

# EMERGING CONCEPTS, TECHNOLOGIES AND OPPORTUNITIES FOR MEZZO-SCALE TERAHERTZ AND INFRARED FACILITIES\*

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## Abstract

Recent advances in high-current particle beam, bright photoinjector, laser and radiofrequency technologies, combined with innovative techniques such as energy recovery and laser-slicing of particle beams, have opened up new scientific opportunities with terahertz and infrared sources. They present new scientific frontiers not just in sources but in basic research applications involving timescale measurements and investigations at the quantum level. Such long-wavelength sources complement high-energy, short-wavelength x-ray sources by allowing collective processes and their ‘function’ in complex systems to be probed in a fashion complementary to probing ‘structure’ via x-rays. This paper outlines and gives examples of the scientific reach of such sources and discusses some actual and envisioned facilities worldwide. Such facilities fall in the mezzo-scale category, bracketed by tabletop lasers and large synchrotrons. They offer unique and directed advances in life, materials and other sciences.

## INTRODUCTION

A particle beam’s usefulness can go far beyond its mere ‘directed’ momentum and energy. Beams can provide bursts of energy in pulses suitably packaged in space and time, and can thereby serve emerging dynamic fields beyond conventional particle/nuclear physics and synchrotron radiation sciences; e.g., high-field atomic and molecular physics, laboratory astrophysics, biomedical instrumentation, and nano- and bio-sciences. A relativistic electron beam can be manipulated to produce pulses of electromagnetic waves from a picosecond to an attosecond in duration, and used to study features from a few micrometers to a few nanometers with wavelengths that can probe with submillimeter to atomic resolution. Facilities producing such probes for research require a combination of particle/light beam and microwave/optronics/photonics technologies. In these facilities, the brightness, space-time structure, polarization, coherence, and the concurrent usability of diverse but synchronized multiple pulses are critical. This paper briefly overviews several such facilities—actual, under construction, or proposed—with special attention to the underexploited far-infrared realm of terahertz radiation [1], which lies at the interface between electronics and photonics.

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## REPRESENTATIVE MEZZO-SCALE LONG-WAVELENGTH FACILITIES

Infrared and terahertz facilities are based on multiparticle coherent emission (called “super-radiance” by laser scientists) from relativistic electrons in short bunches [1,2] produced by linacs [3], energy-recovering linacs [4,5,6,7] or storage rings operated in a new mode [8] and often assisted with powerful lasers to manipulate electron beams in phase space [9]. Normalized spectral curves, independent of particular facilities, but depending only on bunch length and charge, are plotted in Figures 1(a) and 1(b).

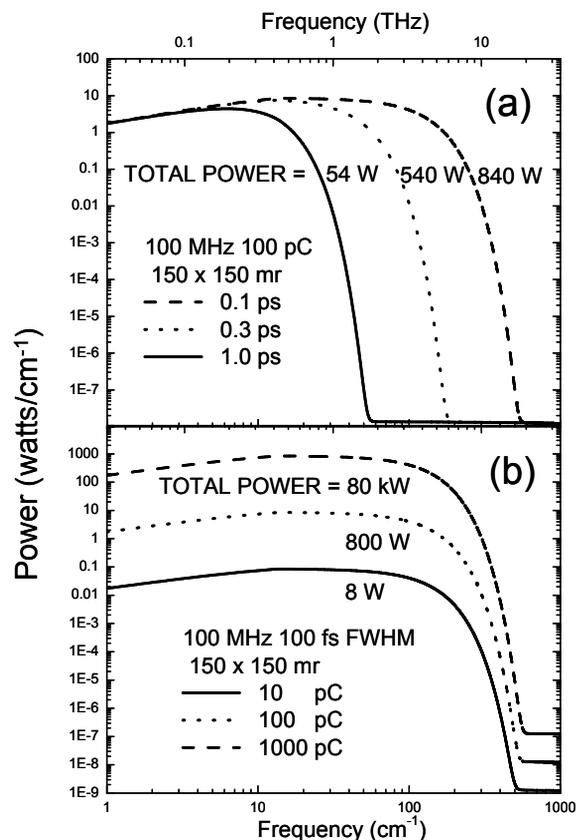


Figure 1(a,b): THz Spectra vs. bunch length and charge.

In the following we will describe first, as category A, two existing facilities which provide THz light: the free-electron laser (FEL) at the University of California at Santa Barbara (UCSB) and the Source Development Lab at Brookhaven National Laboratory.

We then describe, as category B, three emerging facilities: the existing and continually evolving Jefferson Lab FEL/ERL [4,5], the planned Daresbury 4GLS ERLP [6] and the Cornell ERL prototype [7], all based on the novel energy-recovering linac scheme. In these facilities mutual two-way exchange of energy between charged particle bunches and radiation waves in a continuous mode allows for higher average beam currents and hence radiation power for the same installed wall-plug power. Further, in addition to orders of magnitude higher average powers and fluxes, these facilities promise to have ultrashort femtosecond-scale pulse lengths and intrinsically high peak brightnesses compared to conventional third-generation light sources. In the infrared/THz domain, the light is also substantially coherent both temporally and transversely, the particle-beam phase-space volume being smaller than or comparable to the radiation phase-space volume determined by its wavelength cubed.

The final class of facilities, category C, use the conventional storage ring in novel ways: as a very low momentum compaction magnetic lattice to achieve very short bunches for coherent THz emission from an electron beam (the BESSY-II ring in Berlin) [8] or by a specially designed compact circular ring with short pulses, enhanced even further via laser-pulse slicing techniques (as in the proposed CIRCE ring at Berkeley) [9].

### **A 1. UCSB FEL**

UCSB's Center for Terahertz Science and Technology uses FELs as narrowband sources of tunable, coherent, kilowatt-scale far-infrared radiation [3]. The MM-FEL delivers light from 2.5 mm to 338  $\mu\text{m}$  (0.12 to 0.89 THz) at peak powers from 1 to 15 kW and pulse lengths from 1 to 6  $\mu\text{s}$ . The FIR-FEL delivers light from 338 to 63  $\mu\text{m}$  (0.89 to 4.76 THz) at peak powers from 1 to 6 kW and pulse lengths from 1 to 20  $\mu\text{s}$  at a pulse repetition rate up to 7.5 Hz. UCSB has also developed a third FEL to extend out to 30  $\mu\text{m}$  at the relatively low beam energy of 6 MV by lasing on the third harmonic. For these FELs, a 6 MV, recirculating electrostatic accelerator generates a high-quality 2 A beam. A separate 2 MV, cw, mm-wave FEL is expected to have unique properties, including high average power and stable, single-frequency operation, demonstrating "next generation" principles. The average power and pulse lengths are further enhanced in the Brookhaven facility described next.

### **A 2. BNL Source Development Lab**

The short-bunch linac of Brookhaven's Source Development Lab delivers a nanocoulomb per bunch, resulting in peak THz power of  $2.6 \times 10^8$  W (average power 80 W). The significant enhancement in peak and average power is achieved via a photocathode electron gun delivering up to 0.7 nC charge ( $N = 4.4 \times 10^9$  particles) per pulse. The 200 MeV linac produces "chirped" electron bunches, allowing for compression via dispersion in the dipole chicanes that follow. The THz light is produced as 'transition radiation' from mirrors

inserted into the beam, or as dipole bending magnet radiation. RMS bunch lengths as short as 300 fs produce coherent output to over 1 THz.

### **B 1. Jefferson Lab 10 kW IR-FEL**

JLab's upgraded FEL is on-line and completing commissioning as a subpicosecond, cw, >10 kW average power infrared (1–14  $\mu\text{m}$ ) source offering a combination of high repetition rate (up to 75 MHz) and high power per pulse (120  $\mu\text{J}$ ; >1 mJ with stacking cavity). The FEL operates in regimes unattainable by subpicosecond tabletop lasers, even at a specific wavelength. It builds on the successes of JLab's kilowatt-scale IR Demo FEL, which operated for scientific users from 1999 to late 2001, yielding many successful scientific experiments for the first time [10]. A program is in place to shorten the light pulses from femtoseconds to the hundreds-of-attoseconds regime to meet frontiers of time as well as high field in a fully wavelength-tunable device.

The IR Demo was the first demonstration of energy recovery from a 1–10 mA, 100 MeV-class electron beam and yielded kW-scale IR and THz light. Driving the FEL was a superconducting energy-recovering linac, or ERL. The ERL itself—using a bending magnet—produced broadband THz light over four orders of magnitude brighter than achieved anywhere before [2]. As of June 2004, the upgraded FEL's ERL had yielded another factor of 4 in THz brightness.

This FEL is the first of a new generation of accelerator-based light sources in which each electron circulates only once rather than being stored, as it would be in a typical synchrotron light source. Each electron's energy is recovered and almost immediately imparted to another electron [4, 5, 11]. The technique allows efficient transfer of energy to and fro between particles and radiation, leading to unprecedented average powers and beam brightnesses.

### **B 2. Daresbury 4GLS ERLP**

Under construction at the Daresbury Laboratory, Cheshire, U.K., is a 35 MeV ERL, the ERL Prototype [6]. It will drive an IR FEL based on the wiggler from the IR Demo FEL that has recently been upgraded at Jefferson Lab, and it will explore relevant physics and R&D issues in advance of construction of the envisioned large-scale 4GLS, a fourth-generation light-source facility comprising an ERL and a suite of FELs and spontaneous output devices. A key ERLP component is a high-brightness injector that begins with a DC photocathode gun based on the one used in the IR Demo. The ERLP radiation output will be similar to the JLab FEL/ERL, with the eventual integration of this facility into the 4GLS x-ray ERL source in mind.

### **B 3. Cornell prototype ERL**

In a manner similar to Daresbury, the Cornell High Energy Synchrotron Source (CHESS) in Ithaca, N.Y., plans to develop a high-current (100 mA), high-energy (multi-GeV) ERL-based light source facility via a first

prototyping step: a 100 MeV, 100 mA (cw) ERL delivering high-current, low-emittance beams. An important R&D challenge for scaling up the prototype is the photoinjector. Like Daresbury, Cornell is working in collaboration with Jefferson Lab.

### C 1. BESSY II

Recent innovative “low alpha” optics mode operation of the BESSY II electron storage ring in Berlin has proven the principle of the CIRCE proposal (see below) for producing broadband coherent THz light. Magnetic field adjustments were used to shorten the ring’s 5 mm bunches to 1 mm, closely corresponding to THz wavelengths. The light was delivered at an average power of 1 W and a peak power of 2 kW and enabled the first application [12].

### C 2. CIRCE at LBNL

The Coherent InfraRed Center (CIRCE) at Lawrence Berkeley National Laboratory [9] has been envisioned and designed as a 600 MeV, 1.5 GHz electron storage ring atop the booster ring of the Advanced Light Source, sharing the ALS’s injector. It is optimized for generating coherent synchrotron radiation (CSR) in the THz frequency range. Operation would include three possible modes based on trading between bandwidth and power: ultra-table CSR, femtosecond laser slicing CSR, and broadband SASE. CSR will allow CIRCE to produce an extremely high THz flux. CIRCE would be a flexible source with exciting possibilities including the possibility of synchronized multi-photon beams for electro-optic detection and exotic pump-probe experiments at 1.5 GHz repetition rates.

## OPPORTUNITIES FOR SCIENCE

This necessarily brief discussion does not exhaustively cover the burgeoning interest in mezzo-scale long-wavelength radiation sources and related accelerator developments. Just in these proceedings, for example, relevant papers appear from many laboratories worldwide, including laboratories in Singapore, Thailand and France not mentioned above. Nor is it yet even close to possible to identify every opportunity that the mezzo facilities offer for multidisciplinary scientific research. However, the science outlook for the Jefferson Lab ERL/FEL—now about to be back in operation after upgrading—does indicate the wide scope of future opportunities for such mezzo facilities generally.

The JLab facility, as a prototype of these types of facilities, supports experiments extending far outside the confined spectral regions previously available, both in photon energy and electric field. Thus nonlinear as well as linear spectral response functions can be determined for materials in equilibrium and out of equilibrium and both linear and nonlinear dynamics can be studied in the time domain using multiple photons. The FEL presents opportunities for studies of material behavior, from protein folding and protein specific function (photosynthesis, metabolic pathways) to complex materials, non-Fermi metals, superconductors, and

semiconductors. It enables studies of chemical reaction dynamics and energy partition and flow in atoms and molecules, including studies of Rydberg states. An external cavity will allow 100 pulses to be combined to increase the power per pulse at the expense of the repetition frequency. Peak electric fields are  $10^{13}$  V/m at 1  $\mu$ m wavelength. Terahertz light with fields of  $10^7$  V/m will be available from 0.1–5 THz, allowing—for the first time—nonlinear optical studies of critical materials in this regime. In condensed-matter physics an understanding of correlated effects, described by theoretical formalisms such as the Luttiger liquid formalism, can be obtained from frequency-dependent conductivity measurements for both ground and excited states. Biology profits from increasingly sophisticated measurements of protein and genomic form, but functional dynamics experiments require sophisticated tools that can tune to specific protein intramolecular vibrational modes, since these likely determine folding and functional behavior.

As this one already-operating long-wavelength facility’s research outlook suggests, for facilities designated “mezzo” in size, the reach of scientific opportunity goes far beyond that designation [13].

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