INTEGRATION OF THE OPTICAL REPLICA ULTRASHORT ELECTRON BUNCH DIAGNOSTICS WITH THE CURRENT-ENHANCED SASE IN THE LCLS*

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Abstract

In this paper, we present a feasibility study of integrating the optical replica (OR) ultrashort electron bunch diagnostics with the current-enhanced SASE (ESASE) scheme in the LCLS. Both techniques use an external laser to energy-modulate the electron beam in a short wiggler and then convert the energy modulation to a density modulation in a dispersive section. While ESASE proposes to use the high-current spikes to enhance the FEL signal, the OR technique extracts the coherent optical radiation produced by a density modulated electron beam for frequency resolved optical gating (FROG) diagnostics. We discuss the optimization studies of combining the OR method with the ESASE after the second bunch compressor in the LCLS. Simulation results show that the OR method is capable of reproducing the expected double-horn current profile of a 200-fs bunch. The possibilities and limitations of reconstructing the longitudinal phase space profile are also explored.

INTRODUCTION

Current-enhanced SASE (ESASE) is a recent proposal by Zholents [1] to manipulate the electron beam with an optical laser to enhance the SASE FEL performance. In this technique, the electron peak current is significantly enhanced by inducing an energy modulation in an upstream wiggler magnet via resonant interaction with an optical laser, followed by microbunching of the energy-modulated electrons before entering the SASE undulator. The uniformly-spaced, high-current spikes within the electron bunch amplify the SASE radiation much faster than the rest of the bunch, allowing for a shorter saturation length, natural synchronization with the optical laser, and controllable x-ray time structure. A detailed study of its application in the LCLS can be found in Ref. [2].

Based on the optically modulated electron beam, Saldin et al. propose an optical replica (OR) synthesizer for ultrafast electron bunch diagnostics [3]. Similar to ESASE, the OR technique induces an energy modulation on the electron beam by a seed optical laser in the first wiggler (energy modulator). A dispersion section following the modulator converts the electron energy modulation to an adjustable amount of the density modulation. After passing a second wiggler (radiator), the density-modulated electron bunch emits coherent optical radiation that is proportional to the

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electron bunch current. This optical replica of the electron bunch can be analyzed with the frequency resolved optical gating (FROG) to reveal the high-resolution bunch current profile as well as slice beam parameters.

Since both techniques share some common components to manipulate the electron bunch and offer unique improvements to the operation of an x-ray FEL, we investigate here the application of the OR bunch diagnostics in the LCLS in combination with the ESASE scheme. Simulation studies show that OR technique is effective in diagnosing the electron bunch density and energy profiles at fs time resolution. Hence it should be a useful tool for the reliable operation of an x-ray FEL facility.

OPTICAL REPLICA SETUP

A schematic of the OR setup in the LCLS is shown in Fig.1. The main elements include an infrared laser, an energy modulator (wiggler-1), a radiator (wiggler-2), and a dispersive section (chicane) between the wigglers. The location of the energy modulator is right after the second bunch compressor (BC2), where the electron beam energy is 4.3 GeV. The layout is very similar to a seeded optical klystron FEL. Compared with the ESASE setup, the dispersion section and wiggler-2 are two more new elements, and a relatively longer laser pulse is required to modulate the entire electron bunch. The electron pulse will be timed to overlap with the central portion of the laser pulse, while in ESASE, a shorter laser pulse with high peak power is adopted to modulate only part of the electron bunch in order to produce very short x-ray pulse. Considering the ESASE design parameters in LCLS [2], we use the same wiggler-1 parameters and same laser wavelength of 800nm but at a lower peak power of no more than 1.0 GW. The laser beam is focused at the center of the 8-period modulator. The radiator has 4 periods, and the radiation power from the radiator can be adjusted by changing the momentum compaction factor R_{56} of the chicane. To separate the seed laser pulse from the optical radiation generated by the radiator, the two planar wigglers can be put in crossed positions with different polarizations.

We summarize the main OR parameters in Table 1 for LCLS normal design case. We can see that for ESASE, we only have to increase the seed laser power to 10 GW and switch off the chicane and wiggler-2. ESASE will need another chicane buncher prior to the SASE undulator as discussed in [2].

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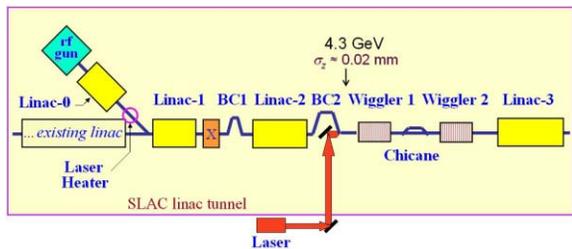
Figure 1: (color) Schematic of the OR setup at LCLS

Table 1: Main parameters for OR

Parameter	Symbol	Value
electron energy	E	4.3 GeV
electron current	I	3.4 kA
laser wavelength	λ_L	800 nm
laser power	P_L	0.1~1.0 GW
wiggler-1,-2 period	λ_u	25 cm
wiggler-1,-2 parameter	K	31.5
wiggler-1 length	L_{w1}	2.0 m
wiggler-2 length	L_{w2}	1.0 m
chicane compaction factor	R_{56}	10μm~0.4 mm

DIAGNOSING BUNCH CURRENT PROFILE

Suppose a fundamental Gaussian mode laser copropagates with a round electron beam in a modulator of length L_{w1}, which is short compared to both the Rayleigh length of the laser and the beta functions of the electrons. Neglecting small changes in laser and electron beam sizes during the resonant interaction, we may write the amplitude of the electron energy modulation δ_m after the interaction as

$$\delta_m = \sqrt{\frac{P_L}{P_0}}\frac{KL_{w1}}{\gamma^2\sigma_r}[J_0(\frac{K^2}{4+2K^2}) - J_1(\frac{K^2}{4+2K^2})] \quad (1)$$

where P_L is the laser power, P_0 is the electron beam power, K is the wiggler parameter, γ is the electron energy in units of its rest mass, σ_r is the rms laser spot size in the modulator, and $J_{0,1}$ are Bessel functions.

After the dispersion section the electron beam is density modulated, and will generate coherent radiation in the radiator. If the radiator length is short (no FEL exponential amplification yet), the coherent emission field amplitude $A(t)$ can be written as:

$$A(t) \propto I(t)b(t) = I(t)J_1(kR_{56}\delta_m)e^{-k^2R_{56}^2\sigma_\delta^2/2} \quad (2)$$

where $I(t)$ is the electron current, $b(t)$ is the electron bunching factor, $k = 2\pi/\lambda$ is the resonant wave number, R_{56} is the momentum compaction factor of the chicane structure, and σ_δ is the electron rms energy spread.

In Eq. (2), if $k^2R_{56}^2\sigma_\delta^2/2 \ll 1$, the exponential suppression effect is negligible. In this case, we have $A(t) \propto I(t)$, where the shape of the radiation amplitude is an optical
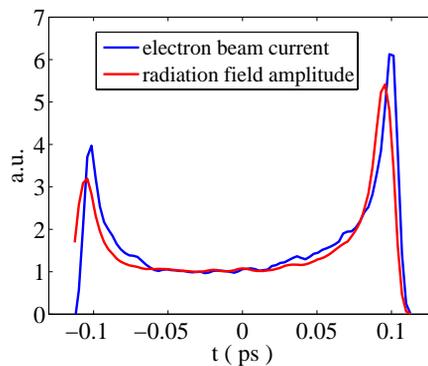
Figure 2: (color) The radiation field amplitude from the radiator and the electron current profile for the LCLS 1 nC case, bunch head at left.

replica of the electron current profile. According to the standard FROG apparatus, e.g., Grenouille, the sensitivity is 1 μJ for the single shot mode[4]. For the LCLS nominal design case with 1 nC charge, we choose the laser power of 1 GW, and $R_{56} = 10\mu m$. GENESIS[5] simulations show that the radiated power from wiggler-2 is about 20 MW, which will satisfy the FROG requirement for the rms electron bunch length of 73 fs. For the low charge design case of 200 pC with rms bunch length of 23 fs, we use a laser power of 1 GW and $R_{56} = 30\mu m$. The radiated power is then increased to 45 MW. With these parameters, it is a good approximation to assume $A(t) \propto I(t)$.

Figure 2 shows an example of the simulated profiles of the radiation field amplitude and the input current of the electron bunch. The resolution is limited by the length of the radiator. With 4 periods of the radiator, the slippage length is 3.2 μm, which determines a potential OR resolution of about 10 fs.

DIAGNOSING THE SLICE ENERGY SPREAD AND ENERGY PROFILE

The exponential suppression factor in Eq. (2) can not be ignored while increasing R_{56} due to the slice energy spread $\sigma_\delta(t)$. According to Eq. (2), the maximum bunching occurs at $kR_{56}\sigma_\delta \approx 1$ when $\delta_m/\sigma_\delta < 1$. By scanning R_{56} and recording the time-resolved radiation intensity in multiple shots, we can find the optimal $R_{56}^{opt}(t)$ for the maximal radiation intensity a given time t. The slice energy spread can be estimated as [3]

$$\sigma_\delta(t) \approx \frac{1}{kR_{56}^{opt}(t)}. \quad (3)$$

Based on the standard LCLS design, $\sigma_\delta \sim 3 \times 10^{-4}$ for the central part the electron bunch at 4.3 GeV. This requires $R_{56} \sim 0.4$ mm to get the maximum bunching at $\lambda_L = 800$ nm. The relatively large R_{56} used for the slice energy spread measurement also reduces the requirement on the laser power to 0.1 GW. Figure 3 shows a simulated measurement result of the slice energy spread with this method.
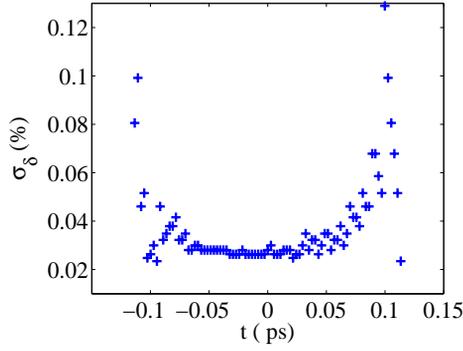
Figure 3: (color) The slice energy spread obtained from Eq.(3) by scanning R_{56}, bunch head at left.

Figure 4: (color) The simulated measurement of the electron beam longitudinal phase space (using Eq.(6), red dots) and the ELEGANT simulation result (blue dots).

It is in good agreement with the ELEGANT[6] simulation result in the middle section of the beam at 3×10^{-4}. The head and tail sections are over-compressed with relative large energy spread as expected.

The FROG technique decodes both the amplitude and phase of the radiation field simultaneously. The electric field from the radiator can be written as

$$E(t) = A(t) \exp[i(\omega_r t - \phi(t))], \qquad (4)$$

where $\phi(t)$ is the time-dependent phase of the pulse. In the modulator, the electron beam is modulated at the wavelength of the seed laser λ_L. If there is no energy chirp after the modulator, this modulated electron beam will emit radiation in the radiator at the laser wavelength λ_L. However, an energy chirp in the electron beam together with the momentum compaction factor R_{56} in the dispersion section can shift the modulation wavelength after the chicane. In this case, the radiation frequency ω_r can be written as $\omega_r = \omega_L/(1 + hR_{56})$, with ω_L being the seed laser frequency, and $h = d\delta/dt$ being the electron energy chirp. The difference on the frequency between the radiation and the seed laser $\Delta\omega = \omega_r - \omega_L$ is just the derivative of phase $-d\phi/dt$. When $| hR_{56} |\ll 1$, we may write

$$\frac{d\phi}{dt} = R_{56}\omega_L \frac{d\delta}{cdt}. \qquad (5)$$

In Eq. (5), If $\delta(t)$ is a single-valued function, we may further get longitudinal phase space $\delta(t)$ from radiation phase $\phi(t)$ directly as

$$\delta(t) = \phi(t)/(R_{56}k_L). \qquad (6)$$

Due to the strong longitudinal wakefield, the head and tail portions of the nominal LCLS bunch will be over-compressed and lead to a double horn current profile after BC2. The energy-time correlation in head and tail sections becomes a double-valued function. Hence Eq. (6) can not be used in this part of the bunch. One possible method to get a single-valued energy-t function after BC2 for this longitudinal phase space diagnostics is to adjust the linac-2 phase or BC2 compaction factor to reduce the compression ratio. Figure 4 gives an example of the electron longitudinal phase space deduced from the radiation field phase information. In this example, we adjust the accelerating phase of linac-2 from $-41°$ to $-26°$ to get a single-valued function $\delta(t)$ after BC2. This longitudinal phase space retrieval method can be used to analyze the energy chirp and the linac wakefield.
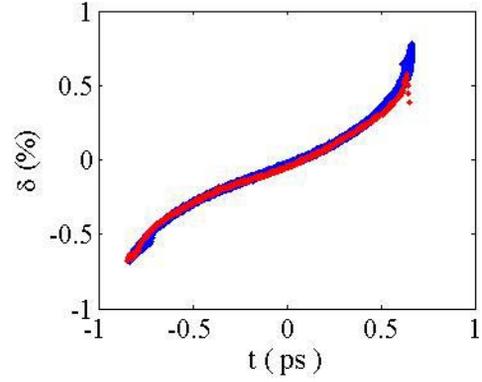
DISCUSSIONS

A seed laser wavelength of about 2 μm is also discussed in the ESASE scheme[2]. In this setup, the radiator for the OR diagnostics may operate at the second harmonic wavelength of about 1 μm. To produce sufficient radiation for FROG measurements, a larger R_{56} (about $100\mu m$) may be necessary and may lead to some distortions of the OR signal at the head and tail parts of the electron bunch where the slice energy spread is large. Nevertheless, the bunch length and slice energy spread in the bunch core can still be retrieved with this method.

Finally, we note that the slice emittance diagnostics described in [3] is not practical in our case. An extremely large beta function (about 1000 m) is required to make the electron transverse beam size large enough to affect the radiation intensity emitted by the bunch.

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