Observation of Stimulated Transition Radiation

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Stimulated, coherent transition radiation (STR) has been observed at the Stanford SUNSHINE facility. Far-infrared light pulses of coherent transition radiation emitted from femtosecond electron bunches are recycled in a special cavity to arrive back at the radiator coincident with subsequent incoming electron bunches. This overlap enables the electrons to do work on the electromagnetic field, thus stimulating the emission of more radiated energy than would be possible without this external field. The experimental setup to observe STR via cavity detuning measurements and experimental results is discussed. [S0031-9007(96)00309-2]

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Recent progress in particle beam control allows the compression of relativistic electron beams into short bunches of sub-psec duration. Such bunches can emit coherent electromagnetic radiation [1] at far-infrared (FIR) wavelengths determined by the Fourier transform of the electron distribution. Spontaneous coherent radiation was observed first in the form of synchrotron radiation [2] and later also in the form of transition radiation [3]. In this Letter, we report the first observation of stimulated transition radiation (STR) which is emitted when electrons pass through the interface between two media of different dielectric constants in the presence of an external electromagnetic field in phase with spontaneous TR. The special phase relation enables the electrons to do work on the external field so that additional energy is transferred from the electrons to the radiation field [4,5].

While passing through a metallic foil each high energy electron ($\gamma \gg 1$) radiates spontaneous TR with a spectral energy of $\Delta E(\omega)/\Delta\omega = (r_c mc^2/\pi c)\ln\gamma$ [5] into a 2π half plane, where r_c is the classical electron radius and $mc^2\gamma$ the electron energy. Multiplying by the square of the number of electrons per microbunch and by the Fourier transform or form factor of the particle distribution and integration over all frequencies gives the total radiation energy emitted by a single microbunch. Theoretically, a radiation energy of 0.8 μJ per 600 fsec microbunch could be expected at the Stanford SUNSHINE facility which agrees well with the measured value of 0.13 μJ considering a 39% collection efficiency in the detection optics, 52% absorption due to humidity, and 13% window losses. With 3000 microbunches per pulse at 10 Hz this radiation source provides 3.9 mW of average FIR radiation in a Fourier transform limited spectrum down to below 100 μm and into a radiation cone of ± 100 mrad. This radiation power is at least 3 orders of magnitude higher than available from both a blackbody or a synchrotron radiation source in the same wavelength range and acceptance. The goal of developing a radiation source based on STR is to further enhance this intensity by 1 or 2 orders of magnitude.

Theoretically the effect of STR can be derived from the linear wave equations as the combination of two solutions [5]: one describing the external radiation field $\mathbf{E}_{\rm ext}$ alone and the other being the particular solution $\mathbf{E}_{\rm sp}$ to the inhomogeneous equation including the electron current. The former part is equivalent to Fresnel's equations for reflection and refraction, while the latter is just the spontaneous TR field. In the case of perfect temporal coincidence of $\mathbf{E}_{\rm ext}$ with the arrival of an electron bunch at the radiator, the emitted radiation field becomes $\mathbf{E}_{\rm ext} + \mathbf{E}_{\rm sp}$ and the total radiation intensity is proportional to $|\mathbf{E}_{\rm ext} + \mathbf{E}_{\rm sp}|^2$. The extra radiation energy $\Delta\mathcal{E} = |\mathbf{E}_{\rm ext} + \mathbf{E}_{\rm sp}|^2 - |\mathbf{E}_{\rm ext}|^2 - |\mathbf{E}_{\rm sp}|^2 = 2\,\mathrm{Re}(\mathbf{E}_{\rm ext}\cdot\mathbf{E}^*_{\rm sp})$ is due to stimulation or work done by the electrons on the external field. By continuously recycling radiation pulses while ignoring cavity losses, this process increases the field in the optical cavity linearly until all electron bunches have passed the radiator. At the same time, the cavity energy increases quadratically. Of course, reflection and other losses limit the maximum achievable cavity energy.

Stimulated transition radiation was observed in this experiment via detuning measurements of a special cavity. A pulse of about 3000 equidistant electron bunches is produced from a 3 GHz rf gun and a 30 MeV linear accelerator at the SUNSHINE facility [6,7]. In a magnetic compression system the duration of each microbunch is reduced to about 600 fsec, and spontaneous, coherent TR is emitted while particles pass through a thin aluminum foil. The radiation is then recycled in an optical cavity to serve as the external field for stimulation of subsequent electron bunches.

To observe STR a special optical cavity, BRAICER (broadband radiation amplifier via inducing and circulating emission of radiation), has been designed and is described in more theoretical and technical detail in [8]. A

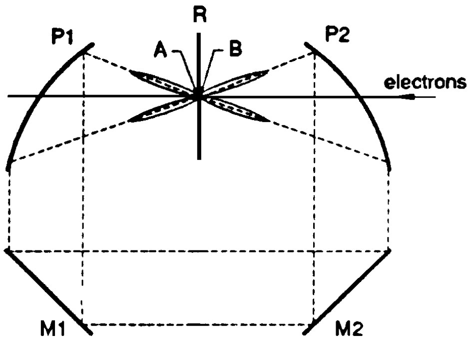

FIG. 1. Conceptual diagram of the BRAICER cavity.

conceptual diagram of the BRAICER cavity is shown in Fig. 1 and a schematic layout of the actual cavity as used in this experiment is shown in Fig. 2. It consists of a thin foil radiator and reflector (R), two thin foil reflectors (F1 and F2), two gold coated off-axis parabolic reflectors of 152-mm effective focal length (P1 and P2), two gold coated first-surface mirrors (M1 and M2), and a 127-μm-thick Mylar beam splitter (BS). All reflectors (R, F1, and F2) are made of 8-μm-thick Al foils. The source points A and B in Fig. 1 are the focal points of P1 and P2, respectively. The divergent TR beam emitted from, for example, A becomes parallel by the parabolic mirror P1 and propagates through M1 and M2 to P2, which will focus the ray again to the focal point at B. The mirrors (M1 and M2) and the beam splitter (BS) are mounted on a remotely controlled linear translation stage which allows the path length in the cavity to be changed without affecting the alignment. A small fraction of radiation is coupled out by the beam splitter (BS) and collected into a room-temperature pyroelectric bolometer to monitor the cavity energy. The bolometer electronics is slow compared to the electron beam pulse duration of 1 μs and therefore records the total energy radiated from all bunches.

Stimulation of TR is observed by recording the bolometer signal as a function of the cavity path length varied by a computer controlled actuator. In the absence of stimulation, the total radiated energy from all bunches would be independent of the cavity length. On the other hand, if stimulation occurs, an enhancement of the radiated energy should be recorded by the bolometer at intervals of the cavity path length which are consistent with the distance between electron bunches. To interpret the observed bolometer signal let the cavity length (e.g., A $\rightarrow$ P1 $\rightarrow$ M1 $\rightarrow$ M2 $\rightarrow$ P2 $\rightarrow$ B) be equal to the distance between two electron bunches within a train of N identical, equidistant bunches. No loss in the cavity is assumed. The first bunch passing through the radiator at A and B causes forward (to the left hand side) and backward (to the right hand side) TR. Considering only the forward radiation the emitted field is $\mathbf{E}$ and the radiation intensity is proportional to $|\mathbf{E}|^2$. This radiation pulse travels from A counterclockwise to B and arrives there at the same time with another electron bunch. The total radiated field is now $\mathbf{E}$ from the first bunch reflected by R plus an equal field $\mathbf{E}$ from the spontaneous backward radiation emitted by the second bunch. The radiated energy is now proportional to $|\mathbf{E} + \mathbf{E}|^2 = 4|\mathbf{E}|^2$, and the extra, stimulated energy is proportional to $2|\mathbf{E}|^2$. Through the presence of the external field, the second electron bunch therefore emits more energy than the first electron bunch. The combined radiation pulse then travels from B clockwise to A and arrives there coincident with a third electron bunch. This time, the external radiation field from previous bunches is $2\mathbf{E}$ plus the field $\mathbf{E}$ from the third bunch. The energy in the radiation pulse is then proportional to $|2\mathbf{E} + \mathbf{E}|^2 = 9|\mathbf{E}|^2$, and the extra stimulated energy is proportional to $4|\mathbf{E}|^2$. This process goes on until all electron bunches have passed through the radiator. If the cavity path length is chosen arbitrarily, this extra radiation energy is not generated, in which case the radiation pulses from all electron bunches would be oscillating independently in the cavity and the bolometer signal would not depend on the cavity path length. In a nonresonant condition the total radiation energy would scale only linearly with the number of electron bunches N whereas STR scales like N^2. The source of this extra energy is the electron beam.

The cavity energy scales quadratically with the number of contributing electron bunches. If the path length in the cavity is m times as long as the distance d_{ib} between adjacent electron bunches, the cavity energy scales like $2m(N/m)^2|\mathbf{E}|^2$, where N is the total number of electron bunches. The factor of 2 arises from the fact that TR pulses start independently as forward and backward radiation. Furthermore, there are m independent radiation pulses from the m sets of every mth electron bunch.

For the experiment described here, the SUNSHINE facility produced particle pulse trains of about 3000 microbunches at 10 Hz and an energy of 30 MeV. Each microbunch consists of about 2×10^8 electrons uniformly distributed within a bunch length of 180 μm and an interbunch distance of $d_{\mathrm{ib}} = 10.5$ cm. For this first exploratory experiment the BRAICER cavity has been placed in air and the electrons were extracted from the evacuated beam line through a 75-μm-thick stainless steel window to cross the cavity through the foils F2, R, and F1. This

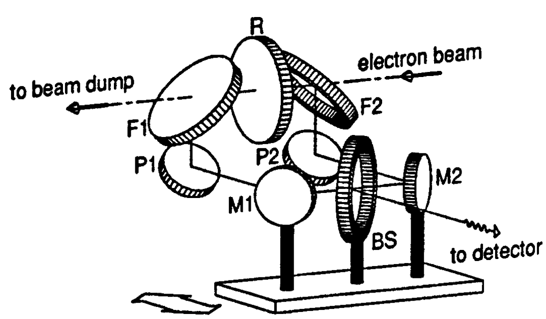

FIG. 2. Schematic setup of the BRAICER cavity.

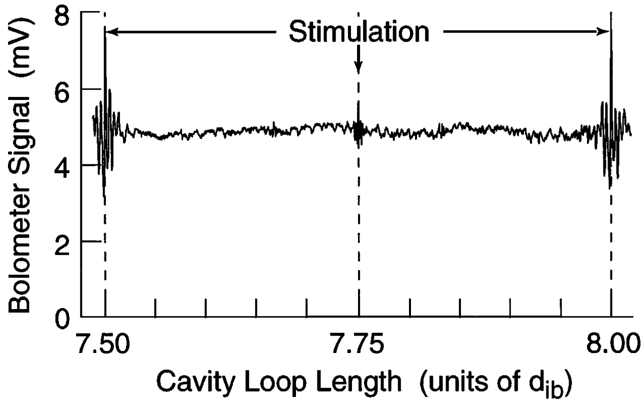

FIG. 3. Typical detuning scan varying the cavity length from $7\frac{1}{2}d_{\mathrm{ib}}$ to $8d_{\mathrm{ib}}$.

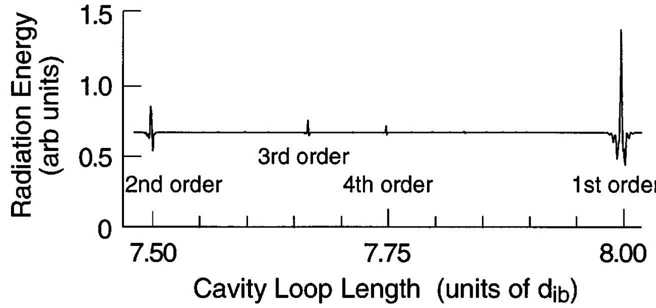

FIG. 4. Numerical simulation of the bolometer signal from a perfectly aligned BRAICER cavity.

method seemed to be appropriate to demonstrate the effect of stimulation although the spontaneous TR signal was significantly reduced by an increased electron beam cross section caused by multiple scattering in the stainless steel window. Furthermore, the cavity energy was significantly reduced by water absorption in ambient air. Unwanted radiation like Cherenkov radiation or TR from the surfaces F2 and F1 is eliminated by the selectivity of the paraboloidal mirrors which properly focus only radiation from the radiator R.

In addition to the first order resonance described above, where the radiation pulses meet electron bunches every time they arrive at the radiator, other configurations are possible where the radiation pulse, for example, has to travel twice, three times, or n times through the cavity before it meets another electron bunch at the radiator again. We identify these conditions as the second, third, or nth resonance. Stimulation of an nth order resonance can be observed when the cavity path length is m or n times as long as d_{ib}, where m is an integer. One can scan through different resonances as shown in Fig. 3 where the cavity path length has been varied from $7\frac{1}{2}$ to 8 interbunch distances d_{ib}. Three resonances are apparent in this range located at $7\frac{1}{2}d_{\mathrm{ib}}$, $7\frac{3}{4}d_{\mathrm{ib}}$, and $8d_{\mathrm{ib}}$. The increase of the bolometer signal under these conditions indicates an increased energy flow from the electron bunches into the cavity and then to the bolometer. Since the physical conditions at the transition radiator and the electron beam conditions are not changed while varying the cavity length, energy conservation requires that more radiation is emitted by the electrons on-resonance compared to an off-resonance situation.

A numerical simulation of the expected bolometer signal for a perfectly aligned cavity-beam system, in which the electron bunches cross the focal points of P1 and P2 (cf. Fig. 1), is shown in Fig. 4. To match signal amplitudes of simulation and measurements the cavity losses were adjusted in the simulation to 70% to give the same absolute radiation signal on the bolometer for the second order resonance. With this adjustment the observed intensity ratio of the second (at $7\frac{1}{2}d_{\mathrm{ib}}$) and fourth order resonance (at $7\frac{3}{4}d_{\mathrm{ib}}$) agree well with simulations. There are, however, two major discrepancies: first the third order resonance at $7\frac{2}{3}d_{\mathrm{ib}}$ in the measurement does not show the expected amplitude, and second the resonance at $8d_{\mathrm{ib}}$ being a first order resonance should have a much higher amplitude compared to the second and fourth order resonances.

The difference between measurement and simulation can be explained by a misalignment detected after the experiment was disassembled. Inspection of the oxidation traces on the reflectors R, F1, and F2 indicate that the electron beam passed through the radiator R at an offset from the focal points A and B of P1 and P2, respectively. The effect of this misalignment between cavity and electron beam is demonstrated in Fig. 5. Considering an integer resonance, the radiation emitted at C will not arrive at D to meet another bunch because the image point of C is displaced to I and therefore no stimulation occurs. After reflection at the radiator this radiation, however, travels back to C where stimulation is possible. This condition is now consistent with a second order resonance because the

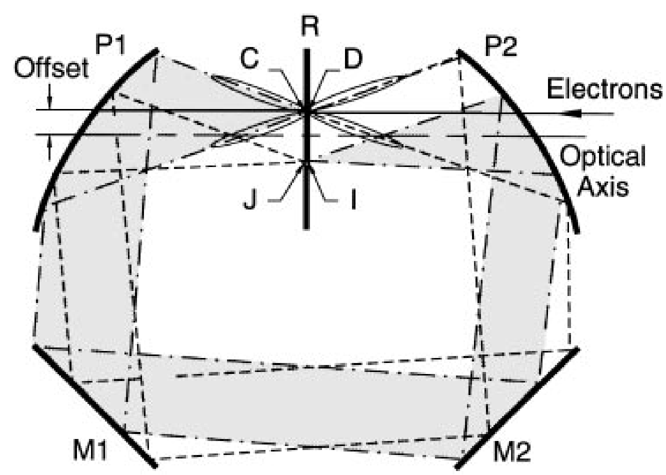

FIG. 5. A misaligned BRAICER cavity in which the electron trajectory at C and D is offset from the optical axis defined by P1 and P2. The image points of C and D are displaced to I and J, respectively.

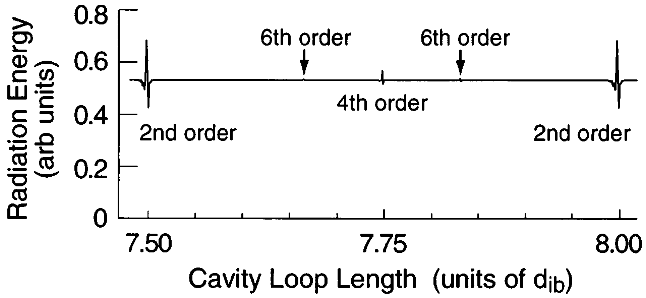

FIG. 6. Numerical simulation of the bolometer signal for a misaligned BRAICER cavity.

radiation pulse had to traverse the cavity twice. The radiation intensity at $8d_{\mathrm{ib}}$ in Fig. 6 is, therefore, comparable to the second order signal at $7\frac{1}{2}d_{\mathrm{ib}}$. Furthermore, all odd order resonances are suppressed by this misalignment which is the reason why the third order resonance does not show up. There seem to be small remnants of a sixth order resonance visible in the measurements at the locations where they should show up.

To exploit this process and create a high intensity far infrared radiation source a new cavity is under design to eliminate losses in the window and humidity and to maximize mirror reflection as much as possible. A vacuum installation with a combined total mirror reflectivity of 96% is expected to result in a tenfold increase of the available STR through the beam splitter compared to the intensity from single pass TR boosting the FIR intensity to some 40 mW distributed over a wavelength range of about 1 mm down to below 150 μm. This intense radiation is coherent and comes in bursts of 600 fsec. Alternative cavity designs with less mirrors and therefore higher overall mirror reflectivity promise to increase this by another order of magnitude.

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