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Dynamic desynchronization of a free-electron laser resonator

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In a free-electron laser oscillator operating with short electron bunches, the desynchronism between electron bunches and optical pulses resulting in the shortest buildup time to saturation is different from that giving the largest saturated power. In this Rapid Communication we present an experimental demonstration of the dynamic variation of the cavity desynchronism. This is achieved by ramping the electron-bunch repetition frequency during part of each 12-μs machine pulse. A high small-signal gain and a high saturated power are obtained simultaneously.

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In a free-electron laser (FEL) oscillator, the radiation emitted by relativistic electrons traveling through a periodic magnetic structure, the so-called undulator, is captured in an optical cavity and amplified on successive passes through the undulator [1]. An electron energy of several tens of MeV is required for FEL operation in the infrared spectral range, which usually leads to the choice of a radio-frequency accelerator to provide the electron beam. The electron beam then consists of short bunches, which are separated by fixed periods. The light wave in the FEL cavity mimics this temporal structure.

Electrons slip back relative to an optical micropulse on their mutual travel through the undulator, due to the difference in forward velocity. Combined with the basic FEL property that the amplification grows toward the downstream end of the undulator [1], this has the consequence that the micropulse is amplified mainly at its trailing edge. In other words, the optical group velocity is somewhat smaller than the vacuum value. However, when the intensity approaches saturation, the gain experienced by the optical pulse begins to drop off, with the consequence that the optical group velocity returns to the vacuum value [2].

The temporal overlap of the optical field and the electrons can be adjusted by changing the cavity length. The cavity is deemed perfectly synchronized when the roundtrip time for a freely propagating optical pulse matches an integer number of the electron-bunch repetition period. In view of the reduced optical group velocity during the amplification stage, a micropulse stored in a perfectly synchronized resonator would continue to narrow and retard on successive passes through the undulator, with the consequence that the growth of the laser power is impeded. This effect is known as "laser lethargy" [3]. In order to restore the gain, it is necessary to slightly desynchronize the resonator, which usually is done by reducing the cavity length. At the desynchronism resulting in the largest small-signal gain per pass, the optical pulse and the electron bunches are optimally overlapped on successive passes through the undulator during the buildup stage. In contrast, the largest saturated power is obtained at a desynchronism close to zero, due to the larger optical group velocity at saturation. The cavity desynchronism also has a strong influence on the duration and temporal profile of the optical micropulses. The pulse duration decreases with a desynchronism closer to zero, due to the reduced temporal overlap with the electrons during the buildup stage [4].

The influence of the cavity desynchronism on the small-signal gain per pass and on the saturated power is most pronounced when the slippage of the electrons on a pass through the undulator is comparable to, or larger than, the electron-bunch length [1]. In this case it is tempting to first operate the laser at the cavity length that gives maximum gain, and then return to a longer cavity as the optical field approaches saturation, in order to maximize the saturated power [5]. This had not been done previously because of the short duration of the train of electron bunches (the so-called macropulse, which has a duration typically of 10 μs in FEL's employing a normal-conducting accelerator) and the relatively large change in resonator length (typically 10–100 μm, depending on the radiation wavelength). In this Rapid Communication we present a demonstration of dynamic cavity desynchronization, as achieved with the free-electron laser for infrared experiments (FELIX). FELIX is the first FEL to operate in the regime of large slippage [6], due to the combination of long radiation wavelength (up to 100 μm) and short bunch length (of the order of 1 mm). These parameters have been chosen to enable experiments in nonlinear spectroscopy in a part of the spectrum where no other powerful, short-pulse lasers are available.

The cavity desynchronism is defined as the difference between (i) the cavity roundtrip time for a freely propagating optical pulse, and (ii) the electron-bunch repetition period multiplied by the number of stored pulses. Denoting the "normal" cavity length and electron-bunch repetition frequency (for which combination the cavity is perfectly synchronized) as L and f, respectively, we straightforwardly find that the desynchronism $\Delta\tau$, normalized to the nominal cavity roundtrip time τ, is

$$\frac{\Delta\tau}{\tau}=\frac{\Delta L}{L}+\frac{\Delta f}{f}\ , \tag{1}$$

where ΔL and Δf denote a (small) deviation from the

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nominal values. Hence a cavity-length detuning ΔL has the same effect as a frequency detuning $\Delta f = f\Delta L/L$. In FELIX, the nominal cavity length is $L=6$ m and the nominal repetition frequency is $f=1$ GHz (which, incidentally, has the consequence that 40 pulses are stored in the resonator).

In the experiment reported here, the desynchronism is varied by ramping the electron-bunch repetition frequency. To this end, a suitably chosen ramp signal is fed to the FM input of the master oscillator (a Rohde and Schwarz signal generator, type SMG 801.0001.52) of the rf system that provides the input power for the chain of accelerator components: a triode electron gun, prebuncher, buncher, and two linear accelerators. The setup of the rf system is discussed in detail in Ref. [7]. The response of the system is, of course, determined by the response time of the rf amplifiers in the various branches of the rf system and by the filling time of the accelerating structures. A detailed discussion of the response time is outside the scope of this report, but in measurements of the phase at the buncher input we have found that the frequency change is delayed typically by 3.5 μs with respect to the ramp signal.

In Fig. 1(a) we show three experimentally obtained optical macropulses for a wavelength of 42 μm. At a fixed repetition frequency of 1 GHz and a fixed cavity length, a buildup time to saturation close to the shortest possible value (roughly 3.5 μs, taking into account the beam-loading transient of 1.5 μs at the start of the electron macropulse) is obtained at a cavity-length detuning $\Delta L=-27$ μm. The corresponding small-signal gain per pass is of the order of 20% net. The largest saturated power, however, is obtained at a detuning of -4 μm. In this case the net gain per pass is very small (of the order of 7%), with the consequence that the time at which saturation is reached fluctuates typically by 1–2 μs from macropulse to macropulse. The applied ramp of the electron-bunch repetition frequency in the dynamic cavity desynchronization experiment is shown in Fig. 1(b). The nominal repetition frequency, for which $\Delta f=0$, is approximated by the experimentally found fixed frequency at which the small-signal gain has just dropped below the threshold for oscillation. For convenience we also indicate in Fig. 1(b) the equivalent change in cavity length, as calculated with Eq. (1), taking into account the estimated 3.5-μs response time of the chain of rf components. The optical macropulse in this case has the anticipated feature of a high initial gain per pass (the same as at a fixed detuning $\Delta L=-27$ μm) and a high saturated power (even somewhat higher than at $\Delta L=-4$ μm). The macropulse-to-macropulse reproducibility is much better than at $\Delta L=-4$ μm: the time at which saturation is reached fluctuates typically by only 100 ns.

The power spectra for the three cases in Fig. 1(a) are shown in Fig. 2. These spectra were measured with a Bentham spectrometer equipped with a 20-lines-per-mm grating, operated in (ambient) air. The measured full width at half maximum (FWHM) spectral width is 1.1%

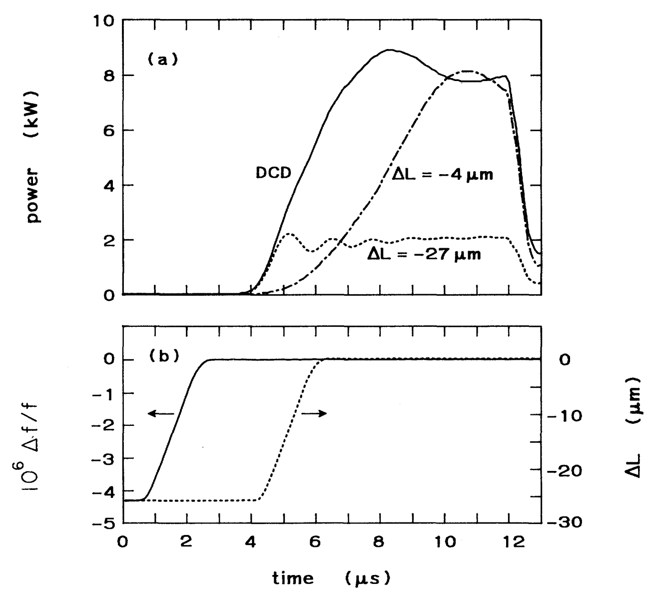

FIG. 1. Optical macropulses measured at a wavelength of 42 μm (a), as obtained at a fixed cavity desynchronism giving a large single-pass gain ($\Delta L=-27$ μm), at a desynchronism giving a large saturated power ($\Delta L=-4$ μm), and with the dynamic cavity desynchronization (DCD) shown in (b). The electron beam macropulse starts at $t=0$, the beaming-loading transient in the accelerator has died out at $t=1.5$ μs, and the macropulse ends at $t=12$ μs. The full line in (b) gives the applied ramp signal to the FM input of the maser oscillator. The dotted line gives the equivalent cavity length detuning, when the observed 3.5-μs delay in response of the rf system is taken into account.

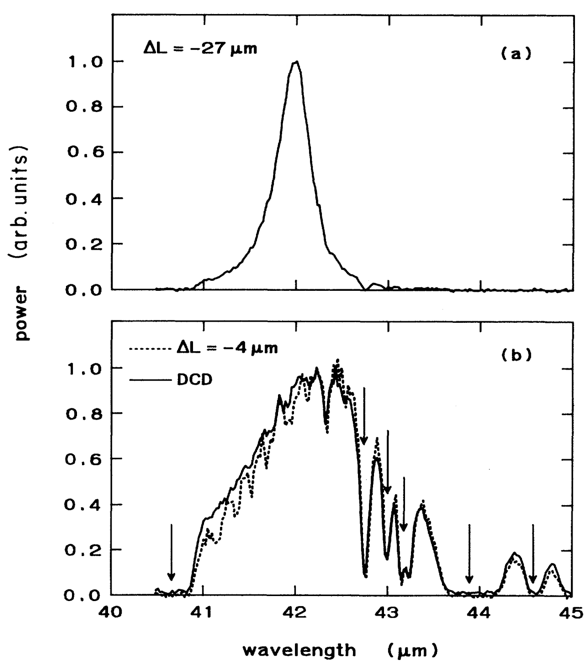

FIG. 2. Power spectrum corresponding to the three cases shown in Fig. 1(a). The arrows indicate absorption lines in ambient water vapor in the spectrometer setup. The spectra are integrated over the macropulse. Each spectrum is measured by scanning the spectrometer during 200 successive macropulses. The power scale is different in (a) and (b).

at $\Delta L = -27$ μm and, in view of the fact that FELIX radiation has been found to be transform limited [8], this suggests that the FWHM duration of the optical micropulses is 5.6 ps. A quantitative interpretation of the spectra measured for the two other cases is obscured by absorption in ambient water vapor. However, we can draw the important qualitative conclusion that the spectrum measured at a fixed detuning of $\Delta L = -4$ μm can hardly be distinguished from the spectrum measured with dynamic cavity desynchronization. This strongly suggests that the FWHM micropulse duration is the same in these two cases. The estimated width of the spectral envelope of 5% indicates a pulse duration of the order of 1 ps. This implies that the micropulse peak power is a factor 20 larger than in the $\Delta L = -27$-μm case.

The origin of the oscillation of the saturated power, as observed in Fig. 1(a), has been reported earlier [6]. This effect is a consequence of the fact that, at a fixed desynchronism, the optical micropulse begins to move forward relative to the electrons when saturation sets in, due to the increase in optical group velocity. After a number of cavity transits, the optical pulse gradually loses contact with the electrons, and a new subpulse can grow from its trailing edge. This is similar to the "superradiance" phenomenon in single-pass FEL's [9]. Each micropulse eventually evolves into a train of subpulses, which are separated by the slippage length and decay in amplitude at a rate dictated by the cavity roundtrip loss. This temporal evolution of the micropulses is reflected in the oscillation of the power envelope. The rate at which subpulses are formed is largest in the case of a large cavity desynchronism [6], which explains why the smallest oscillation period, 1.3 μs, is obtained at $\Delta L = -27$ μm. The much larger oscillation period in case of a dynamically altered cavity desynchronism, of the order of 5 μs, illustrates the improved stability of the micropulse shape during the saturated part of the macropulse.

In conclusion, we have shown that the combination of high small-signal gain per pass and high saturated power, which until now could be obtained only with long-pulse FEL's, can be obtained also with a short-pulse FEL when the cavity desynchronism is matched to the increase in optical group velocity as the stored field approaches saturation. Besides the obvious advantage that this improves the integrated macropulse energy, this technique also has the advantage of a much better macropulse-to-macropulse reproducibility, as compared to the case in which the cavity desynchronism is set at the (fixed) small value resulting in the largest saturated power. This is important because the shortest micropulses are obtained at a small desynchronism, and short micropulses are essential for many FEL applications [10]. For these applications it is also advantageous that the evolution of each micropulse into a train of subpulses appears to take place on a much longer time scale than at a (fixed) large desynchronism. Hence the micropulse temporal profile during the saturated part of the macropulse is much more constant.

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