fig. 2. Basic structure of the optical cavity (exaggerated tilt angle).

separated mirrors [4,5], as shown in Fig. 2. The optical axis is defined as the straight line passing through the centers of curvature, $M1$ and $M2$ of the two end mirrors.

When a mirror is tilted by an angle $\Delta\theta$, the optical axis will be rotated by an angle ϕ, resulting in a shift of optical mode and an off-center Δy of the mode spot on the mirror. Using Fig. 2 and some simple geometry, we can define this displacement as $\Delta y = R{\cdot}\phi$ with an angle tilt $\phi = \Delta\theta/(1+g)$, where $g = 1 - L/R$ is the resonator parameter. It is clear that the optical mode cannot be rotated outside the electron beam because of their interaction. In other words, the displacement should be no larger than the beam radius W on the mirror. Thus, the limiting condition is

$$\Delta y \le W$$

where the spot radius is given by

$$W = \left(\frac{L\lambda_s}{\pi}\cdot\sqrt{\frac{1}{1-g^2}}\right)^{1/2}$$

Using the parameters of the electron beam and the optical cavity in Table 1, we can calculate the maximum off-center displacement on the mirror $\Delta y_{max} = 8.9$ mm and the mirror's maximum angular tolerance

$$\Delta\theta_{max} \approx 400\ \mu\text{rad}$$

Fig. 3 plots the dependence of the normalized output power on the mirror tilt angle around the x or y-axis. To obtain the optimum FEL output power, the tilt angle should be less than 200 μrad for both mirrors. The simulation result is more severe than the theoretical estimate when considering output efficiency.

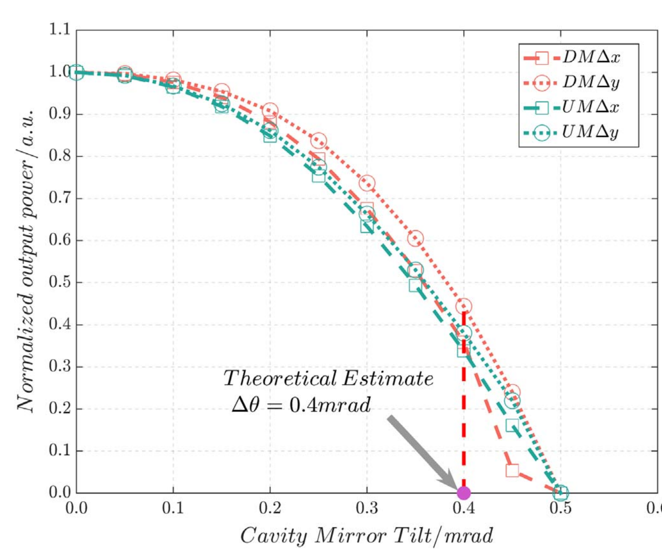

Fig. 3. Normalized output power (without any misalignment) vs. mirror angular tilt. DM and UM are the downstream and upstream mirror, respectively.