ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG73

STUDY OF THE RADIATION FIELD FROM MULTIPLE OUT-COUPLING HOLES IN AN INFRARED FREE ELECTRON LASER OSCILLATOR *

Mengqi Xia, Nanrui Yang, Yuanfang Xu, Zhouyu Zhao, Heting Li†
National Synchrotron Radiation Laboratory,
University of Science and Technology of China, Hefei, Anhui, China

Abstract

A new infrared Free-Electron Laser (FEL) facility FELiChEM has been established as an experimental facility at the University of Science and Technology of China. It consists of two free electron laser oscillators which produce mid-infrared and far-infrared lasers covering the spectral range of 2-200 μm at the present stage. The output power is a crucial parameter for users, and it is usually achieved by an out-coupling hole located in the center of a cavity mirror. Nevertheless, the spectral gap phenomenon has been observed in FEL oscillators with partial waveguides as the output power is highly dependent on the mode configuration before the out-coupling mirror. Such power gaps have an adverse effect on experimental results since numerous experiments require continuous spectral scanning. In this paper, we propose the utilization of multiple out-coupling holes on the cavity mirror, instead of relying solely on a central out-coupling hole, to reduce the adverse impact of the spectral gap phenomenon.

INTRODUCTION

The free electron laser (FEL) is a high-coherence and high-power light source with a wide tunable wavelength range that offers a variety of application prospects [1]. The FEL oscillator is a compact and well-recognized device for the generation of tunable, intense photons, which is widely used in the infrared to ultraviolet range. In an oscillator, optical pulses are trapped and oscillating in a resonant cavity, with gain continually amplified when they interact with an electron bunch train traveling through an undulator inside the cavity. Notable examples of such facilities include FELIX in the Netherlands, CLIO in France, and KU-FEL in Japan and so on.

The IR-FEL experimental facility for energy chemistry research, named FELiChEM, where the first lasing was achieved in 2019, has been constructed and commissioned at the University of Science and Technology of China [2]. The FELiChEM facility consists of two oscillators driven by one electron linac. For suppression of the diffraction effect in the resonant cavity of the FEL oscillator, FELiChEM uses two partial rectangular waveguides. Both oscillators have the same cavity length of 5.04 m and adopt one-hole coupling outputs. In comparison with a beam splitter, this solution does not introduce optical absorption, especially at large wavelengths where transparent materials are rare and have poor optical quality. However, the ratio between the output power and the intracavity power is strongly influenced by the transverse distribution of the laser mode at the output mirror [3]. The maximum macropulse energy of the detected MIR light from the out-coupling hole is 182 mJ [4]. Despite the fact that the laser spectrum covers the designed wavelength range, the FEL power at certain wavelengths is quite low due to a phenomenon called the “spectral gap" [3].

In a waveguide FEL, the distribution of the radiation field will be far away from the Gaussian distribution. We thus investigate the operation of FELiChEM with multiple out-coupling holes on the cavity mirror and analyze its impact on FEL performance. The primary objective is to minimize the number of spectral gaps, ensuring the feasibility of users' experiments, particularly spectral scanning.

SIMULATION FRAMEWORK

GENESIS is a three-dimensional simulation code that models the interaction between electrons and a co-propagating optical field through an undulator line [5]. Considering the conductive boundary conditions, a modified GENESIS code has been developed for the FEL using a rectangular waveguide, as detailed elsewhere [6]. The optics propagation code (OPC) [7] can be employed to simulate oscillators or propagate an optical field from the end of the undulator line to a specific point of interest. Combining the modified GENESIS code with the OPC code enables us to effectively simulate the interaction between the radiation field and the electron beam, as well as the propagation of the radiation field through various optical elements within the oscillator cavity.

The simulation parameters used here are very similar to those currently used in the operation of the far-infrared oscillator at FELiChEM [4]. The electron beam is generated from one pulser-gated thermionic gun and then is accelerated to the energy range of 12 MeV to 60 MeV with the RMS length of the electron microbunch is about 4.5 ps. The repetition frequency of the electron microbunch can be set at 119 or 59.5 MHz, while the cavity length of the far-infrared oscillator is 5.04 m. The cavity is formed by two spherical mirrors, each with a curvature radius of 3.018 m. The output power from the oscillator is obtained through a central hole of outcoupling mirror (in the downstream cavity). In the example presented here, the parameters of the resonant cavity are summarized in Table 1. The undulator module of length 2.24 m has 40 periods of wavelength λ_u = 5.6 cm. The rectangular waveguide, with a total length of 2.24

* Work supported by the National Natural Science Foundation of China under Grants (11975233, 12241501).
† liheting@ustc.edu.cn

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG73

m, accommodates only the undulator section, leaving the remainder of the resonant cavity in free space.

Table 1: FEL System Parameters of the Resonant Cavity

Parameter	Value	Unit
Beam energy	17.0	MeV
Energy spread (RMS)	1.125	%
Peak current	94.0	A
Normalized emittance	35.0	mm · mrad
Undulator parameter (a_u)	0.73 – 2.58	-
Undulator period	5.6	cm
Number of periods	40	-
Resonant cavity length	5.04	m
Waveguide size ($a \times b$)	40 × 18	mm × mm
Curvature radius of mirror	3.018	m
Reflectivity of mirror	98.5	%
Diameter of mirror	10.0	cm

SIMULATION RESULTS

We have carried out the steady-state simulation combing the modified GENESIS code with the OPC code. At the current stage, the output power from the FIR oscillator of FELiChEM is obtained through a central hole, with a selectable outcoupling hole diameter of 1.0/2.0/4.0 mm. As shown in Fig. 1, when the diameter of outcoupling hole is 1.0 mm, both the output power and the outcoupling rate are low, and there is also the phenomenon of spectral gaps. On the whole, with an increase in the outcoupling hole radius, the output power as well as the outcoupling rate tend to increase. It must be noted, however, that the improvement at certain wavelengths is limited, and the phenomenon of spectral gaps is more pronounced. In Fig. 2, the transverse power profiles, scaled with respect to the peak power, are plotted after saturation at different wavelengths within the optical cavity. One can observe that in the waveguide FEL, at certain radiation wavelengths, the radiation field at the center of the cavity mirror can be approximated as a Gaussian distribution. However, at some wavelengths, the radiation field deviates significantly from the Gaussian distribution. This results in a low power density at the center of the outcoupling mirror. Consequently, the radiation field output through the outcoupling hole will exhibit significant variations, leading to spectral gap phenomena.

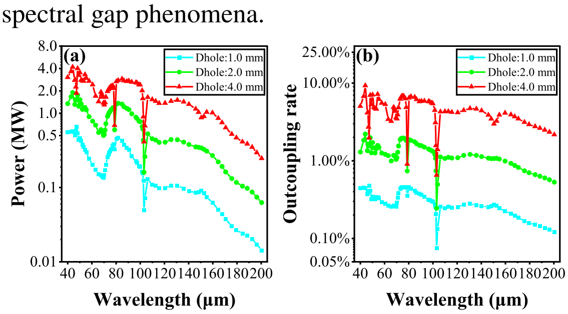

Figure 1: (a) The radiation output power and (b) outcoupling rate as a function of the diameter of outcoupling holes.

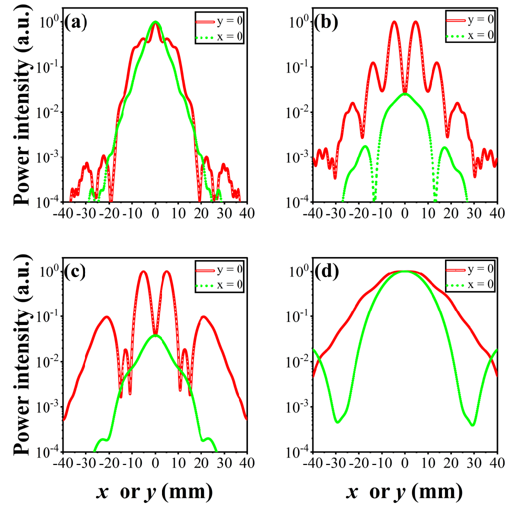

Figure 2: The normalized on-axis saturation power intensity before the outcoupling mirror, at the wavelength of (a) 44 μm, (b) 79 μm, (c) 103 μm and (d) 200 μm. The diameter of the outcoupling hole is fixed at 4.0 mm.

Generally speaking, in the case of a long-wavelength FEL oscillator with strong waveguide effects, the total cavity loss mainly includes outcoupling loss, boundary loss at the waveguide entrances (optical losses when the radiation pulse travels from free space into the waveguide) and absorption loss from the mirror material. One possible solution to reduce spectral gaps is to further increase the outcoupling hole size. As shown in Fig. 3, we can observe that as the outcoupling hole size increases, the overall output power at various wavelengths tends to increase. However, the phenomenon of spectral gaps still persists. Moreover, when the outcoupling hole diameter is too large, the FEL fails to oscillate at certain wavelengths, leading to no radiation output.

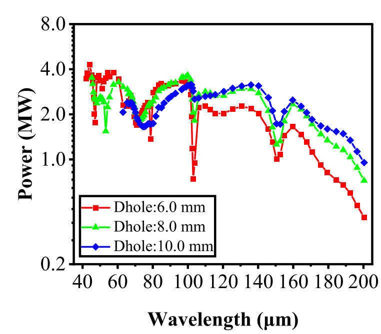

Figure 3: The radiation output power as a function of large outcoupling hole diameters. It should be noted that at certain short radiation wavelengths, the FEL power may not reach saturation or even initiate lasing.

For the purpose of comparison, we have carried out numerical simulations for both outcoupling scheme and the proposed scheme. The proposed five-hole outcoupling scheme includes a circular hole placed at the center of the cavity mirror, with additional holes positioned along both the X-axis and Y-axis directions on both sides. The circular hole located at the center of the downstream cavity mirror is re-

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG73

ferred to as the main hole, while the remaining four holes are termed vice holes. All holes have a radius of 1.75 mm, and the distance from the center of the main hole to the center of each vice hole is 6 mm. The relationship between output power and radiation wavelength is shown in Fig. 4. We can observe that with the adoption of this novel outcoupling method, there are no spectral gap phenomena observed at the operating wavelengths, and the performance of the waveguide FEL has been greatly enhanced. The evolution of the radiation field, as a function of distance through the outcoupling mirror is depicted in Fig. 5. The simulation is conducted at a radiation wavelength of 103 µm, where the spectral gap phenomenon is most pronounced in the original center-hole outcoupling scheme. It can be observed that although the radiation field undergoes output through five outcoupling holes, after a certain distance, due to diffraction effects, the radiation field will converge into an approximately circular spot shape. This will be advantageous for conducting scientific experiments. It should be noted that at longer wavelengths, the radiation field passes twice through the waveguide each round trip, resulting in a significant amount of boundary loss. Consequently, it is foreseeable that as the wavelength continues to increase, the intra-cavity power will decrease significantly, thereby impacting the output power. Another promising approach to address spectral gaps is to utilize a four-mirror ring resonant cavity instead of the conventional two-mirror cavity [8]. In this innovative configuration, the transverse profiles of radiation fields will exhibit an approximate Gaussian distribution. Additionally, the radiation field passes through the waveguide only once per roundtrip, thereby reducing boundary losses.

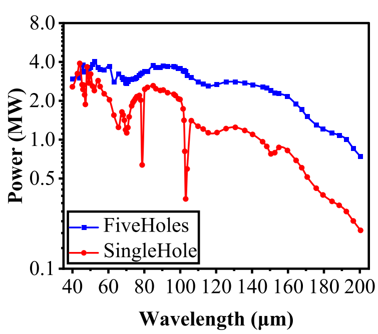

Figure 4: Comparison of output saturation power between the original single center-hole outcoupling scheme (red) and the proposed five-hole outcoupling scheme (blue).

CONCLUSION

In this paper, we have considered the operation of FELiChEM with a five-hole outcoupling scheme and analyzed its effect on FEL performance. By applying small size holes at different positions on the outcoupling mirror, it can effectively increase the output power from the intra-cavity, where the transverse radiation field exhibits a non-Gaussian distribution before the outcoupling mirror. Compared to the traditional single center-hole outcoupling scheme, this novel outcoupling scheme can significantly increase the output

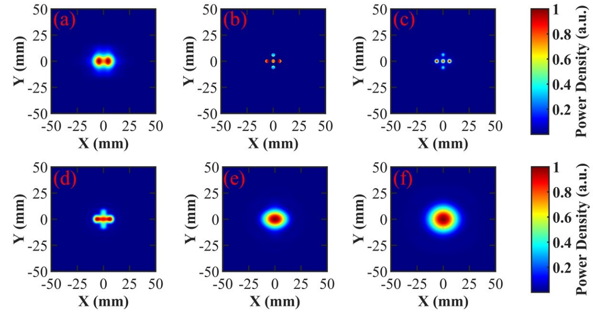

Figure 5: The normalized transverse distribution for the radiation wavelength of 103 µm is depicted at various positions after saturation, including (a) before outcoupling mirror, (b) output from outcoupling hole, (c) 0.1 m after outcoupling hole, (d) 0.2 m after outcoupling hole, (e) 0.4 m after outcoupling hole, and (f) 0.6 m after outcoupling hole.

power at spectral gap positions. It becomes possible to enhance the performance of the FEL and expand the tuning range of radiation wavelengths, greatly facilitating users in conducting spectral scanning experiments.

REFERENCES

[1] H.P. Freund and T.M. Antonsen, Jr., *Principles of Free Electron Lasers, third edition*, Springer International Publishing, New York U.S.A. (2018). doi:10.1007/978-3-319-75106-1

[2] H. T. Li and Q. K. Jia, "Commissioning and First Lasing of the FELiChEM: A New IR and THz FEL Oscillator in China," in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, pp. 15–19. doi:10.18429/JACoW-FEL2019-MOA07

[3] R. Prazeres, F. Glotin, and J.-M. Ortega, "Analysis of periodic spectral gaps observed in the tuning range of free-electron lasers with a partial waveguide," *Phys. Rev. Spec. Top. Accel Beams*, vol. 12, no. 1, pp.010701, Jan. 2009. doi:10.1103/physrevstab.12.010701

[4] H. Li, et al., "Hefei infrared free-electron laser facility," Chinese Journal of Lasers, vol. 48, no. 17, p. 1700001, 2021. doi:10.3788/cjl202148.1700001

[5] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, no. 1–3, pp. 243–248, Jun. 1999. doi:10.1016/s0168-9002(99)00114-x

[6] W. Li, Z. Zhao, R. Huang, *et al.*, "Fully 3D time-dependent simulation of free electron laser within an overmoded rectangular waveguide," *IEEE Open J. Instrum. Meas.*, vol. 15, no. 03, pp. P03008–P03008, Mar. 2020. doi:10.1088/1748-0221/15/03/p03008

[7] J. G. Karssenberg, K.-J. Boller, J. W. J. Verschuur, I. Volokhine, and P. J. M. van der Slot, "FEL-Oscillator Simulations with Genesis 1.3", in *Proc. FEL'06*, Berlin, Germany, Aug.-Sep. 2006, paper TUPPH037, pp. 407–410.

[8] M. Xia, Y. Xu, Z. Zhao, and H. Li, "Solving the spectral gap problem with a four-mirror bow-tie cavity in waveguide free-electron laser oscillators," *J. Manage. Sci. Rep.*, vol. 13, no. 1, pp. 22653, Dec. 2023. doi:10.1038/s41598-023-49803-w

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.