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Stimulated Transition Radiation in the Far-infrared*

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

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STIMULATED TRANSITION RADIATION IN THE FAR-INFRARED

Chitrlada Settakorn, Michael Hernandez and Helmut Wiedemann
Applied Physics Department, Physics Department and Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309 [*]

Abstract

Stimulated transition radiation is generated by recycling coherent far-infrared light pulses of transition radiation in a special cavity. The cavity length is designed to be adjustable. At specific intervals the light of a previous bunch coincides at the radiator with the arrival of a subsequent bunch. In this situation, the external electromagnetic field stimulates the emission of higher intensity transition radiation. It is expected that the extracted energy from the cavity will be about 17 times more than would be possible without recycling.

1 INTRODUCTION

Electromagnetic radiation can be produced over a wide spectrum from radiowaves to hard x-rays through a variety of physical effects. Specifically, electron beams can be used to produce coherent or incoherent radiation. Coherent radiation is emitted when particle density fluctuations or modulations exist on the scale of the radiation wavelength. Such density modulations are used to produce microwaves in, for example klystrons, or shorter wavelength radiation from free electron lasers. In this paper we present a new way to produce broadband coherent far-infrared radiation from relativistic electron beams. The principle combines the emission of coherent radiation from electron bunches with the stimulation of such radiation by an external field with the source of the external field being the radiation emitted by an earlier electron bunch.

At the **S**tanford **Un**iversity **Sh**ort **In**tense **E**lectron source (SUNSHINE) high intensity electron bunches of sub-picosecond duration are produced from an rf-gun and a bunch compressor[1]. At wavelength equal and longer than the electron bunch length coherent radiation can be produced with an intensity scaling like the square of the number of electrons per bunch. With typical electron populations the intensity of such coherent radiation exceeds that of incoherent radiation by a factor of 10^8 or more. Since the shortest electron bunch lengths that can be directly produced are of the order of tens to hundreds of µm's the coherent radiation emitted falls into the far-infrared(FIR) spectral regime. This is the wavelength range where no readily available high intensity sources exist except for a few free electron lasers.

Coherent radiation can be produced, for example, in form of synchrotron, Cherenkov, Smith-Purcell or like in the case of the SUNSHINE experiment in form of transition radiation. Transition radiation (TR) is generated when a charged particle passes through an interface between media with different dielectric constants[2]. The most effective transition occurs at the interface from vacuum ($\varepsilon_1 = 1$) into metal ($\varepsilon_2 \rightarrow \infty$). At the SUNSHINE facility a thin aluminum foil is employed to serve as the radiator. This foil is tilted by 45° with respect to the electron path and the backward TR is emitted at 90° with respect to the beam axis for easy separation from the electron beam through a polyethylene window. The total spectral energy W radiated per unit solid angle is

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

where θ is the emission angle with respect to the electron beam axis. The radiation intensity vanishes along the beam axis and increases to a maximum at $\theta = 1/\gamma$. The total spectral radiation energy per electron becomes

$$\frac{dW}{d\omega} \approx \frac{2\, r_c mc^2}{\pi\, \beta\, c} \ln\gamma$$

after integration over a 2π half space.

Of this total radiated energy 51.2% can be collected within an acceptance angle of $\theta = 0.245$ rad in the set up described here. The single electron TR spectrum is uniform up to very high frequencies and folds with the spectrum of the electron bunch which is the Fourier transform of the particle distribution called the form factor. For sub-picosecond electron bunches of the SUNSHINE facility the form factor is close to unity for wavelength down to about 100 µm and the available spectral energy is for example $dW/d\omega = 3.73\times10^{-19}$J-s for $N_e = 6\times10^8$ electrons per micro bunch. The spectral radiance exceeds that of black body radiation by several orders of magnitude due to its efficient collimation in the forward direction. Furthermore, the radiation is broad band, coherent, polarized and of sub-picosecond, Fourier transform limited duration.

2 STIMULATED TRANSITION RADIATION

A possible way to further increase the intensity of this coherent FIR TR is to stimulate the emission process with an external electromagnetic field. To obtain stimulated transition radiation (STR), we recycle the TR from one bunch by mirrors such that the radiation pulse arrives back at the radiator just in time when another electron bunch arrives there as well [3]. The recycled radiation pulse serves now as an external field $\mathbf{E}_{ex}$. In case of perfect temporal coincidence with the arrival of an electron bunch this external field adds to the spontaneous TR field $\mathbf{E}_{sp}$ emitted from the electron bunch for a combined radiation field $\mathbf{E}_{sp}+\mathbf{E}_{ext}$. Since the radiation intensity is proportional to the square of the field we get from this electron bunch an extra radiation energy of

$$\Delta\varepsilon = |\mathbf{E}_{sp}+\mathbf{E}_{ext}|^2 - |\mathbf{E}_{sp}|^2 - |\mathbf{E}_{ext}|^2 = 2\mathrm{Re}(\mathbf{E}_{sp}\mathbf{E}_{ext}^*).$$

The extra energy is the stimulated radiation which is due to the work done by the external field on the electrons [3]. STR has been observed at SUNSHINE.[3,4] by measuring the radiation intensity as a function of the cavity length. STR is observed at cavity lengths matched to the stimulating condition. In the absence of stimulation, the total radiated power from all bunches would be independent of the cavity length. As visible in Fig.1, the radiation intensity increases whenever the cavity path length is an integer, half integer, third integer etc. multiple of the electron bunch distance. In case of fractional integers the radiation pulse has to travel twice, three and more times through the cavity before it meets another electron bunch at the radiator.

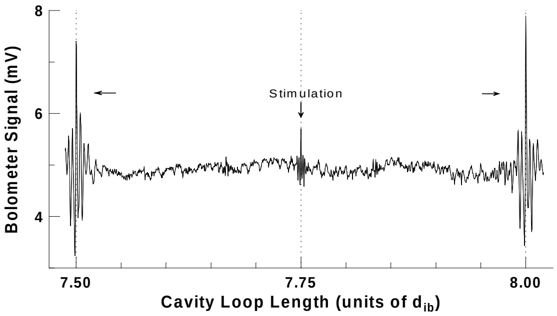

Figure:1 The STRdetuning scan[4,5]

3 OPTICAL CAVITY FOR STR

First let us consider a lossless cavity with a total round trip path length d equal to the distance Δ between adjacent electron bunches. The first electron bunch generates TR at the radiator and the forward radiation of intensity $|\mathbf{E}|^2$ travels through the cavity to arrive back at the radiator at the same time with another electron bunch. The total intensity is now $|\mathbf{E}+\mathbf{E}|^2 = 4|\mathbf{E}|^2$ producing an extra energy $2|\mathbf{E}|^2$. Interaction with the third electron bunch, the energy of the radiation increase to $|2\mathbf{E}+\mathbf{E}|^2 = 9|\mathbf{E}|^2$. The field in the cavity builds up until the last (N-th) electron bunch arrives at the radiator with the radiation energy scaling proportional to N^2. At SUNSHINE, for example, N=3000 and one would expect an increase of the instantaneous radiation intensity by a factor of 3000^2 and an increase by a factor of 3000 in the total number of photons per pulse.

If the cavity length is mΔ, the radiation pulse arriving at the radiator after one round trip will meet the m^{th} subsequent bunch. For a train of N electron bunches per pulse, the radiation energy in the cavity then scales like $m(N/m)^2|E|^2$ with m independent radiation pulses in the cavity. Since the optical cavity is composed of several reflectors, there exist unavoidable losses and the intensity of STR can be greatly diminished. This makes it imperative to use mirrors of maximum reflectivity.

For the purpose of generating STR, a cavity as shown in Fig.2 has been studied and constructed. The cavity is composed of a metallic foil as the TR generator(R) and several reflectors(F,P1,P2,M). Although it is important to minimize the number of mirror to decrease losses, the cavity requires a specific mirror arrangement. Due to the divergent nature of TR from the radiator, one cannot use a flat mirror to recycle the radiation back to the radiator. After separating the radiation from the electron beam by a 45° thin metallic reflector(F), two parabolic mirrors(P1, P2) are required to generate a parallel beam for path length adjustment and a correct polarization condition of the recycled radiation at the radiator. The focal points of P1 and P2 are aligned to the center of R and flat mirror(M). In the cavity we insert a beam splitter(BS) to extract some of the radiation field while the rest remains circulating in the cavity.

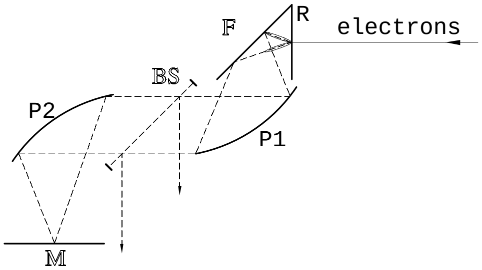

Figure:2 The schematic of STR cavity.

Based on the electron beam parameters at SUNSHINE, the efficiency of the optical cavity can be calculated. The SUNSHINE facility produces electron pulses at 10-20 Hz each containing a train of 3000 bunches at an energy of 28 MeV. Each bunch has an effective length of 180 μm and includes up to 6×10^8 electrons. From the form factor we derive a spectrum for the STR ranging from 100 - 1000 μm. The cavity path length is adjustable within $7\Delta \leq d \leq 8\Delta$, where Δ=10.5cm.

As described earlier, the intensity of STR in a lossless cavity is $(N^2/m)|E|^2 = 1.28\times10^6|E|^2$. Considering reflection losses, we define α as the remaining fraction of field after one round trip being equal to the product of the reflectance from all reflectors. The radiation intensity in the cavity after a train of N electron bunches pass through the radiator becomes

$$|\mathbf{E}_{cav}|^2 = |\mathbf{E}+\alpha\mathbf{E}+\alpha^2\mathbf{E}\ldots+\alpha^M\mathbf{E}|^2 = |\mathbf{E}|^2(1-\alpha^{M+1})/(1-\alpha), \quad (1)$$

where M is the nearest integer less than (N-1)/m. From (1) we conclude that the reflectivity of metal surfaces will ultimately determine the losses in the optical cavity. Reflectance calculation for gold surfaces based on Drude's model[5] shows that the reflectance can be better than R=0.995 for FIR, approaching unity for longer wavelengths. At λ=200μm the reflectance of a gold surface is 0.996407 and for 8 reflections per round trip α=0.971615. The radiation intensity in the cavity reaches a maximum in a short fraction of the beam pulse limited only by radiation production and overall losses.

The extracted radiation is determined by the reflection coefficient(r) of BS and can be only a small fraction of the cavity energy since it adds to the losses in the cavity. The fraction of the cavity field after passage through BS is αt, where t is the transmission coefficient of BS satisfying $|t|^2+|r|^2=1$. The amount of radiation coupled out of the cavity must be chosen carefully. If too much radiation is being extracted the cavity field cannot build up to significant intensity. Conversely, if too little radiation is extracted, the cavity field builds up to higher values, however it is not available to the user. The optimum extraction efficiency must be determined.

The STR energy in each micro pulse obtained from the cavity in units of spontaneous TR from one electron bunch is shown in Fig.3 as a function of r of BS assuming constant r and t within the spectrum of interest.

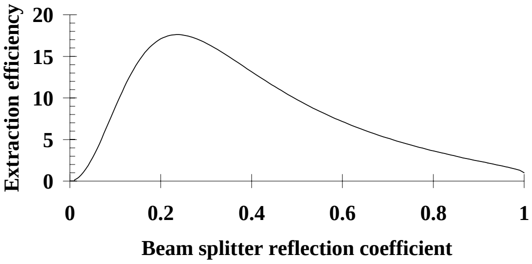

Figure:3 Radiation extraction efficiency as a function of beam splitter reflection coefficient.

It becomes obvious that maximum extraction efficiency is reached for r=0.24 which is equivalent to extracting 5.76% of the cavity energy per pass. Including all losses, the radiation energy after p bunches pass through the radiator can be written as

$$\left|E_{out}(p)\right|^2 = |E|^2 |r|^2 \alpha_0{}^2 \begin{cases} \left[\dfrac{1-(\alpha t)^{\lfloor p/m \rfloor + 1}}{1-\alpha t}\right]^2 & 0 \le p < N \\ \left[\dfrac{(\alpha t)^{\lceil (p-N)/m \rceil} - (\alpha t)^{\lfloor p/m \rfloor + 1}}{1-\alpha t}\right]^2 & p \ge N \end{cases}$$

Here, α_0 and α are the remaining fraction of the field from the radiator to the BS and for one round trip in the cavity, respectively. The symbol $\lceil\ \rceil$ and $\lfloor\ \rfloor$ are round up and round down operations. Fig.4 shows the available radiation energy in units of spontaneous TR as electron bunches pass through the cavity for an optimized BS reflection coefficient R=0.24. The total STR energy per macropulse is $5.07\times10^4\ |E|^2$ .The gain compared with radiation from a single pass of 3000 electron bunches is 16.91.

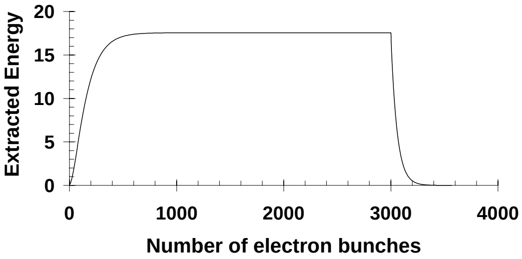

Figure:4 The available radiation for R=0.24.

4 STR INTENSITY

The STR radiance greatly exceeds that of black body radiation as shown in Fig.5. The width of the spectrum can be extended toward short wavelength as it becomes possible to reduce the bunch length further. Between 100 μm and 1000 μm STR exceeds black body and synchrotron radiation by 3 to 8 orders of magnitude. Furthermore the radiation is polarized and comes in subpicosecond Fourier transform limited pulses.

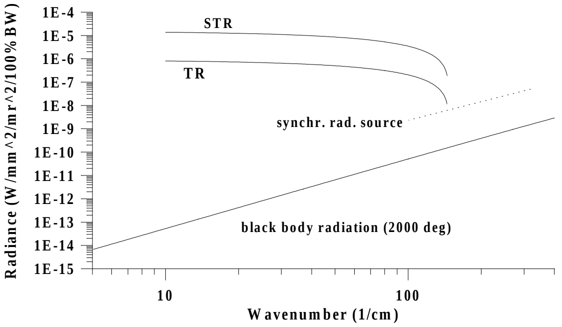

Figure:5 STR radiance

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