

Induced and Spontaneous Interpulse Phase Locking in a Free-Electron Laser

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We present the first experimental demonstration of phase locking between successive optical micropulses in a free-electron laser in which the electron pulses are separated by a fraction of the optical-cavity round-trip time. A Fox-Smith interferometer arrangement has been used to induce a high degree of interpulse phase coherence. Surprisingly, a substantial amount of coherence has also been observed without the phase-locking arrangement. A tentative explanation of this phenomenon is given.

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The free-electron laser (FEL) is a valuable tool for fundamental research in physics and chemistry. Especially in the infrared to far-infrared spectral regions, where no other powerful tunable lasers are available, many new applications are possible [1]. A radio-frequency (rf) accelerator is commonly used as the source of the electrons in an FEL, except for submillimeter wave generation, where an electrostatic accelerator can provide sufficiently energetic electrons. An rf accelerator produces an electron beam in the form of macropulses with a duration in the microsecond range, each consisting of micropulses with a duration in the picosecond range. In most existing FELs, the interval between micropulses equals one optical-cavity round-trip time. As a result, the laser operates as a synchronously pumped mode-locked laser. This is very useful for applications of the FEL in studies of fast dynamical processes and nonlinear effects. On the other hand, the linewidth of such a laser is broad due to the short duration of the micropulses, which prohibits its use in high-resolution work, where long-range coherence is required. There is, of course, coherence over multiples of the optical-cavity round-trip time, as in any laser oscillator, and the spectrum consists of discrete cavity modes, each with a width much smaller than the full laser bandwidth. However, as the optical-cavity length of an FEL normally amounts to several meters, the mode spacing is very small, and external selection of a single mode is virtually impossible. In addition, each mode contains only a very small fraction of the total power, because the number of modes contributing to the pulse essentially equals the ratio of the round-trip time to the micropulse duration. It is not possible to make such a laser operate in a single axial mode due to the efficient mode locking effected by the short electron pulses.

If the electron micropulse repetition rate is a multiple of the optical-cavity round-trip frequency, then a number of separate optical pulses circulate simultaneously in the cavity. As each optical pulse evolves independently out of the noise, and interacts with different electron pulses, there will, in general, be no fixed phase relation between them. Thus, the power spectrum of the output will be the same as for a single optical pulse, apart from its magnitude. If, however, the successive pulses are identical and

in phase, then the spectrum is that of a harmonically mode-locked laser with the shorter pulse repetition time, and a correspondingly wider mode separation. Selection of a single mode is then possible for a sufficiently high pulse repetition rate. Proposals to induce the required phase locking by means of an interferometric device in the laser cavity have been made, and numerical simulations have shown their feasibility [2-4].

In this paper we present the first experimental demonstration of phase-locked operation in the free-electron laser for infrared experiments (FELIX) [5]. This laser uses an rf linear accelerator with a micropulse repetition frequency of 1 GHz to permit harmonic mode locking. The length of the optical cavity is 6 m, so that forty pulses circulate concurrently. Presently, FELIX operates in the 20-100- μm wavelength range. Extension of the range towards 5 μm is in progress. FELIX will be operated primarily as a users facility providing a powerful source of infrared and far-infrared radiation with a high degree of flexibility in pulse structure and spectral characteristics, including the possibility of producing extremely narrow-band radiation. The present work relates to the latter feature, which is unique in the field of rf-accelerator FELs.

The layout of the experiment is shown schematically in Fig. 1. The spherical, gold-plated copper mirrors $M1$ and $M2$ constitute the main laser resonator cavity. A fraction of the intracavity radiation is coupled out through a hole in $M1$, collimated by an inverted Newtonian telescope, and transported to a diagnostic area via evacuated tubes. The laser operation depends strongly on the degree of synchronism between the circulating light pulses and the repeating electron pulses, as in other synchronously pumped lasers [6,7]. To adjust the synchronism, $M2$ can be scanned under servo control of a He-Ne interferometer monitoring the distance between $M1$ and $M2$.

A Fox-Smith arrangement (FS) is used to induce phase coherence between successive pulses. The FS consists of an additional cavity, formed by $M1$ and $M3$, coupled to the main cavity by means of the beam splitter BS1. The length of the FS cavity is chosen such that its round-trip time is equal to the interval between micro-

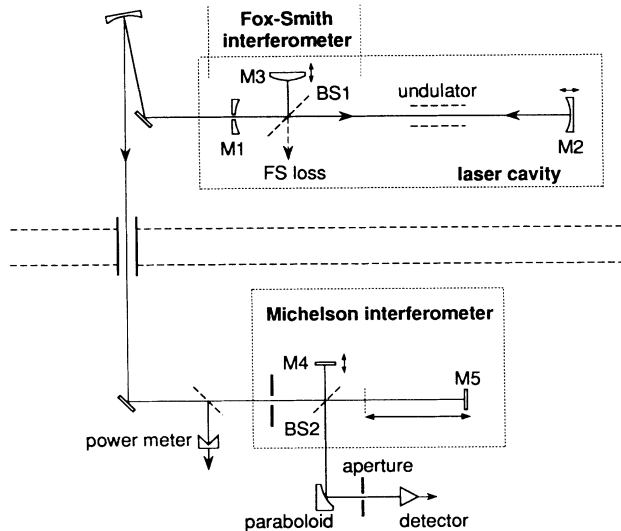


FIG. 1. Schematic diagram of the FELIX free-electron laser with a Fox-Smith phase-locking arrangement and a Michelson interferometer analyzer. See text for details.

pulses. The effect of the FS on the reflection of an optical beam incident from $M2$ is identical to that of a standard Fabry-Pérot etalon used in transmission. Those wavelengths that fit on the FS length are reflected back toward $M2$ with high efficiency, while others are rejected in the direction marked "FS loss" so that they experience no net gain [8].

With the FS adjusted to the micropulse repetition frequency, the modes retained in the cavity are just those that sum up to form the required train of identical coherent pulses. Some power will be lost initially due to the rejection of the unwanted modes, but the gain for the remaining modes is the same as without the FS, apart from additional absorption loss in the beam splitter and mirrors [4]. The quality of the FS as a filter depends on the reflectivity of the beam splitter in the same way as for a transmission etalon. An 18- μm -thick polyethylene film was used as the beam splitter in the present measurements. The reflectivity of this beam splitter depends on the wavelength because of thin-film interference. The measurements described below have been performed at $\lambda = 33 \mu\text{m}$, where the calculated reflectivity is 30%, with the exception of the one shown in Fig. 2, where the wavelength was 58 μm and the estimated reflectivity 10%.

A Michelson interferometer is used to analyze the coherence of the radiation emitted by the FEL. Mirror $M5$ (see Fig. 1) is mounted on a slide allowing a path difference between the interferometer arms from 0 to 610 mm, while $M4$ can be finely scanned over 8 mm by means of a motorized micrometer. The interfering beams are focused by an off-axis paraboloid onto a 0.25-mm-diam aperture and detected by a pyroelectric detector. A gallium-doped germanium detector has been used for higher sensitivity in measurements of single-pass radia-

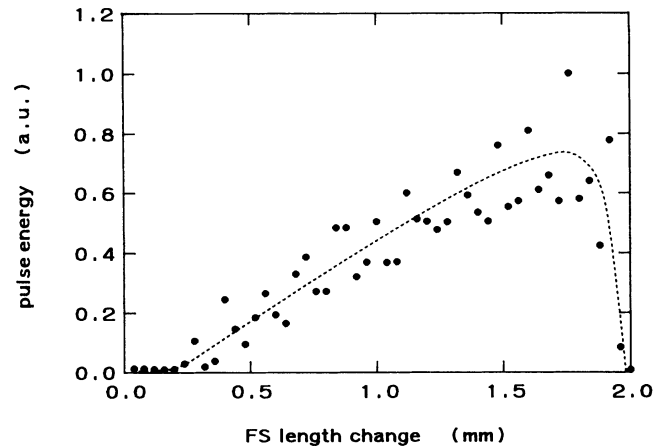


FIG. 2. Detuning of the Fox-Smith interferometer. Dots represent the energy of successive macropulses while mirror $M3$ (see Fig. 1) is being translated. The laser wavelength is $\lambda = 58 \mu\text{m}$.

tion.

With the FS well aligned and its effective length approximately matched to the electron pulse repetition frequency, we found the laser to operate virtually without change from its operation without the FS. Macropulse power was the same (1.2 kW at 58 μm) to within the measurement accuracy of 5%. From the decay of the optical signal after the end of the electron macropulse, we found an increase in the cavity losses of only 1% per pass, while the time to reach saturation was lengthened from 3.1 to 3.7 μs . An increased buildup time should be expected, as the selected modes contain only a fraction of the initial spontaneous emission. The above facts already indicate that coherence between pulses has been obtained, as otherwise the losses caused by the FS would be prohibitive. Indeed, misaligning the FS mirror $M3$, or changing its position to spoil the match between the FS modes and the mode-locking frequency, inhibits laser operation. The latter effect is illustrated in Fig. 2, which shows the measured macropulse energy while the FS mirror, $M3$, was scanned. This graph is similar to the desynchronization curve obtained on scanning the main cavity length, and shows that adequate overlap of the pulses is necessary for above-threshold operation. The apparent scatter in the data points represents a modulation with a period of one laser wavelength. This modulation, which is observed more clearly when $M3$ is scanned at a slower speed, is explained by the varying match between the modes of the coupled cavities.

A direct proof of the coherence induced has been obtained with the analyzing interferometer. On scanning the interferometer path difference in the vicinity of 300 mm, the distance between successive micropulses, we observed interference fringes with a visibility approaching 100%. Around a path difference of 600 mm, i.e., when correlating pulses with their next-nearest neighbor,

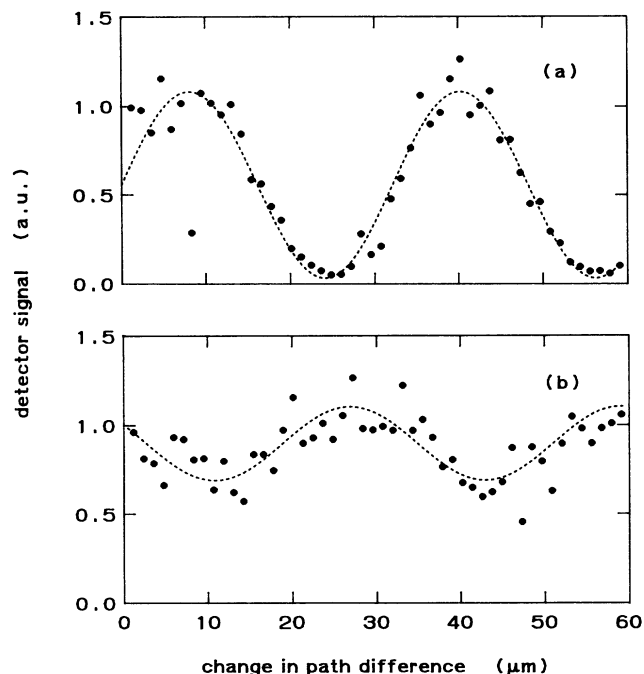


FIG. 3. Michelson interferometer signal. Dots represent the detector signal, integrated over the macropulse, for successive macropulses while mirror $M4$ (see Fig. 1) is being translated. The total path difference between the beams from $M4$ and $M5$ is roughly 600 mm. The laser wavelength is $\lambda = 33 \mu\text{m}$. In (a) the Fox-Smith arrangement is operating, and in (b) the beam splitter BS2 is removed; other operating conditions are identical.

fringes were also observed, with a visibility of over 90%. In Fig. 3(a) we show a part of the latter scan. The dots represent the integrated detector signal for successive macropulses while the interferometer path difference varied at a rate of $5.9 \mu\text{m}$ per pulse. The signal is clearly modulated at a wavelength of $33 \mu\text{m}$. The fact that the modulation is almost 100% while the signals are integrated over the macropulse duration proves that the phase relation between successive pulses is fixed, at least over most of the macropulse. The absolute positions of the maxima and minima in the interferogram are also found to be stable on a time scale of minutes. Given the path difference of two micropulse distances in the interferometer, this means that the mode frequencies are stable, on this time scale, to a fraction of the optical frequency over twice the pulse repetition frequency, i.e., $< 1:10^5$. In fact the stability of these frequencies is determined by the stability of the optical cavities, and does not depend on the details of the interaction between the electrons and the optical field. The analyzing interferometer probably was the least stable element in these measurements. Interferometry over still larger path differences has not yet been performed, but from the present results it seems

likely that most of the main cavity modes in between the FS modes are effectively suppressed.

It has been found in measurements to be discussed elsewhere that the full bandwidth of the laser, without the FS, can be made as narrow as 30 GHz. In the phase-locked case this would mean thirty active FS modes, as the FS mode spacing equals the electron repetition frequency of 1 GHz, while the overall bandwidth is not influenced. External selection of one of these modes to obtain narrow-band radiation seems quite possible. From the simulations [4] it can be concluded that the selected radiation will be concentrated in one cavity mode, with a minor contribution from one or two adjacent modes at the spacing determined by the cavity length, i.e., in our case 25 MHz. The spectral width of the separate modes is expected to be of the order of 1 MHz.

In Fig. 3(b) we illustrate the result of an interferometer scan under the same conditions as the one in Fig. 3(a), apart from the absence of the FS beam splitter in the laser cavity. Although much less clearly than in the previous case, there is a modulation visible, indicating interference between light pulses separated by two electron pulse repetition periods. For adjacent pulses, i.e., at an interferometer path difference of 300 mm, we have even observed fringes with a visibility of 70%. This implies that there can be appreciable phase locking between pulses without the added element of the FS. There are two different ways in which this coherence can arise: (1) One optical pulse influences the phase of the radiation emitted by the electrons in the next pulse, via spurious reflections or scattering, and (2) each electron pulse radiates independently with a reproducible preferred phase.

Although a small amount of optical coupling is sufficient to induce phase locking, there are no obvious mechanisms providing the right amount of optical delay without appreciable loss.

The second explanation also does not seem very likely at first sight, but is supported by the following observation: When the laser cavity is spoiled by misaligning a mirror or mismatching its length, so that the optical feedback is eliminated, we still see interpulse coherence. This means that the phase of the single-pass (amplified) spontaneous radiation is not entirely random. The explanation for this effect probably lies in the combination of long wavelengths and short electron pulses in FELIX. It is conceivable that, especially at the edges of the electron micropulse, there are systematic density variations on the scale of the optical wavelength. These will then generate radiation with a predetermined phase, leading to coherence between pulses when, in addition, the interpulse separation is constant to within a wavelength. The latter requirement can be fulfilled because of the long wavelength and the high- Q resonator structure of the accelerator. An indication that the single-pass radiation is not due to the inherent statistical charge fluctuations, but to reproducible structure in the micropulse, is the fact that its intensi-

ty was found to depend very strongly on accelerator parameters that influence the micropulse profile. Coherently enhanced spontaneous emission has been observed recently in an FEL with pronounced micropulse structure on a wavelength scale [9].

In summary, we have shown that phase locking between successive optical pulses in an rf FEL can be effectively induced by an intracavity interferometric device. This will make it possible to produce narrow-band radiation with considerable power in the (far) infrared. Spontaneous phase locking has been found to occur, and is attributed to the unique combination of short electron micropulses and long wavelengths in FELIX.

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