INVITED PAPER

# Compact, High-Power Electron Beam Based Terahertz Sources

*These sources can generate high average power and very high peak power at controlled THz wavelengths and bandwidths to serve mobile or laboratory-based analytical tools.*

By Sandra G. Biedron, *Senior Member IEEE*, John W. Lewellen, *Member IEEE*, Stephen Val Milton, Nachappa Gopalsami, *Senior Member IEEE*, John F. Schneider, Laura Skubal, Yuelin Li, Mathew Virgo, *Member IEEE*, Gian Piero Gallerano, Andrea Doria, Emilio Giovenale, Giovanni Messina, and Ivan Panov Spassovsky

**ABSTRACT** | Although terahertz (THz) radiation was first observed about 100 years ago, this portion of the electromagnetic spectrum at the boundary between the microwaves and the infrared has been, for a long time, rather poorly explored. This situation changed with the rapid development of coherent THz sources such as solid-state oscillators, quantum cascade lasers, optically pumped solid-state devices, and novel coherent radiator devices. These in turn have stimulated a wide variety of applications from material science to telecommunications, from biology to biomedicine. Recently, there have been two related compact coherent radiation devices invented able to produce up to megawatts of peak THz power by inducing a ballistic bunching effect on the electron beam, forcing the beam to radiate coherently. An introduction to the two systems and the corresponding output photon beam characteristics will be provided.

**KEYWORDS** | Bunching; coherent radiation; electron beam; free-electron laser; intense particle beams; radiation sources; terahertz

Manuscript received February 23, 2007; revised April 6, 2007. The work of S. G. Biedron, J. W. Lewellen, S. V. Milton, J. F. Schneider, N. Gopalsami, L. Skubal, Y. Li, and M. Virgo is supported at Argonne National Laboratory by the Office of Basic Energy Sciences, U.S. Department of Energy under Contract DE-AC02-06CH11357 and by the Office of Naval Research. The work of G. P. Gallerano, A. Doria, E. Giovenale, G. Messina, and I. P. Spassovsky is supported by ENEA the Italian Agency for New Technologies, Energy, and the Environment.

**S. G. Biedron**, **J. W. Lewellen**, **S. V. Milton**, **N. Gopalsami**, **J. F. Schneider**, **L. Skubal** and **Y. Li** are with the Argonne National Laboratory, Argonne, IL 60439 USA (e-mail: biedron@anl.gov).

**M. Virgo** is with the Argonne National Laboratory, Argonne, IL 60439 USA and also with the University of Maryland, College Park, MD 20742 USA.

**G. P. Gallerano**, **A. Doria**, **E. Giovenale**, **G. Messina**, and **I. P. Spassovsky** are with the Dipartimento Tecnologie Fisische e Nuovi Materiali, Centro Ricerche Frascati, ENEA, 00044 Frascati Italy.

Digital Object Identifier: 10.1109/JPROC.2007.898858

## I. INTRODUCTION

There are numerous sources of terahertz (THz) radiation available. For a comprehensive review of THz technology the reader is invited to a recent paper by Siegel [1]. A separate paper documenting the development and perspectives of THz radiation sources was presented at the 2004 International Free-Electron Laser Conference [2]. Furthermore, a recent beam dynamics newsletter was dedicated to the activity of coherent synchrotron radiation in storage rings [3]. Finally, a recent publication documenting scientific applications of THz radiation that was a result of a workshop sponsored by the U.S. Department of Energy, the U.S. National Science Foundation, and the U.S. National Institute of Health is also available [4]. In this paper, it is the intent to focus on the generation of high-power, continuously tunable radiation through the mm-wave to THz from compact electron sources as a viable mobile or laboratory-based compact analytical tool.

## II. BACKGROUND ON ELECTRON BEAM BASED LONG-WAVELENGTH SOURCES

Traveling wave tubes and backward wave oscillators in the 100 GHz and 1.2 THz range respectively prove useful for low average (~1–100 mW) and relatively low peak powers. To overcome the necessity of reducing the physical size of the source components as the frequency is increased, different schemes were developed that force the electrons to exchange momentum for THz radiation emission. A frequently used method is use of the magnetic undulator originally proposed by Motz [5], which was employed by Phillips in the Ubitron [6] back in 1960 to generate

mm-wave radiation and which led to the realization of the first free electron laser (FEL) in 1977 [7]. The power of the FEL is in its ability to force the electrons to emit their radiation in a coherent fashion thus dramatically increasing the overall power of the emission. Other free electron coherent emission FEL devices are the Cerenkov FEL, based on the interaction with a dielectric loaded waveguide [8], and the metal grating FEL, based on the Smith–Purcell effect [9].

In his pioneering work on undulator radiation [5], Motz pointed out that in a uniform electron beam the contributions of individual electrons to the radiation field are random in phase, and therefore the square of the total field equals the quadrature sum of the individual fields. However, if the electrons were bunched within a distance comparable to the wavelength of the radiation, their fields would add up in phase, resulting in the emission of coherent radiation with a power level several orders of magnitude higher than the noncoherent radiation generated by a uniform beam. The idea of generating coherent radiation in the THz region utilizing bunched electron beams, such as those produced by radiofrequency (RF) accelerators, was indicated in [5], and different coupling structures, designed to extract energy at a harmonic of the bunch repetition rate, were investigated [10]. More recently the coherent spontaneous emission from an RF-modulated electron beam at wavelengths comparable to the electron bunch length has been the object of renewed interest because of its relevance in the generation of short pulses of coherent THz radiation [11]–[13]. Issues like the dependence of the emitted radiation on the bunch shape [14] and the observation of emission at discrete frequencies, which are harmonics of the fundamental RF [15], have also been addressed both theoretically and experimentally and have led to the realization of compact FELs in the THz region [16], [17].

Historically, the first FEL facility to provide THz radiation to users has been the UCSB-FEL, which is driven by an electrostatic accelerator and operates in a quasi-CW mode. It provides tunable terahertz radiation in the region from 120 GHz to 4.8 THz (2.5 mm–60 $\mu$m) with a peak output power in the range from 500 W to 5 kW and a pulse duration of 1–20 $\mu$s at a 1 Hz repetition rate [18]. Several facilities have been built to operate in the infrared region and most of them can reach or plan to extend into the THz region. Besides the University of California Santa Barbara FEL, we recall here the Israeli EAFEL (100 GHz), based on a 6 MeV EN-Tandem Van der Graaff accelerator [19], the Stanford FEL (15–80 $\mu$m) [20], FELIX (3–250 $\mu$m) with its planned FELICE extension for intracavity experiments at FOM-Nieuwegein [21], CLIO at LURE-Orsay, which has plans for a new hybrid resonator to reach wavelengths in the range 100–300 $\mu$m [22], ELBE, which has recently lased at 20 $\mu$m and has plans to extend its operation to 150 $\mu$m [23], the work at the KAERI facility [24], and the THz-FEL at Novosibirsk, based on a CW energy recirculated linac (ERL) and providing about 100 W in the spectral range 120–180 $\mu$m [25].

The principle of coherent, spontaneous emission is also exploited to generate THz radiation from bending magnets at FEL facilities and Synchrotron facilities. About 100 W of CW radiation have been produced from bending magnets in the band from 0.1 to 3 THz at JLAB [26]. The JLAB ERL accelerator overcomes some of the limitations of conventional linacs and storage rings. It produces 500 fs, 135 pC electron bunches at a very high repetition rate (75 MHz) by using superconducting RF cavities and then recovering the energy of the spent electron beam. Coherent THz emission from a linac driven beam has been demonstrated at Brookhaven National Laboratory (see below). Coherent synchrotron radiation has also been observed in storage rings [27]–[30]. A coherent THz beam line is operating at BESSY-Berlin and several others are planned at Lawrence Berkeley National Laboratory (CIRCE), Cornell University, and Daresbury (4 GLS).

## III. "TABLE-TOP," HIGH-POWER, ELECTRON-BEAM BASED TERAHERTZ DEVICES

There are a number of prototypical "table-top" terahertz devices presently being investigated that have the potential to achieve high peak and average powers and also be continuously tunability over more than one octave. We wish to acknowledge the work of our community and then to focus upon the types and characteristics of emission for our two sources of similar characteristics—that of Argonne National Laboratory (Argonne) and of Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) Frascati.

### A. Overview of Compact FELs and Table-Top Free Electron Radiators

These accelerator-based THz sources, which can fit on or scale to the size of a table-top, are predominately proof-of-principle experiments and should be looked upon as ideas that can be specified and tailored for particular types of experiments. Development work on electron beam based sources is under way at several facilities. The RF-gun derived sources described below will benefit from ongoing design work, especially if electron guns can be made superconducting, permitting higher average power operation. Laser wake-field accelerators are actively being researched as possible alternative solutions for high energy systems and are still in the early stages of development. Some of these sources could be designed to produce half-cycle pulses of THz radiation.

In a table-top free electron radiator based on an RF modulated electron beam with short bunches, the modulator, klystron, waveguide, cooling, magnets, electron gun, accelerating structure, and all other peripheral accelerator components could easily be fitted into the space of 3 $m^3$. The FEL-CATS source at ENEA-Frascati [31] and the

source under development at Argonne [32] are examples of this compactness. Further engineering work and improved design in the X-ray shielding of the accelerator will also increase the compactness of these systems. These will be discussed in further detail below.

In the frame of collaboration between University of Maryland and the Brookhaven National Laboratory (Source Development Laboratory) a proof-of-principle experiment based on the modulation induced on an electron bunch has been recently carried out [33]. This device uses a laser to generate a bunch train of electrons through photoemission. Each bunch is about a picosecond long, and they are separated by about a picosecond. An electron accelerator takes these short bunches and accelerates them up to 70–72 MeV. At this point the beam is intercepted by a metallic mirror or metal foil. When the environment around the beam changes from vacuum to metal, transition radiation is emitted. Because of the way the electrons are bunched, there is strong emission in the THz frequency range. The frequency spectrum can be controlled by controlling the way the electrons are initially bunched. The result is a tunable terahertz source that could be used for a wide variety of additional experiments.

At the Source Development Laboratory, Brookhaven National Laboratory, a linac-based source of coherent THz pulses has been developed. In this device electron bunches are compressed to $\sim$300 fs rms. The degree of compression can be varied with the perspective of reaching 100 fs and possibly shorter pulse duration. Electron bunches produce single-cycle coherent THz pulses as transition radiation or dipole radiation. An energy per pulse of $\sim$100 $\mu$J and peak electric field up to $>$1 MV/cm has been demonstrated [34]. The method could be improved to produce shorter electron bunches and a broader spectral range. A pulsed laser driving the linac photocathode provides synchronized IR pulses for electrooptic coherent detection of THz pulses. Advanced energy systems (AES) has plans to develop a multi-watt (50–100 W eventual goal; 5 W in this initial prototype), tunable, compact THz source.

Intense THz radiation from ultrashort electron bunches has been generated by a laser wakefield-based linac at Lawrence Berkeley Laboratory. This source is based on the production of ultrashort ($<$ 50 fs rms), high charge (0.3–5 nC) relativistic electron bunches by using a laser excited plasma wave with large enough amplitude to trap background electrons and accelerate them in mm distances to tens of MeV. As the electrons exit the plasma, a burst of transition radiation is produced. The source performance is controlled by the electron bunch properties and the density and transverse size of the plasma at the exit boundary. The THz radiation is intrinsically synchronized with an external laser and experiments are underway to measure the THz pulse structure with electrooptic sampling. Time averaged spectra have been measured and show that the spectrum with the present configuration is centered around 2 THz. Whereas present energy levels on the order of 0.1 $\mu$J/pulse have been collected, modeling indicates that significantly higher power can be achieved by optimizing the plasma properties (transverse size and longitudinal profile) and could be as high as 100 $\mu$J/pulse [35]. Further progress on the laser driven accelerator performance is underway, including the production of quasi-monochromatic (few % energy spread) relativistic electron bunches (100 MeV).

### B. Detailed Conceptual Description of the Argonne and ENEA Systems

The coherent prototype radiator at Argonne can employ three different cathode modes—thermionic, photogated thermionic, or photocathode. Even at a low RF repetition rate, as well as normal conducting, relatively high average powers are achievable if a laser gates the thermionic cathode. The electron beam pulse length changes depending upon the cathode mode of operation and the degree of compression. Although this source is a prototype, it can be easily adapted to a specific experiment and packaged into a small space. The repetition rate, pulse width, and average and peak power can be improved significantly. This compressed high-power electron beam is then passed through a magnetic field, either a dipole or tailored field such as an undulator, or through a thin conductive foil or tailored stack of such foils. Electromagnetic radiation is then produced either directly from the transverse acceleration of the primary electrons or from transverse acceleration of the image charge electrons respectively.

At ENEA-Frascati the recently built source FEL-CATS utilizes a high-efficiency generation scheme based on the mechanism of coherent spontaneous emission, which allows operation in the frequency range between 70 GHz and 0.7 THz. Tunable operation has been obtained in the spectral region between 0.4 and 0.7 THz with a relative linewidth of about 10% FWHM [36]. The radiation has a pulsed structure composed of wavepackets in the 3 to 10 ps range, spaced at a repetition frequency of 3 GHz. A 5 $\mu$s long train of such pulses (macropulse) is generated and repeated at a rate of few Hz. The measured power in the macropulse is 1.5 kW at 0.4 THz.

The principle of operation of the source is based on the coherent spontaneous emission from short bunches of relativistic electrons. The FEL source utilizes a 2.5 MeV RF linac to generate the electron beam, which is injected into a linearly polarized magnetic undulator composed of 16 periods, each 2.5 cm long with a peak magnetic field of 6000 Gauss. A second RF structure, called the phase matching device (PMD), is inserted between the linac and the undulator and is controlled in phase and amplitude to correlate the electron distribution in energy as a function of time in the bunch [37]. In this way the contributions to the total radiated field by individual electrons in the bunch are added in phase, leading to a manifold enhancement of the coherent emission.

## IV. RADIATION EMISSION POSSIBILITIES FROM THE ARGONNE AND ENEA SOURCES

An electron transversely accelerated by a magnetic field emits electromagnetic (EM) radiation whose properties are very well understood. The emission from an ensemble of electrons is also very well understood; however, it is obvious that the electron ensemble distribution affects the properties of the emitted EM radiation. Depending on its properties an electron bunch can exhibit transverse and/or longitudinal coherent EM emission. In both cases tremendous gains in the photon brightness can be obtained. We will provide a review of the EM emission from an ensemble of electrons emitting through the mechanisms of transition radiation and spontaneous radiation. Particular attention will be given to coherent emission at longer wavelengths (micrometers to millimeters).

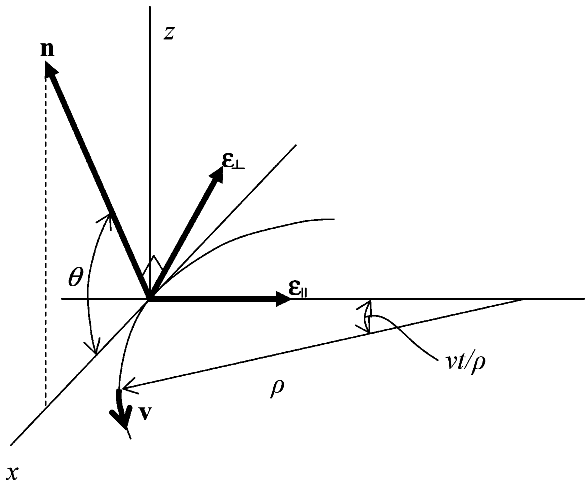


**Fig. 1.** *Emission of synchrotron radiation.*

### A. Synchrotron Radiation

The energy distribution of the photons radiated by a relativistic electron in an instantaneous circular motion is [38]

$$\frac{d^2I}{d\omega d\Omega} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{3\pi^2 c}\left(\frac{\omega\rho}{c}\right)^2\left(\frac{1}{\gamma^2}+\theta^2\right)^2 \times \left[K_{2/3}^2(\xi)+\frac{\theta^2}{(1/\gamma^2)+\theta^2}K_{1/3}^2(\xi)\right] \quad (1)$$

where $I$ is the energy emitted by electrons, $\omega$ is the frequency, $\Omega$ is the solid angle, $e$ is the charge of the electron, $c$ is the speed of light, $\rho$ is the radius of curvature, $\gamma$ is the relativistic normalized energy of the electron, and $K$ is the modified Bessel function where

$$\xi = \frac{\omega\rho}{3c}\left(\frac{1}{\gamma^2}+\theta^2\right)^{3/2} \quad (2)$$

with $\theta$ as shown in Fig. 1.

To give a flavor of the Argonne and ENEA systems, assuming $\gamma = 5$, $\rho = 1$ cm, and $\theta = 0$ rad, one can calculate the incoherent spectrum for a relativistic electron in circular motion. The result of this calculation is shown in Fig. 2.

The critical wavenumber, defined as the wavenumber above which the intensity rapidly drops off, is

$$\frac{1}{\lambda_c} = \frac{3\gamma^3}{4\pi\rho}. \quad (3)$$

If, in the plane of motion of the electron (horizontal plane), the detector can collect radiation emitted with an opening angle of

$$\theta_c \approx \frac{1}{\gamma}\left(\frac{\omega_c}{3\omega}\right)^{1/2} \quad (4)$$

the intensity integrated over the spectrum as a function of perpendicular angle $\theta$ can be calculated and is shown in Fig. 3.

Assuming a single $TEM_{00}$ mode, one can calculate the effective optical emittance and the Rayleigh length. The

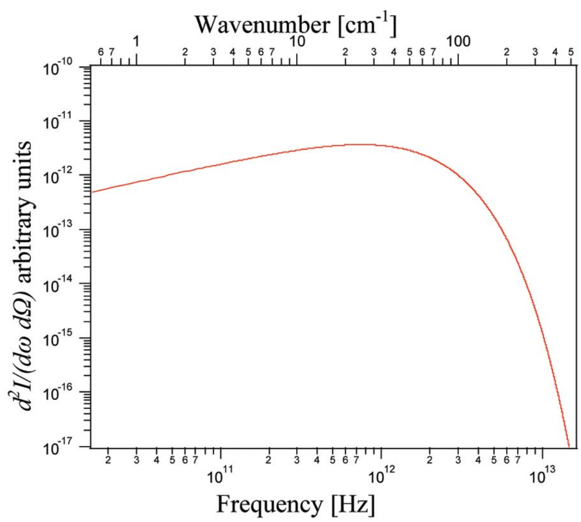


**Fig. 2.** *Synchrotron radiation spectrum.*

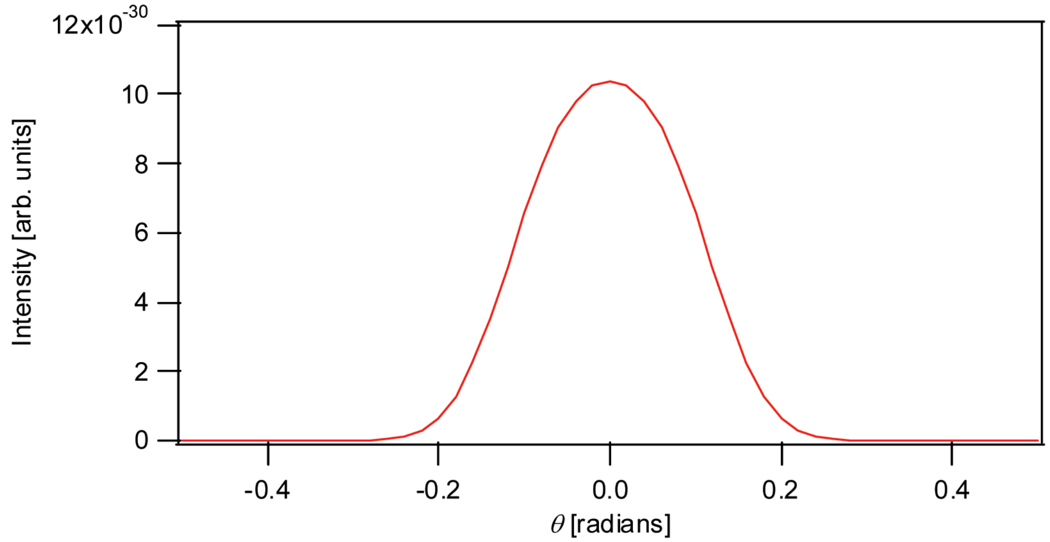


**Fig. 3.** ***Angular distribution of synchrotron radiation.***

effective optical emittance of the transverse phase space for a source size $\sigma$ is given by

$$\varepsilon_{\rm rad} = \frac{\lambda}{4\pi} \quad \text{or} \quad \varepsilon_{\rm rad} = \sigma\theta \tag{5}$$

and the Rayleigh length is

$$L_R = \frac{4\pi\sigma^2}{\lambda}. \tag{6}$$

## B. Transition Radiation

When a charged particle passes from a region with one set of electromagnetic properties into a region with different electromagnetic properties, its field undergoes a rapid rearrangement. As a result of the rearrangement, a radiation field is generated. This radiation field is known as transition radiation.

In the case of primary interest for accelerators, a relativistic electron passes through a metal foil. For infrared and terahertz wavelengths, the foil can be considered perfectly reflecting. The distribution of radiation produced by a relativistic electron passing into a perfectly reflecting foil is [39]

$$\frac{d^2I}{d\omega d\Omega} = \frac{1}{4\pi\varepsilon_0}\frac{\beta^2 e^2}{\pi^2 c}\left(\frac{\sin(\theta)}{1-\beta^2\cos^2(\theta)}\right)^2 \tag{7}$$

where $\theta$ is the angle between the particle trajectory and the observation point. The intensity of the radiation is azimuthally symmetric. It is strongly peaked at $\theta = 1/\beta\gamma$ (or $\theta \approx 1/\gamma$ for a relativistic particle). It is also uniform over the spectrum, at least to up to frequencies where the metal can be approximated as a perfect conductor. Because our interest here is terahertz radiation, this will be a reasonable approximation. A plot of the angular distribution of the transition radiation is shown in Fig. 4.

The total energy produced at a given frequency can be found by integrating (7) over the hemisphere $0 < \theta < \pi/2$

$$\begin{aligned}\frac{dI}{d\omega} &= \int \frac{d^2I}{d\omega d\Omega}d\Omega \\ &= \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\pi c}\left\{-1+\left(\beta+\frac{1}{\beta}\right)\tanh^{-1}\beta\right\}.\end{aligned} \tag{8}$$

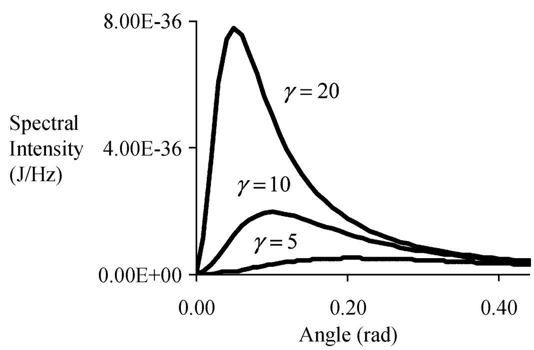


**Fig. 4.** ***Polar angle distribution of transition radiation for three electron energies. This distribution is azimuthally symmetric. Each curve has a maximum at $\theta = 1/\gamma$.***

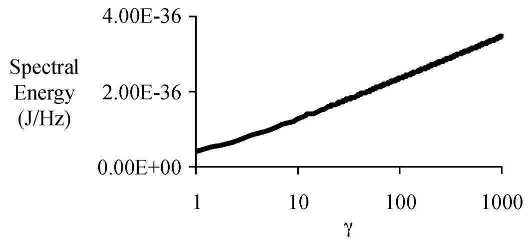


**Fig. 5.** *Spectral energy as a function of electron energy. For the Argonne and ENEA systems, we have assumed $\gamma \approx 5$.*

For relativistic electrons ($\gamma > 1$), this is approximately

$$\frac{dI}{d\omega} \approx \frac{1}{4\pi\varepsilon_0} \frac{e^2}{\pi c} (.4 + 2 \ln \gamma). \tag{9}$$

The dependence of radiated energy on electron energy is illustrated in Fig. 5.

Looking back to Fig. 4, it is clear that, at low energy, the radiation is spread over a large angle. Depending on the experimental arrangement, only a fraction of the radiation may be collected. If, for instance, an opening angle of 100 mrad is captured, roughly 50% of the radiation is collected when $\gamma = 20$, but less than 25% of the radiation is captured when $\gamma = 5$.

### C. Coherent Radiation From Bunched Beams

For multiple electrons, there are two cases. If the electrons are independently radiating then the phases of their electric fields are random with respect to one another and the radiated power scales as the number of electrons. If the electrons are in lock synch, then coherent emission is possible and the electric field grows linear with the number of electrons. The power then goes as the square of the field, and if $N$ is very large one can get an enormous gain in power emitted. This is the essence of the coherent radiation emission process. Conceptually, this can be seen in Fig. 6(a) and (b).

The coherent radiation intensity for the electron bunch in Fig. 7 [40] is

$$I(\lambda) \sim |E(\lambda)|^2 \tag{10}$$

where the component of the electric field from an electron seen by the detector at wavelength $\lambda$ is

$$E_k(\lambda) = E_1(\lambda) \cos\left(\frac{2\pi}{\lambda} \mathbf{n_k} \bullet \mathbf{r_k}\right) \tag{11}$$

where $E_1$ is the radiation from a single electron at the origin as measured at the detector, and $E_k$ is the radiation from a single electron at point $\mathbf{r_k}$ as measured at the detector. The total field of all electrons is

$$E_{\text{tot}}(\lambda) = E_1(\lambda) \sum_{k=1}^{N} \cos\left(\frac{2\pi}{\lambda} \mathbf{n_k} \bullet \mathbf{r_k}\right) \tag{12}$$

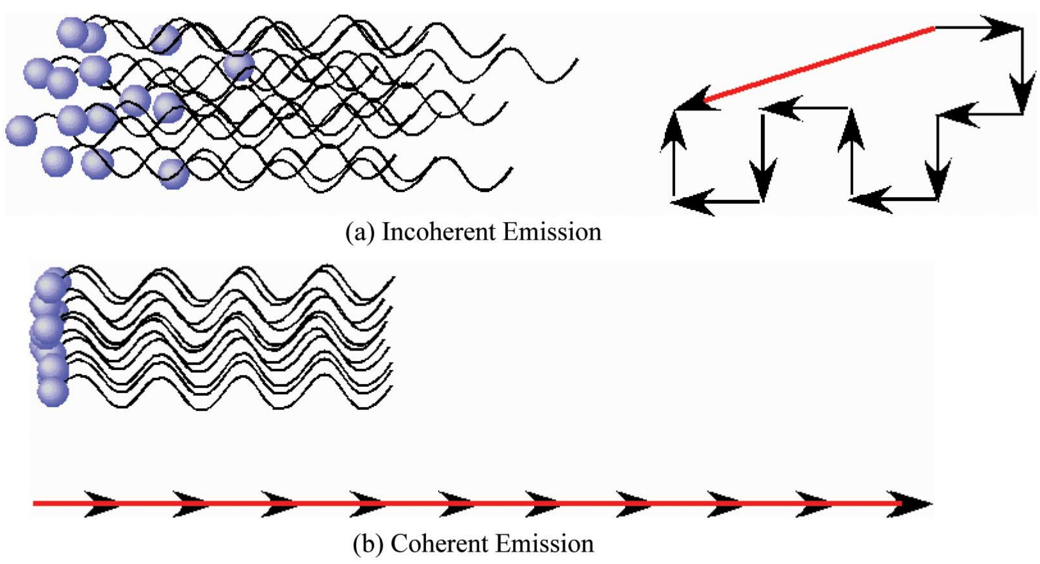


**Fig. 6.** *The conceptualization of the radiation emission and addition of phases for both: (a) incoherent and (b) coherent emission from an ensemble of electrons.*

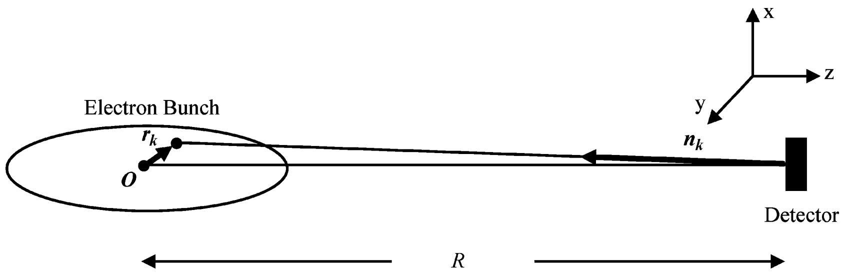


**Fig. 7.** *Radiation intensity seen at the detector for a bunched electron beam.*

and the total intensity is

$$I_{\text{tot}}(\lambda) = I_1(\lambda)\left(\sum_{k=1}^{N}\cos\left(\frac{2\pi}{\lambda}\mathbf{n_k}\bullet\mathbf{r_k}\right)\right)^2 \quad (13)$$

$$= I_1(\lambda)N + I_1(\lambda) \times \left(\sum_{j\neq k}^{N}\cos\left(\frac{2\pi}{\lambda}(\mathbf{n_k}\cdot\mathbf{r_k} - \mathbf{n_j}\cdot\mathbf{r_j})\right)\right)^2 \quad (14)$$

where the first term is the incoherent term and the second is the coherent term.

If we assume a normalized distribution symmetric about the origin, the total intensity becomes

$$I_{\text{tot}}(\lambda) = I_1(\lambda)[N + N(N-1)f(\lambda)] \quad (15)$$

$$I_{\text{tot}}(\lambda) = I_{inc}(\lambda)[1 + (N-1)f(\lambda)] \quad (16)$$

where

$$I_{inc}(\lambda) = NI_1(\lambda) \quad (17)$$

is the total incoherent intensity emitted by the bunch of $N$ particles and (replacing the sum in (14) with an integral)

$$f(\lambda) = \left|\int dz\cos\left(\frac{2\pi}{\lambda}z\right)S(z)\right|^2 \quad (18)$$

is the form factor for the normalized bunch distribution $S(z)$, where we have assumed that the detector is located at a distance much larger than the length of the electron bunch. As an example, we examine the Argonne system where we assume a Gaussian form factor that is given by

$$S(z) = \frac{\exp\left[-(z/\sigma_z)^2\right]}{\pi^{1/2}\sigma_z} \quad (19)$$

where

$$f(\lambda) = \exp\left(\frac{-\alpha^2}{2}\right) \quad (20)$$

and

$$\alpha = 2\pi\sigma_z/\lambda. \quad (21)$$

For the electron beam parameters listed in Table 1, corresponding to the ANL system except the repetition rate of the radiofrequency source, we can calculate the integrated coherent and incoherent contributions to the intensity, 120 mW and 283 pW, respectively, as seen in Fig. 8.

### D. Undulator Emission

Further enhancement centered at a specific frequency can be achieved by using multiple, evenly spaced, equal strength, alternating field magnets—undulators or wiggler magnets. The resonant wavelength for the output radiation is given by [41]

$$\lambda_{\text{rad}} = \frac{\lambda_o}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad (22)$$

where $\gamma$ is again the normalized electron beam total energy, $\lambda_0$ is the spatial period of the undulator, and the

Table 1 Hypothetical Parameters of a Table-Top Device Based on the Performance of the Argonne Source

| *Parameter* | *Value* |
|---|---|
| $\gamma$ | 5 |
| **Electron Beam Energy (MeV)** | 2.6 |
| **$\sigma_z$ (μm)** | 50 |
| **Charge per Bunch (pC)** | 100 |
| **Useful duration of RF pulse (μs)** | 2 |
| **RF Frequency (MHz)** | 2856 |
| **RF repetition rate (Hz)** | 60 |
| **Radius of Curvature (cm)** | 1 |
| **Magnetic Field (T)** | 0.9 |

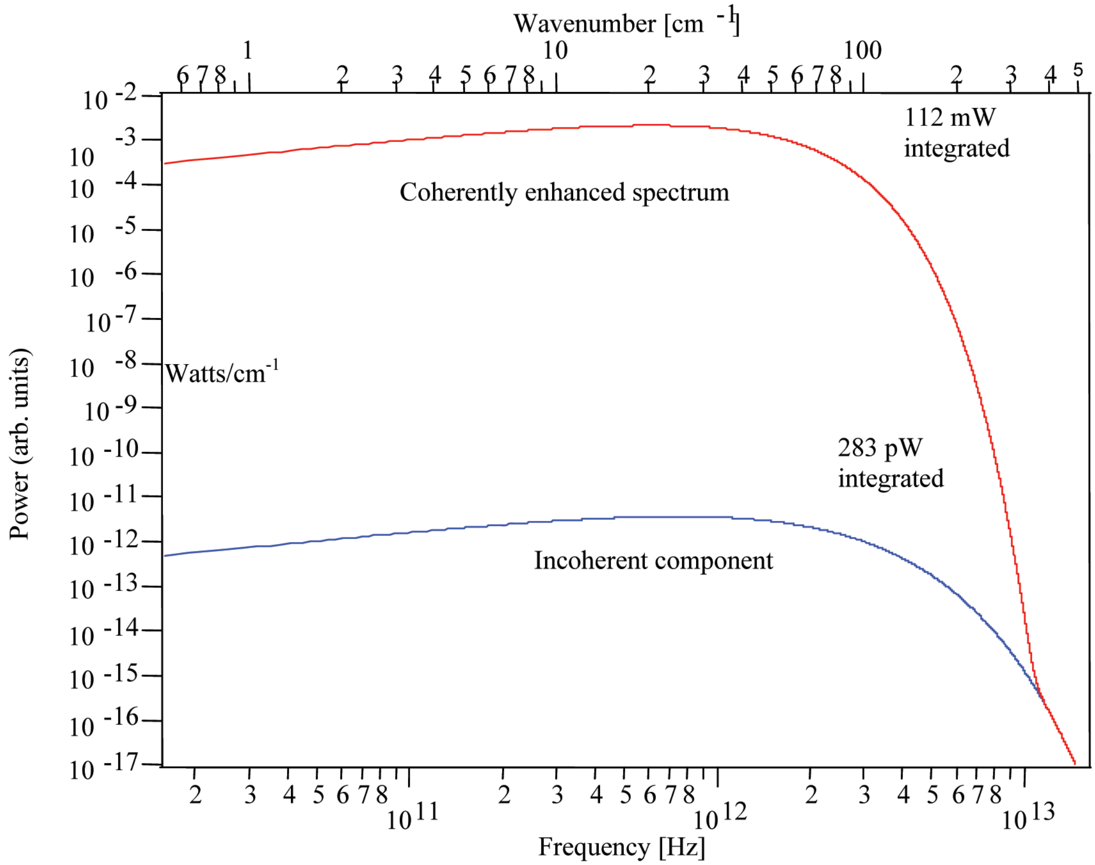


**Fig. 8.** *Comparison of coherent and incoherent synchrotron radiation (see Table 1 for beam characteristics).*

normalized undulator parameter is

$$K = 0.934\lambda_o[\text{cm}]B_{max}[T]. \quad (23)$$

The ENEA system has and the Argonne system will be installing undulators with near identical characteristic parameters—$K = 1$, $\lambda_0 = 2.5$ cm. The ENEA system has a 16 period device, whereas the TEUFEL undulator, on loan from the University of Twente to Argonne [42] is a 50 period device. The integrated intensity for the Argonne case for the electron beam parameters in Table 1 in conjunction with the TEUFEL undulator is shown in Fig. 9. By shifting the electron beam energy or adjusting the gap on the undulator, the central frequency can be adjusted.

## V. EXPERIMENTAL RESULTS

In the Argonne system, we have measured the emission using two generating methods: coherent synchrotron radiation and coherent transition radiation. Measurements of the coherent transition radiation, made with a pyroelectric detector, can be seen in Fig. 10. On the left, we see that the spatial distribution clearly exhibits the lobe structure characteristic of transition radiation. Radiated power as a function of time is shown on the right. Here, the beam is being generated by a nanosecond-pulse laser with a repetition rate of 6 Hz. Ten watts of transition radiation power were produced in the macropulse, or a time-average power of 64 mW. The introduction of cathode laser emission gating increased the beam currents by a factor of 100, leading to peak THz powers around a MW not compensating for losses through the system.

In the ENEA FEL-CATS we have measured the dependence of the emitted power as a function of the relative phase between linac and phase modulation device (PMD) and compared it with the predicted behavior discussed in [37], as shown in Fig. 11. The experimental data fit quite well the theory for decelerating (negative) values of the phase, while the measured emission is generally higher than the calculated one at accelerating values of the phase. This could be due to the presence of harmonics of the fundamental frequency not yet included in the model.

A maximum emitted power of about 1.5 kW in a 5-$\mu$s pulse duration has been measured at the peak of the phase-tuning curve when the RF field in the PMD ($E_{\text{PMD}}$) was set

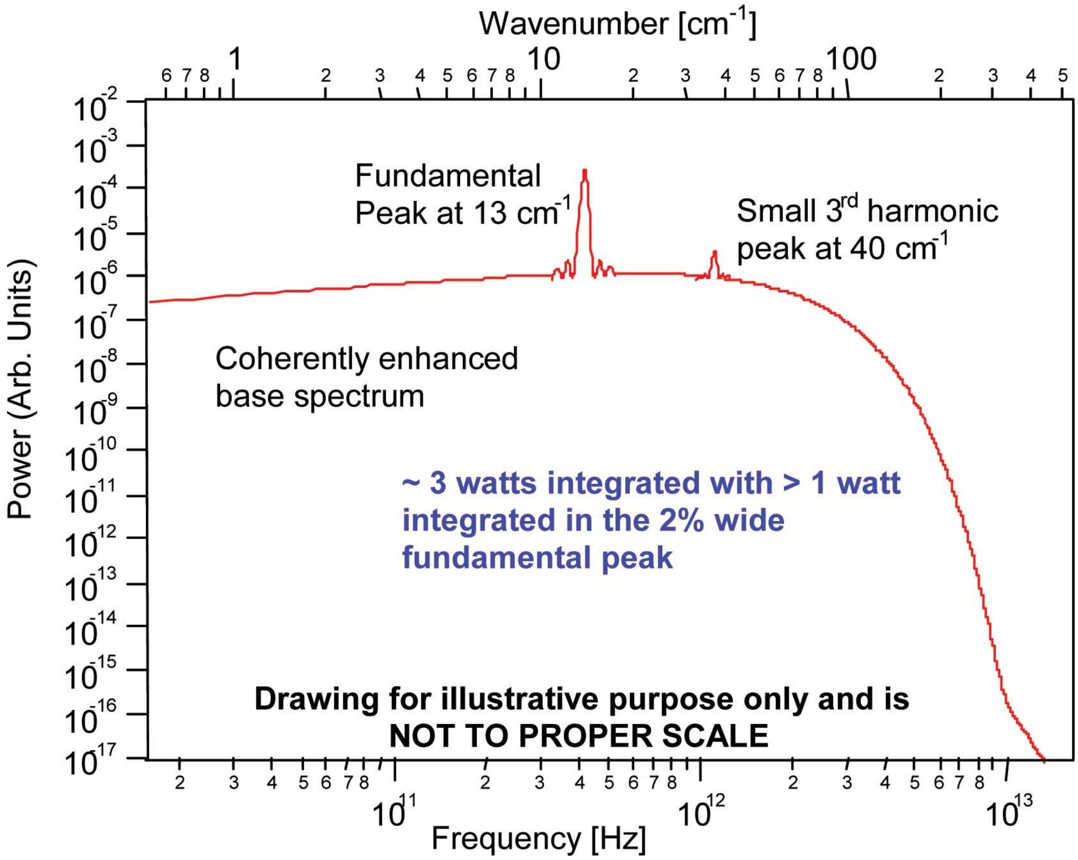


**Fig. 9.** ***Intensity of the undulator emission of the Argonne compact THz system.***

to about 0.5 the field in the linac ($E_{\text{linac}}$). The central wavelength of the emission in these operating conditions is 760 $\mu$m (0.4 THz). Lowering the RF field in the PMD to a value $E_{\text{PMD}} = 0.2\ E_{\text{linac}}$ does not change the position of the central frequency, confirming that the mean electron energy is unchanged at zero crossing. The intensity of the emitted radiation at $E_{\text{PMD}} = 0.5\ E_{\text{linac}}$ is, however, about a factor 50 higher than the one at $E_{\text{PMD}} = 0.2\ E_{\text{linac}}$ [36]. This is ascribed to the higher correlation in phase of the field radiated by the electrons in the bunch, which has been produced by a rotation of the particle distribution in the longitudinal phase space.

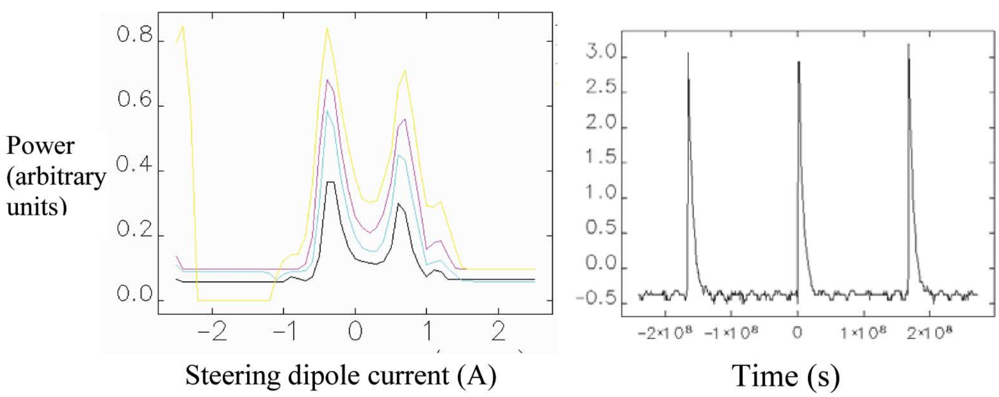


**Fig. 10.** ***The Argonne system measurements. (Left) Transition radiation lobe signal (arbitrary units) made apparent by electron beam steering. (Right) Terahertz signal (arbitrary units) versus time (ns).***

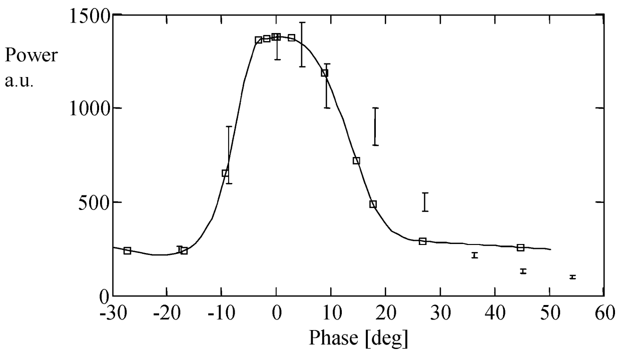


**Fig. 11.** *Output THz power versus relative phase of the ENEA electron gun and phase modulation section.*

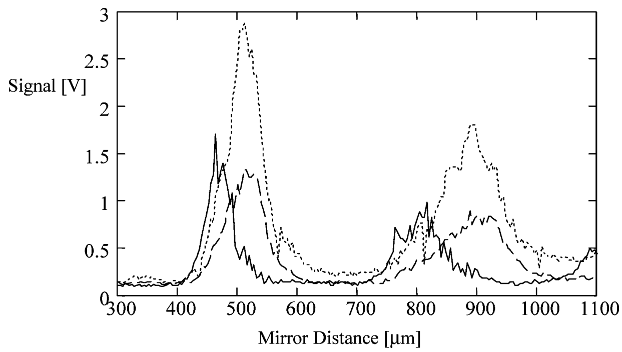


**Fig. 12.** *FP Interferograms of the ENEA FEL-CATS THz emission as a function of the relative phase of the varied PMD to the gun.*

A Fabry-Pérot (FP) interferogram of the emitted radiation showed a well-shaped spectrum with a relative bandwidth of about 10% (dotted line of Fig. 12). Easy and reproducible wide band tunability of FEL-CATS has been achieved by varying the phase in the PMD as it is shown in Fig. 11, where three interferograms demonstrate operation between 600 $\mu$m and 800 $\mu$m (0.4–0.5 THz).

As the phase is varied, the requirement on the energy-phase correlation is gradually released and the mean kinetic energy of the e-beam is either increased or decreased. This results in the emission at a different frequency and, in general, at a lower power level, as it is observed from the graphs. Further tunability up to 0.7 THz ($\lambda = 450\ \mu$m) was obtained by increasing the power in the PMD to get an electron kinetic energy of about 3 MeV.

## VI. SUMMARY

We have provided an overview of current THz sources and then focused on the development of electron beam based THz sources that utilize methods that allow the electrons to emit in a coherent fashion over the wavelength range of interest. The basic theory of this coherent emission was given as well as examples of the power levels obtainable. Such electron beam based sources have the capability of generating many watts of average THz power and very high peak powers into a control wavelength and bandwidth. Such source can also be built compactly and so show promise of bringing such powerful THz sources to a wide range of geographically dispersed science and technology applications. ■

## REFERENCES


[1] P. Siegel, "Terahertz technology," *IEEE Trans. Microw. Theory Tech.*, vol. 50, pp. 910–927, 2002.

[2] G. P. Gallerano and S. G. Biedron, "Overview of terahertz radiation sources," in *Proc. 2004 Free-Electron Laser Conf.*, 2004, pp. 216–221.

[3] C. Biscari, Ed. (2004, Dec.). "Coherent Synchrotron Radiation in Storage Rings," *ICFA Beamdynamics Newsletter*. [Online]. *35*, pp. 20–124. Available: http://icfa-usa.jlab.org/archive/newsletter.html

[4] M. S. Sherwin, C. A. Schmuttenmaer, and P. H. Bucksbaum, Eds. (2004). *DOE-NSF-NIH Workshop Opportunities in THz Science*. [Online]. Available: http://www.sc.doe.gov/bes/reports/files/THz_rpt.pdf

[5] H. Motz, "Applications of the radiation from fast electron beams," *J. Appl. Phys.*, vol. 22, pp. 527–535, 1951.

[6] R. M. Phillips, "History of the ubitron," *Nucl. Instrum. Methods Phys. Res.*, vol. A272, pp. 1–9, 1988.

[7] D. A. G. Deacon, L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith, "First operation of a free-electron laser," *Phys. Rev. Lett.*, vol. 38, pp. 892–894, 1977.

[8] F. Ciocci, A. Doria, G. P. Gallerano, I. Giabbai, M. F. Kimmitt, G. Messina, A. Renieri, and J. E. Walsh, "Observation of coherent millimeter and submillimeter emission from a microtron-driven Cherenkov free-electron laser," *Phys. Rev. Lett.*, vol. 66, pp. 699–702, 1991.

[9] G. Doucas, M. F. Kimmitt, A. Doria, G. P. Gallerano, E. Giovenale, G. Messina, H. L. Andrews, and J. H. Brownell, "Determination of longitudinal bunch shape by means of coherent Smith–Purcell radiation," *Phys. Rev. ST Accel. Beams*, vol. 5, pp. 072802-1–072802-8, 2002.

[10] M. D. Sirkis and P. D. Coleman, "The harmodotron—A megavolt electronics millimeter-wave generator," *J. Appl. Phys.*, vol. 28, pp. 944–950, 1957.

[11] A. Doria, R. Bartolini, J. Feinstein, G. P. Gallerano, and R. H. Pantell, "Coherent emission and gain from a bunched electron beam," *IEEE J. Quantum Electron.*, vol. 29, no. 5, pp. 1428–1436, May 1993.

[12] A. Gover, F. V. Hartemann, G. P. Lee Sage, N. C. Luhmann, Jr., R.S. Zhang, and C. Pallegrini, "Time and frequency domain analysis of superradiant coherent synchrotron radiation in a waveguide free-electron laser," *Phys. Rev. Lett.*, vol. 72, pp. 1192–1195, 1994.

[13] P. Kung, H. Lihn, H. Wiedemann, and D. Bocek, "Generation and measurement of 50-fs (rms) electron pulses," *Phys. Rev. Lett.*, vol. 73, pp. 967–970, 1994.

[14] D. A. Jaroszynski, R. J. Bakker, C. A. J. van der Meer, D. Oepts, and P. W. van Amersfoort, "Coherent startup of an infrared free-electron laser," *Phys. Rev. Lett.*, vol. 71, pp. 3798–3801, 1993.

[15] G. P. Gallerano, A. Doria, E. Giovenale, and G. Messina, "Coherence effects in FEL radiation generated by short electron bunches," *Nucl. Instrum. Methods Phys. Res.*, vol. A358, pp. 78–81, 1995.

[16] J. Schmerge, J. Lewellen, Y. C. Huang, J. Feinstein, and R. H. Pantell, "The free-electron laser as a laboratory instrument," *IEEE J. Quantum Electron.*, vol. 31, no. 6, pp. 1166–1171, Jun. 1995.

[17] G. P. Gallerano, A. Doria, E. Giovenale, and A. Renieri, "Compact free electron lasers: From Cerenkov to waveguide FELs," *Infrared Phys. Tech.*, vol. 40, pp. 161–174, 1999.

[18] G. Ramian, "The new UCSB free electron laser," *Nucl. Instrum. Methods Phys. Res.*, vol. A318, pp. 225–229, 1992.

[19] A. Gover *et al.*, "Radiation measurements in the new tandem accelerator FEL," *Nucl. Instrum. Methods Phys. Res.*, vol. A528, pp. 23–27, 2004.

[20] K. W. Berryman, E. R. Crosson, K. N. Ricci, and T. I. Smith, "Coherent spontaneous radiation from highly bunched electron beams," *Nucl. Instrum. Methods Phys. Res.*, vol. A375, pp. 526–529, 1996.

[21] A. F. G. van der Meer, "FELs, nice toys or efficient tools?" *Nucl. Instrum. Methods Phys. Res.*, vol. A528, pp. 8–14, 2004.

[22] R. Prazeres, F. Glotin, and J. M. Ortega, "New results of the 'CLIO' infrared FEL," *Nucl. Instrum. Methods Phys. Res.*, vol. A528, pp. 83–87, 2004.

[23] P. Michel *et al.*, "First lasing of the ELBE Mid-IR FEL," in *Proc. 2004 Free-Electron Laser Conf.*, 2004, pp. 8–13.

[24] Y. U. Jeong *et al.*, "First lasing of the KAERI compact far-infrared free-electron laser driven by a magnetron-based microtron," *Nucl. Instrum. Methods Phys. Res.*, vol. A475, pp. 47–50, 2001.

[25] V. P. Bolotin *et al.*, "Status of the novosibirsk terahertz FEL," in *Proc. 2004 Free-Electron Laser Conf.*, 2004, pp. 226–228.

[26] G. L. Carr, M. C. Martin, W. R. McKinney, K. Jordan, G. Neil, and G. P. Williams, "High-power terahertz radiation from relativistic electrons," *Nature*, vol. 420, pp. 153–156, 2002.

[27] H. Tamada *et al.*, "Features of the compact photon storage ring," *Nucl. Instrum. Methods Phys. Res.*, vol. A331, pp. 566–571, 1993.

[28] M. Abo-Bakr, J. Feikes, K. Holldack, G. Wüstefeld, and H. W. Hübers, "Steady-state far-infrared coherent synchrotron radiation detected at BESSY II," *Phys. Rev. Lett.*, vol. 88, p. 254 801, 2002.

[29] G. L. Carr, S. L. Kramer, J. B. Murphy, R. P. S. M. Lobo, and D. B. Tanner, "Observation of coherent synchrotron radiation from the NSLS VUV ring," *Nucl. Instrum. Methods Phys. Res.*, vol. A463, pp. 387–392, 2001.

[30] J. M. Byrd *et al.*, "Observation of broadband self-amplified spontaneous coherent terahertz synchrotron radiation in a storage ring," *Phys. Rev. Lett.*, vol. 89, p. 224 801, 2002.

[31] A. Doria, V. B. Asgekar, D. Esposito, G. P. Gallerano, E. Giovenale, and G. Messina, "Long wavelength compact-FEL with controlled energy-phase correlation," *Nucl. Instrum. Methods Phys. Res.*, vol. A475, pp. 296–302, 2001.

[32] S. Biedron, J. W. Lewellen, and S. V. Milton, U.S. Patent Application.

[33] J. G. Neumann, P. G. O'Shea, D. Demske, W. S. Graves, B. Sheehy, H. Loos, and G. L. Carr, "Electron beam modulation using a laser-driven photocathode," *Nucl. Instrum. Methods Phys. Res.*, vol. A507, pp. 498–501, 2003.

[34] G. L. Carr, private communication, 2004.

[35] W. P. Leemans *et al.*, "Observation of terahertz emission from a laser-plasma accelerated electron bunch crossing a plasma-vacuum boundary," *Phys. Rev. Lett.*, vol. 91, p. 074 802, 2003.

[36] A. Doria, G. P. Gallerano, E. Giovenale, G. Messina, and I. Spassovsky, "Enhanced coherent emission of THz radiation by energy-phase correlation in a bunched electron beam," *Phys. Rev. Lett.*, vol. 93, p. 264 801, 2004.

[37] A. Doria, G. P. Gallerano, E. Giovenale, S. Letardi, G. Messina, and C. Ronsivalle, "Enhancement of coherent emission by energy-phase correlation in a bunched electron beam," *Phys. Rev. Lett.*, vol. 80, pp. 2841–2844, 1998.

[38] J. D. Jackson, *Classical Electrodynamics*, 2nd ed. New York: Wiley, 1975, p. 672.

[39] I. Frank and V. Ginsburg, "Teoriya perekhodnogo izlucheniya (Theory of transition radiation)," *J. Phys. (Moscow)*, vol. 9, pp. 353–362, 1945.

[40] J. S. Nodvick and D. S. Saxon, "Suppression of coherent radiation by electrons in a synchrotron," *Phys. Res.*, vol. 96, pp. 180–184, 1954.

[41] M. W. Poole *et al.*, "Development of an undulator for the SRS," *Nucl. Instrum. Methods Phys. Res.*, vol. 208, pp. 143–148, 1983.

[42] P. van der Slot, Univ. Twente, private communication.


## ABOUT THE AUTHORS

**Sandra G. Biedron** (Senior Member, IEEE) is the Director of the Department of Defense (DOD) Project Office in Applied Science and Technology Associate Laboratory Directorship of Argonne National Laboratory and is an Associate Director of the Argonne Accelerator Institute, Argonne, IL. She is also participating on the FERMI project at Elettra at Sincrotone Trieste as a consultant. She is a physicist whose main research is in beam and laser source development and use. She is cross trained in chemistry, biology, and electrical engineering. She was one of the team members who proved the SASE FEL concept in the visible to VUV wavelengths. Biedron was also the ANL representative and participant on the BNL/ANL high-gain harmonic generation FEL experiment. She has been involved with electron guns for over 12 years and was the first in the world to predict and measure the nonlinear harmonic growth on two types of high-gain free-electron lasers—an important component of many new FEL projects worldwide. She has managed and led the international work-group FEL Exotica for over eight years that examines exotic beam and photon schemes, including exotic undulator designs. Biedron is a member of the Leadership Circle of the SPIE, the Education Committee, and was chair of the Scholarships and Grants Committee for two years. She served as the Secretary and Treasurer of the Chicago Section, Nuclear and Plasma Sciences/Magnetics Society, and served on the Program Committee of the 2003 Particle Accelerator Conference jointly sponsored by the IEEE and APS. Since 2005, she is the Particle Accelerator Science and Technology Elected Representative to the Nuclear Plasma and Sciences Society of the IEEE. She has served on a variety of international program and organizing committees and has organized a number of conferences, workshops, and plenary sessions.

**John W. Lewellen** (Member, IEEE) is the Deputy Director and Beam Physics Lead for the Department of Defense (DOD) Project Office in the Applied Science and Technology Associate Laboratory Directorship of Argonne National Laboratory, Argonne, IL. His current interests include novel injectors such as the ballistic bunch compression electron gun, rf gated electron sources, high-efficiency photocathode materials, electron beam transport, bunch compression, undulator design,and optical radiation transport, and diagnostics development, coherent synchrotron radiation, beam transport, and long-wavelength radiation production, compact, far-infrared FELs (design and operation), high-efficiency undulator for mid-IR FELs, and variable-period undulators for use with x-ray storage rings. He holds two patents on advanced electron gun and undulator designs, and has several other patents pending in the fields of beam generation, As part of the SASE-FEL experimental program at APS.

**Stephen Val Milton** received the Ph.D. degree in physics from Cornell University, Ithaca, NY.

Before his arrival at Argonne National Laboratory (ANL), Argonne, IL, he worked at the Paul Scherrer Institute, Villigen, Switzerland, as well as Bell Laboratories in Murray Hill, NJ. When first arriving at ANL in 1992, he was manager of the 19M USD Injector Synchrotron at the Advanced Photon Source. He led the low-energy undulator test line efforts from 1996 until 2002. This project demonstrated for the first time a self-amplified spontaneous emission free-electron laser operation at saturation in the visible to ultraviolet regimes. He was promoted to ANL Senior Scientist in 2002 after serving as group leader for Accelerator Physics for six years. He is presently an employee of Argonne National Laboratory on a leave of absence and is currently serving as the FERMI free-electron laser project director at Sincrotrone Trieste, Trieste, Italy. Before this he was the Linac Coherent Light Source Director, Argonne National Laboratory (ANL), responsible for the delivery of a 55M USD undulator system to the Stanford Linear Accelerator Center. He is an Adjunct Professor at Lund University in Sweden.

Dr. Milton is a Fellow of the American Physical Society. He was awarded the 2003 Particle Accelerator Science and Technology Award, IEEE, Nuclear and Plasma Sciences Division, and the 1996 Award for Distinguished Performance, Argonne National Laboratory. He has served on a number of committees, including serving as the Program Committee Chairman for the 2002 International Free-Electron Laser Conference; Editor for the 2002 International Free-Electron Laser Conference; Chairman, International Machine Advisory Committee, Australian Synchrotron Project; Member, Steering Committee, Center for Accelerator Physics, Brookhaven National Laboratory; Member, Accelerator Advisory Committee, Fermi National Accelerator Laboratory. He is also a reviewer for *Physical Review—Special Topics*; *Applied Physics Letters*; *Journal of the Optical Society of America*; and the National Science Foundation; and the Civilian Research and Development Foundation.

**Nachappa "Sami" Gopalsami** (Senior Member, IEEE) received the B.E. and M.S. degrees in electrical engineering from the University of Madras, India, and the Ph.D. degree in electrical engineering and computer science from the University of Illinois, Chicago.

He joined Argonne National Laboratory, Argonne, IL, in 1980 where he is currently a Senior Electrical Engineer in the Sensors and Instrumentation section of the Nuclear Engineering Division. He has published over 150 technical papers in the area of sensors and NDE and has four U.S. patents to his credit. His current research interests include development of radio frequency, microwave, millimeter-wave, and terahertz sensors and imaging systems for national security, biosensing, environmental monitoring, and materials applications.

Dr. Gopalsami is a member of Sigma Xi and SPIE. He has received an R&D 100 award from the Research and Development Magazine; an outstanding paper award from the American Society of Nondestructive Testing; and an Outstanding Mentor award from the DOE Office of Science Undergraduate Research Programs.

**John F. Schneider** received the B.S. degree in chemistry from Elmhurst College, Elmhurst, IL, and the M.S. degree in analytical chemistry from Northern Illinois University, DeKalb.

He is the Analytical Capabilities Lead for the Department of Defense (DOD) Project Office in the Chemistry Division of Argonne National Laboratory, Argonne, IL. He has been at ANL for 21 years. His team is involved in analytical method development; environmental analysis, field and process analytical method development; and developing new field sampling and analytical procedures. He has authored over 40 journal articles and technical reports. His technical interests include environmental sampling and analysis, chemical sensor development, field analytical chemistry, gas chromatography (GC), GC/IR, GC/MS, FTIR, solid phase microextraction (SPME), Chemical warfare agent analysis, and X-ray fluorescence analysis for metals in the field.

Mr. Schneider is a member of the American Chemical Society and the Chicago Chromatography Discussion Group.

**Laura Skubal** received the B.S. degree in environmental engineering from Northwestern University, Evanston, IL, the M.S. degree in environmental engineering from the University of Illinois, Champaign, and the Ph.D. degree in environmental engineering from Pennsylvania State University, State College.

She is the Novel Sources Lead for the Department of Defense (DOD) Project Office in the Chemistry Division of Argonne National Laboratory, Argonne, IL. Her work has focused upon the development of novel processes for environmental cleanup and contaminant detection. Recently she has developed a novel photocatalytic wastewater treatment. Her research is the first published effort to demonstrate that cadmium could be photochemically reduced by titanium dioxide. Her work in sensor technology has led to the development of electrocatalytic sensors for field use. She has research interests in environmental remediation to remove organics, tritium, and chemical agents from soil, identifying heavy metal contamination in chemical warfare agents, and terahertz radiation for contamination detection.

**Yuelin Li** received the Ph.D. degree in physics at Shanghai Institute of Optics and Fine Mechanics, China.

He was a Visiting Scientist or Postdoctoral Research Scientist at a number of research institutions including Lawrence Livermore National Laboratory, Rutherford-Appleton Laboratory in Great Britain, and Max-Planck Institute for Quantum Optics (MPQ) in Germany. He is currently a Physicist at Accelerator Systems Division of Argonne National Laboratory, Argonne, IL. Over the years he has made contributions in short wavelength coherent radiation source development and related laser plasma physics. His current research is focused on application laser techniques in accelerator R&D, including laser-electron beam interactions, electron beam diagnostics, laser pulse shaping, and associated beam dynamics in a photoinjector.

**Mathew Virgo** (Member, IEEE) is working toward the Ph.D. degree at the University of Maryland, College Park.

He was a student at the University of Maryland, where he determined the photoemissive properties of dispenser cathodes and designed and built an evaporation system for fabricating semiconductor photocathodes. He is currently an Electrical Engineer in the Energy Systems Division at Argonne National Laboratory, Argonne, IL. He works closely with the Department of Defense (DOD) Project Office in Applied Science and Technology Associate Laboratory Directorship of Argonne National Laboratory. He is currently involved with cathode investigations for a high-average power electron gun project for the Office of Naval Research and the Department of Defense's Joint Technology Office.

**Gian Piero Gallerano** received the Ph.D. degree in physics from the University of Rome, Italy, in 1980.

He is a Senior Staff Member at ENEA, Rome, Italy. He is the scientist in charge of the ENEA participation in the EUROFEL program. His current interests include generation of THz radiation and its application in the biological, biomedical and environmental fields, THz imaging techniques, coherent emission from RF modulated electron beams, free electron lasers and their applications, spectroscopy of solid-state and biological materials, solid-state lasers, design of optical resonators, and diagnostics in the infrared. He is responsible for the "TERAHERTZ" project at the Department of Physics Technologies and New Materials—ENEA Research Center—Frascati, Italy and for the realization of the Compact Advanced THz Source, FEL-CATS (0.4–0.7 THz). As coordinator of the European project THz-BRIDGE in the frame of the "Quality of Life" program of the EU, he led researchers at ten research institutes in the study the interaction of THz radiation with biological systems. He has authored more than 90 refereed papers and has served on many international scientific committees including being a member of the International Organizing Committee of the Infrared and Millimeter Wave & Terahertz Conference since 2005.

Dr. Gallerano has been a member of the Italian Physical Society since 1981.

**Andrea Doria** received the Laurea degree in physics from the University of Rome, Italy, in 1987.

He has been a Permanent Staff Member of the experimental free electron laser (FEL) group of ENEA, Frascati, Italy, since 1988. His research interests are Cerenkov based FELs, compact FEL sources in the millimeter and far IR regions, and coherence and correlation effects on FEL power output. He collaborated in designing and operating user application experiments on THz interaction with biological systems, using the compact FEL sources of ENEA. He recently joined the ENEA group of the SPARC/SPARX projects for the realization of a VUV and soft X-ray FEL operating in SASE and external-seeding regime. He is coordinating the group for the radiation diagnostics, but he is also involved in the magnetic undulator design and measurements.

**Emilio Giovenale** received the Laurea degree in physics, from the University of Rome La Sapienza, Italy, in 1988.

He has been a Permanent Staff Member at ENEA, Frascati, Italy, since 1990. Since 1992 he has been a Staff Member of the experimental Free Electron Laser (FEL) group of ENEA. Since 1996 he has also been Contract Professor in the Physics Department of the University of Rome Tre, Italy. His first research activities included solid-state lasers and solid-state physics, compact FEL sources, operating in the THz spectral region, and theories related to the optimization of the performances for such long wavelength sources (coherent emission and energy-phase correlation). He contributed to the realization of user experiments using the ENEA compact FEL, in the fields of FEL physics, solid-state physics, and, more recently, in the field of biology and medicine. He is part of the ENEA group that is involved in the SPARC/SPARX projects for the realisation of a VUV and soft X-ray FEL operating in SASE and external-seeding regime, working mainly on controls, diagnostics, and undulator measurements.

**Giovanni Messina** was born in Trapani, Italy, on May 4, 1948, He received the Laurea degree in physics from the Physics Institute of Pisa University, Italy, in 1973.

He has held a permanent position since 1979 as Researcher at ENEA, Frascati, Italy, on the staff of the electron accelerators laboratory, devoted to the development of accelerator based systems (microtrons and linacs) for FEL, medical, and other scientific applications.

**Ivan Panov Spassovsky** received the Ph.D. degree in physics from the University of Sofia, Bulgaria.

He gained several years of experience (1992–1993 and 1998) in the Plasma Physics Laboratory at the Instituto Nacional de Pesquisas Espaciais (INPE), Brazil. There he was involved in research and development of 35 GHz gyrotron. Later in 1995 he moved to Korea where he had a two-year contract with the Laboratory for Quantum Optics at the Korean Atomic Energy Institute (KAERI). At KAERI he participated the construction of microtron driven far infrared free electron laser. He joined the Institute for Plasma Research of the University of Maryland in 1999 as a Visiting Researcher and worked there until 2002 on the experimental evaluation of second harmonic gyroklystron. He is currently a Researcher in the Free Electron Laser Laboratory at ENEA Research Centre, Frascati, Italy. His earlier research at Sofia was concentrated on the physics and applications of intense electron beams and high-power microwaves. His major research interests focus on development of terahertz free electron laser. He participates also the SPARC project which is a first stage of R&D activity towards X-rays FEL sources.