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Coherent Startup of an Infrared Free-Electron Laser

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Coherent enhancement of the spontaneous undulator radiation by several orders of magnitude has been observed in a free-electron laser at wavelengths from 40 to 100 μm. The coherent emission can be explained by details of the electron-beam micropulse structure. Furthermore, it has been found that the phase of the optical micropulses is fixed by the electron pulse structure and that the coherence extends over successive optical micropulses, which gives rise to interference effects as a function of the optical cavity length in a laser oscillator.

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In a free-electron laser (FEL), a relativistic electron beam is passed through a periodic magnet array, the undulator, to produce electromagnetic radiation in a wavelength range determined mainly by the electron energy and the undulator period. Amplification occurs through a second-order nonlinear interaction between the optical field and the electron motion, and leads to a powerful output that can be used in a variety of experiments in physics, chemistry, and biology.

A convenient description of the operation of an FEL is obtained by transforming to the rest frame of the electron beam [1]. In this frame, the undulator field transforms into an electromagnetic wave propagating toward the electrons. This wave is scattered by the electrons and appears with a Doppler upshift in the laboratory frame as the undulator radiation. In the electron frame the backscattered wave and the original wave combine to form a standing wave pattern. Enhanced stimulated scattering occurs due to the formation of a density grating in the electron distribution under the influence of the ponderomotive force associated with the standing wave. In an FEL oscillator, the radiation is trapped in an optical cavity, and through further stimulated enhancement the scattered field builds up to saturation over tens or hundreds of round trips.

The initial optical field generated by scattering from the undisturbed electron beam is known as spontaneous emission. As in other instances of light scattering, the spectrum is determined by the distribution of scatterers in the scattering volume [2]. One can distinguish incoherent and coherent scattering. The incoherent contribution originates from statistical fluctuations in the number density of the scatterers, as in Rayleigh scattering or incoherent Thomson scattering, and its power is proportional to this density. The coherent contribution arises from density variations on the scale of the radiation wavelength and its power is proportional to the square of the fluctuation density. The power scattered by an ensemble of $\mathcal{N}$ scatterers can be written as

$$P(k) = \mathcal{N}P_1 + \mathcal{N}^2 P_1 f(k)\,, \tag{1}$$

where P_1 is the power for a single electron, which depends on the undulator parameters, and $f(k)$ is a form factor depending on the macroscopic density distribution within the scattering volume. The first term gives the incoherent contribution and the second the coherent one. The spontaneous undulator emission in the laboratory frame is described by the same expression, with $f(k)$ given by

$$f(k) = \left| \int \exp(ikz) S(z)\, dz \right|^2 , \tag{2}$$

where $S(z)$ is the normalized longitudinal density distribution of the electron pulse, and $k = k_s - k_u \approx k_s$ where k_s and k_u are the wave numbers of the radiation and of the undulator, respectively.

When the electron beam is pulsed, one expects a strong coherent contribution at wave numbers smaller than the inverse of the electron pulse length, as was already mentioned by Motz in 1951 [3]. This form of radiation is also known as superradiance [4]. Coherently enhanced emission has recently been observed at millimeter wavelengths, using 15-ps-long electron pulses from a radio-frequency linear accelerator (rf linac) [5]. A smooth distribution $S(z)$ with a characteristic length σ_z leads to small values of $f(k)$ for all k appreciably larger than $1/\sigma_z$. Even with pulses of a few picoseconds, as achievable with an rf linac, one would not readily expect coherent emission at wavelengths much smaller than a millimeter. However, as the number $\mathcal{N}$ is usually very large in an FEL, the second term in Eq. (1) is extremely sensitive to any small scale structure in $S(z)$. Coherent undulator radiation has been observed at a wavelength of 7.4 mm with electron pulses of 8 ns, and has been attributed to substructure on a 30–100 ps time scale [6]. The small-scale structure required for coherent emission at infrared and shorter wavelengths has previously been obtained only in the stimulated FEL emission process mentioned in the introduction. In this Letter we report the first observation of coherent enhancement of the spontaneous emission at wavelengths from 40 to 100 μm, and illustrate its relation to the electron micropulse shape. In addition, we show the influence of coherent effects on the startup of a multipass free-electron laser oscillator.

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We have performed measurements of the coherent enhancement of spontaneous emission in FELIX, the free-electron laser for infrared experiments [7]. FELIX uses an rf linac producing electron macropulses in the form of a train of micropulses, each with a duration in the order of 3 ps and containing 1.2×10^9 electrons. Two linac sections and two undulators are used to cover the wavelength range from 6.5 to 110 μm. The experiments discussed in this Letter were performed in the long-wavelength branch at an electron energy of 16.5 MeV.

To estimate the coherent enhancement, we have compared the saturated output power of the laser with the initial spontaneous power. The latter was determined by fully desynchronizing the optical and electron micropulses, i.e., by adjusting the length of the laser cavity such that the circulating optical pulses did not overlap new electron pulses. In this case, the measured signal appeared at the same instant as the first electron bunches and did not grow due to amplification during the macropulse. In fact, the power later in the macropulse was often much smaller than that at the start, where the electron beam has not yet reached a steady-state condition. This shows that the normal multipass FEL gain was indeed absent in this case. A number of optical attenuators were used to relate the detector signal in the normal saturated-lasing case to that of the spontaneous emission. A gallium-doped germanium photoconductive detector operating at 4 K was used, and measurements were made at a wavelength of 79 μm. A long-wave pass filter was used to eliminate harmonics with $\lambda < 30$ μm. The measured spontaneous power was found to be 2.5×10^{-5} times the saturated power, whereas a factor of 10^{-8} to 10^{-9} is expected with the parameters of FELIX. The saturated output power has been measured with a calorimetric power meter and was found to correspond to an energy per micropulse of 1 μJ at the diagnostic table, and so the spontaneous emission amounted to 25×10^{-12} J per micropulse. The incoherent emission, $\mathcal{N}P_1$, can be calculated using well-known expressions [8], which in our case gives 19×10^{-15} J per micropulse emitted into the fundamental cavity mode, of which we expect 2×10^{-15} J at the detector. The experimental value thus shows an enhancement by a factor of roughly 10^4 over the calculated incoherent power.

Another indication of enhanced initial power is the time to reach saturation of the laser output. With a net gain of 12% per pass, as determined from the rising edge of the optical macropulse signal, a growth of 10^8 to 10^9 in power would require 6 to 7 μs, while we have observed a growth time of around 3 μs. A spontaneous power enhancement by a factor of 10^4 can indeed account for a reduction of the startup time by about 3 μs.

The spontaneous power was found to be very sensitive to the accelerator settings, in particular the rf-phase differences between the prebuncher, the buncher, and the linac. Variations in power by more than 2 orders of magnitude could be obtained by adjusting these parameters. This shows the sensitivity of the coherence effects to the shape of the electron pulse.

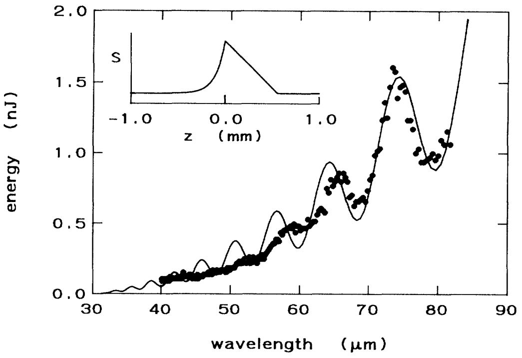

FIG. 1. Points: measured spontaneous emission signal in FELIX vs $\lambda(K)$; solid line: calculated total spontaneous energy for an electron pulse as shown in the inset, with an energy of 16.5 MeV and containing 1.25×10^9 electrons, in an undulator with $\lambda_u=6.5$ cm, $N_u=38$.

Information on details of the electron micropulse shape can be obtained from the wavelength dependence of the coherent spontaneous-power enhancement, as this is directly related to the Fourier transform of the electron pulse shape [see Eqs. (1) and (2)]. We have performed measurements of the spontaneous emission power as a function of wavelength, or more precisely, as a function of the undulator strength K. The rms K was swept from 0.5 to 1.3, with a resulting variation of the resonance wavelength from 40 to 82 μm, while the spontaneous emission power was recorded. Absorption by atmospheric water vapor was minimized by placing the detector immediately behind the exit window of the evacuated optical beam tube. No correction has been made for the wavelength dependences of the detector sensitivity, of the outcoupling efficiency, and of the beam transport system losses. The overall response of the system is assumed to be sufficiently uniform to determine the qualitative behavior.

In Fig. 1 we plot experimental data against $\lambda(K)$ together with a calculated curve. In Fig. 2 we show the calculated incoherent and total spontaneous micropulse energy on a logarithmic scale for comparison. The total spontaneous emission was calculated from the standard incoherent contribution, P_1, and using Eqs. (1) and (2) for an electron pulse containing 1.2×10^9 electrons and having a shape $S(z)$ as illustrated in the inset. This pulse shape has been chosen such that the oscillations in the calculated curve, caused by the triangular part of the pulse, agree reasonably with the observed features, both in amplitude and position. The width of the pulse was used to fit the absolute value of the enhancement at $\lambda=80$ μm and the overall wavelength dependence to the experimental results. The resulting pulse shape is not too

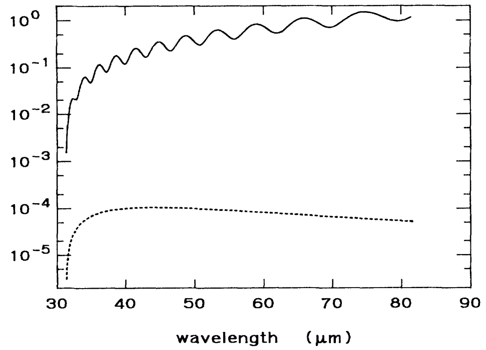

FIG. 2. Calculated spontaneous emission energy vs $\lambda(K)$ for an electron pulse as in Fig. 1. Full line: total; dashed line: incoherent part only.

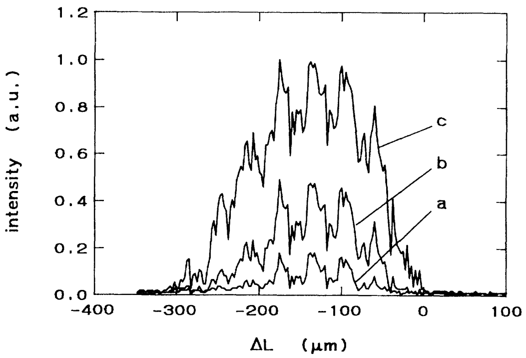

FIG. 3. Small-signal cavity detuning curves at $\lambda = 75$ μm showing modulation of the power with a period $\Delta L = \lambda/2$ due to interference of the coherent spontaneous emission, at (a) 1.25 μs, (b) 1.5 μs, and (c) 1.9 μs after the start of the electron macropulse. Depending on ΔL, saturation sets in after 3 to 4 μs.

different from pulse shapes expected from simulations of the accelerator operation [9]. As mentioned above, the emission can be influenced strongly by variation of the accelerator settings, and the position and the period of the oscillations then change as well. We have also observed cases where the measured curve is quite smooth, which shows that the oscillations are not due to variations in the sensitivity of the detection system. We have found that the measured power and the period of the observed oscillations generally increase or decrease in unison, consistent with a changing electron pulse shape.

In addition to enhanced emission due to coherence within a micropulse, we have observed effects of coherence over much longer distances. In FELIX, the electron micropulses arrive at a rate of 1 GHz, while the cavity round-trip frequency is 25 MHz, so that forty independent optical pulses circulate through the cavity concurrently. The coherent spontaneous emission is related to the macroscopic shape of the electron pulses and, hence, has a fixed phase relative to the electron pulses. If the electron pulse repetition frequency is stable to within half an optical period over a pulse repetition period, then there will be a fixed phase relationship between successive optical pulses. Such an interpulse coherence has indeed been observed by analyzing the radiation with a Michelson interferometer in which consecutive micropulses were made to interfere. A coherence between adjacent pulses of 85% has been observed. As the laser gain process amplifies the field in phase with the incoming pulse, the coherence between successive pulses is preserved in the saturated output of the laser oscillator, as we indeed observed [10]. The degree of coherence decreases with increasing separation between the interfering pulses as a result of jitter in the electron micropulse arrival times. However, some coherence still remains on longer time scales, because the accelerator frequency is extremely stable. This results in an increased or decreased growth of the power depending on the exact length of the optical cavity while spontaneous radiation is added on successive passes. We have observed, indeed, a clear modulation of the output power with a period of $\lambda/2$ on variation of ΔL, the cavity length detuning. These measurements were made over a large range of ΔL values, at an early time in the macropulse where the influence of the spontaneous emission is still important. An example is given in Fig. 3. Although the contribution of the spontaneous emission decreases at later times in the macropulse, the modulation of the output power as a function of ΔL has been found to persist up to times close to saturation.

In conclusion, the observed enhancement of the spontaneous radiation is explained by coherent emission associated with the electron pulse shape. The presence of an important coherent contribution can be expected to considerably facilitate the startup of short-pulse FELs at still longer wavelengths. It is conceivable that the electron pulses can be shaped such that a useful output power at submillimeter wavelengths can even be obtained in a single pass with negligible amplification. The phase stability of the electron micropulses has been found to lead to interference effects between different optical pulses. This effect has consequences in experiments related to narrow-band operation of the laser [10].

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