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Invited Paper

High power terahertz production from relativistic electron beams

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Abstract: Relativistic electron beams are highly suitable as generators of high power terahertz radiation. The intensity of the radiation is greatly enhanced by the γ^4 scaling of synchrotron emission. In addition it is possible to take advantage of collective effects. For wavelengths longer than an electron bunch the electric fields coherently add and the power scales in quadrature. Given that typical electron bunches in accelerator-driven relativistic electron beams contain on the order of 10^9 electrons, this enhancement factor can be significant. For single bunches of electrons undergoing transverse acceleration such as bending in a static magnetic field, the radiation is broadband and the enhancement extends in wavelength from the beampipe dimensions down to the electron pulse length [1].

Collective effects also can be enhanced in devices such as free electron lasers (FELs) where the electrons undergo microbunching at the optical (in this case terahertz) wavelength and the radiation becomes narrowband and fully coherent [2]. FELs have been around since 1977 providing not only a test bed for the physics of optics and electron/photon interactions but as a workhorse of scientific research. Recent extensions in average current by the application of energy recovery to the accelerator [2, 3] further enhance the power capability of these systems. The characteristics that have driven the development of these sources are the desire for high peak and average power, high micropulse energies, wavelength tunability, timing flexibility, and wavelength production unavailable from more conventional laser sources. Operation of FELs in the FIR to THz regime poses special challenges which have been and are being addressed at a number of facilities around the world. This talk will review the mechanisms of radiation production by relativistic electron beams both as broadband collective sources and coherent sources such as FELs. We will give status and examples of linacs and FELs operating in this regime and discuss future efforts. Applications for use of the radiation have evolved from simple imaging to complex pump probe tests of insulator/metal transitions and energy flow in organic molecules. We will also discuss the technologies for generating and controlling the IR/FIR/THz radiation and mention some of the unique applications of such sources.

Keywords: Terahertz, Free electron laser, Accelerator

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1. Introduction

The generation of radiation by accelerated electrons is well described by Maxwell's equations. In the case of relativistic electron beams substantial enhancement of the radiation occurs and is exploited in numerous light source user facilities worldwide. See Eq. 1. The power can be substantial since it is proportional to the fourth power of the beam energy.

$$\text{Larmor's Formula: Power} = \frac{3e^2a^2}{2c^3}\gamma^4 \text{ (cgs units)} \tag{1}$$

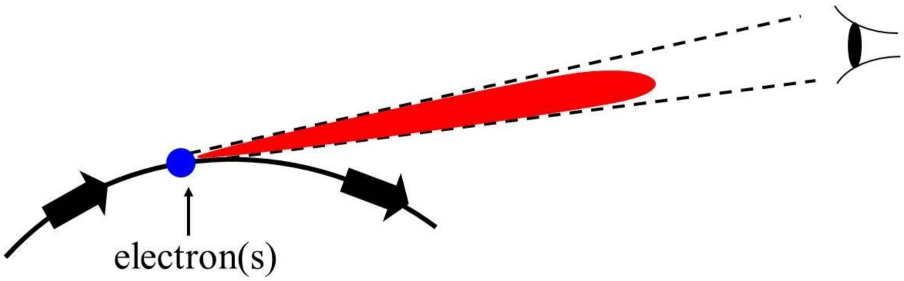


Fig. 1 Schematic illustration of relativistic electrons radiating to an observer as they are bent by a magnetic field.

A special case of interest for those involved in long wavelength radiation is the generation of terahertz radiation. The physical mechanism is easily viewed as the coherent superposition of the electric fields from individual electrons which takes place when the electron bunch is shorter than the wavelength being emitted. The process is illustrated graphically in Fig. 2. For wavelengths shorter than the electron bunch length, the electric fields of each individual radiator sum but not in a coherent fashion. The power output is therefore proportional to the total number of individual radiators. However, for wavelengths longer than the electron bunch, the electric fields of all electrons sum together.

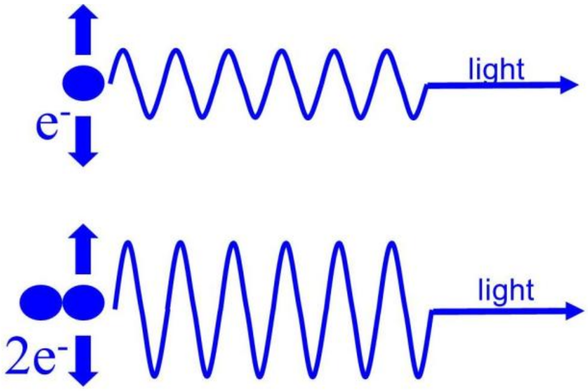


Fig. 2 Enhancement of the electric field by coherent addition of the radiated electric field vectors is illustrated for these two electrons radiating at wavelengths longer than their separation. The electric fields sum together resulting in 4 *times* the power.

Since the power goes like the square of the electric field, the power out is proportional to the square of the number of electrons. This number is quite large, on the order of 10^9. In terms of frequency space, the radiation is illustrated in Figure 3. Electron accelerators commonly produce electron bunches shorter than 1 *ps* and often accelerate nanocoulomb level charges. Coupled with electron beam energies which may be in the *GeV* range, it is easy to imagine generation of extremely high power THz photon pulses. When focused down on a material sample, electric fields in the *GV/m* range may be achievable.

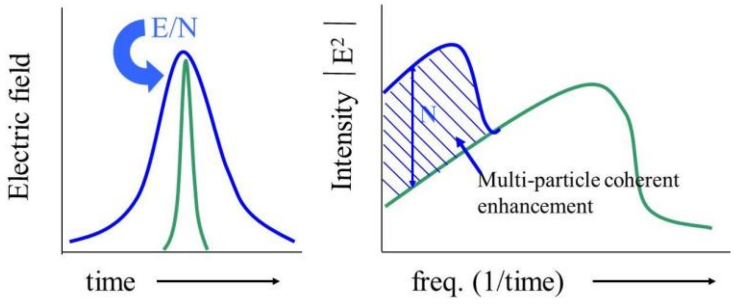


Fig. 3 Multiparticle enhancement of longer wavelength radiations is proportional to an additional factor of N, the number of electrons. It is compared to the Electric field and Intensity produced by single electrons or an ensemble of electrons radiating incoherently.

2. Experimental results for collective synchrotron emission

The first experimental demonstration of this effect confirmed the analytic predictions [1] as regards both power and polarization of the field. Radiation from the bending activity can be predicted from a number of codes and propagated if desired though the use of electromagnetic propagation codes. In the case of the Jefferson Lab Energy Recovering Linac facility [3], a dedicated optical transport line was constructed to allow the radiation's use in a User facility located outside the accelerator vault. A layout of the optical transport line is illustrated in Figure 4. Also shown are intensity distributions of the radiation at various locations through the system. A key aspect of the radiation is its broadband nature with a relatively flat spectral density from the length of the electron bunch out to the limiting aperture of the transport system. Figure 5 shows the measured and calculated image at the output.

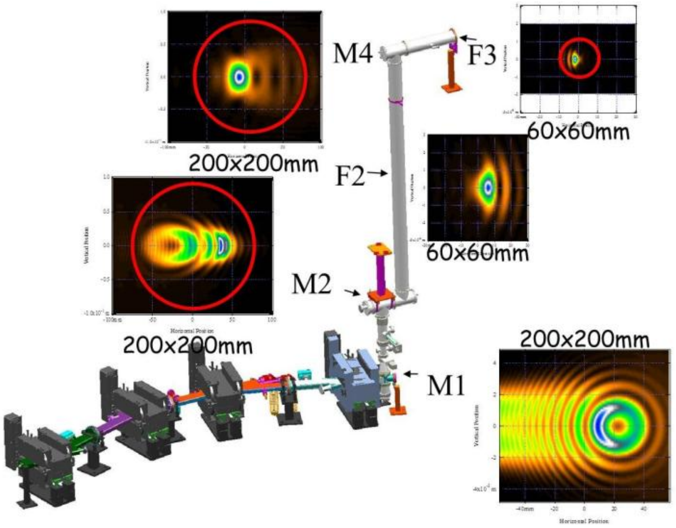
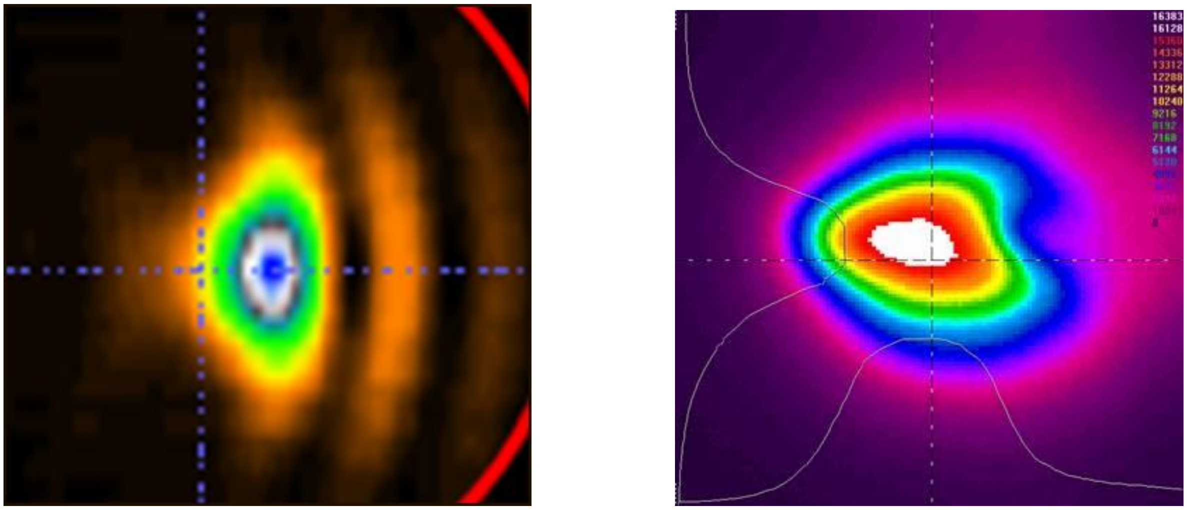


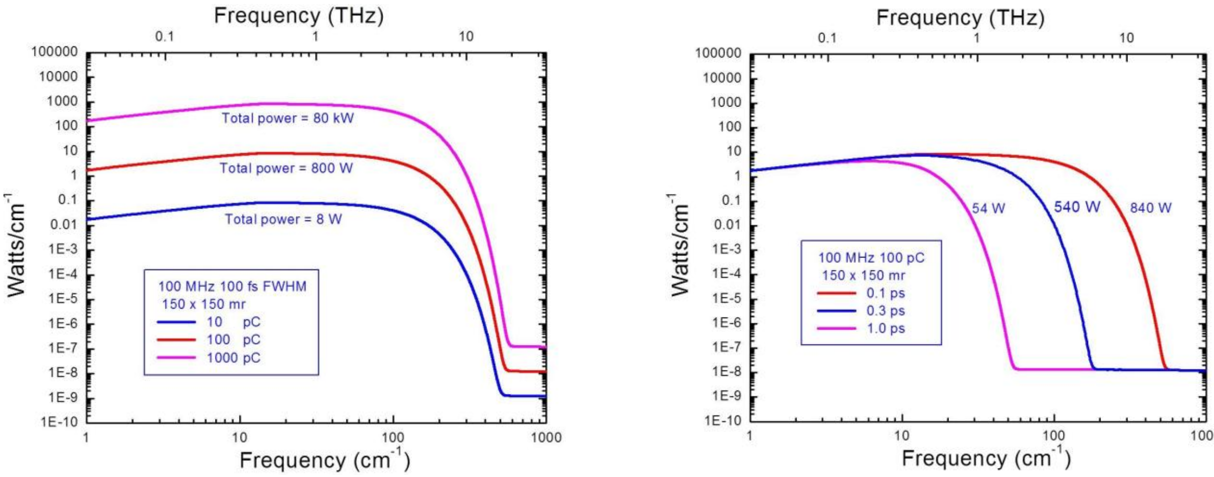
Fig. 4 An illustration of the THz optical transport line with predicted images of the THz radiation at the various mirrors and apertures through the transport.



(a) (b)

Fig. 5 a) Predicted and b) measured beam profiles at the output window of the THz transport line. The beam spot in on the order of 1 *cm* diameter.

The projected power generation of the system as a function of bunch length and bunch charge is shown in Figure 6. Measurements confirmed the power projections for the specific setup as shown in Figure 7 though the measurement is contaminated by atmospheric absorption lines. Total power in the laboratory was up to 100 *W* average in the terahertz region.



(a) (b)

Fig. 6 Projected power versus frequency as a function of a) bunch charge and b) pulse length to illustrate the dependencies. The Jefferson Lab system typically runs with 135 *pC* of charge and 300 *fs* pulse lengths though variations around these values are possible.

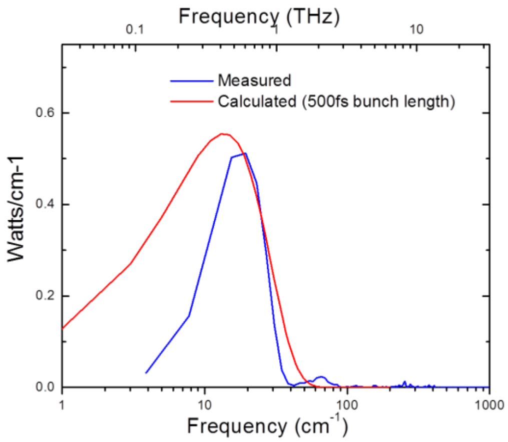


Fig. 7 Measured and calculated power versus as a function of wavenumber. The measurements were performed in air so absorption by water vapor is a factor in the measurements. Cutoff at the long wavelength end was determined by limiting apertures. From [1].

3. High power free electron lasers

Collective effects also enhance radiation in devices such as free electron lasers (FELs) where the electrons undergo microbunching at the optical (in this case terahertz) wavelength and the radiation becomes narrowband and fully coherent due to the interaction of the optical field and a static alternating magnetic field termed an undulator. The optical power builds in a resonator to saturation at which point non-linear effects resist any further microbunching of the electrons. FEL oscillators have been used to provide tunable radiation in the mm to IR region since 1977 [5, 6]. Extensions in average beam current by the application of energy recovery to the accelerator [2-4] have served to enhance the high average power capability of these systems.

An illustration of an energy recovering linac driving FELs is shown in Figure 8. The IR/UV Upgrade produces continuously over 10 *kW* in the IR in the band from 1 to 14 microns and has the capability of over 1 *kW* in the 250 to 1000 *nm* range. The injector is the critical technology for operation of systems such as this; it must produce high average currents at high brightness. This system utilizes a DC photocathode operating at 350 *kV* to produce a 74.85 *MHz* pulse train of 135 *pC*. This gun produces the high average brightness and delivered in excess of 5.3 kilocoulombs from a single GaAs crystal at 1% quantum efficiency operating in the green from a doubled Nd:YLF laser beam.

The system uses energy recovery of the beam to reduce required rf power, virtually eliminate activation of components, and reduce power handling requirements on the dump. After lasing the electron beam is sent back through the superconducting cavities 180 degrees out of accelerating phase and the beam energy is converted back to the stored accelerating field with almost 100% efficiency. The machine delivers beams of high power THz, IR, and UV to a set of User Labs for scientific and applied studies. Such studies have already been extremely successful in exploring vibrational dynamics of interstitial hydrogen in crystalline silicon, carbon nanotubes, and pulsed laser deposition [7, 8]. Other applications include microengineered structures, non-linear dynamics in atomic clusters, and metal amorphization.

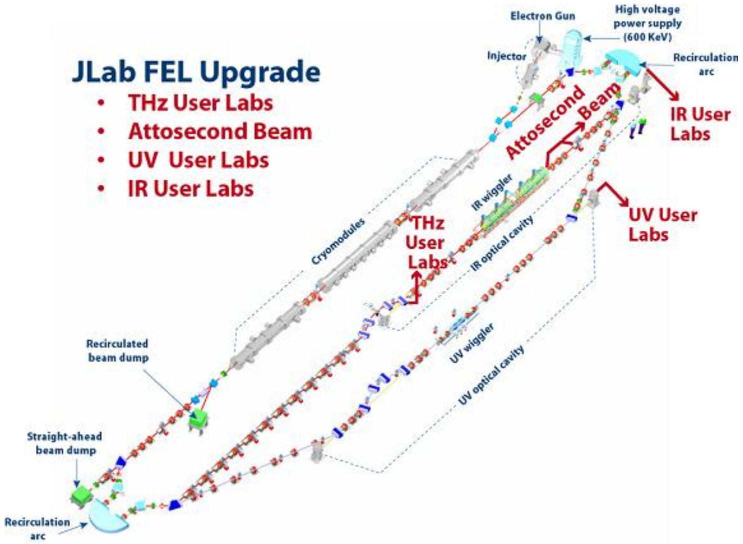


Fig. 8 The Jefferson Lab IR/UV Upgrade FEL. It utilizes a 150 *MeV* electron beam with an average current up to 10 *mA* CW to produce lasing in two oscillators, an infrared one operating in the 1 to 6 micron region and a UV one producing output from 250 *nm* to 1 micron. THz is provided from collective synchrotron radiation.

The characteristics that have driven the development of these sources are the desire for high peak and average power, high micropulse energies, wavelength tunability, timing flexibility, and wavelength production unavailable from more conventional laser sources. One of the most successful in this regard is the Multipass Energy Recovering system at Budker Institute in Novosibirsk [2, 4]. Figure 9 shows this diagrammatically in a hardware layout. The Novosibirsk FEL utilizes an electron beam of up to 30 *mA* at energies of up to 42 *MeV*. The system has produced 500 *W* of average power at 60 microns wavelength.

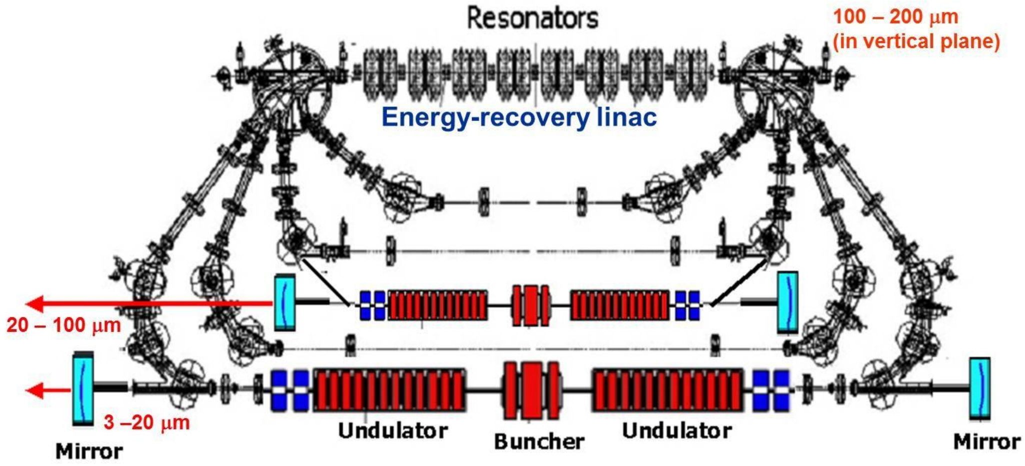


Fig. 9 The Novosibirsk FEL at the Budker Institute. It utilizes a 50 *MeV* electron beam with an average current up to 150 *mA* CW to produce far infrared lasing at very high average powers.

This is the only operational multipass energy recovering linac system and the value of this approach can be seen in the multiple wavelength bands it can produce at high average power. This unique source has generated great interest from users with over 20 groups presently doing experiments on diffractive optical elements, generation of ultrasonic waves in liquids, metamaterials, micro- and nanoparticles, vaccines, polymers, interferometry, holography, ellipsometry and imaging in the terahertz region, surface plasmons, polaritons, flame and gas detonation, ultrafast time-domain spectroscopy, and biological and medical experiments [9-12].

4. Low average power terahertz user facilities

In addition to these very high power systems mounted by national lab organizations there are a number of more facilities providing significant capability in the terahertz region for a number of applications. The new THz FEL called FLARE at Nijmegen, The Netherlands, is designed for specific support of high magnetic field studies [13]. It operates from 0.1 to 1.5 *mm* wavelength with a micropulse repetition rate of 3 *GHz* providing 10 to 200 *ps* pulses in a 10 *μs* macropulse at 10 *Hz*. It has been joined in a facility with an FEL previously located at FOM providing FEL outputs from two systems in bands at 16-250 microns or 4-30 microns at 10 *Hz* with 100 *mJ* produced per macropulse.

Many FELs are installed on the 165 *MeV* linac at FELI in Japan [14] providing wavelengths from 100 down to 0.28 microns. The laser produced 1.5 *mJ*/pulse in 24 *μs* macropulses at 20 *Hz*. The compact microtron THz FEL source at ENEA in Italy provides output in the 90-150 *GHz* range producing 1.5 *kW* in 4 *μs* [15]. The FEL-CATS system there provides 400 and 700 *GHz* in 10 *μs* pulses [16]. The 40 *MeV* accelerator at Tokyo University of Science [17] produces light in the mid-IR range from 5 to 14 *μm* with 350 *ps* pulses in a 2 *μs* long pulse train at 5 *Hz*. In Dresden, a superconducting FEL called ELBE is performing studies of condensed matter under high magnetic field conditions [18]. There are several FELs on that linac system providing long wavelength output. The most interesting is a FIR FEL with output from 100 *μm* to 3 *mm* with 10 *W* average power in a 13 *MHz* pulse train. The MIR FELs provide similar output in the 3 to 230 *μm* range. Research areas include quantum dots, quantum wells and graphene [19-23]. Users have also taken advantage of pump/probe tests using both IR and THz [24]. Another system which has recently begun operation is the Fritz-Haber Institute in Berlin which operates an IR and THz FEL with output in the 4 to 500 *μm* range from a beam of 50 *MeV* [25].

5. Summary

A wide range of electron beam driven sources are providing THz/FIR capabilities for studies in biological, solid state, atomic and molecular physics at wavelengths unobtainable from other sources. The scope of these facilities range from major efforts utilizing the capability of national lab scale organizations to smaller, user-operated systems at the scale of university departments. Both broadband collective radiation from accelerator beams and coherent lasing from Free Electron Lasers are satisfying the needs of a sizeable and growing research community.

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