SIMULATION STUDY OF THE FULL WAVEGUIDE DESIGN FOR HIFEL*

Guanzheng Wu, Zhouyu Zhao, Yuanfang Xu†, Heting Li‡
National Synchrotron Radiation Laboratory,
University of Science and Technology of China, Hefei, Anhui, China

Abstract

Hefei infrared Free Electron Laser (HiFEL) facility aims to provide high-quality lasers with wavelengths covering the mid to far infrared range. However, there is an obvious decrease in the output power at long wavelengths. The mode field mismatch and truncation loss at the waveguide to free space region are the main reasons for low output power. We propose a full waveguide design and simulation results suggest that compared to partial waveguide configurations, the full waveguide structure improves the saturated output power in the long wavelength range.

INTRODUCTION

Free Electron Lasers (FELs) are high-power, high-beam-quality, and widely tunable sources of coherent radiation that cover a wide spectral range from microwaves to hard X-rays and have broad application prospects [1]. In the infrared (IR) range, one of the main operation modes named FEL Oscillator (FELO) has attracted considerable attention because of its capability to produce narrow linewidth, high-intensity coherent radiation with a relatively compact configuration. Accordingly, various FELO facilities have been developed worldwide.

The Hefei infrared Free Electron Laser (HiFEL), also known as FELiChEM, is China's first FEL user facility covering the mid- to far-IR range. This facility is dedicated for energy chemistry research, providing laser radiation for applications in condensed matter physics, materials science, and surface chemistry [2]. It consists of two FEL oscillators driven by a 60 MeV linac, capable of generating mid-IR (2-50 µm) and far-IR (20-200 µm) laser radiation independently. As a cavity-based FEL facility, HiFEL relies on the multi-pass interaction between the electron beam and the radiation field within the resonant cavity to achieve exponential amplification and saturation. As the radiation wavelength increases, diffraction effects become sharply pronounced, leading to rapid expansion of the optical beam's transverse size within the cavity. The diffracted optical beam tends to undergo losses in the undulator vacuum chamber, greatly reducing the FEL gain and efficiency, which may make lasing impossible.

For suppression of the diffraction effects, HiFEL uses the partial rectangular waveguide configuration to confine the transverse size of the optical beam. However, during the actual operation, there is an obvious decrease in output power at long wavelengths, particularly in the far-IR range. This is probably because when the long-wavelength radiation field enters the waveguide from the free space region between the undulator and the cavity mirrors, its transverse profile changes rapidly. This abrupt geometric transition induces severe mode field mismatch and truncation loss. Such high intra-cavity losses greatly decrease the single-pass gain, ultimately resulting in the obvious decrease in output power.

Several ways are proposed including using a full waveguide cavity, which has been applied in experiments [3]. Consequently, to overcome this power decrease, we propose a full waveguide cavity design for HiFEL and analyze its impact on FEL performance through simulations, so as to improve the saturated output power in the long wavelength regime.

WAVEGUIDE DESIGN

The existing partial waveguide structure of HiFEL is engineered to confine the optical mode solely within the undulator section, as Fig. 1(a) shows. While this configuration effectively suppresses diffraction loss within the undulator region, it introduces an unavoidable abrupt transition of transverse boundary at the waveguide entrance and exit. This discontinuity triggers two dominant loss mechanisms, one is the severe mode field mismatch between the guided mode and the free-space diverging mode, which breaks the multi-pass coherent resonance condition; the other one is obvious truncation loss at the waveguide edge, where the expanded optical field is partially blocked and absorbed by the cavity. These losses increase with wavelength, directly causing the observed power drop in the far-IR regime.

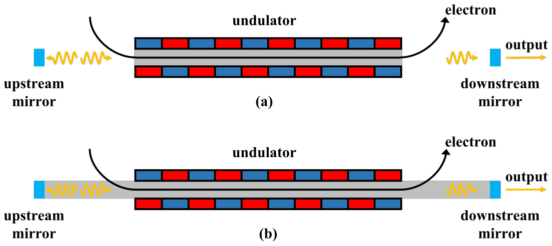

Figure 1: Side views of the two distinct waveguide configurations, where (a) partial waveguide design and (b) full waveguide design.

In order to avoid the existence of interfaces between the waveguide and free space, we propose a full waveguide design by extending the waveguide structure throughout the entire resonant cavity, which can establish a continuous, closed optical path from the upstream cavity mirror to the downstream cavity mirror, as illustrated in Fig. 1(b). It fully encloses the entire resonant cavity, including the undulator

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† xyf1224@ustc.edu.cn

‡ liheting@ustc.edu.cn

section, drifting space, and mirror coupling regions. By confining the light beam within the waveguide across the entire cavity, this design can effectively eliminate all free-space propagation segments within the optical resonator and stop the beam from spreading out sideways.

Besides, to minimize the difficulty in adjusting the actual device, we only modified the waveguide length while keeping all other parameters unchanged.

SIMULATION FRAMEWORK

To investigate how the full waveguide design improves the output power of HiFEL compared with the original partial waveguide design, three-dimensional simulations have been carried out using wGenisis [4] and OPC [5]. On the basis of GENESIS 1.3 [6], which is a widely used FEL code to simulate the interaction between electrons and the co-propagating optical field in an undulator, wGenesis is a modified version of that. It is specially developed for rectangular waveguide FELs considering the conductive boundary conditions. The optics propagation code (OPC) is used to simulate the optical field propagation outside the undulator section, and it can work smoothly with FEL codes such as GENESIS to model a complete resonant cavity of a FELO structure.

By combining wGenesis with OPC, we establish a simulation framework that can model the complete FELO process on actual resonator structures with arbitrary waveguide configurations on a computer [7], including the electron beam dynamics, optical field evolution and so on. The main parameters used in the HiFEL simulations are listed in Table 1.

Table 1: HiFEL Facility Parameters for FELO Simulations

Parameter	**Value**	**Unit**
Electron beam energy	12.0	MeV
Energy spread	1.25	%
Peak current	94.0	A
RMS emittance	30.0	mm·mrad
Undulator parameter K	1.34-2.36	-
Undulator period	56	mm
Number of undulator periods	40	-
Optical cavity length	5.04	m
Waveguide size (a×b)	30×16	mm×mm
Curvature radius of mirror	3.018	m
Reflectivity of mirror	98.5	%
Diameter of mirror	10.0	cm
Diameter of coupling hole	2.5	mm

SIMULATION RESULTS

Validating simulation results against experimental measurements is of great importance for establishing confidence in our computational models and predicting the performance of the proposed full waveguide design. Figure 2 shows the comparison between simulation- and measurement-based output power for the partial waveguide configuration in the HiFEL facility across the 100–200 µm wavelength range.

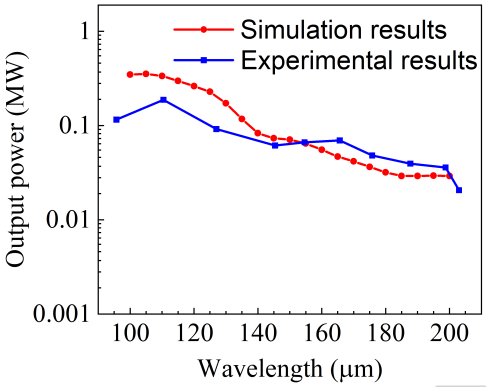

Figure 2: Comparison of the simulation-based and the measurement-based output power for HiFEL's partial waveguide configuration in the 100–200 µm wavelength range.

The red line represents the simulated output power through the coupling hole, while the blue line corresponds to the power calculated based on macropulse energy data measured during experiments at the line station. Both of them exhibit a consistent decreasing trend with the increase of wavelength: the simulated output power remains relatively stable at a high level below 120 µm, then declines sharply with the further increase of wavelength; the experimental results follow the same variation tendency, with the power showing a synchronous decrease as the wavelength rises.

The simulation results show excellent agreement with the experiments as the power decrease in both datasets becomes more severe with increasing wavelength. This overall consistency confirms the reliability of our wGenesis–OPC framework, validating its ability to accurately reproduce the wavelength-dependent performance of a waveguide design.

Figure 3 compares the simulated output power curves for both partial and full waveguide configurations, and it reveals a remarkable enhancement in power with the full waveguide design throughout the wavelength range. In contrast to the partial waveguide curve where the power continuously decreases with wavelength, the full waveguide design can sustain the output power at MW-level across nearly the entire range. Despite there are two noticeable dips, at 130 µm and 185 µm respectively, the overall power remains one to two orders of magnitude higher than the partial waveguide design, thereby effectively preventing the severe performance degradation that occurs at longer wavelengths.

Figures 4 and 5 present the transverse intensity distributions of optical field in the partial and full waveguide cavity at three different wavelengths (100 µm, 150 µm and 200 µm) and three key positions respectively: (a) the entrance of the undulator, (b) the output coupling mirror prior to outcoupling, and (c) the final coupled output light spot.

It can be seen that the full waveguide design provides stronger transverse mode confinement compared to the partial waveguide configuration, with less light field extending beyond the waveguide boundaries. However, as Fig. 5 shows, the full waveguide design reveals more complex transverse

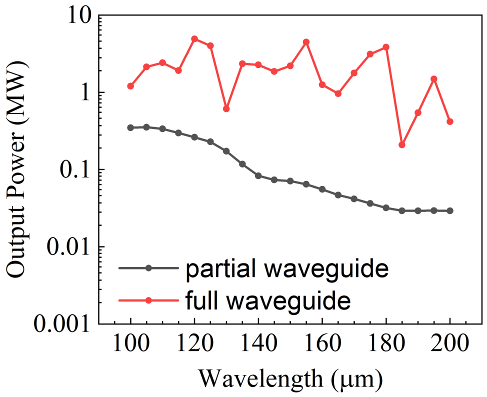

Figure 3: Comparison of the simulated output power between the partial waveguide and the full waveguide configurations for HiFEL in the 100–200 μm wavelength range.

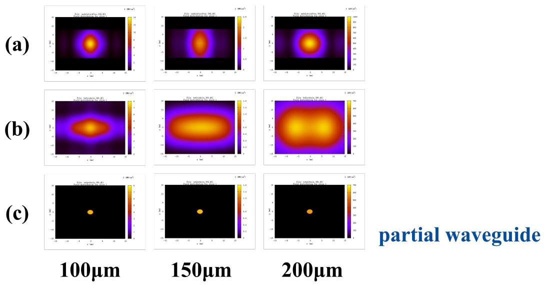

Figure 4: Transverse optical field intensity distributions in HiFEL's partial waveguide cavity.

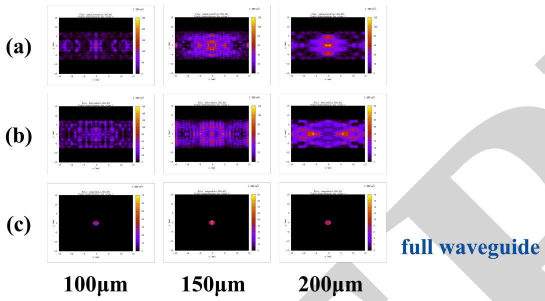

Figure 5: Transverse optical field intensity distributions in HiFEL's full waveguide cavity.

mode patterns, indicating enhanced higher-order mode excitation. While this continuous waveguide structure eliminates the waveguide-to-free-space interfaces, it also introduces more complex modes and strengthens the 'spectral gap' phenomenon [8], which refers that the laser power falls down at some particular wavelengths in the tuning range, whatever the beam adjustments are [3], but its overall impact on output power remains positive at long wavelength range, and the four-mirror bow-tie cavity design may offer a solution for the gaps [9].

CONCLUSION

In this work, we propose a full waveguide cavity design for HiFEL to solve the severe output power decrease in the far-IR regime caused by the partial waveguide configuration. Three-dimensional simulations show that the full waveguide design can basically enhance the saturated output power by around one to two orders of magnitude across the 100-200 μm wavelength range. This design eliminates the free-space propagation segments and avoids boundary transitions, reducing loss and increasing output power. While enhanced higher-order mode excitation and more distinct spectral gaps are observed in the full waveguide structure, its overall impact on long-wavelength output power remains consistently positive.

This design offers a practical optimization solution for far-IR FELOs and provides insights for other cavity-based FEL facilities. Future work will include experimental verification, further parameter optimization and exploration of new advanced waveguide materials to better improve HiFEL performance.

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