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Chitrlada Settakorn, Michael Hernandez, Kristina Woods and Helmut Wiedemann
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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Abstract

Intense, coherent, polarized far-infrared (FIR) radiation can be derived from relativistic f-sec electron bunches [1,2,3]. At the SUNSHINE (Stanford UNiversity SHort INtense Electron Source) facility, such radiation is generated in the form of transition (TR), stimulated transition (STR) and undulator radiation (UR) at wave length from 47 μm up to mm waves. The radiance of this radiation greatly exceeds that available from conventional black body radiation or synchrotron radiation thus providing an effective new tool for FIR research. The techniques for producing such radiation as well as the newly discovered process of stimulated transition radiation will be described and discussed.

1 INTRODUCTION

The FIR regime of the EM spectrum is not well covered by intense sources except for few FEL's. New developments are required to cover this regime with high brightness radiation sources. Utilizing f-sec electron bunches can provide such a broadband source with a brightness far exceeding that from a black body or synchrotron radiation source. In principle, any method to produce radiation from electric charges can be used to generate coherent, polarized radiation in the FIR. In this note, we concentrate specifically on the generation of TR and UR.

2 FEMTOSECOND ELECTRON BUNCHES

To obtain coherent FIR radiation f-sec electron bunches are generated first in a rf-gun[4]. The rf-gun consists of 1½ S-band cavities and a thermionic cathode attached to one wall of the first ½ cell. The electric field strength in the rf-gun is designed such that the first particles in each S-band cycle exposed to an accelerating field leave the ½ cell just before the field turns negative again, therefore, experiencing maximum acceleration. Any later particles will accumulate less acceleration. By this process, higher energy particles will emerge first from the rf-gun followed by lower energy particles, consequently generating a well-defined correlation between energy and time.

20-30 ps electron bunches coming at 2.6 MeV from the rf-gun are compressed in an α–magnet, where the particle path length increases with energy. The lower energy particles emitted later in each bunch thus are able to catch up for effective bunch compression. At the end of this process, the bunches are compressed to less than one ps. After acceleration in a 3m single section S-band linac up to 30 MeV, the electron beam is guided to experimental stations to generate coherent FIR.

3 COHERENT FIR RADIATION

Intense, coherent FIR radiation can be produced from f-sec electron bunches at wavelengths longer than or equal to the bunch length. The total radiation from an electron bunch is the summation of the electric fields emitted by each individual electron and the total radiated energy is then equal to the square of the total electric field. The coherent radiation energy is proportional to the square rather than linear proportional to the number of radiating electrons. Since there are 10^8 to 10^9 electrons in each bunch, the radiation intensity is enhanced by that same large factor over incoherent radiation. The coherent spectrum depends greatly on the particle distribution in the bunch. The total radiated power from a mono-energetic bunch of N electrons can be written as $P(\lambda)=P_0(\lambda)[N + N(N-1)f(\lambda)]$, where $P_0(\lambda)$ is the radiated power from a single electron. The *form factor*, $f(\lambda)$, is the Fourier transform of the longitudinal bunch distribution. The second term in the square bracket describes the coherent radiation. For wavelengths shorter than the bunch length the form factor reduces to zero and approaches unity for longer wavelengths. For a Gaussian distribution, $f(\lambda) = \exp(-4\pi^2\sigma^2/\lambda^2)$ and for a rectangular distribution $f(\lambda) = \sin^2(x)/x^2$, where $x = \pi l/\lambda$ and l is the bunch length. Whatever method is used to generate radiation, the coherent radiation enhances the intensity by a factor of $Nf(\lambda)$.

3.1 Transition Radiation

TR is emitted when a charged particle passes through an interface between two media with different dielectric constants. At the SUNSHINE facility a thin Al foil is employed to serve as the radiator which represents the transition between vacuum and metal. The foil is tilted by 45° with respect to the electron path and the backward TR emitted at 90° with respect to the beam axis exits through a polyethylene window. The spectral-angular distribution of the emitted radiation energy is given by

$$\frac{d^2 W}{d\omega\, d\Omega} = \frac{r_c\, mc^2 \sin^2\theta}{\pi^2 c\,(1-\beta^2\cos^2\theta)^2},$$

where θ is the emission angle with respect to the electron beam axis. The energy increases from zero in the forward direction to a broad peak at an angle $\theta = 1/\gamma$. The single electron TR spectrum is uniform up to a very high frequency, but for coherent TR this uniform spectrum folds with the form factor of the electron bunch. Fig.1

shows the coherent TR spectrum obtained at the SUNSHINE facility from f-sec electron bunches. The radiation is broadband and its spectrum reaches from microwaves to 100 cm^{-1} wavenumber.

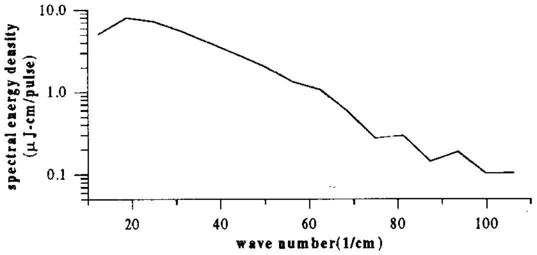

Figure 1: TR Spectrum from short electron bunches

A characteristic of coherent radiation is its quadratic dependence on the electron intensity. This is shown in Fig.2 for the case of TR generated by pulses of 3000 microbunches at 10 Hz. The quadratic dependence of the TR intensity on the electron beam current is obvious.

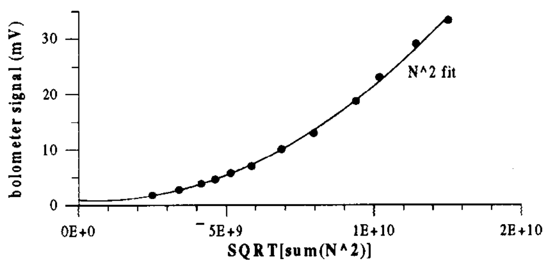

Figure 2: TR intensity as a function of beam current[1]

The spatial distribution of TR was measured by moving a bolometer across the TR beam. The results are shown in Fig.3.

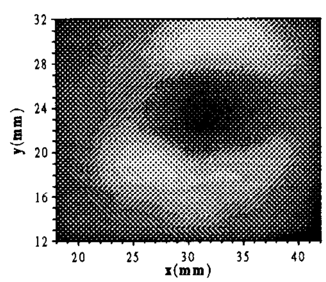

Figure 3: Spatial distribution of transition radiation

Integration over a solid angle of $\Delta\Omega$ = 0.086 sr results in a total radiation energy per pulse of ΔE = 260 µJ. The radiation is radially polarized, broadband, coherent and comes in extremely short bursts of some 250 fs. The generation of TR is simple and is a convenient source of radiation for f-sec bunch length measurement[8,9]. This broad spectrum is specifically suitable for Fourier transform spectroscopy. As an example, Fig.4 shows the absorption spectrum of L-methionine as measured with a Michelson Interferometer and a room temperature bolometer. The intense radiation allows the measurement to reach a very high resolution.

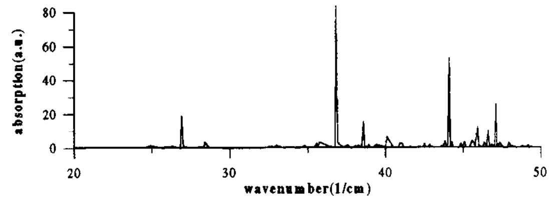

Figure 4: Absorption spectrum of a L-methionine sample

3.2 Stimulated Transition Radiation

To further increase the intensity of FIR TR, it is possible to stimulate the emission process with an external electromagnetic field. We observed such an effect for the first time by recycling the TR from one bunch such that the radiation pulse arrives back at the radiatior coincident with the arrival of another electron bunch. The recycled radiation serves as the external field to stimulate emission due to the work done on the electron[5]. Fig.5 shows the set of the cavity and the observed radiation as a function of the cavity length. At a cavity length equal to the electron bunch interval, the radiation intensity increases due to stimulation. Presently, we are in the process of commissioning an in-vacuum set-up, which should produce a large increase above ordinary TR in the form of STR.

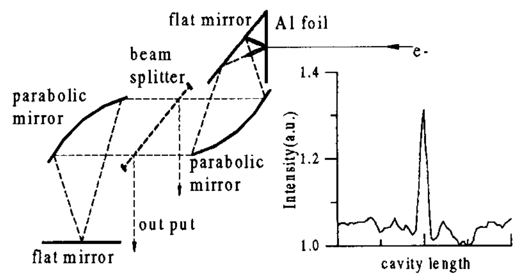

Figure 5: The STR cavity and intensity vs. cavity length

3.3 Undulator Radiation

High power, coherent, narrow-band, FIR radiation can be produced by passing the electron beam through a periodic magnetic structure called undulator[6,7]. The energy radiated by a single electron of energy γmc^2 passing through an undulator is

$$E = \frac{4}{3}\pi^2 r_c mc^2 \frac{N_u}{\lambda_u} K^2\gamma^2 ,$$

where N_u is the number of undulator periods, λ_u is the period length, and $K = \gamma\theta$ is the undulator strength parameter with a deflection angle θ per half pole. Typical parameters for the generation of coherent UR at SUNSHINE are N_u =26, K = 0.3 to 3.0, λ_u =0.077m, and γ = 31. The UR is separated from the particle beam by a 45° mirror. The central wavelength is changed by

[1] The authors thank N. Lai for participating in this measurement.

varying the undulator strength parameter K, and Fig.6 shows the UR energy per pulse as a function of K[7].

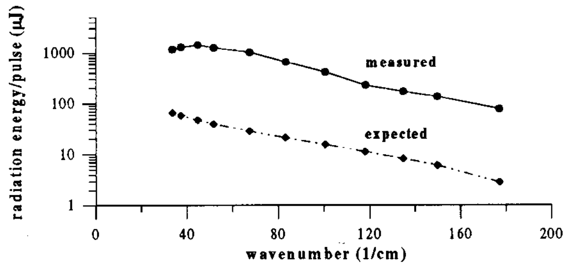

Figure 6: Measured and expected radiation energy per pulse vs. wavenumber

It should be noted that the radiation energy measured exceeds that expected by a factor of up to 30. This is due to an exponential growth of radiation along the undulator from self-amplified spontaneous emission (SASE). This exponential growth has been observed for the first time in the optical regime at SUNSHINE and Fig.7(a) shows this growth along the undulator at a wavelength of 53 μm.

UR is emitted from N_u periods in a narrow spectrum around the wavelength $\lambda=\lambda_u/(2\gamma^2)*(1+K^2/2)$ due to interference as shown in Fig.7(b).

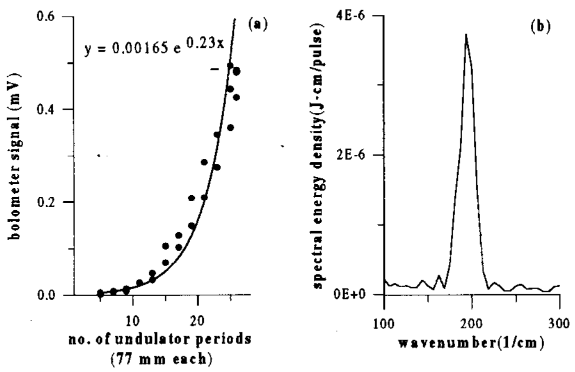

Figure 7: Exponential growth of UR at 53 μm due to SASE[6,7] (a) and spectral distribution (b)

The collimation of undulator radiation agrees with the expectation at short wavelengths, with diffraction effects showing up at longer wavelengths. The theoretical and experimental opening angles are respectively σ_θ=5.4/5.2mr at 52 μm, 7.4/9.8mr at 91 μm and 10.8/19.0mr at 227 μm.

4 FIR RADIATION SOURCE

With the availability of f-sec electron bunches it is possible to generate high brightness, coherent, polarized, narrow and broadband FIR. The radiation pulses come in very short bursts of f-sec duration reflecting the electron bunch length and time structure. At SUNSHINE the electron pulses consist of about 3000 microbunches at a repetition rate of 10 Hz. Single microbunches could be produced by installation of a suitable chopper or a gridded cathode. The radiation is collimated into the forward direction with a characteristic angle of $1/\gamma$ or less in case of UR.

It is useful at this point to recollect the present potential in the production of FIR radiation from f-sec electron bunches. Table 1 shows radiation characteristic achieved so far at SUNSHINE for TR and UR. The FIR radiation brightness for wavenumbers below 200 cm^{-1} greatly exceeds that of a black body as well as that of a synchrotron radiation source as shown in Fig.8.

Table1: FIR radiation characteristics at SUNSHINE

Transition radiation		
Spectral range	5 to 100	cm^{-1}
Total radiation energy/pulse	260	μJ
Peak power (microbunch)	306	kW
Pulse power (3000 bunches)	260	kW
Average power (at 10 HZ)	2.6	mW
Microbunch duration	283	f-sec
Undulator radiation		
Spectral range	30 to 215	cm^{-1}
Total radiation energy/pulse	80 to 1440	μJ
Peak power (microbunch)	7.8 to 27.6	MW
Pulse power (3000 bunches)	80 to 1440	kW
Average power (at 10 HZ)	0.8 to 14.4	mW
Microbunch duration	26 λ	

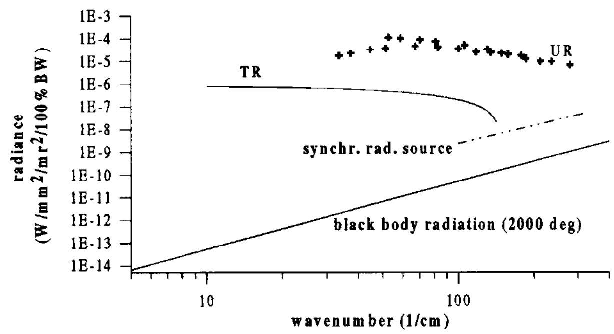

Figure 8: FIR radiation obtained from f-sec electron bunches compared with black body radiation and synchrotron radiation

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