Accelerators for Discovery Science and Security Applications

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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, will be highlighted. 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 ($< 20 \pi$ 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 μ s. 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.

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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 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

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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 Figure 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.

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.

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 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

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

Table 1: Accelerator deliverable and achieved performance.

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.

An integration of the EPICS-based FEL control system with the facility control system and with the user experimental control systems has been implemented [5].

Figure 2 shows a recent “day-in-the-life” of user operations delivering optical beams from 20 to 47 μm at pulse energies on the order of 10 mJ and pulse widths around 1.5% FWHM. The next upgrade step for users will install a pulser to permit the selection of bunches at pulse repetition frequencies (PRF) of 27.75, 55.50 and 83.25 MHz within the macropulse.

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.

3. High-Brightness Ultrafast Electron Diffraction System

Ultrafast, high-brightness, electron beams are desired as injectors for light source facilities, FELs, and other accelerator systems. They are also actively sought after as tabletop instruments for ultrafast electron diffraction (UED), that is used for time-resolved chemical imaging and as a tool in drug-cell interaction analysis. Space-charge forces play a fundamental role in emittance dilution and bunch lengthening within these devices requiring precise management of transverse and longitudinal space charge effects to achieve the necessary beam brightness. Several velocity bunching and magnetic compression techniques are being developed [6-8] but each has drawbacks. We propose the system shown in Figure 3 that utilizes cavity geometry optimization in a high-accelerating-field X-band

Fig. 3: Proposed tabletop X-band accelerator system for UED. The emittance compensation magnet shown is oversized and only used for its known field map. It will be much smaller in practice within an overall system footprint of $\sim 1 \text{ m}^2$.

Fig. 4: Beam dynamics analysis for a 20 pC bunch. The target location is 45 cm from the cathode where the beam energy is 2.7 MeV, the rms bunch length is 70 fsec, the rms normalized transverse emittance is 0.6 mm-mrad achieving a beam brightness of $6 \times 10^{14} \text{ A/m}^2$.

brightness is achievable over existing S-band systems in addition to the significantly more compact footprint. Operation up to a duty factor of 10^{-4} should be possible with addition cooling.

electron gun with coaxial coupling [9] from the rear to achieve, in simulations, a more than threefold improvement in electron beam brightness over competing schemes. The geometrical optimization delivers a small bunch at the target while the rapid acceleration of the high X-band accelerating gradient minimizes bunch emittance growth.

Beam dynamics analysis predicts the performance shown in Figure 4. The target is located 45 cm from the cathode where the 20 pC bunch has an rms length of 70 fsec, even though this is before full emittance compensation is achieved at around 100 cm and before the transverse waist at 85 cm. This optimum point occurs as the longitudinal bunch lengthens in the drift region after the gun. The use of RF coupling from the rear minimizes the drift to target. The normalized rms transverse emittance is 0.6 mm-mrad delivering the extremely high beam brightness of $6 \times 10^{14} \text{ A/m}^2$.

Figure 5(a) shows the resonant WR-90 rectangular to coaxial waveguide coupling. The coaxial waveguide and the cavity resonate as a TEM mode and TM mode, respectively. Figure 5(b) shows the normalized S-parameter for the coupling structure. The cavity resonant frequency is 11.426 GHz. The magnetic fields in the waveguide and coaxial section were determined from the geometry and the 4.23 MW input power level. The magnetic fields and the wall resistance were used to determine the local power loss on the walls, which was then modified for the temperature dependent resistance of the walls. An iterative solution was used to update the wall resistance from the calculated temperature. The resultant thermal analysis predicts that the proposed design is thermo-mechanically robust and can operate up to a duty factor of 4×10^{-5} with rudimentary cooling.

The described tabletop X-band UED device is presently in final design. A prototype will be fabricated and then tested at the BNL ATF facility to validate the performance achieved. Our analysis projects a threefold improvement in beam

Fig. 5. Rectangular to coaxial waveguide and cavity coupling analysis (left) and the resultant calculated S-parameter (right).

4. High-Power, Compact, THz Radiation Source

The generation of tunable, narrow instantaneous bandwidth, coherent, terahertz (THz) and submillimeter radiation is a topic of great interest across a wide variety of disciplines and applications including materials science, non-destructive analysis of chemical and biological specimens, industrial quality control, security imaging, and ultra-high-bandwidth communications. Of particular interest in the context of security is the application of THz and submillimeter radiation to chemical, biological, explosive or contraband detection and imaging. Primary modalities of interest are active and passive imaging as well as detection of spectroscopic signatures [10]. Examples and reviews of passive and active systems and their associated considerations are given in references [10-12]. The signals arriving at any detection system are a complex combination of illumination, emissivity, reflectivity, and absorption, both of the subject of interest and of the surrounding environment [11]. The signal-to-noise ratio (SNR) of passive techniques is inherently limited by emissivity, reflection, and ambient illumination; however, active imaging can, in principle, achieve an arbitrarily high SNR by the use of an external source [10]. Furthermore, high power illumination provides for longer range, increased target penetration, and higher throughput.

To be ultimately useful in the field, the source must be compact, efficient, and powerful. Even for high-power sources, atmospheric absorption will likely limit the desired frequency range to between 100 GHz and 1 THz [11]. AES is developing a source architecture with the output power and flexibility needed to find application in a variety of active imaging systems. The AES concept is a cylindrical extension of the so-called Smith-Purcell free-electron laser (SPFEL). The SPFEL is a type of backward-wave oscillator (BWO) that lases on an evanescent wave (surface wave) supported by an open slow-wave structure (SWS) [13].

When an electron passes in close proximity to an open, periodic, metallic grating, energy is transferred from the electron to radiative modes of the grating. This so-called Smith-Purcell radiation (SPR) is emitted over a broad spectrum with the wavelength of the emitted photons being correlated to the angle of emission [14]. The SPR is always at a higher frequency than the backward wave, except when the fundamental is confined laterally on a scale comparable to its wavelength [15]. When the electron beam is bunched by the backward wave interaction the SPR power is dramatically increased and is strongly peaked at angles corresponding to harmonics of the bunching frequency [16]. Under these conditions the SPR is said to be superradiant and significant power output can be generated at high frequencies.

The radiation output of a SPFEL is then a combination of the fundamental and the superradiant SPR at its harmonics. The power in the backward wave is much higher than the SPR power; however, because the backward wave is nonradiative, some form of outcoupling is required. Straightforward, optimized grating structures can deliver efficient, high-power outcoupling in the forward or backward directions. Furthermore, the SPFEL can easily be designed for a specific center frequency by adjusting the grating geometry and the beam energy. An active-

tuning range is achieved via adjustment of the beam energy. Ultimately, the highest frequency achievable will be determined by current density, energy spread, ohmic losses in the grating, and fabrication tolerances. This is highly dependent on the specifics of the system design; however, for practical beam and grating properties this will likely be 1 THz. Higher frequency output, albeit at lower power, may be provided by the coherently enhanced SPR or by using other advanced schemes.

The AES concept, which utilizes a cylindrical SWS and a high-power annular electron beam, is compatible with established transport and compression techniques from the microwave-tube industry. Furthermore, the cylindrical geometry provides for maximum grating surface area in a compact package. The open grating design provides significant flexibility in the generation and extraction of fundamental and harmonic radiation; this is a point of contrast with other e-beam driven sources.

This system is a significant departure from previous designs. As such, it was determined that the demonstration of key concepts at microwave frequencies would provide an important reference point for theoretical and experimental efforts, and would help ensure the success of a THz prototype. Over the past year, a joint effort between AES and the *Commissariat à l'énergie atomique et aux énergies alternatives* (CEA) has successfully achieved first lasing of a cylindrical SPFEL, both at 5 and 15 GHz; these experiments were carried out at CEA's *Centre d'études scientifiques et techniques d'Aquitaine* (CESTA) facility.

Fig. 6: Experimental configuration for the 15-GHz demonstration.

Fig. 7: Beam imprint on thermal paper just before the anode aperture (left) and at the beam dump for a 0.5-mm aperture (center). Backside illumination of the anode aperture with an imprint of the beam (right).

waveguide positioned inside of the chamber. These radiation diagnostics are monitored directly using a 33-GHz fast oscilloscope. A few-kHz to 50-GHz synthesizer was used to calibrate all cables and fixed attenuators several times.

Figure 8 shows a typical B-dot signal during one of the more than 100 shots taken. These data were taken with the probe located 3 mm above the third groove in the grating. The signal oscillates because the high current in the experiment causes over-saturation of the interaction. Also shown in Figure 8 is a fast Fourier transform (FFT) of the signal and a sliding FFT. These analyses indicate a strong peak at ~ 14.6 GHz, which is very close to the expected frequency of the evanescent mode. Based on the inductance of the probe and the calibration measurements of attenuation in the measurement system, we estimate the magnetic field strength to be ~ 17 G at this location.

The basic experimental configuration for these microwave demonstrations is shown in Figure 6. An electron gun diode is situated at the end of a 200-kV, 500-A sub-microsecond cable generator. The electron source is an explosive electron emission cathode with an annular geometry. The electron beam is shaped, and its current reduced, using an adjustable aperture at the anode. Various beam currents, thicknesses, and beam-grating separations can be investigated in this way; typical beam imprints on thermal paper are shown in Figure 7. The typical energy and current of the transmitted beam is 80 keV and 50 A. The grating is machined to the desired geometry from a single piece of aluminium, and an isolated beam stop is located at the downstream end. The entire apparatus is housed in a large plastic vacuum chamber operating at $\sim 10^{-4}$ Torr, and a pulsed solenoid surrounds the vacuum chamber, providing a confinement field of approximately 5 kG during the beam pulse. The surface wave is measured using a B-dot probe that can be moved throughout the chamber. The SPR is collected using either a microwave horn on the exterior of the downstream end of the apparatus or a section of WR-28

Fig. 8: B-dot signal (top), FFT (center), and sliding FFT (bottom) for a typical shot.

The B-dot probe was subsequently placed at four different positions in azimuth to determine the homogeneity of the field strength; several shots were taken at each location. The field strength was nearly uniform in azimuth for this longitudinal position. A sliding FFT of a typical second-harmonic signal is shown in Figure 9. As expected, the signal is dominated by a single frequency (~ 29.2 GHz) that is exactly twice the fundamental. The observed frequency variation is consistent with that expected from the time dependence of the beam energy depicted in the figure with the red trace. This superradiant SPR was also found to be uniform in the azimuthal coordinate.

Fig. 9: Sliding FFT of the radiation collected by the WR-28 waveguide. The intensity map shows the FFT vs time, the black line is the nominal centroid of the distribution, the red line shows the variation of the beam voltage, and the green line is the theoretical operating frequency multiplied by two.

Simulations of the device have been carried out using two different PIC codes: MAGIC 3D and VORPAL, and the agreement between these codes was found to be excellent. Figure 10 shows intensity maps of the azimuthal magnetic field during the lasing process and after saturation. The second harmonic is clearly visible in the top image at $\sim 70^\circ$ above the horizontal. Ultimately, for this simple grating, the radiation output is dominated by scattered fundamental radiation from the upstream end of the grating. The fundamental frequency in these simulations, 14.3 GHz, is very close to the 14.6 GHz measured in the experiments. Also, good agreement was found for the field strength of the fundamental and second harmonic. The simulations predict a fundamental power

Fig. 10: Intensity maps of the azimuthal magnetic field during lasing (top) and after saturation (bottom).

of 200 kW with a second harmonic power of 5 kW. Further simulations have been carried out on devices operating at 50 and 100 GHz (fundamental). We are presently planning experimental demonstrations at these higher frequencies using the same electron gun and power systems.

We are now designing a 220-GHz prototype that will utilize existing cathode technology and a reliable, low-voltage, compressionless gun design. Small-signal SPFEL theory is being used for initial design and optimization, while in-depth PIC simulations are being used to examine saturated performance and more complex grating structures. Careful attention is given to the use of appropriate longitudinal and transverse energy spreads in these simulations. In initial studies, high-power outcoupling of the fundamental into a half angle of $\sim 25^\circ$ is achieved at the downstream end of the device. Furthermore, the achievable current density with existing cathode technology is well beyond the start-current requirements of the device. Subsequent systems between 400 and 700 GHz will build on the successes of the 220 GHz device.

5. Accelerators for Contraband Detection

We have developed, and in some cases tested, radiation source concepts for active SNM detection [17], non-intrusive photon beam inspection [18] and intra-pulse, variable energy [19, 20] applications. In each case, the accelerating structures derive from the concept demonstrated with the FHI linacs.

Fig. 11: High-duty factor, S-band 9 MeV concept for transportable photon beam inspection.

Our 3 to 7 (or 9) MeV variable-energy, electron linac with intra-pulse energy adjustment capability is conceived as an X-ray source for cargo portals, train and vehicle scanning. It is magnetron-based for low cost but the energy stability requires improved control and the energy switching must be completed in less than a microsecond. For compactness and transportability we have designed the water-cooled, 6.5 cell, C-band $\pi/2$ structure shown in Figure 12 that can operate with up to 1.5 kW of beam power into a tantalum target.

A transportable, 9 MeV S-band electron accelerator with greater than 1% duty-factor is needed for the photon beam inspection application. Here, the average power specification requires the use of a klystron or solid state RF rather than a magnetron. Consequently, the RF cost for high duty factor stresses the customer cost target. This concept is illustrated in Figure 11. For scale reference, the accelerator beamline is roughly 3.5 m in total length. The accelerator rigidity is maintained by the strongback with precision linear rails allowing for thermal expansion. The accelerator is pinned at the right end of the accelerator near the mirror bend to maintain alignment.

Fig. 12: C-band variable-energy electron linac with intra-pulse energy adjustment targeted for cargo portals, train and vehicle scanning.

6. Conclusions

AES is delivering accelerator applications for Discovery Science and the Security marketplace. A mid-infrared (MIR) FEL at the Fritz-Haber-Institut (FHI) in Berlin, Germany, primarily targeted for physical chemistry research, has been described and is now in daily user operation. The performance of this system is the state-of-the-art for this class of FEL devices. A tabletop X-band UED device that will find application in time-resolved chemical imaging and as a resource for drug-cell interaction analysis, has been discussed. It is presently in final engineering design. The prototype of this product will be tested at the BNL ATF within a year to confirm the projected three times increase in brightness over existing systems. Finally, we have described the active development of improved-performance accelerators for security applications. The exciting results of a prototype 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, were noted. Finally, we described different AES contraband detection system concepts that are under development and in testing for improved stand-off and portal detection.

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