CHIRPED PULSE AMPLIFICATION EXPERIMENT AT 800 nm

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Abstract

We report the chirped pulse amplification (CPA) experiment carried out using 800 nm direct seeding and NISUS undulator as free electron laser amplifier at SDL of BNL. The experiment indicated that due to saturation in the center part of the chirped electron bunch the output pulse shape has a dip in the middle, as result the edge of the bunch has higher power than the center. Hence the output spectrum also showed a dip in the center, resulting in a larger FWHM bandwidth than the seed. An interesting result is that the 800 nm chirped FEL output was compressed down to a pulse length shorter than what the seed pulse itself can be compressed to.

INTRODUCTION

Chirped pulse amplification (CPA) [1-4, 8] can be used to generate short high intensity pulse in FEL, and it has been shown theoretically possible to generate pulse shorter than what the seed can be used to generate [2]. Initial CPA experiment has been carried out in HGHG process at 266 nm but without the final compression of the pulse [5]. The experiment showed that by matching the electron bunch energy chirp with that of the seed pulse properly we were able to maximize the bandwidth of the output pulse while maintaining coherence. First SPIDER traces were measured and quadratic optical phase dependence along the pulse was obtained [7]. However, due to limited beam time, we were unable to finish the compression of the output pulse at 266 nm so far. In this paper, we report our preliminary result on the CPA at 800 nm with direct seeding.

EXPERIMENT SETUP AND CPA EXPERIMENT

A schematic diagram of the 788 nm experiment is shown in figure 1. The 788 nm seed pulse with pulse length of 2.5 ps and bandwidth of about 6 nm is chirped with the head of the pulse at longer wavelength. The 103 MeV electron bunch with charge of 500 pC is compressed down to about 2.5 ps and chirped using the last section of the linac to about 0.5% of projected energy spread with head at lower energy. During the experiment the chirp is adjusted to maximize the output bandwidth. The seed and the electron beam are sent into the FEL undulator NISUS and aligned to overlap in the first section of the undulator. The seed has a Rayleigh range of 1.95 m. We used first two pop-in monitors inside the NISUS undulator to carry out the alignment. Since the seed table where the seed is injected into the undulator beam line by a 45° mirror is 7 meters away from the entrance of the NISUS undulator, the physical limitation of the system made it impossible to match the seed beam size to the electron beam size at the beam waist of the seed, which is about 0.6 m inside of the entrance. As a result the laser beam size is much larger than the electron beam. This is illustrated in figure 2

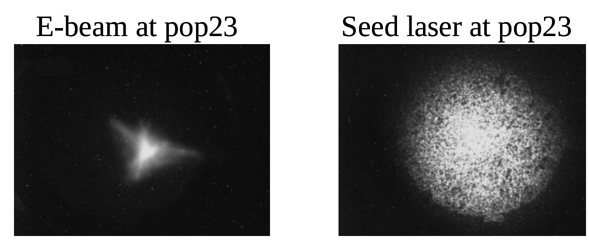

Figure 2: Images of the beam (left) and seed laser (right)

where we show the images of the seed and electron beam at the first pop in monitor in the NISUS. Thus this FEL amplifier setup is not very efficient. But it is sufficient to be used for a demonstration of the CPA process. The NISUS undulator has a period of 3.9cm with K=1.126.

The electron bunch length is measured by the zero-

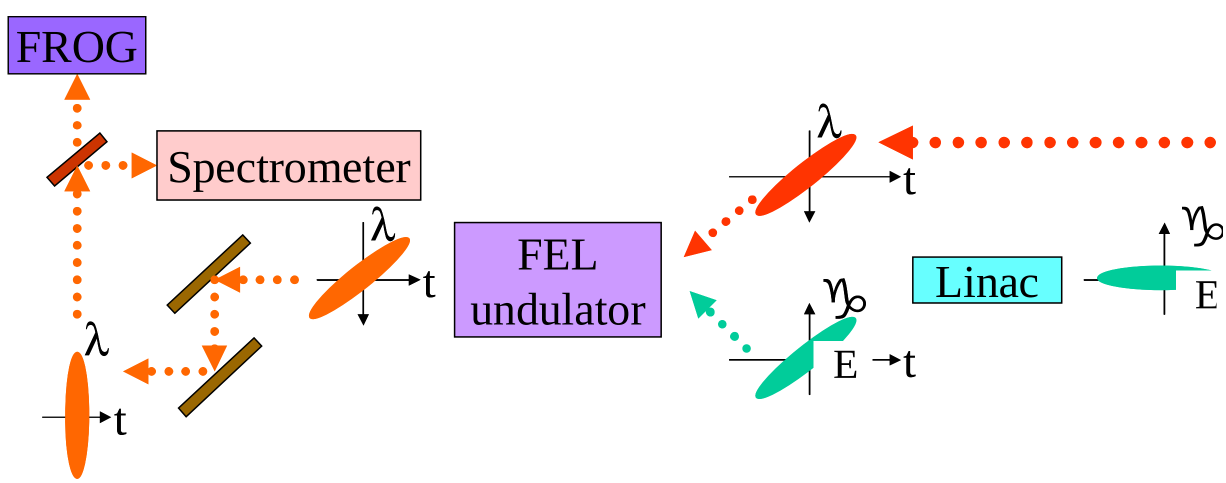

Figure 1: Layout of the experimental set-up.

phasing method using the dipole right after the last linac section as the energy spectrometer. The images of the measurement at 90 and -90 degree of the RF phase are shown in figure 3.

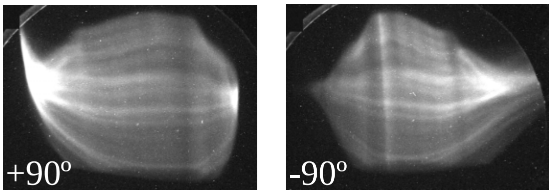

Figure 3: Measurement of bunch length

The synchronization between the electron bunch and the seed laser pulse is realized by observing the significant increase of energy spread when they temporally overlap. The energy spread is measured using the monitor after the beam passes through the undulator and the last dipole. This is shown in figure 4. The upper picture shows that the energy spread is adjusted to about 0.5% when the seed laser is turned off (the full screen corresponds to 1.5% of energy spread). When we turn on the seed laser and change the seed pulse time delay by an optical trombone so it overlaps with the electron bunch, the energy spread is increased significantly and hence the image of the electron beam occupies the full screen.

The seed laser pulse energy is 13.4 μJ before sent into the NISUS undulator during the CPA experiment. To ease the synchronization procedure before we achieve the overlap between the seed and the electron bunch, we remove the attenuation (which is 10 when the pulse energy is 13.4 μJ) so the energy spread increase will be more visible even when the tail of

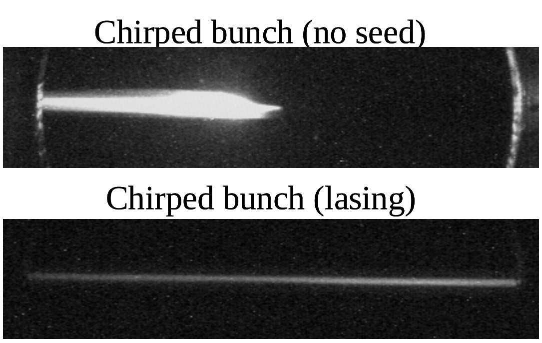

Figure 4: Electron beam energy spectra before (upper plot) and after (lower plot) interaction with electron beam

the electron bunch overlaps with the seed. This helps to increase the step size that we used to move the optical trombone and complete the synchronization procedure faster.

Due to energy and phase jitter and drift of the electron bunch (energy jitter is about 0.2% rms, time jitter about 140 fs rms), during the scan for synchronization for each trombone position we also scan energy within about 0.5% range then move to next position about 100 μm apart. Once the synchronization is found, we send the amplified FEL output to the spectrometer to fine tune the synchronization. Since the seed laser is chirped, and the output wavelength is determined by the seed, if the tail of the electron bunch overlaps with the head of the laser pulse the output pulse wavelength is centered at longer wavelength of around 795 nm. When the head of the electron bunch overlaps with the tail of the seed, the wavelength moves to shorter wavelength of around 785

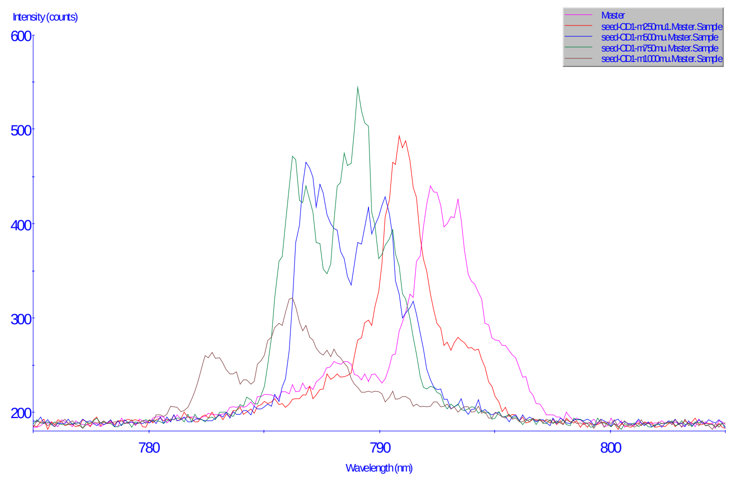

Figure 5: Measured FEL spectra

nm. This helps us to determine which direction and how much we should move the trombone to maximize the overlap. In figure 5 we show the measured FEL output spectrum at different positions of the optical trombone micrometer. The center of the spectrum is at 790 nm.

During the scan the FEL pulse central wavelength is

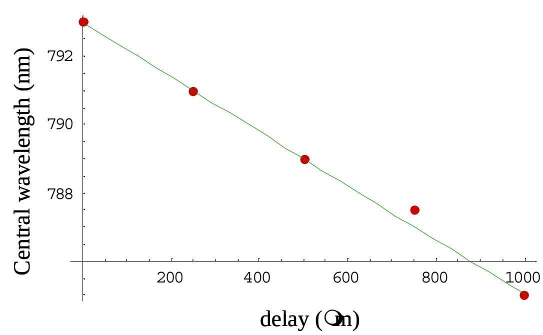

Figure 6 Central FEL wavelength for different delays between seed and electron bunch

also measured and plotted against the micrometer position, as shown in figure 6.

The figure 6 shows the wavelength has a linear dependence on the delay of electron bunch relative to the seed laser, as determined by the micrometer position. The slop of the curve (2.6 nm/ps) is the measured chirp of the seed by FEL process. This is to be compared with the chirp setup by the seed laser compressor-stretcher system, which is 6 nm/2.5 ps=2.4 nm/ps, providing with a reasonable agreement.

The gain length of the FEL process is measured using SASE output pulse energy as function of distance in the NISUS by kicking the electron beam away from axis sequentially at different longitudinal locations inside the NISUS undulator with the horizontal trajectory correctors. The result is shown in figure 7. Considering the spacing between the monitor is 0.62 m, the power gain length is obtained from this plot as 1m.

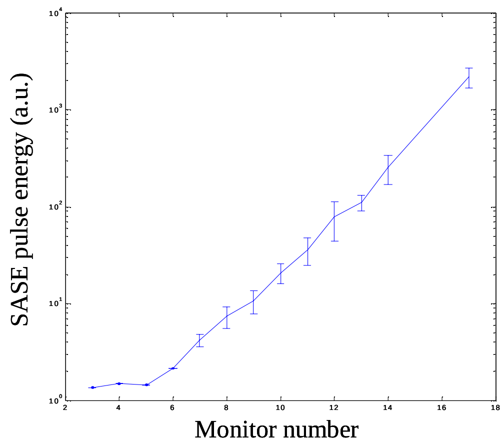

Figure 7: SASE gain length measurement

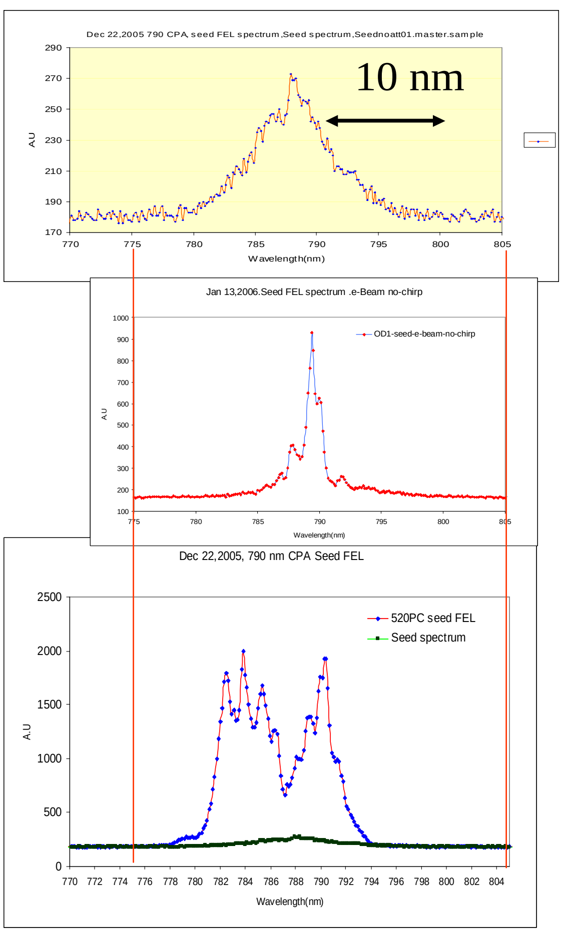

Figure 8: Measurements of seed (upper), unchirped FEL (middle) and FEL output with matched chirp (lower plot)

The normalized emittance was measured to be 6 mm-mrad by fitting with the beam profile measurement in the NISUS undulator. Once the synchronization is achieved, we tune electron beam chirp by adjusting the last linac section to vary the energy spread and observing the bandwidth of the FEL output until we reach the maximum bandwidth. When the chirp is optimized and when the

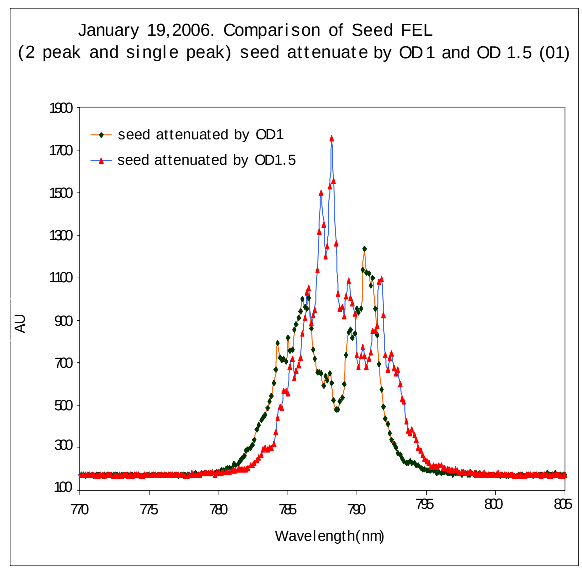

Figure 9: Spectra of the seeded FEL output for two values of attenuation 10 (OD1) and 30 (OD1.5)

seed laser is turned off, the image of the energy spread is shown in the top of the figure 4.

In the top plot of figure 8 we show the measurement of the seed spectrum. The middle plot of the same figure is the spectrum of the FEL output when the electron bunch is not chirped (when energy spread is minimized with the seed laser turned off). Lower plot shows the FEL radiation spectrum for the case when the chirp of the electron bunch is optimized. To be able to compare the bandwidth, we align the three plots vertically so that they use the same horizontal scale. It is seen that when the electron bunch is not chirped, the output bandwidth is narrower than the seed, showing that only the part of the seed pulse with the wavelength in resonance with the electron beam energy is amplified, and the width of the line is clearly determined by the bandwidth of the amplifier.

It is interesting to remark here that figure 8 shows when the energy chirped to match the seed chirp, the bandwidth increases to about 10 nm, significantly larger than the seed bandwidth of about 6 nm. And in particular there is a pronounced dip near the center of the FEL output spectrum. This can be explained by deep saturation in the central part of the electron bunch. If the current at the central part of the electron bunch is and since the central part of the seed is also at peak, the FEL amplifier can be oversaturated so that power is lower than at the edge of the bunch where the FEL is just reaching saturation, thus creating a dip in the spectrum because due to linear chirp, the spectrum corresponds to time.

To further test this interpretation, we expect that when the seed power is lowered properly so that the central part of the bunch just reach saturation, the dip in the central part of the pulse will disappear, and hence the double peaks in the spectrum should be replaced by a single peak. And indeed, when we increase the attenuation from 10 to 30, we did observe that the double peaks are replaced by a single peak. This is shown in figure 9.

Because of the output bandwidth is larger than the seed bandwidth we expect that when compressed, the final pulse width can have a smaller pulse length than the fourier-transform-limited seed pulse length. This has been confirmed by our next step of the experiment, the compression and measurement of the compressed pulse.

MEASUREMENT OF THE COMPRESSED PULSE BY FROG

As shown in figure 1, the output FEL pulse is sent through a compressor, compressed and sent to a FROG (Frequency-Resolved Optical Gating) device [6]. This device is designed to measure spectral and temporal distribution of short laser pulse simultaneously, and generate the amplitude and phase as function of time for the pulse. It is compact and, in particular, easy to align. The schematic diagram of the arrangement of compressor, spectrometer and FROG is shown in figure 10. In figure 11, we show the FROG result of compressed chirped FEL output pulse. In the picture, the upper right one is the measured FROG image while the upper left one is the retrieved image from the reconstructed pulse shape, the agreement between these two pictures testifies the correctness of the FROG result. The lower left is the reconstructed temporal pulse while the lower right one is the reconstructed spectrum.

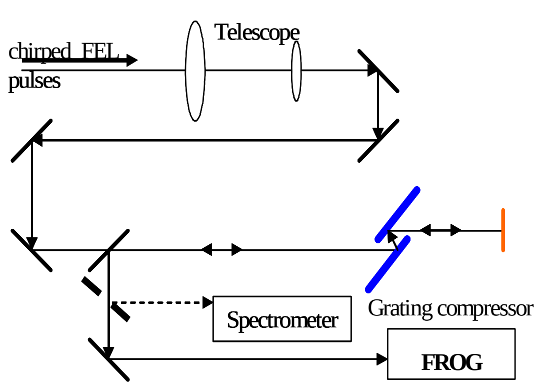

Figure 10: Time- and spectrum measurements set-up.

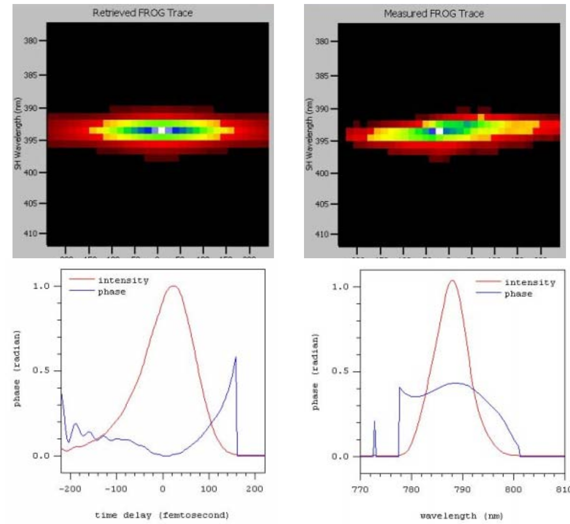

Figure 11: FROG traces of the compressed FEL pulse.

The result shows that pulse length is 122 fs FWHM. We remark that resolution of the spectrum obtained from the FROG is not as good as that of the spectrometer we used, so that in the reconstructed spectrum we could not see the double peaks feature as shown in figure 8 and 9.

This is to be compared with a fourier-transform-limited compressed seed. With the seed bandwidth of 6 nm at 800 nm, assuming minimum wave packet of Gaussian shape, the FWHM pulse length and FWHM bandwidth product is Log(2)/π*0.8 μm/(0.3 μm/fs) = 1.17. So the pulse FWHM length should be 1.17*800 nm/6 nm =156 fs. Hence even if the seed is fourier-transform-limited, it is still significantly longer than the CPA result.

In conclusion, we carried compressed CPA from FEL output at 800nm and obtained shorter pulse than what can be obtained from compressed seed. The result can be explained by the deep saturation of the FEL output. This illustrated the potential in the future to generate short pulse using CPA process in an FEL device.

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