THE IR AND THz FREE-ELECTRON LASER AT THE FRITZ-HABER-INSTITUT

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Abstract

A mid-infrared oscillator FEL with a design wavelength range from 4 to 50 μm has been commissioned at the Fritz-Haber-Institut in Berlin, Germany, for applications in molecular and cluster spectroscopy as well as surface science. A second FEL covering the FIR and THz from 40 to 500 μm is planned. The accelerator consists of a thermionic gridded electron gun, a subharmonic buncher and two S-band standing-wave copper structures. The device was designed to meet challenging specifications, including a final energy adjustable in the range of 15 to 50 MeV, low longitudinal emittance (< 50 keV-psec) and transverse emittance (< 20 π mm-mrad), at more than 200 pC bunch charge with a pulse repetition rate of 1 GHz and a macro pulse length of up to 15 μs. In this paper, we present measurements of the electron beam and results from lasing in the wavelength range from 8 to 24 μm.

INTRODUCTION

At the Fritz-Haber-Institut in Berlin, Germany, a new IR and THz FEL has been commissioned for applications in gas-phase spectroscopy of (bio-)molecules, clusters, and nano-particles, as well as in surface science [1-4]. To cover the wavelength range of interest from about 4 to 500 μm, the system design, shown in Fig. 1, includes two FELs; a mid-infrared (MIR) FEL for wavelengths up to about 50 μm and a far-infrared (FIR) FEL for wavelengths larger than about 40 μm. A normal conducting S-band linac provides electrons of up to 50 MeV energy to either FEL.

As of August 2013, commissioning of the accelerator and electron-beam transport system (designed and installed by Advanced Energy Systems, Inc.) is nearing completion [5,6]. Commissioning of the MIR undulator (STI Optronics) [7] and oscillator cavity (Bestec GmbH), as well as of the first five IR user beam lines has been completed. First lasing of the MIR FEL was achieved at a wavelength of 16 μm in 2012 [2]. The FIR FEL has not yet been installed. In this paper, after a brief summary of the electron accelerator, we report on lasing of the MIR FEL in the range from 8 to 24 micron and describe measurements of the electron beam passing through the FEL.

ELECTRON ACCELERATOR

In Table 1 we summarize the projected top-level electron beam performance. The design of the accelerator and beam transport system has been described elsewhere [2-6]. In brief, it consists of a 50 MeV accelerator driven by a gridded thermionic gun with a beam transport system that feeds two undulators and a diagnostic beamline. The first of two 3 GHz S-band, normal-conducting electron linacs accelerates the electron bunches to a nominal energy of 20 MeV, while the second one accelerates or decelerates the electrons to deliver any final energy between 15 and 50 MeV. A chicane between the structures allows for adjustment of the bunch length as required.

Table 1: Summary of Electron Beam Parameters

Parameter	Unit	Specification	Target
Electron energy	MeV	20 - 50	15 - 50
Energy spread	keV	50	< 50
Energy drift per hour	%	0.1	< 0.1
Bunch charge	pC	200	> 200
Micro-bunch length	ps	1 - 5	1 - 10
Micro-bunch rep. rate	GHz	1	1
Micro-bunch jitter	ps	0.5	0.1
Macro-bunch length	μs	1 - 8	1 - 15
Macro-bunch rep. rate	Hz	10	20
Normalized rms transverse emittance	π mm mrad	20	20

The final design has optimized the specifications of the linac that are most relevant for the IR and THz FEL performance. For instance, the target bunch charge of the micro-pulses, which are repeated at rate of up to 1 GHz, has been increased to 300 pC. In addition, the target length of the macro-bunches has been increased to 15 μs.

MID-INFRARED OSCILLATOR FEL

Both, the MIR FEL and the FIR/THz FEL, consist of an undulator placed within an IR cavity as summarized in Table 2. The MIR FEL includes a 2-m-long planar wedged-pole hybrid undulator manufactured by STI Optronics with a period length of 40 mm. A detailed description of the MIR undulator is provided in Ref. [7]. At a minimum gap of nominally 16.5 mm, a maximum root-mean-square undulator parameter K_{rms} of more than 1.6 is reached. This, in combination with the minimum electron energy of 15 MeV corresponds to a theoretical maximum wavelength of more than 60 μm [2-4].

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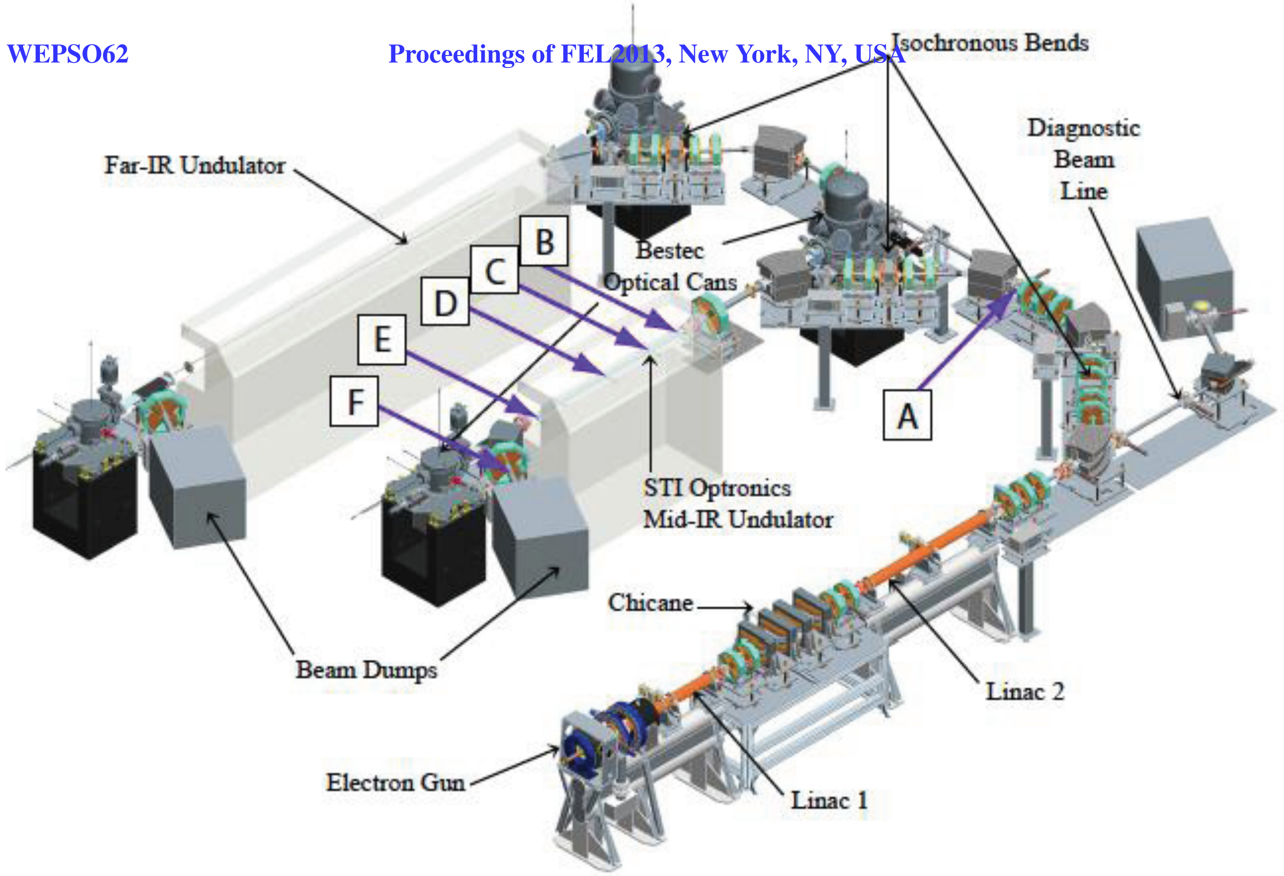

Figure 1: Schematic overview of the IR and THz free-electron laser at the Fritz-Haber-Institut. Blue arrows with labels indicate the locations of the OTR view screens used to observe the images presented in Fig. 2.

Table 2: Mid-IR and far-IR FEL Optical Parameters

Undulator	MIR	FIR
Type	Planar hybrid	Planar hybrid or PPM
Material	NdFeB	NdFeB or SmCo
Period (mm)	40	110
No. of periods	50	40
Length (m)	2.0	4.4
$K_{\rm rms}$	0.5 – 1.6	1.0 – 3.0
IR-cavity	**MIR**	**FIR**
Length (m)	5.4	7.2
Waveguide	none	1-D 10 mm high

The MIR undulator is placed asymmetrically within a 5.4 m long IR cavity with the undulator position being offset by 50 cm from the cavity center in the direction away from the out-coupling mirror. The reason for the offset is the effect of hole-outcoupling on the optical mode in the cavity. Simulations reveal that, close to the outcoupling hole, a hollow mode can be formed, resulting in a significant reduction of the outcoupled photon flux as compared to a Gaussian mode. Shifting the undulator and, hence, the cavity mode waist 50 cm away from the outcoupling mirror reduces this effect to a negligible level.

Another consequence of hole-outcoupling is that different hole diameters are needed to optimize performance at different wavelengths. Therefore a motorized in-vacuum mirror changer has been installed. It permits the precise positioning of either one out of five cavity mirrors with outcoupling-hole diameters of 0.75, 1.0, 1.5, 2.5, and 3.5 mm. The mirror at the other cavity end has no hole and is mounted on a precision translation stage to enable cavity length adjustment with a nominal precision of 1 μm. The cavity-end mirror and the outcoupling mirrors are gold-plated copper mirrors of spherical concave shape with a radius of curvature of 2.65 m and 3.51 m, respectively. As a result, the waist of the cavity mode is shifted by 50 cm away from the cavity center and, hence, it matches the undulator center.

Steering of the electron beam through the MIR FEL can be monitored by OTR view screens. Four beryllium OTR view screens that can be moved in and out of the electron beam path are mounted to the undulator vacuum chamber as indicated in Fig. 1. They are located near the upstream and downstream end of the chamber (labelled 'B' and 'E' in Fig. 1, respectively), at the chamber center ('D'), and between the upstream end and the chamber center ('C'). Screen 'C' is located several centimeters upstream from the 1st quarter position. This arrangement of four undulator view screens allows to observe possible betatron oscillations in the magnetic field of the undulator. In addition to the beryllium screens, there are aluminum screens located upstream ('A' before the 90 degree bend) and downstream ('F' in front of the dump) of the MIR FEL as indicated in Fig. 1. The view screen setups along the undulator can also be seen in the photograph presented in Fig. 4.

Fig. 2 shows images of the electron beam spot on the OTR view screens for a 35 MeV beam with a bunch charge of 190 pC at 1 GHz micropulse repetition rate. Small holes in the screens (clearly visible in 'B', for instance) make it easy to reference the x and y positions of the beam spot to the view screen center. Comparison

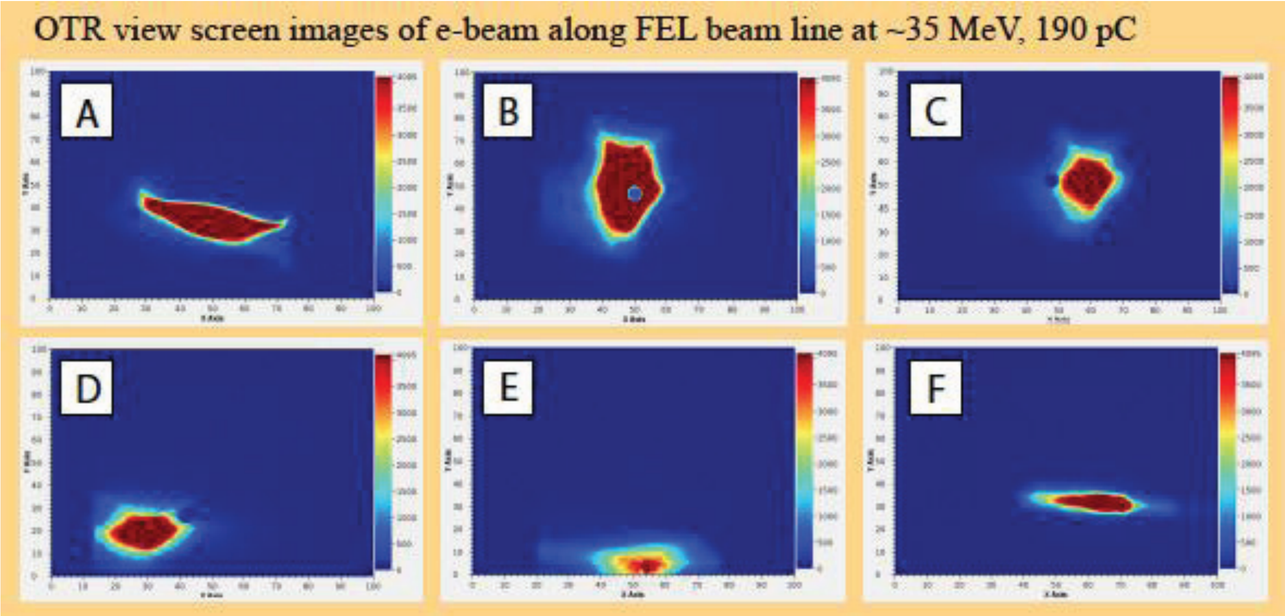

Figure 2: Electron beam spots observed with OTR view screens along the MIR FEL beam line at the locations indicated in Fig. 1.

with the spots of an on-axis HeNe alignment laser (not shown in Fig. 2) allows to verify that the electron beam is well aligned to the FEL axis. Note that neither the holes in the screens nor the camera field-of-view centers are aligned to the FEL axis. This explains why the images in ‘D’ and ‘E’, for instance, appear lower than those in ‘B’ and ‘C’. The images of Fig. 2 were observed for a fully opened undulator gap of about 150 mm. Upon closing the gap to get the FEL lasing (less than ~33 mm) one observes the anticipated horizontal stretching of the beam spot on screen ‘F’ as well as some vertical squeezing of the in-undulator spots ‘B’ to ‘E’.

LASING RESULTS

Figure 3 presents lasing results of the MIR FEL in the wavelength range from 8 to 24 micron. The figure shows a series of IR macropulse-energy measurements for four different cavity lengths. In these measurements the electron energy was constant at 25.2 MeV and the undulator gap was varied for a given cavity length. The microbunch charge was 150 pC at a macrobunch length of 10 µs and micropulse and macropulse repetition rates of 1 GHz and 1 Hz, respectively. The cavity length was detuned from the nominal length of 5.40 m by precise translation of the cavity end-mirror. The out-coupling mirror that was used has a 1.5 mm diameter hole. As can be seen in the figure, a maximum IR pulse energy of more than 100 mJ was observed for 12 µm wavelength.

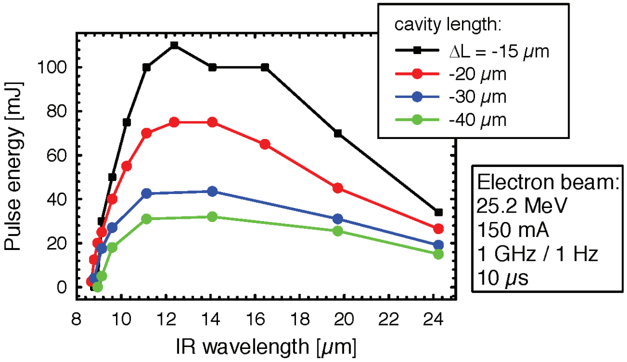

Figure 3: Energies of IR macropulses measured for four different FEL cavity lengths detunings.

FACILITY INFRASTRUCTURE

The IR beam, extracted from the MIR FEL, enters the IR beam line through a CVD diamond window under Brewster angle. The window separates the ultra-high vacuum of less than 1 x 10e-8 mbar in the undulator and cavity-mirror chambers from the high vacuum (10e-4 to 10e-6 mbar) in the IR beam line. The IR beam line consists of 10 cm inner-diameter stainless steel pipes interconnected at right angle by 20 cm side-length cube vacuum chambers housing broadband 45°-incidence IR mirrors. The mirrors are either flat or torroidal and are made out of copper with a non-protected gold coating. The nominal mirror reflectivity in the mid IR amounts to 99.2%. A total of 6 such mirrors (3 flat, 3 torroidal and focussing) steer the IR beam from the FEL cavity in the vault to the IR diagnostic station located in the neighboring building (user building) over a total length of 18 m.

The diagnostic station comprises different commercial IR detectors including a liquid-nitrogen cooled MCT (HgCdTe) detector (Judson) and a large area (5 cm diameter) pyro detector (VEGA Ophir). The latter was used to measure the data shown in Fig. 3. Additional equipment in the diagnostic station includes a Czerny-Turner grating spectrometer (Acton) as well as a 5 stage IR beam attenuator (LASNIX).

Another IR beam line system (user beam line) connecting the diagnostic station with the first five experimental stations has been installed and commissioned. It transfers the IR beam to either one of the user experiments which are located on two floors of the user building. As of August 2013 five experiments from the area of gas-phase spectroscopy of bio-molecules and clusters have been installed and are ready to use the MIR FEL radiation [1]. To this end, an integration of the EPICS-based FEL control system with the facility control system and with the users' experimental control systems has been implemented [8].

SUMMARY AND OUTLOOK

A new mid-infrared FEL has been commissioned at the Fritz-Haber-Institut in Berlin. It will be used for spectroscopic investigations of molecules, clusters, nano-particles and surfaces. The oscillator FEL is operated with 15 – 50 MeV electrons from a normal-conducting S-band linac equipped with a gridded thermionic gun and a chicane for controlled bunch compression. Lasing has been observed from 8 to 24 µm with a peak macropulse energy in excess of 100 mJ, and the first five user beam lines have been commissioned. First user experiments are expected to take place before the end of 2013. In addition, a second FEL branch covering the FIR/THz regime from 40 to 500 µm has been designed, allowing for a future system upgrade.

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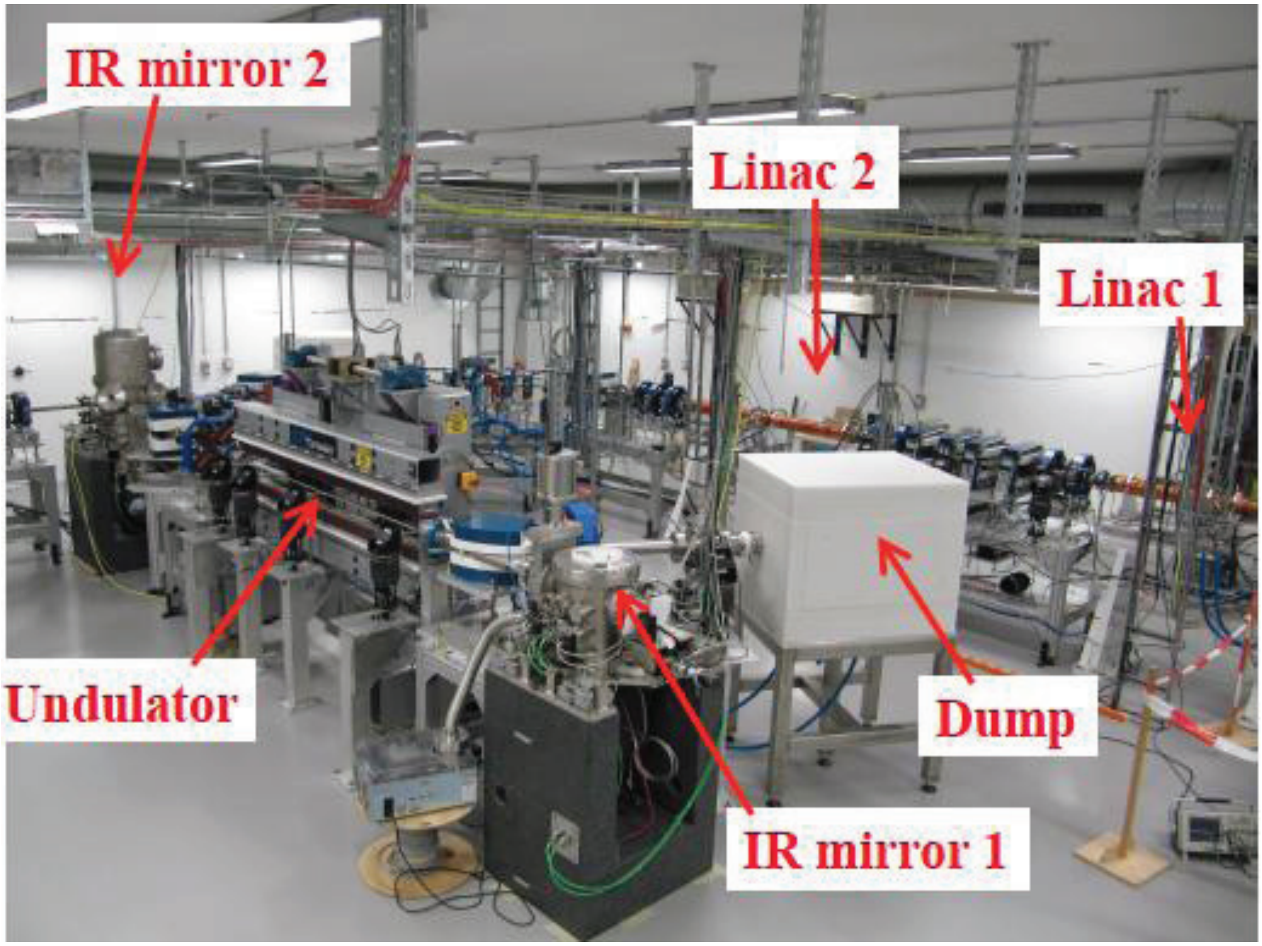

Figure 4: Photograph of the mid-infrared free-electron laser at the Fritz-Haber-Institut.

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