DESIGN OF THE MID-INFRARED FEL OSCILLATOR IN CHINA

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Abstract

In 2014, Xiamen University and other three research organizations received the approval to realize an infrared free electron laser (IR-FEL) for fundamental of energy chemistry. The IR-FEL covers the spectral range of 2.5-200 μm and will be built in NSRL. Two FEL oscillators driven by one Linac will be used to generate mid- infrared and far-infrared lasers. In this article we describe the design studies for the mid-infrared FEL oscillator.

INTRODUCTION

Under the financial support of Natural Science Foundation of China, the project of infrared laser for fundamental of energy chemistry is building up an infrared light source in Hefei. The National Synchrotron Radiation Laboratory (NSRL) of USTC is responsible for the design, construction and commissioning of IRFEL apparatus. It will be a dedicated experimental facility aiming at energy chemistry research, whose core device is a free electron laser (FEL) generating 2.5-200 μm laser for photo excitation, photo dissociation and photo detection experimental stations. Similar as the IR-FEL at the Fritz-Haber-Institute in Berlin [1,2], two oscillators driven by one Linac will be used to generate mid- infrared (2.5-50 μm) and far-infrared (40-200 μm) lasers.

The MIR-FEL is planned to laser earlier and in this paper, we will focus on the design of the MIR-FEL oscillator. To meet the user requirements, the undulator, optical cavity and electron beam for the MIR-FEL are designed and described. Then simulations using Optical-Propagate Code (OPC) [3] have been done and the results will be shown. We finally summarize in the last section.

DESIGN GOAL

As mentioned above, there will be three experimental stations in the first stage. The users of these stations have brought out their requirements on the IR-FEL performance, as given in Table.1. In addition, some users have extra requirements, for example, the photo excitation and dissociation stations require that the peak and average power of IR-FEL should be as high as possible. in the next section.

It is worth pointing out that the broad wavelength range and high radiation intensity brings us much difficulties in the design of electron Linac and optical cavities. For example, the short-wavelength FEL requires short electron bunch to achieve high peak current while the long-wavelength FEL requires long electron bunch to suppress the slippage effect, and the short-wavelength FEL requires a short Rayleigh length of the optical cavity to get a considerable big spot size and an appropriate outcoupling on the mirror while the case of the short-wavelength FEL is opposite. Therefore, the design is to find a balance for the object wavelength range.

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Table 1: Design Goal of the IR-FEL

Parameters	Specification
Covering spectrum	2.5 ~ 200 μm
MIR FEL oscillators	2.5 ~ 50 μm
FIR FEL oscillators	40 ~ 200 μm
Macro-pulse length(FW)	5~ 10 μs
Repetition of macro-pulse	20 Hz
Macro-pulse energy	~100 mJ
Micro-pulse length (RMS)	5 ~ 10 ps
Micro-pulse energy	1 ~ 50 μJ
Bandwidth	0.3 ~ 3 %
Continuous tunability	200 ~ 300 %

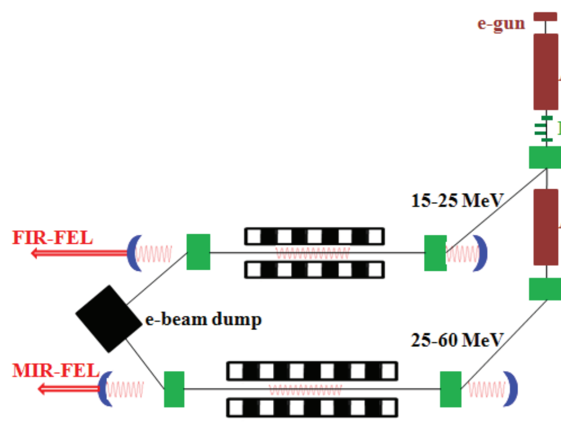

Figure 1: Schematic of the projected IR-FEL.

MIR-FEL DESIGN

Layout

As shown in Fig. 1, the IR-FEL is composed of two FEL oscillators driven by one electron Linac. Two accelerating tubes are used to accelerate the electron beam. Between the first and the second accelerating tube, a four-dipole magnetic chicane is designed as an optional operation condition. Its purpose is to reduce the micro-pulse length and increase the peak current of the electron bunch for the short-wavelength FEL, and for the long-wavelength FEL, it also can increase the micro-pulse length to suppress the slippage effect.

It is very important that we choose the thermionic electron gun as the electron source [4]. Using special gate control system, the electron bunch chain will be extracted from the gun, with micro-pulse length of 1 ns, optional

ISBN 978-3-95450-134-2

repetition frequency of 476/238/119/59.9 MHz, and the charge of larger than 1 nC.

The electron beam energy for FIR oscillator is lower (15-25 MeV), and one accelerating tube is capable of reaching this energy level. Therefore, we extract the beam into the FIR oscillator after the first accelerating tube, for leaving enough space between the two oscillators. Between the electron Linac and FEL oscillators, the achromatic transfer lines are designed, where energy collimators will be used to eliminate the electrons with large energy spread, and the quadrupole doublets will be used to adjust transverse matching between the electron beam and the laser beam inside the oscillators.

Undulator

In a planar undulator, the FEL radiation wavelength is determined by the resonance condition. On the other hand, there is an empirical formula describing the relations between the peak magnetic field and the ratio of g/λ_u, where g is the undulator gap.

Briefly speaking, we need to determine the undulator period appropriately, so that we can achieve the FEL in the objective wavelength range with appropriate electron energies, and furthermore, combining with the design of undulator length we can get enough high FEL gains at all the wavelengths. In addition, we have to consider the continuous tunability of the FEL wavelength.

Table 2: Undulator Parameters for MIR-FEL

Parameter	Specification
Period length	46 mm
Period number	50
Min. gap	16 mm
Strength parameters	0.5~3.2
Peak magnetic field	0.1~0.72 T

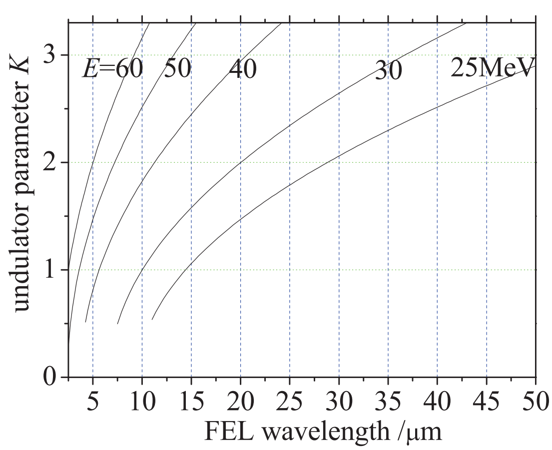

Figure 2: The wavelength tunability with different electron beam energy for MIR-FEL.

In this project, a planar hybrid undulator with NdFeB permanent magnets is used and the remanence of NdFeB is selected to be 1.2 T. The designed undulator parameters for MIR-FEL are given in Table 2. Under this condition, the radiation wavelength tunability with different electron beam energy is shown in Fig. 2, from which one can find that the continuous tunability can easily reach 300%. Note that the the maximum electron beam energy is designed to be 60 MeV, mainly for enhancing the performance of radiation around 2.5 μm, as shown in Fig. 3.

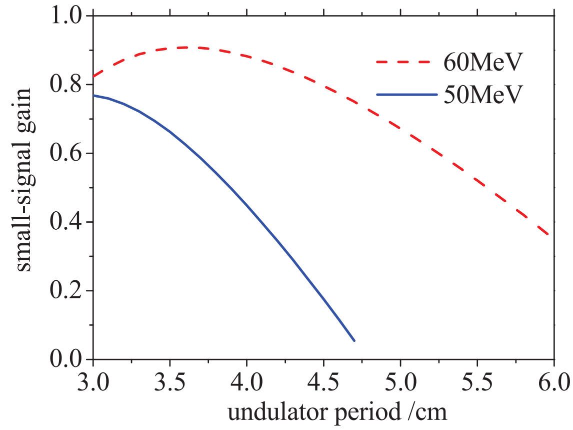

Figure 3: The variation of small signal gain of 2.5 μm FEL with the undulator period.

Optical Cavity

There are several key parameters for the optical cavity, such as cavity length, reflectivity of mirrors, curvature radius of mirrors and outcoupling hole size, and so on. The cavity length is determined by following factors, such as installation space of other components, the time structure of the electron beam, the saturation time of the radiation field, the requirements of optical beam sizes on mirrors, etc. The curvature radius of the mirrors determines the Rayleigh length, stability factor, optical beam size on the mirrors, and the matching of the electron beam and the optical beam. The size of the outcoupling hole contributes to the single-pass loss and then affects the saturation process. When the FEL wavelength varies in a broad range, these relations become more complicated.

In this project, two same mirrors are used to form a symmetrical optical cavity. The 2.3 m long undulator will be symmetrically placed in the optical cavity such that we have 1.37 m of space available for beam transport and diagnostic on the two sides. We once considered asymmetrical placement but unfortunately our architectural condition enforce the FEL being extracted from the downstream mirror so that the undulator can't be moved closer to the upstream mirror since there is no space in that side. The parameters of the optical cavity are shown in Table 3. The Rayleigh length is designed to be one third of the undulator length (0.77 m), which is mainly for the consideration of 2.5 μm FEL case. Figure 4 shows the intra-cavity modes, from which one can note that 2.5 μm FEL has a small spot size on the mirror, and at this moment the outcoupling of 1 mm hole is about 8%. from Fig. 4 we also can find that only for the wavelength longer than 30 μm there is a little diffraction loss.

ISBN 978-3-95450-134-2

Table 3: Parameters of MIR Optical Cavity

Parameter	Specification
Cavity length	5.04 m
Curvature radius of mirrors	2.756 m
Rayleigh length	0.77 m
Reflectivity	99%
Diameters of coupling hole	1.0, 1.5, 2.5, 3.5 mm

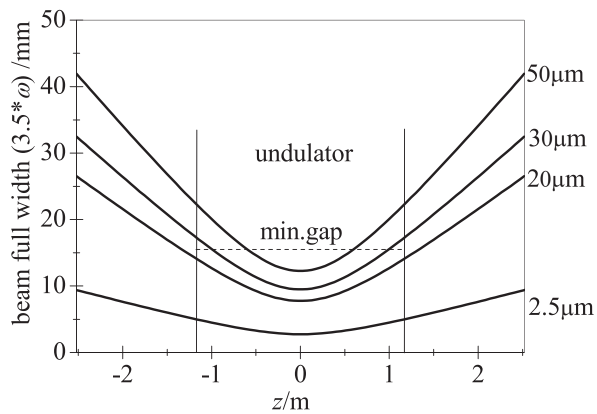

Figure 4: The modes in the MIR optical cavity.

Electron Beam

When the electron gun type is determined, the possible quality of the electron beam is roughly fixed. After optimization, the requirements of the electron beam for MIR-FEL are given in Table 4.

Table 4: Parameters of Electron Beam for MIR-FEL

Parameter	Specification
Energy	25-60 MeV
Energy spread	<240 keV
Emittance	<30 mm•mrad
Charge	1 nC
Pulse length (RMS)	2-5 ps

MIR-FEL PERFORMANCE

Based on the designed parameters in the previous Part, the small signal gain of MIR-FEL is calculated and given in Fig. 5. We can see that the gain is very high in the wavelength range of 4-30 μm. For short wavelength, small *K* leads to the small gain while for short wavelength, large relative energy spread and slippage effect are the reasons. In Fig. 6, we give the macro-pulse energy of MIR-FEL simulated by OPC code. Note that the cavity length detuning is fixed to be two times the radiation wavelength. One can find that the macro-pulse energy can reach the 100 mJ level for most of the object wavelengths. We still can enhance the macro-pulse energy by increase the micro-pulse repetition rate.

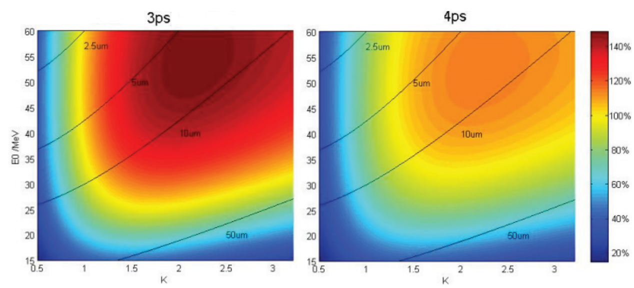

Figure 5: The small signal of MIR-FEL.

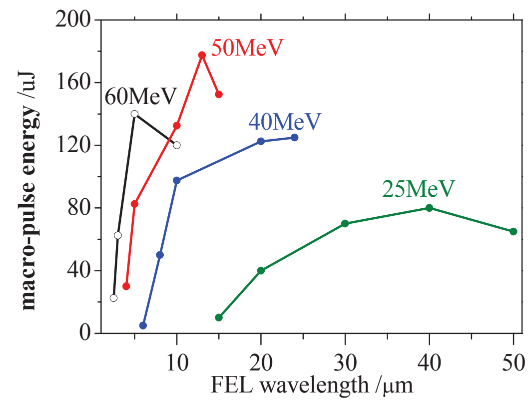

Figure 6: The macro-pulse energy of MIR-FEL based on the micro-pulse repetition rate of 119 MHz.

SUMMARY

In summary, we have introduced the IR-FEL project to be built in NSRL and designed the MIR-FEL oscillator. Brief design results are given in this paper and tell us that it should be possible to achieve the design goal. In fact, the design is more detailed and considers much more specific aspects, such as the discussion of each system's error effects, the feasibility of every designed parameter, and so on. Much more design work is underway, such as the FIR oscillator design, the S2E simulations and so on. However, all the design work will keep on till the machine lasers well.

ACKNOWLEDGEMENT

It is a pleasure to thank the FHI, CLIO and FELIX people for generously sharing their valuable experience in IR-FEL oscillator. This work is support by National Natural Science Foundation of China (21327901).

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ISBN 978-3-95450-134-2