Free-Electron Laser Efficiency Enhancement, Gain Enhancement, and Spectral Control Using a Step-Tapered Undulator

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We present a new method of enhancing the efficiency of a Compton free-electron laser. Measurements and a theoretical analysis show that the efficiency of a short pulse free-electron laser can be almost doubled using a two-section step-tapered undulator with the downstream undulator having the higher magnetic field, i.e., reversed with respect to conventional tapering. We also show that the stability of the laser and the spectral purity are improved at the highest output powers because sidebands in the spectrum due to synchrotron oscillations are suppressed. Smooth subpicosecond optical pulses with peak powers of 100 MW have been produced in the midinfrared.

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The free-electron laser (FEL) produces high intensity monochromatic optical radiation when a high energy electron beam passes through a periodic magnetic structure called an undulator [1,2]. Spontaneously produced radiation is trapped in an optical cavity and amplified by a process of stimulated Compton backscattering. The electron dynamics are governed by a ponderomotive potential associated with the beat wave of the undulator and the laser field.

In this Letter we present a new method for enhancing the efficiency and improving the spectral and temporal properties of the FEL. Experimental observations, supported by theoretical analysis, show that the efficiency of the FEL can be almost doubled by using a two-section reverse step-tapered undulator (RSTU) where the rms undulator deflection parameter K [1] is increased in a single step between the two similar sections [3]. We have also observed that the small signal gain is increased, the spectral brightness of the FEL is improved because sidebands due to synchrotron oscillations are suppressed, and that the FEL operates with improved stability at its peak power output producing smooth optical pulses free of temporal subspikes. The improved properties of the RSTU FEL operation are now routinely being used in applications which use the FEL output radiation in other areas of physics.

The experimental observations have been carried out on two similar rf linac-driven FEL's operating in the infrared as user facilities: CLIO [4], situated in France, and FELIX, in the Netherlands [5–7]. The undulators of the FEL's have two identical independently adjustable deflection parameters, K_1 and K_2, the upstream and downstream K, respectively. In CLIO the optical radiation is coupled out of the cavity using a slightly dispersive ZnSe plate. In FELIX the optical radiation is coupled out using a hole in one of the mirrors. Table I gives other important parameters for the two lasers. The small signal gain per pass of CLIO is in the intermediate range of $g_0 = 1-2$ because of a high current, 80 A [4]. The single pass gain allows saturation to occur with one undulator section only. This intermediate high gain operation of CLIO has made it possible for the FEL to operate with two colors simultaneously [3]. FELIX, however, has a lower gain, $g_0 = 0.2-0.5$, because of its longer wavelength and lower peak current.

In a Compton FEL with a uniform undulator, the efficiency, defined as the fraction of the energy extracted from the electrons, is limited to $\eta \approx 1/2N_u$, where N_u is the number of undulator periods [2]. This is usually not attained in oscillator experiments. Saturation commences when the optical field strength is such that electrons begin to oscillate in the ponderomotive potential and reabsorb radiation. At saturation these so-called synchrotron oscillations are responsible for the development of sidebands in the optical spectrum [2], limit cycle oscillations of the optical power and pulse shape [8,9], and spiking [10]. At very high intracavity power, in a FEL oscillator, the efficiency is enhanced by a stochastic diffusive deceleration of the electrons [11–13] and a broad chaotic optical spectrum that develops from synchrotron instabilities [2,11], making it less suitable for utilization. In a short electron bunch

TABLE I. Laser parameters of CLIO and FELIX.

	CLIO	FELIX	
Electron energy	30–50	15–45	MeV
Bunch charge	900	200	pC
Bunch length	2.2	1	mm
Electron energy spread (rms)	0.2	0.25	%
Normalized emittance (rms)	50	50	π mm mrad
Undulator period	40	65	mm
Maximum undulator K (rms)	1.8	1.41	
Number of undulator periods	48	38	
Wavelength range	2–17	6–110	μm

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FEL the efficiency is enhanced because of the limited interaction length due to slippage and lethargy [14–16].

The traditional method of increasing or enhancing the efficiency of the FEL amplifier is to use a modified undulator [17], usually accomplished by varying the undulator parameters gradually in such a way that the electrons remain trapped in the ponderomotive potential as they traverse the undulator [2]. The tapering is achieved by either smoothly increasing the period λ_u [17] or by decreasing K along the undulator [17]. A disadvantage of these methods for a FEL oscillator is that the small signal gain coefficient is reduced, thereby increasing the buildup time to saturation. Because the developing radiation field frequency depends on the laser dynamics, it is in general not at an appropriate value for efficiency enhancement [18]. The efficiency depends on the number of incident electrons trapped in the ponderomotive potential [19] which in turn depends on the optical radiation frequency [2]. The highest efficiency in an oscillator with a tapered undulator is not attainable without injection locking [18,19]; it is indeed preferable to reverse the taper of the undulator [18] as in the phase displacement undulator [17,19].

Measurements on CLIO have shown that the FEL oscillator efficiency is not enhanced with a smoothly tapered undulator. We have found that it is preferable to abruptly change K part way down the undulator. From measurements and simulations we have found that the efficiency is enhanced by as much as a factor of 2 for a positive step in K, $\Delta K \approx 0.02-0.04$, corresponding to a decrease of the undulator gap of the order of a few tenths of a millimeter. On the other hand, negative steps, $\Delta K < 0$, lead to a decrease in the efficiency. Figure 1(b) shows typical measurements of the output optical micropulse energy as a function of ΔK for CLIO operating at 40 MeV with $\lambda = 8$ μm. An efficiency of 0.7–1.0% for $\Delta K \approx 0.03$ is deduced. Similar efficiency has been measured at 50 MeV and $\lambda = 5$ μm. Within the uncertainties of determining the total power lost from the optical cavity, the maximum efficiencies are still lower than or, at most, equal to the natural efficiency, $\eta = 1/2N_u \approx 1\%$ expected for CLIO. The enhancement of efficiency for RSTU operation has also been observed more directly in the FELIX FEL by measuring the electron energy spectrum after FEL interaction. The fractional electron energy loss $\delta\gamma/\gamma$ as a function of ΔK for 45 MeV and $\lambda = 12$ μm is shown in Fig. 1(f). The largest efficiency found at $\Delta K \approx 0.03$ was 1.2%, a factor of 1.75 higher than for $\Delta K = 0$ but approximately equal to the expected natural efficiency for FELIX. However, preliminary measurements at longer wavelengths show that the efficiency can be higher and, moreover, even higher efficiency operation may be possible with longer macropulses or dynamic desynchronism of the optical cavity length [14,15,20]. We have also observed, as shown in Fig. 1(e), that the RSTU mode of operation does not lead to an increase in the energy dispersion of the electrons exiting the undulators consistent with the

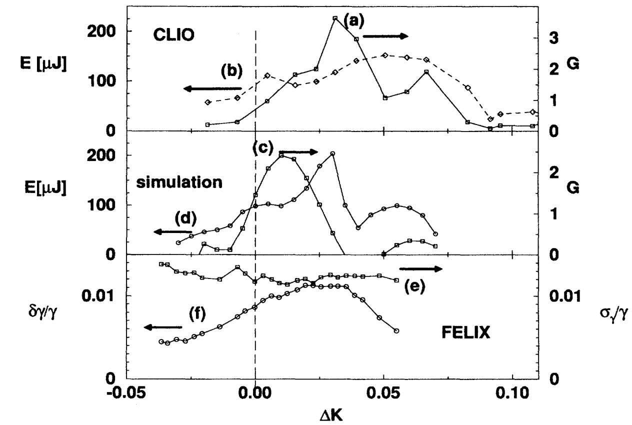

FIG. 1. Experimental and theoretical ΔK scans. CLIO: Measurement of small signal gain (a) and total output optical pulse energy (b). CLIO: Simulation of small signal gain (c) and saturated output optical pulse energy (d). FELIX: Measurement of mean electron energy dispersion σ_γ/γ (e) and electron energy reduction $\delta\gamma/\gamma$ (f).

incease in optical power. This property of RSTU operation may have beneficial applications in storage ring FEL's.

To examine the processes governing RSTU enhancement we consider a planar undulator and electrons interacting with the ponderomotive potential. The resonance wavelength $\lambda_0 = \lambda_u/2\gamma^2(1 + K^2)$ is fixed by γmc^2, the electron energy, λ_u, and K. To simulate RSTU operation we have numerically solved the coupled Maxwell-Lorentz equations in the slowly varying amplitude approximation and in one dimension [2,8]. The coupling with the Gaussian optical mode is modeled using a transverse filling factor [2]. The influence of inhomogenous effects is included through an initial phase-space distribution of the electrons, and the electron pulse shapes are taken as triangular consistent with measurements and simulations of the electron bunch shape [4,21–24]. Our model can also include dispersion in the optical cavity for comparison with CLIO. For RSTU FEL operation the deflection strength K changes from K_1 to K_2 in a step of $\Delta K = K_2 - K_1$ halfway down the undulator. The normalized phase velocity of the electrons in the ponderomotive potential, relative to an optical field with a wavelength λ, defined as $\nu = 2\pi N(1 - \lambda_0/\lambda)$ [2], changes from ν_1 to ν_2 such that $\nu_2 = \nu_1 + \delta\nu = 2\pi N_u(1 - \mu) + \nu_1\mu$ where $\mu = (1 + K_2^2)/(1 + K_1^2)$.

We find fair agreement between numerical simulations and the corresponding measured data. Figures 1(d) and 1(c) show simulations of the output optical pulse energy and the small signal gain for CLIO. In other simulations for CLIO, not presented here, we find that if we omit dispersion in the optical cavity from our model a second much larger peak in the enhancement of the efficiency occurs at $\Delta K \approx 0.06$. The absence of this second larger peak in the measurements has been ascribed to the influence of dispersion in the optical cavity [3]. However, it may be possible to observe this second peak at $\Delta K = 0.06$ if an alternative nondispersive method of coupling the radiation out of the cavity is used. To investigate the possibility, in principle, of reaching saturation with $\Delta K \approx 0.06$ we have measured the small signal gain as a function of ΔK and found gains greater than 100% at $\Delta K = 0.06$, as shown in Fig. 1(a). These typical measurements also show that the gain has a maximum at $\Delta K \approx 0.03$ and also exhibits a modulation due to the mutual interference between the two undulator sections [3,25–27]. The largest gain that has been measured for $\Delta K \approx 0.03$ is 700%, a factor of 2 or 3 higher than at $\Delta K = 0$, placing CLIO in the high gain regime.

To understand how the electrons evolve in phase space as they pass through the two undulator sections we have simulated the electron evolution in the amplifier, neglecting electron energy spread and using input field and electron parameters established from the simulated oscillator evolution at saturation, shown in Figs. 1(c) and 1(d). The main features of the phase-space evolution for amplifier and oscillator were very similar, although the advantage of the amplifier simulation is that the ponderomotive potential and hence the separatrix are constant in each undulator section because the optical field frequency and amplitude do not vary as in the case of the oscillator. The starting parameters for the simulated amplifier evolution were a constant normalized input optical field amplitude [2] $|a| = 80$ corresponding to ≈ 750 MW, and an electron current $I = 80$ A. From the oscillator simulations we found an optimum efficiency at a $\Delta K \approx 0.033$, as shown in Fig. 1. The optical wavelength at saturation implies that the electrons enter the first undulator section with a phase velocity $\nu \approx 15$, above resonance of the first section but approximately at resonance with the second undulator section. This is graphically presented in Fig. 2. The solid lines represent the separatrix for the two resonances. The first undulator section acts as a buncher bunching electrons very strongly before they enter the second undulator where a proportion of the electrons are at the bottom of the first potential. The lower energy electrons are then detrapped in the second section, while the higher energy electrons, having been accelerated in the first section, are captured by the second potential and experience an energy loss. The former electrons therefore do not have a strong influence on the optical power and detrapping has the effect of preventing synchrotron oscillations occurring, and therefore the field amplitude tolerable before synchrotron oscillations commence is increased. Figures 2(a) and 2(b) compare the mean reduction in phase velocity for $\Delta K \approx 0.033$ and $\Delta K = 0$. An additional benefit is that the energy spread of the electrons exiting the second undulator is reduced over that for $\Delta K = 0$.

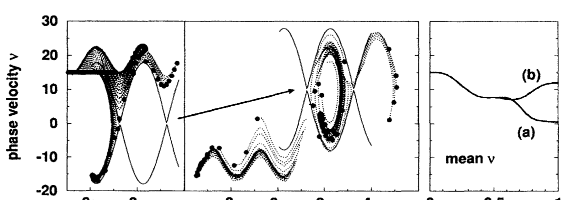

FIG. 2. Phase-space diagrams of electrons at saturation showing detrapping of lower energy electrons and capture of high energy electrons for $\Delta K \approx 0.033$. Solid lines represent the separatrix in each undulator section. The solid dots represent the electrons at the end of each section. The right-hand side shows the mean electron energy down the undulator ($\tau = 0 \rightarrow 1$) for $\Delta K \approx 0.033$ (a) and $\Delta K = 0$ (b). Step in K occurs at $\tau = 0.5$.

The spectral brightness of the FEL is also improved by operating with a RSTU because synchrotron oscillations are suppressed. We observe an increase of the brightness larger than a factor of 2.5 for $\Delta K \approx 0.03$ with other FEL parameters kept fixed. Figure 3 shows comparative measurements of spectra made at the peak of the optical cavity detuning curve (i.e., peak power), on FELIX for 25 MeV, $\lambda = 12\ \mu$m at $\Delta K \approx 0.03$ and $\Delta K = 0$. The measured spectra, in Fig. 3(a), are smooth and lack sidebands associated with synchrotron oscillations and spiking. Similar enhancements have been observed experimentally on CLIO and in our simulations. The featureless spectra also indicate smooth temporal envelopes of the optical pulses. To confirm this, in CLIO, we have inferred the optical pulse shape and duration from second-order autocorrelation spectra measured at the peak of the cavity detuning curve. We infer smooth 350 fs duration optical pulses without substructure at 40 MeV, $\lambda = 9.3\ \mu$m, and the peak of the cavity detuning curve, as shown in Fig. 4 for $\Delta K \approx 0.03$. From these measurements and the energy of a single optical pulse we have deduced a peak output optical power of 100 MW for RSTU operation of CLIO.

A key factor influencing the enhancement of gain is the initial wavelength. By measuring both the spontaneous emission spectrum and the laser spectrum at both low and high fields we have established that the wavelength of the radiation in the RSTU configuration is fixed by the downstream undulator. In the spontaneous emission measurements we have also observed amplified spontaneous emission, where the optical power exhibits a strongly nonlinear dependence on the electron charge.

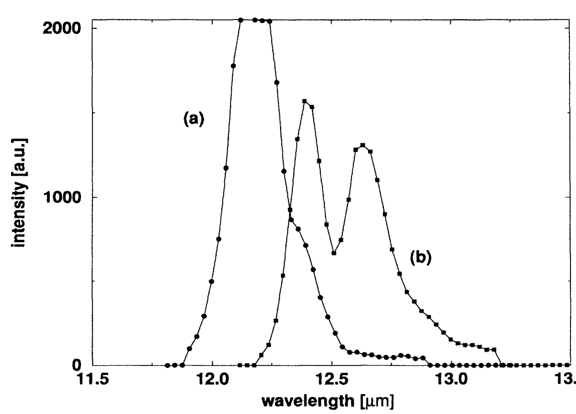

FIG. 3. FELIX optical spectra for $\Delta K \approx 0.03$ (a) and $\Delta K = 0$ (b).

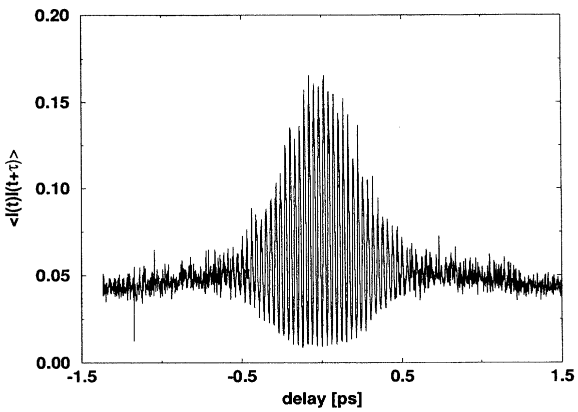

FIG. 4. Second-order autocorrelation measurements of CLIO optical pulses, for $\Delta K \approx 0.03$, implying subpicosecond optical pulses with a peak power of 100 MW.

The peak in the radiation spectrum occurs at the resonance wavelength of the second undulator, implying that the first section acts as a buncher and the second section as a radiator. These measurements indicate that the initial wavelength is very important in obtaining high efficiency and high gain operation of the FEL.

From simple theoretical considerations we expect the efficiency also to increase for a shorter undulator [2]. However, in CLIO, operation with only half the undulator leads to a slight decrease in efficiency. A study of the efficiency as a function of overall undulator length and the influence of the cavity detuning on the efficiency still needs to be carried out.

In conclusion, we have presented a new method of enhancing the efficiency of the FEL using a reverse step-tapered undulator by a combination of (i) detrapping electrons at the bottom of the ponderomotive potential and (ii) trapping of electrons accelerated in the first undulator section. We have also observed gain enhancement and an improvement in the spectral brightness and the stability of the FEL at its highest output powers. We have also shown that the enhancement of efficiency with a RSTU does not lead to a corresponding increase in energy spread of the electrons.

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