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Accelerators for Discovery Science and Security applications

A.M.M. Todd *, H.P. Bluem, J.D. Jarvis, J.H. Park, J.W. Rathke, T.J. Schultheiss

Advanced Energy Systems, 27 Industrial Boulevard, Unit E, Medford, NY 11763, USA

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ABSTRACT

Several Advanced Energy Systems (AES) accelerator projects that span applications in Discovery Science and Security are described. The design and performance of the IR and THz free electron laser (FEL) at the Fritz-Haber-Institut der Max-Planck-Gesellschaft in Berlin that is now an operating user facility for physical chemistry research in molecular and cluster spectroscopy as well as surface science, is highlighted. The device was designed to meet challenging specifications, including a final energy adjustable in the range of 15–50 MeV, low longitudinal emittance (<50 keV-psec) and transverse emittance (<20 π mm-mrad), at more than 200 pC bunch charge with a micropulse repetition rate of 1 GHz and a macropulse length of up to 15 μs. Secondly, we will describe an ongoing effort to develop an ultrafast electron diffraction (UED) source that is scheduled for completion in 2015 with prototype testing taking place at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). This tabletop X-band system will find application in time-resolved chemical imaging and as a resource for drug–cell interaction analysis. A third active area at AES is accelerators for security applications where we will cover some top-level aspects of THz and X-ray systems that are under development and in testing for stand-off and portal detection.

1. Introduction

We describe three areas of recent AES accelerator activity that deliver applications for the Discovery Science and Security marketplace. The first is an operational mid-infrared (MIR) FEL at the Fritz-Haber-Institut (FHI) in Berlin, Germany, for applications in gas-phase spectroscopy of (bio-) molecules, clusters, and nano-particles, as well as in surface science [1–3]. The performance of this system is state-of-the-art for this class of FEL devices. The second is a tabletop X-band UED source that will find application in time-resolved chemical imaging and as a resource for drug–cell interaction analysis. The prototype of this product will be tested at the BNL ATF in the near future to confirm the projected three times increase in brightness over existing systems. Thirdly, AES is actively developing improved-performance accelerators for security applications. We describe a high-power, compact, THz source targeted for spectroscopy and imaging systems that has already lased at 15 GHz and will be tested at 100 GHz this year. Finally, we address contraband detection systems that are under development and in testing for improved stand-off and portal detection.

2. Fritz-Haber-Institut der Max-Planck-Gesellschaft mid-infrared free electron laser [1]

To cover the wavelength range of interest from about 4 to 500 μm, the system design included two FELs; an 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 up to 50 MeV to either FEL. At this time, the MIR FEL, shown in Fig. 1, is in regular operation for scientific research with the first five IR user beam lines completed. The FIR FEL will be installed and commissioned in the near future. First lasing of the MIR FEL was achieved at a wavelength of 16 μm in 2012 [2]. Since then it has lased in the range from 3.4 to 47 microns.

In Table 1 we summarize the top-level electron beam performance achieved as compared to the specifications. Items in parentheses were desired by the customer but not contractually obligated. As can be seen, the machine meets all and exceeds almost all the deliverables. The design of the accelerator and beam transport system has been described elsewhere [2,3]. 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

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* Corresponding author. Tel.: +1 631 790 1397; fax: +1 609 514 0318.
E-mail address: alan_todd@mail.aesys.net (A.M.M. Todd).

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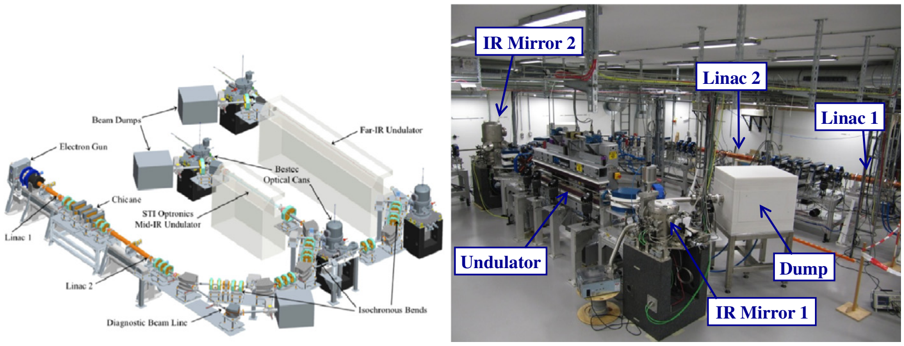

Fig. 1. FHI MIR and THz FEL schematic (left) and installed MIR FEL (right) showing key components. Note that the observation points for the two figures are diametrically opposed.

Table 1
Accelerator deliverable and achieved performance. summary.

Parameter	Unit	Specification	Achieved
Electron energy	MeV	(15) 20–50	15–50
Energy spread	keV	(<) 50	<50
Energy drift per hour	%	(<) 0.1	<0.1
Bunch charge	pC	(>) 200	>215
Micropulse length	psec	1–5 (10)	1–5
Micropulse repetition rate	GHz	1	1
Micropulse jitter	psec	0.5 (0.1)	<0.5
Macropulse length	µsec	1–8 (15)	1–>8
Macropulse repetition rate	Hz	10 (20)	10
Transverse rms emittance	π mm-mrad	20	<13.1

and 50 MeV. A chicane between the structures allows for adjustment of the bunch length as required. The achieved longitudinal emittance of ~50 keV-psec and the beam brightness are exceptional for this class of thermionic-cathode accelerator. During acceptance testing, 102 mJ of IR power was measured on the power meter in the experimental area. The MIR FEL and the FIR/THz FEL utilize an undulator placed within an IR cavity. The MIR FEL has 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. [4]. 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 maximum wavelength of more than 60 µm.

The MIR undulator is placed asymmetrically within the 5.4 m 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 a hollow mode can be formed that results in significant reduction of the outcoupled photon flux as compared to a Gaussian mode. Shifting the undulator and, hence, the cavity mode waist in its center 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, manufactured by Bestec GmbH, has been installed. It permits the precise positioning of either one of five cavity mirrors with outcoupling-hole diameters of 0.75, 1.0, 1.5, 2.5, and 3.5 mm.

The optical beam enters the IR beam line through a CVD diamond window at the Brewster angle. Three flat and three toroidal focusing mirrors made of gold-coated copper steer the IR beam from the FEL cavity in the vault to the IR diagnostic station located in the neighboring user building over a total length of 18 m. The diagnostic station includes a liquid-nitrogen cooled MCT (HgCdTe) detector (Judson), a large area (5 cm diameter) pyro detector (VEGA Ophir), a Czerny–Turner grating spectrometer (Acton) and a 5 stage IR beam attenuator (LASNIX). From here, another IR beam line system transfers the optical beam to either one of the five user experiments located on the two floors of the user building.

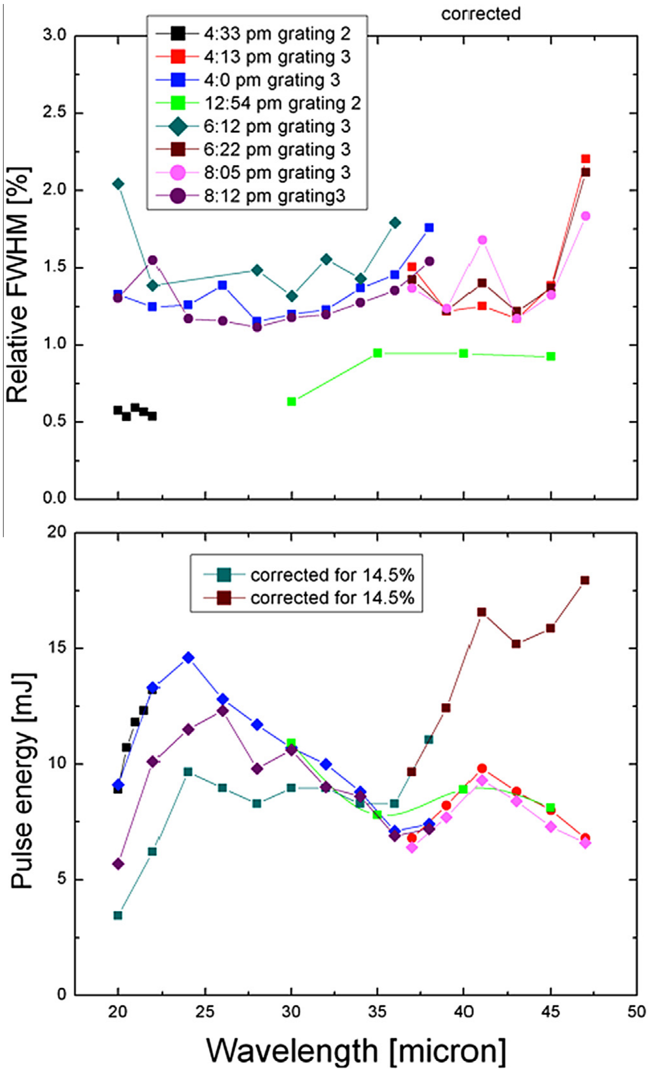

Fig. 2. A "day-in-the-life" of FHI FEL user operations showing the delivered pulse energy and percentage FWHM as a function of the optical wavelength utilizing two of the available spectrometer gratings.