Observation of Self-Amplified Spontaneous Emission in the Mid-Infrared in a Free-Electron Laser

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We have produced and analyzed self-amplified spontaneous emission emitted by a relativistic electron beam passing through an undulator for the first time in the mid-infrared. The spectral behavior of the line exhibits an unexpected growth at the start-up of the process. [S0031-9007(97)02623-9]

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There are many kinds of free-electron lasers (FEL) operating in various wavelength regions from millimeter waves to ultraviolet [1]. The gain medium of the FEL [2] is a relativistic electron beam crossing a magnetic device (called the "undulator"). This system produces synchrotron radiation (called "spontaneous emission") and creates an optical amplification by transfer of energy from the electrons to the optical wave. The undulator is installed in an optical cavity which stores the spontaneous emission and allows the laser operation. The wavelength is easily tunable in a large range by adjusting the magnetic field of the undulator and the electron beam energy. In principle, the FEL is able to work in the x-ray spectral range. However, at present the quality of the optical cavity mirrors and of the electron beam have not been sufficient to produce the FEL oscillation at wavelengths shorter than 240 nm [3]. In the infrared range, the gain can be larger than 100% although only a few percent have been achieved in the uv. Other related techniques, noticeably the vacuum ultraviolet (VUV) harmonic generation in an undulator [4] and x-ray generation by FEL intracavity Compton backscattering [5] have been demonstrated, but are producing small power. Nevertheless, a solution has been proposed about ten years ago to reach the x-ray range [6]. Its principle is to operate a very high gain FEL in single pass configuration, thus avoiding mirrors: The "spontaneous emission" produced by the electrons is amplified in a very long undulator (20 to 40 m) and reaches saturation in one pass. This so-called "self-amplified spontaneous emission" (SASE) requires a very high quality electron beam (high peak current, low energy spread, small emittance). The SASE has so far been observed only in mm waves [7] and in far-infrared [8] spectral ranges. Indeed, the electron beam requirements needed for SASE are more and more demanding as the wavelength decreases. Thus study of SASE in the mid-infrared region is an important step in understanding the process and in extrapolating to the possible development of SASE sources in x-rays.

The SASE process is one aspect of the radiation which occurs in the FEL, and which involves either "spontaneous emission" (SE), "coherent spontaneous emission" (CSE), "FEL gain," or "SASE". SE is the radiation produced by a single electron, traveling along an undulator of N magnetic periods. It is peaking at the so-called resonance wavelength $\lambda_R = \lambda_u(1 + K^2/2)/2\gamma^2$ where λ_u and K are, respectively, the period and the "deflection parameter" of the undulator, and $\gamma \mathrm{mc}^2$ is the electron beam energy. The single electron radiation is a wave train of N periods, corresponding to a length of $N\lambda_R$. The spectral linewidth of the radiation is $\Delta\omega/\omega \cong 1/N$. Considering a bunch of N_e electrons and assuming that the electrons density is uniformly distributed in the bunch, the electrons are incoherent sources, and the energy produced by SE scales as NN_e. CSE is observed if the dimension of the electron bunch is smaller than the emitted wavelength. In this case, the individual sources (electrons) are in phase and the total emitted energy is scaling as NN_e^2, i.e., linearly with the undulator length, and quadractically with the electron current. In most FELs, including CLIO, which is an infrared FEL and a user facility since 1993 [10], the electron bunch length is larger than the emitted wavelength, and the CSE should be negligible. Nevertheless, a partial coherence still occurs if the electron bunch longitudinal density has sharp edges, or more generally, strong components at high frequency in its Fourier spectrum. In this case, a CSE component of intensity $I_{\mathrm{coh}}(\omega)$ adds to the SE intensity $I_{\mathrm{se}}(\omega) = I_0(\omega)N_e$, where I_0 is the intensity emitted by one electron. This CSE component is described by the diffraction theory which yields a coherent intensity $I_{\mathrm{coh}}(\omega) = I_0(\omega)N_e^2 f^2(\omega)$, where $f(\omega)$ is the Fourier transform of the longitudinal electron density. The total intensity $I_T(\omega) = I_{\mathrm{coh}} + I_{\mathrm{se}}$, then, scales as $\sim N(i + f^2 i^2)$, where i is the electron beam average current. f is also a function of i, when the electron longitudinal shape varies with the average current. Both SE and the CSE are spontaneous emission and have, in first approximation, the same spectral distribution. The third way of increasing the emission is by the FEL gain process, induced by the interaction between the electron bunch and an optical wave, which creates a periodical modulation (microbunching) on the electron beam distribution and produces a strong Fourier component at the resonant wavelength. This component adds to the initial optical wave and constitutes the "gain": with an adequate optical cavity, it produces the FEL oscillation [2].

Also, due to the gain, the spontaneous emission which is produced along the undulator is somewhat amplified in a single pass. This kind of radiation is self-amplified spontaneous emission. The analysis of this process has been done by several authors [6,9]. The power of SASE grows exponentially along the undulator axis z, with $P_{\text{sase}} \propto \exp(z/L_g)$, where $L_g = \lambda_u/8\pi\sqrt{(3/2)\rho}$ is the "gain length," which characterizes the exponential growth of SASE and depends on a dimensionless "Pierce parameter" ρ, which is proportional to $(\hat{i}/\sigma_e \gamma^3)$. $\hat{i}$ is the peak electron current, σ_e its transverse size, and γmc^2 its energy. Therefore SASE requires higher intensities and smaller emittance (transverse size) as the energy increases, i.e., as the desired wavelength is smaller. The saturation occurs for $\rho N \cong 1$. Far from saturation ($\rho N \ll 1$), the radiation is the spontaneous emission of an incoherent electron beam, the spectral width being $\sim 1/N$. In the exponential growing regime, one expects a reduction of the spectral linewidth to $\Delta\omega/\omega \cong (\rho N)^{1/2}/N$.

We present here the successful production and observation of SASE in the mid-infrared region at $\lambda = 5$ and 10 μm. These observations are done with the CLIO FEL, which is an infrared free-electron laser and a user facility since 1993 [10]. CLIO is based on a dedicated linear accelerator. The parameters of the experiment are displayed in Table I. With these parameters, the gain length L_g is about 1 m, and the saturation parameter is $\rho \times 2N = 0.07 \ll 1$ in our case. This indicates that the SASE radiation is necessarily far from saturation, which would occur for 500 periods. The radiation is taken in an angular aperture sufficiently small to avoid spectral broadening. The linac must be carefully tuned in order to obtain SASE, even more than for operation of the FEL. The electron transverse section has a strong influence on the SASE intensity. However, the more crucial parameter of the linac, which influences both the SASE/CSE and the FEL, is the phase of the accelerating rf wave with respect to the electron bunches (in the "prebuncher" rf cavity [10]): it determines the electron peak current. The influence of such phase tuning, leaving the average current unchanged, is displayed on Fig. 1: the spontaneous emission intensity is strongly affected. One set of curves ("phase ON") has been obtained with optimum rf phase adjustment, corresponding to a strong maximum of emission intensity, and the other set of curves ("phase OFF") has been obtained with a detuned rf phase. While the average current remains constant, the peak current diminishes by approximately 50% [11]. This is an evident proof that the SASE or CSE process occurs, since the SE is strictly proportional to the average current. The very strong observed effect pleads for SASE rather than CSE, that we discuss below.

The undulator of CLIO has 38 magnetic periods, divided in two half-undulators of $N = 19$ periods, for which each gap is independently adjustable. This feature is made to run the FEL in a two color model [12], but it also allows discrimination between SASE and CSE effects, because CSE scales linearly with the undulator length and quadratically with the current, whereas SASE scales exponentially. Figure 2 shows the spontaneous emission intensity as a function of the electron beam current with one or two undulators of an equal number of periods. The electron beam current has been varied by controlling the aperture of a beam slit on the linac, which in principle does not modify its longitudinal shape. The curve A (two undulators) exhibits clearly a nonlinear behavior (the curve B, for one undulator, also, though less obvious) which implies a coherence effect such as CSE and/or SASE. The curve C is the curve B, multiplied by a factor of 2. Since the CSE (and the SE) scales linearly with the undulator length, the difference between curves A and C is necessarily due to the presence of SASE. Therefore SASE is present, which is also shown by its nonlinear behavior, although some CSE may also exist. The SASE amplification acts on the total spontaneous emission: SE + CSE. It may occur also in the first undulator, what may be responsible for the small nonlinearity of curve B. However, the accuracy is not sufficient to determine whether this behavior is exponential (SASE) or quadratic (CSE) with the current. These curves have been taken with an electron beam transverse size adjusted for the FEL oscillator. When one adjusts the size for maximum SASE, the intensity is only

TABLE I. Parameters for free-electron laser facility CLIO.

Accelerator:	Type	Linear, radio frequency, 3 GHz
	Energy	50 MeV
	Peak current	100 A
	90% emittance	150π mm mrad (normalized)
Time structure:	Macropulse length	10 μs
	Micropulse length	8 ps (measured)
FEL:	Undulator period	50.4 mm
	Number of periods: N	19 (for each undulator)
	Measured gain per pass	Up to 500%
	Pierce parameter: ρ	1.9×10^{-3}

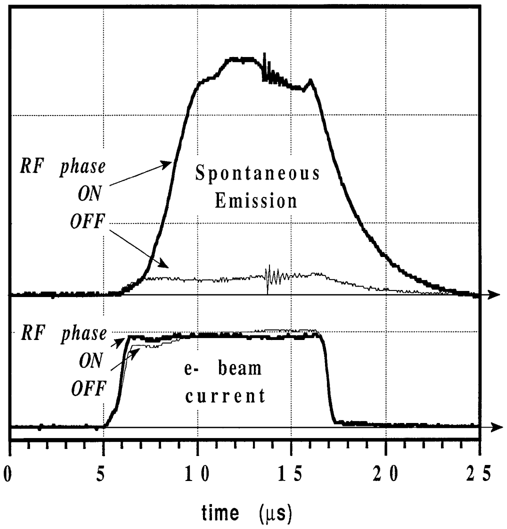

FIG. 1. Influence of the electron peak current (rf phase tuning) on the spontaneous intensity (top curves) during the electron macropulse. The bottom curves show the average electron beam current.

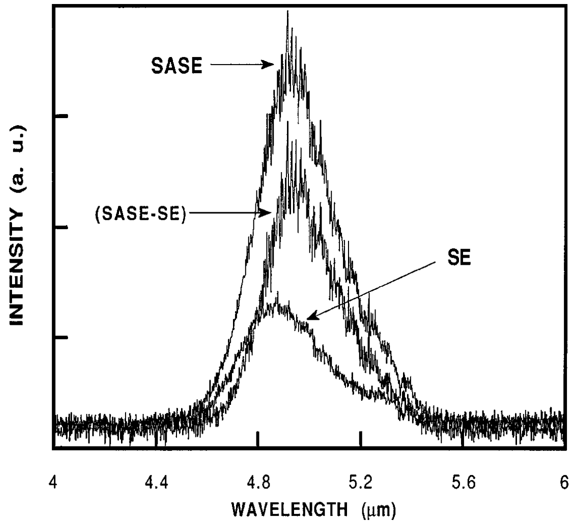

FIG. 3. Spectra of the emission with and without SASE and their difference at $\lambda = 5$ μm, with the FEL adjustment.

slightly increased by the presence of the second undulator: In this case the ρ parameter is maximized by a very small electron beam size in the center of the first undulator. Then ρ becomes almost negligible in the second undulator, due to the divergence of the beam following a very small focus.

The spectrum of the SASE has been measured for various intensities of SASE, by acting on the rf phase. A spectrum is displayed on Fig. 3 for the case corresponding to the beam adjustment of Fig. 2. It is taken at 5 μm, so that we can use a sensitive InSb detector and measure both the SE and SASE. The difference between these two curves represents the amplification experienced by the SE along the undulator: clearly a moderate amplification appears which is located at a slightly longer wavelength than the central wavelength of the SE. This wavelength shift ($\Delta\lambda/\lambda = 1.4\%$) is close to the theoretical value of $\frac{1}{2}N$ expected at moderate FEL gain. In Fig. 4, we have displayed the spectra obtained with the best beam adjustment, taken at 10 μm, where the detector (HgCdTe) is not sensitive enough to measure the SE: When SASE increases, the spectrum linewidth increases and the central wavelength shifts toward large values. The larger spectrum, corresponding to the larger SASE intensity, is displaced by 15% (at 11.5 μm), and has a linewidth of 23%, much larger than the SE one (its theoretical value is 2.6% but it is measured to be about 7% due to the electron beam divergence). The resonance wavelength shift would be explained either by an angular error of 8 mrd or by a

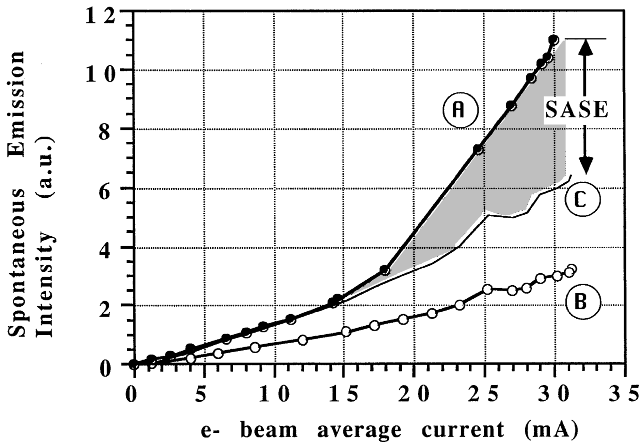

FIG. 2. Intensity of SASE versus electron beam average current. The curves A and B correspond, respectively, to $2N = 38$ and $N = 19$ periods undulators. Curve C is two times the curve B.

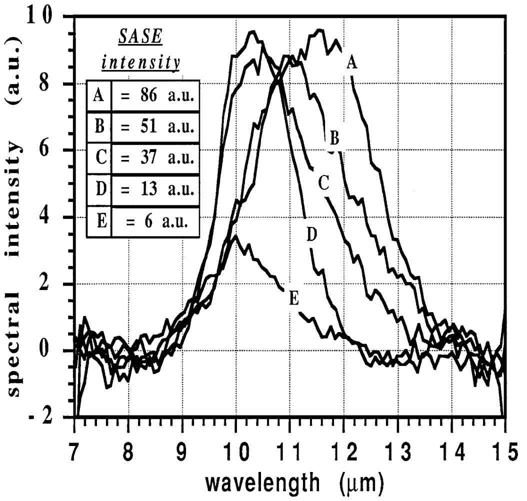

FIG. 4. Spectra of SASE for various SASE intensities (varying the linac peak current) for the best beam tuning at $\lambda =$ 10 μm.

relative energy variation of 7%, which would result in the loss of the beam. The experimental increasing of the linewidth up to 23% is not in agreement with the SASE theory, which predicts a narrowing of the spectrum as compared to the SE. However, this theory considers the exponential growth of intensity rather than the start-up regime, as it is the case here. On the other hand, if we assume this width to be Fourier limited, a linewidth of $\Delta\lambda/\lambda = 23\%$ corresponds to a wave train of about $\Delta z \cong 40$ μm. This cannot be due to a substructure in the electron micropulse, which would give rise, rather than SASE, to a strong broadband CSE. Also, this value is ten times shorter than the length, $N\lambda = 400$ μm, of the SE wave train. It could correspond to a short pulse regime, i.e., a "spiky" behavior of the SASE process. Indeed, measurements of the SASE with a detector of 0.2 μs of rise time shows a noisy intensity from bunch to bunch, with about 100% fluctuations. This pleads for a spiky regime of the SASE which is, intrinsically, not a stable process.

Therefore, the high gain, which can be obtained with the CLIO infrared free electron laser, has allowed us to observe SASE in the mid-infrared region, around 5 and 10 μm. Although far from saturation, since the amplification is only 1 of order of magnitude, we have been able to measure the spectral behavior at start-up and to observe an unexpected growth of the linewidth. In the future, planned improvement of our accelerator should allow us to measure the SASE behavior at higher amplification rates.

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