STUDY OF OPTICAL FREQUENCY CHIRPING AND PULSE COMPRESSION IN A HIGH-GAIN ENERGY-RECOVERY-LINAC-BASED FREE-ELECTRON-LASER

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Abstract

In this paper we report a direct experimental investigation of optical frequency chirping effects induced by ultrashort electron bunches in a high-gain energy-recovery-linac (ERL) free-electron laser (FEL) cavity. Our measurement and analysis show clear evolution of the optical pulse chirp verses the electron bunch energy chirp. Further study also provides important evidence that under certain conditions much shorter FEL pulses can be obtained through properly chirping electron bunches and optical pulse compression. Although studies of chirp measurements on Self-Amplified-Spontaneous-Emission (SASE) FELs have been reported, this paper provides the first observations of the unique temporal and spectral characteristics of ultrashort optical pulses from a high-gain ERL FEL. This is made possible by the stable operation and unique capability of the Jefferson Lab machine to change the electron bunch energy chirp with no curvature.

INTRODUCTION

Although ERLs were first proposed for use in high energy physics in the early 1960s, an ERL based kilowatt FEL with a high-average-current beam that could be efficiently energy-recovered had never been built until 1999 at Jefferson Lab [1] . The IR Demo ERL at Jefferson Lab was constructed in 1997 and operated at up to 48 MeV and with up to 5 mA average current at a 74.85 MHz pulse repetition rate. It could produce 400 femtosecond (fs) rms bunch lengths and enabled the operation of an FEL with over 2 kW CW of power [3]. The success of this machine has been the inspiration for several other ERL designs, many at higher currents and some at much higher energy. One was the IR Upgrade [4] ERL at Jefferson Lab, which produced over 14 kW in sub-ps pulses centered around 1.6 µm wavelength, a power about 4 orders of magnitude above any femtosecond lasers up to date.

FEL pulses present many unique properties of ultra-short optical pulses. Among them, one of the most important is the dispersion and frequency chirp that directly affect the minimum attainable pulse duration. Unlike conventional ultra-short pulse lasers, the gain medium in FELs is a relativistic electron bunch with certain amount of energy spread. The energy chirp that may exist in the electron bunches may be imprinted on the output optical pulses. The effect of a chirp in the electron beam energy has not been adequately studied and was reported only on SASE FELs [2,3]. Due to the fact that the process is initiated by shot noise in the electron beam, limited machine capability, and inherent instability in SASE systems, it is difficult to perform a systematic and reliable characterization of physical phenomena such as frequency chirping effects. However, a FEL oscillator is an excellent tool for such studies. This is especially true for the stable operation of JLab kW ERL-driven FEL, which has the unique capability to change the electron bunch energy chirp with no curvature.

In this paper we report what is to the best of our knowledge the first experimental investigation of optical pulse chirping effects induced by ultrashort electron bunches in a high-gain ERL FEL oscillator cavity. The result shows evolution of the optical pulse chirp verses the electron energy chirp. Our analysis also provides clear evidence that much shorter FEL pulses might be generated with chirped electron bunches.

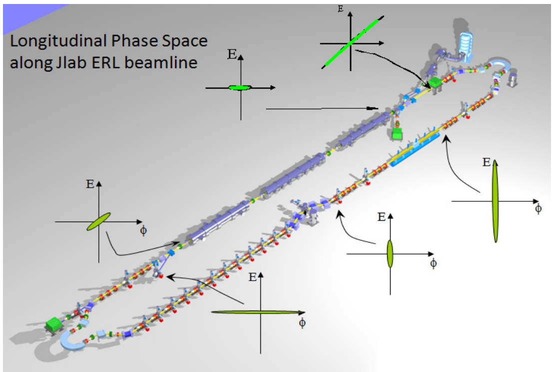


Figure 1: Illustrations of the longitudinal phase space along JLab ERL beam loop.

EXPERIMENT AND RESULTS

Chirping Electron Bunches

Fig.1 is a schematic overview of the IR Upgrade of Jefferson Lab FEL showing the longitudinal phase space at selected locations. The machine design uses an achromatic, non-isochronous 180° Bates bend at either end, which allows us to cancel out RF curvature effects using four sextupoles embedded in each arc. In addition, four trim quadrupoles at each end can be used to set the momentum compaction and linear dispersion. The sextupoles are also used to set second order dispersion and reduce chromatic aberrations. In the second Bates bend, a pair of octupoles are also used to correct the longitudinal phase space to third order. The FEL wiggler was designed for a minimum extraction efficiency of 1% and has demonstrated up to 2.5% extraction efficiency.

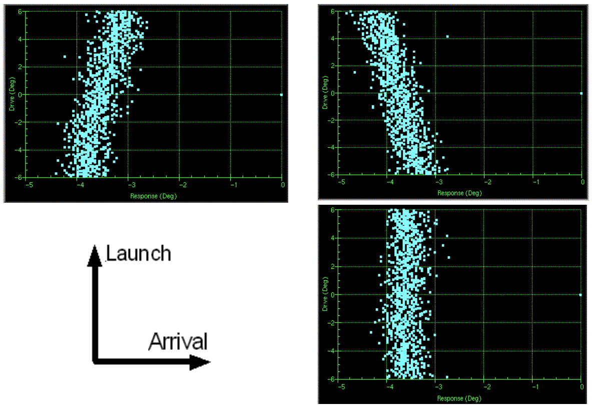


Figure 2: Input phase to linac (vertical) vs. phase at the wiggler (horizontal). The upper left: trim quadrupoles too strong (G=-185). Upper right (G=-245), trim quads too weak, and lower right (G=-215), properly set to produce maximum compression.

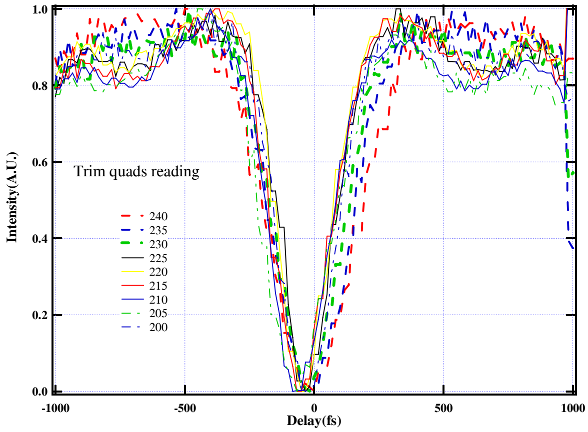


Figure 3: Coherent OTR interferometer autocorrelation scans with different quadrupole magnetic field settings (G=-200~-250).

The nominal longitudinal match is set up by modulating the phase of the injector with respect to the accelerator and looking at the phase response at various points in the transport [4]. Samples illustrating how the trim quadrupoles and sextupoles can be set up in the first Bates bend are shown in Figure 2. Sextupoles are used to straighten the distribution and trim quads are used to maximize the slope or to introduce a chirp on the beam. We use a coherent Optical Transitional Radiation (COTR) autocorrelator (a Martin-Puplett interferometer (MPI)) for the final adjustment at high charge. The electron bunch length can be measured directly by the MPI or using coherent THz pulses [5]. Figure 3 shows a group of signal scans from the MPI when the quadrupole settings (denoted by magnetic field strength G) are adjusted to apply a linear chirp to the electron bunche. We can clearly see how the bunch length changes and where the minimum bunch length position is. At minimal or near zero chirp position, an *rms* bunch length of about 150 fs can be produced, leading to a peak current of 300A. Since the direct result of the linear bunch chirp is bunch lengthening, it is straightforward to estimate the amount of linear chirp applied to the bunch by measuring the bunch length increment relative to the minimal position. The shortest bunch length is achieved around G=-220, which is also the nominal machine operational value. Table 1 gives electron beam parameters.

Table 1: Electron beam parameters

Beam energy	115 MeV
Bunch charge	110 pC
Minimum rms bunch length	0.15 ps
Peak current	300 A
rms uncorrelated energy spread	0.1 %
rms correlated energy spread	0.5 %
rms normalized emittance	8 mm mrad
Wiggler period	55 mm
Number of wiggler period	30
Wiggler parameter K	1.361
Lasing radiation wavelength	1.6 um

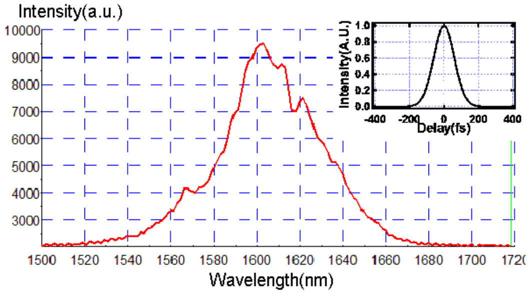


Figure 4: A typical 1.6um FEL spectrum and autocorrelation trace (CW lasing/2KW).

FROG Setup and Measurement

This experiment was performed at JLab 10kW IR Upgrade FEL facility. The FEL resonator consists of an upstream concave high reflector (HR) and a downstream concave output coupler (OC) at the downstream end, comprising a nearly concentric cavity. The radius of curvature of OC and HR are very close to 16 meters. The Rayleigh range can be varied by changing the radius of curvature of the HR. For these measurements we operated the machine at 115 MeV and multi-kW laser power at 1.6 micron (the wavelength at which over 14kW maximum power was achieved). A typical FEL spectrum and an autocorrelation trace are shown in Figure 4. The FEL beam is generated in the accelerator enclosure and transported into any of several user labs by mirrors through an optical transport. A small leakage through the center of one of the transport mirrors provides the beam for all optical diagnostics including the chirp measurement described in this paper.

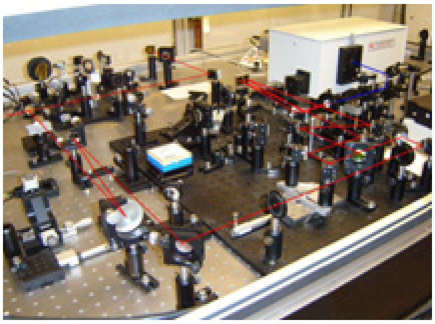
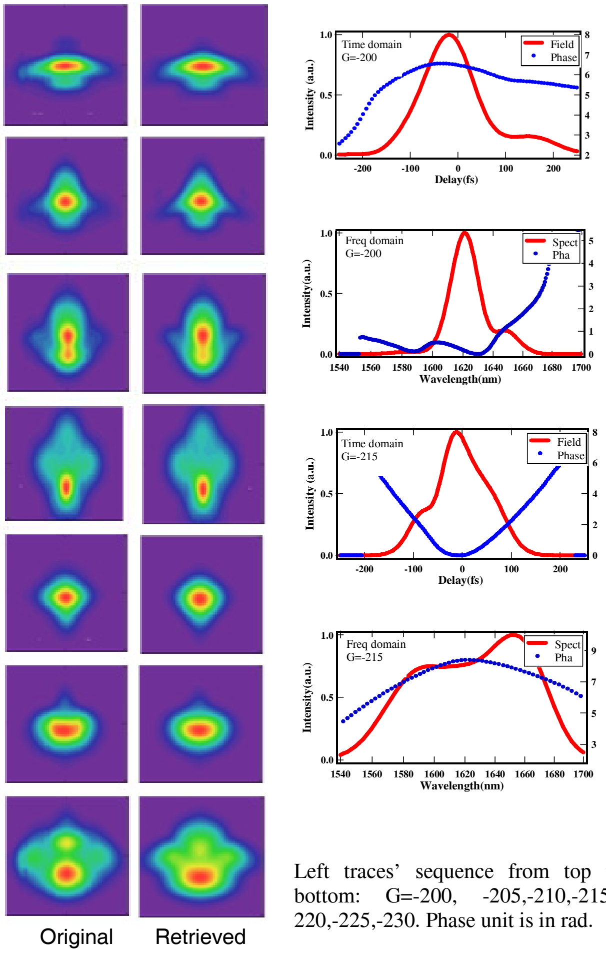


Figure 5: Photo of FROG experimental setup.



Left traces' sequence from top to bottom: G=-200, -205,-210,-215,-220,-225,-230. Phase unit is in rad.

Figure 6: Measured FROG traces with analysis for electron beams under nominal settings. The horizontal and vertical axes are are time and wavelength, respectively.

In order to characterize the optical chirp on the FEL pulses, a Second-Harmonic-Generation (SHG) Frequency-Resolved-Optical-Gating (FROG) system in a single-shot non-collinear configuration was set up. A 0.3mm type-I β-barium borate(BBO) was used as non-linear crystal for SHG generation. The spectrum resolving section is a commercial imaging spectrometer followed by a CCD camera to record the traces. This type of FROG provides high sensitivity and is suitable in cases of low pulse energy. The basic principle of FROG has been detailed in many publications [6]. Our experiment was performed in the way that the electron beam was setup under optimized nominal parameters as listed in Table 1. This corresponds to a trim quadrupole reading of about G=-200. Then the G value was scanned at certain step below and above -200, the FEL cavity length was optimized for highest power, and the FROG traces were recorded accordingly. Figure 6 shows a group of measured FROG traces and the retrieved traces with a 1kW FEL beam. Also in the Figure is the analysis of the intensity and phase distributions in both temporal and spectral domains, providing a complete characterization of the optical pulses. The output coupler of the FEL cavity for these measurements had an 11% transmission.

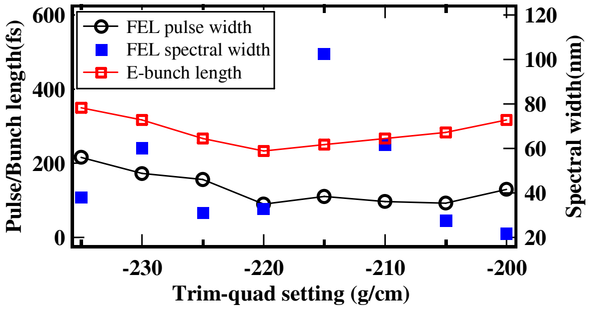


Figure 7: Correlation of time duration between e-beam bunch and FEL pulses at different trim-quadrupole settings. Solid triangle stands for pulse spectral width. All widths are measured by FWHM.

The shapes and dimensions of the FROG traces change significantly as the trim quadrupole strength is varied. The spectral distributions bear great similarity to many previous observations that came with a shoulder on one side. This appears to be characteristic of FEL pulses. Although the FROG traces are symmetrical on the time axis, clear asymmetry can be seen on both the time and spectral retrieved distributions. FROG shows the useful ability to characterize the temporal profile that is impossible to measure with any available devices. The phases, as revealed in the curves for the 2 examples in Figure 6, are parabolic-like, indicating the presence of the 2^{nd} order dispersion along with higher orders of dispersion. This is especially true in the case of G=-215, which means potentially a much shorter pulse may be obtained with proper pulse compression. In order to see how the electron bunches influence the output optical pulses, we have plotted in Figure 7 the bunch length data measured with MPI, the FEL pulse length and spectral width from FROG against trim quadrupole settings. The trend of the FEL optical pulse width basically follows that of the bunch length trend, which is expected. But it appears somehow flat when G is greater than -220. The spectral width, however, does not fit exactly into a conventional hypothesis. When G is lower than -220, the spectral width resembles the time-bandwidth rules except at -230. For G higher than -220, the spectral width changes dramatically faster than the pulse width. It is also easy to see this by simply looking at the FROG traces in Figure 6.

Due to the short electron bunch length, the FEL optical pulses are all less than 250 fs. The shortest pulse is about 90fs at G=-220. Due to the chirp, it is possible to reduce the pulse further using optical compression methods. In Figure 8, we show both the original and the compressed pulses compressed with a compressor. In case of G=–215, the initial 122 fs pulse is compressed to 54fs. while for the G=-200 case, with little chirp, the compression factor is less than 1.2 (from 126fs to 107fs).

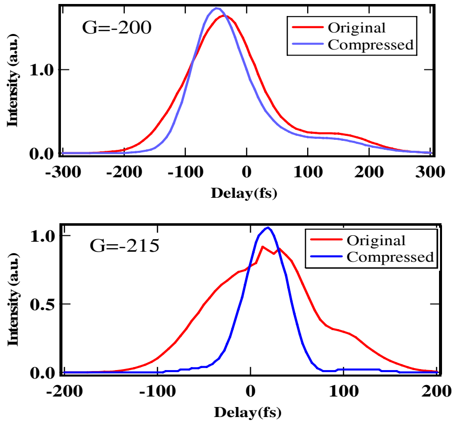


Figure 8: Original and compressed pulses at different trim quadrupole settings. Top, G=-200. Bottom, G=-215.

The FEL pulse characteristics heavily depend on the transmission of the output couplers, which is seen by our FROG measurement. Figure 9 shows samples of three measurement and analysis results with a 5% output coupler at nominal operating e-beam condition. with the behavior is markedly different than the previous 11% case,. The most remarkable difference is that there is little chirp in the optical bunches. The bunch increases in length but the time-bandwidth product does not change much.

It is necessary to mention that good beam stability and stable machine operation has greatly facilitated the data taking process and thereby enhanced measurement accuracy. We have compared the data taken at several minutes' time interval and the results showed no obvious difference for the same e-beam setup. This is in great contrast with the SASE FELs where the large fluctuations dominate the laser pulse output.

We have also been trying to simulate the physical effects observed in the experiment in an effort to understand some of the hard-to-explain phenomena, such as why the pulse compression appears more effective at some specific setting point instead of the two ends of the trim quad range. This effort is ongoing and the results will be presented in subsequent reports.

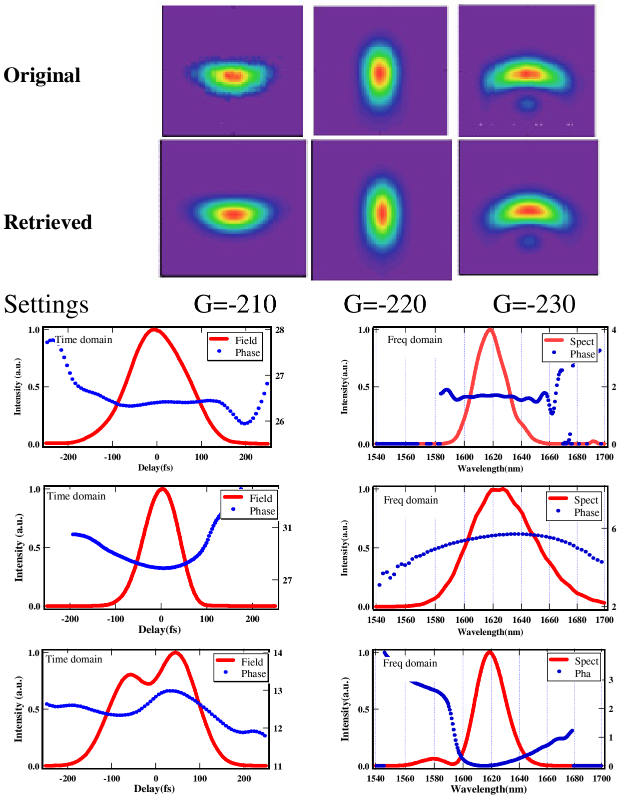


Figure 9: FROG traces for 5% OC cavity. Analysis graphs from top to bottom are for G=-210, -220 and -230, respectively.

CONCLUSION

The frequency chirp induced from the energy chirp on the electron bunch in an ERL FEL oscillator is characterized with a FROG system. The analysis and results showed much shorter pulses can be produced than the original ones from the laser cavity with proper chirp on the electron bunches.

ACKNOWLEDGEMENT

This work was supported by Commonwealth of Virginia and by DOE Contract DE-AC05-060R23171. Authors would like to thanks L. Giannessi for the help with simulation. C. Liu provided assistance in part of data processing.

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