AN EXPERIMENTAL TEST OF SUPERRADIANCE IN A SINGLE PASS SEEDED FEL

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Abstract

Superradiance and nonlinear evolution of a FEL pulse in a single-pass FEL were experimentally demonstrated at the National Synchrotron Light Source (NSLS) Source Development Laboratory (SDL). The experiment was performed using a 1.5 ps high-brightness electron beam and a 100fs Ti:Sapphire seed laser. The seed laser and electron beam interact in the 10 meter long NISUS undulator with a period of 3.89 cm. The FEL spectrum, energy and pulse length along the undulator were measured. FEL saturation was observed, and gain of more the 200 (relative to seed laser) was measured. Both FEL spectrum widening and pulse length shortening were observed; FEL pulses as short as 65 fs FWHM were measured. The superrandiance and nonlinear evolution were also simulated using the numerical code GENESIS1.3 yielding good agreement with the experimental results.

INTRODUCTION

The superradiance regime of a Free-Electron Laser (FEL) had been extensively investigated by Bonifacio *et al.* in the 1980's and 1990's [1-2]. Giannessi *et al* recently extended those earlier works to a high-gain single-pass FEL amplifier using a seed laser significantly shorter than the electron beam [3-4]. For a laser seeded single-pass high-gain FEL, the FEL output will continue to grow after saturation and the pulse length will experience shortening when the seed pulse is shorter than or comparable to a cooperation length in the superradiance regime. In the superradiant regime, the peak power is proportional to the square of the undulator length z, the pulse energy is proportional to $z^{3/2}$ and accordingly the pulse duration decreases as $z^{-1/2}$.

The successes of the single-pass high-gain FEL made it possible to demonstrate the superrandiance and nonlinear evolution of the FEL pulse experimentally [5-7]. An experimental program was initialized at the NSLS SDL to study superradiance and nonlinear evolution of a FEL pulse. The SDL is an ideal platform to study superradiance with femtosecond seeding; SDL is the only operating facility capable of carrying out laser seeded FEL experiments. We have successfully achieved high gain harmonic generation (HGHG) saturation at 266 nm with an 800 nm seed [8]. The main components of the SDL FEL are a high-brightness electron accelerator, HGHG FEL, coupled with sophisticated electron and photon beam instrumentation. The accelerator system of the SDL consists of a 1.6 cell BNL photo-injector driven by a Ti:Sapphire laser system and a five section 2856 MHz SLAC type traveling wave linac capable of producing a 250 MeV electron beam. The magnetic chicane bunch compressor at the SDL produces sub picosecond (ps) long electron bunches with a peak current of a few hundred amperes. The high brightness electron beam transits the 10 meter long NISUS undulator for single pass FEL amplifier operation.

After the presentation of the numerical simulation of the superradiance, we will discuss the experimental measurements of FEL gain, spectrum and pulse length along the undulator.

SUPERRADIANCE SIMULATION

Due to the availability of FEL pulse length diagnostics, the simple FEL amplifier configuration was chosen for our experiment, i.e., the FEL wavelength will be the same as the seed laser ~ 790 nm. To facilitate the experiment and the understanding of the basic characteristics of superradiance we performed a simulation using the computer code GENESIS1.3 [9]. Table 1 summarizes the basic seed laser, undulator and electron beam parameters used for our simulation. We were able to reproduce all features of the superradiance with our experimental conditions [3-4]. The FEL longitudinal evolution along the NISUS undulator, plotted in Fig.1, shows that the FEL evolution consists of three regimes along the undulator: lethargy, exponential gain and superradiance [3].

Table 1: Seed laser, undulator and e-beam parameters.

λ_{seed} (nm)	790	ε (mm-mrad)	3.0
ℓ_{seed} (fs)	150	I (A)	300
P_{seed} (MW)	1.0	E (MeV)	102
K_u	1.1	$\ell_{e\text{-beam}}$ (ps)	1.0
λ_u (cm)	3.89		

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The FEL pulse length along the undulator is shown in Figure 2. It shows the FEL pulse lengthening during the exponential gain regime followed by shortening in the superradiant regime. The evolution of the FEL spectrum along the undulator is shown in Fig. 3. The spectral broadening is predicted in the superradiance regime. Figure 4 (a) shows the spectrum at z = 8 m where there are two peaks; Figure 4 (b) shows the spectral at z=10 m where there are now three peaks. Note that in both cases, the spectra are widened as much as 30 nm peak-to-peak, which is more than a factor two wider than the seed laser.

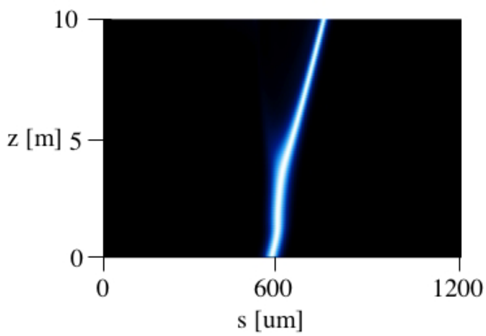

Figure 1: Normalized longitudinal profile of the radiation power along the electron beam coordinate "s" as it evolves along the undulator with coordinate z.

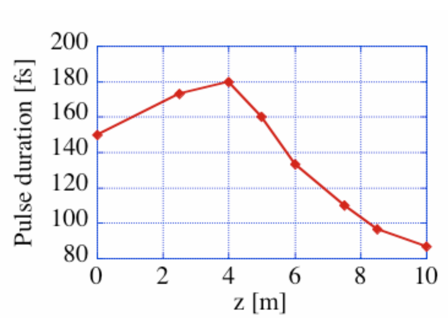

Figure 2: FEL pulse length vs. undulator length.

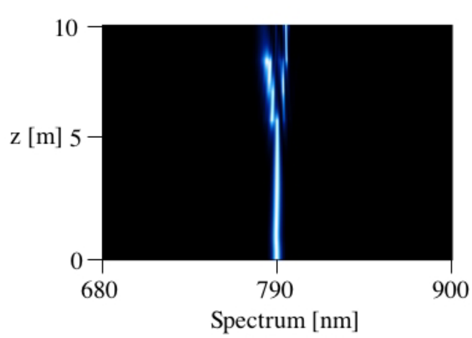

Figure 3: Spectrum evolution along the NISUS undulator.

EXPERIMENTAL CHARACTERIZATION OF SUPERRADIANCE

The FEL amplifier configuration was chosen for superradiance characterization. The same experimental setup used for high power seeded FEL experiments was simply supplemented with additional FEL diagnostics [10]. One of the unique features of the SDL laser system is that it was designed in such way that a single laser system is used to drive both the photocathode RF gun and to provide a seed laser pulse. The amplified laser pulse is divided into two pulses before the final compression. Two independent grating style pulse compressors are used, one compresses the pulse to 4-6 ps for generating the photoelectron beam, and the other compressor is adjustable from 6 ps down to 100 fs for the seeded FEL. For our superradiance experiments the seed laser was set to 100-150 fs.

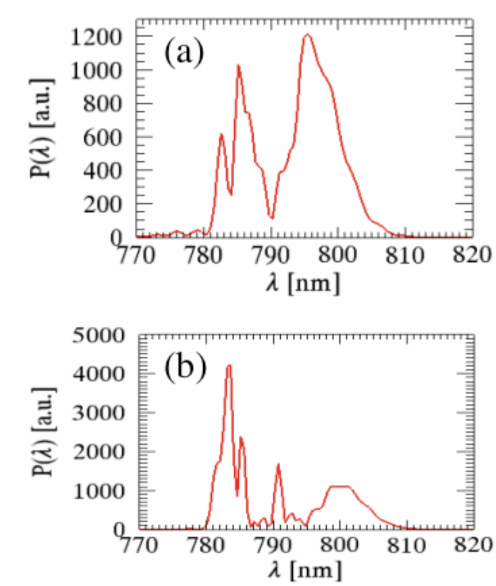

Figure 4: Spectrum at (a) z = 8 m, and (b) z = 10 m.

The FEL output was transported to the diagnostic station for characterization. The diagnostics station allows us to fully characterize the FEL output. Key instruments are a 10 GHz photodiode, a Joule-meter, spectrometers, a CCD camera, a commercial Frequency-Resolved Optical Gating (FROG) and a femtosecond streak camera.

The major steps of the experiment are electron beam and trajectory optimization, seed laser and e-beam synchronization, and FEL output characterization. SASE FEL output was used to optimize the electron beam and the trajectory inside the NISUS undulator. Five orders of magnitude SASE gain was routinely observed [10]. Synchronization of the femtosecond seed laser and the electron beam was realized in two steps. In the first step, the seed laser and SASE were observed using the 10 GHz diode; the seed laser delay line is adjusted to bring the e-beam and seed laser within 50 ps. Final synchronization was achieved by observing the electron beam energy modulation while adjusting the seed laser delay. FEL properties are measured at the exit of the undulator. To study the FEL evolution along the undulator the electron beam was steered off the forward trajectory with steering magnets distributed along the undulator. In the rest of this section the measured properties of the superradiant light are discussed.

Gain curve

The output energy of the superradiant FEL was measured by a Joule meter (Molectron J3S-10) to be 660 mV, while that without an electron beam (i.e., seed laser energy) was 30 mV. Hence a gain of 220 was observed. The energy gain along the undulator is plotted in Fig. 5. Here the highest energy was recorded at each position in order to avoid being affected by a timing jitter. In Fig. 5 the FEL saturates at around 7 m, however, the energy still increases significantly after the saturation. This is in qualitative agreement with the nonlinear effect of superradiance whereby the FEL power keeps growing after saturation due to a constant supply of "fresh electrons" resulting from slippage.

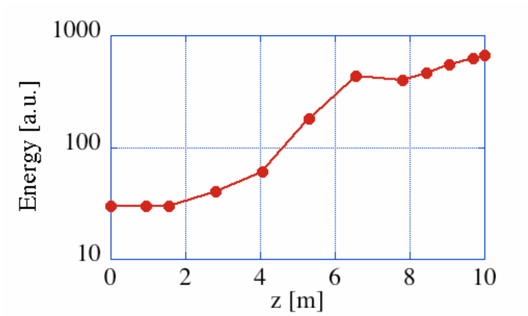

Figure 5: Measured FEL Energy vs. undulator length.

Transverse profile

Transverse radiation profiles of the fundamental, 2nd and 3rd harmonics in superradiance were observed at the exit of the undulator (Fig. 6). The pictures of the 1st and 3rd harmonics are shown in the same scale. RMS sizes at the fundamental were (47, 42) pixels, while the 3rd harmonics was (32, 30) pixels. The third harmonic is about 30% smaller compared with the fundamental. The picture of 2nd harmonic is expanded so that the detail distribution can be seen. Double peaks and an asymmetry between the two peaks are observed for the 2nd harmonic. The presence of the strong higher harmonics is another indication of the saturation of the FEL.

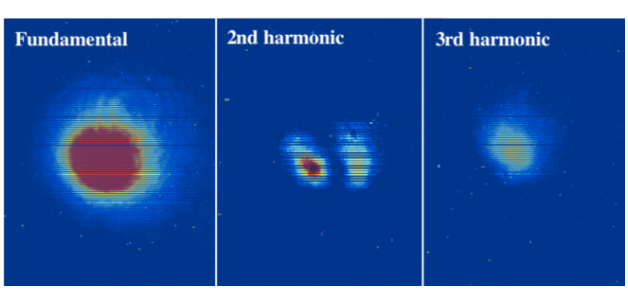

Figure 6: Measured transverse profile of the FEL: fundamental and 3rd are in the same scale, the 2nd harmonic is expanded.

Spectrum

The FEL spectrum was measured at the diagnostic station using a single-shot spectrometer. For the seed laser pulse length longer than the e-beam, a constant spectral width along the undulator was observed [10]. A small sideband appears at longer wavelengths when the FEL reaches deep saturation. For a seed laser much shorter than the e-beam (100 fs vs. 1 ps), a shot-by-shot fluctuation of the FEL spectrum was observed. Figure 7 is one of the typical shots in which two main peaks, as well as small other peaks, can be detected. It can be seen that the spectrum in Fig. 7 has the same structure as that in Fig. 4 (a). In both figures, the bandwidth is ~30 nm (p-p) and the spectrum mainly consists of two peaks.

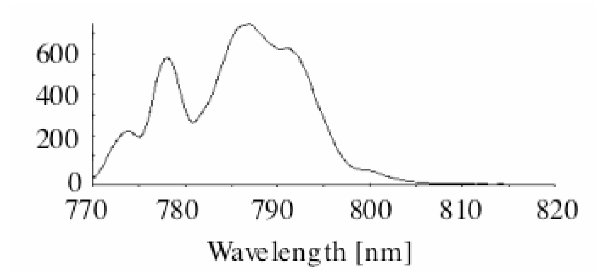

Figure 7: Measured FEL spectrum in superradiance

The widening of the spectrum and the complex structure of the measured output are indications that the FEL has reached the superradiance regime.

Longitudinal evolution

In our experiments a FROG [11] was employed to measure the longitudinal pulse evolution along the undulator. In the first FROG measurements the e-beam energy was resonated with the seed laser and the energy of the seed laser was weaker than the saturated FEL by more than two orders of magnitude (see Fig. 5). The shortest pulse duration that can be measured by the FROG is 50 fs. The pulse durations measured by the FROG along the undulator are summarized in Fig. 9. When an e-beam was turned off and only the seed laser was detected by the FROG the pulse duration was ~100 fs. However, once the e-beam and the seed laser were synchronized, the FEL pulse duration changed along the undulator. As expected from Figs. 1 and 2, the seed laser is stretched until the middle of the undulator and again compressed through the exit. The pulse duration at the end was eventually shorter than that of input seed pulse which was as short as 65 fs.

In the next FROG measurement the e-beam was tuned lower than the resonant energy by about 0.5 % and the seed laser energy was increased until the intensity was comparable to the FEL. Since the bandwidth of the input seed laser is wide (~7 nm), the 0.5 % detuned e-beam was still resonated with the seed laser. This was confirmed by the energy-modulated e-beam after the undulator and the intensely amplified FEL. Therefore, it was not the peak wavelength but the edge of the seed laser which was amplified. Figure 10 shows one of raw images taken by a FROG of which shortest measurable pulse duration was 20 fs. The horizontal axis corresponds to time and the vertical axis is the frequency. Since the frequency of the seed laser and the FEL are different due to detuning, both the seed laser and the FEL are displayed simultaneously. In Fig. 10, one can see that the FEL pulse is shorter than that of the seed laser. The effect of the detuning upon superradiance will be theoretically and numerically analyzed in detail in the future.

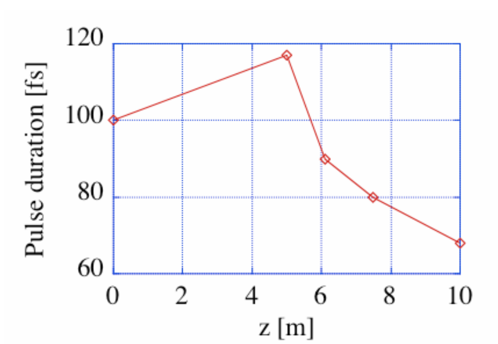

Figure 9: Longitudinal pulse width evolution along the undulator in superradiance.

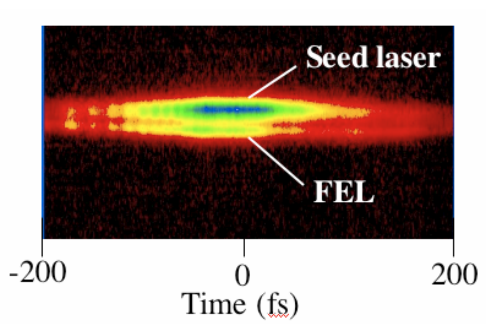

Figure 10: Raw FROG image with e-beam detuned. Horizontal axis is time and vertical axis is wavelength.

CONCLUSION

Superradiance in a single pass seeded FEL was demonstrated. Subpicosecond synchronization between a fs seed laser pulse and a ps electron beam was achieved, resulting in an FEL gain of more than 200. In a gain curve measurement, the nonlinear gain after saturation was observed. Wide bandwidth multi-peak FEL spectrum was observed which agreed well with numerical simulations. Transverse profiles of the fundamental, 2^{nd} and 3rd harmonics were measure in the superradinace regime. While the fundamental and the third harmonic distributions were single-peak structures, the second harmonic consisted of a clear double peaks which are well separated and asymmetric with respect to each other. Longitudinal pulse evolution was measured by a FROG and pulse shortening from 100 to 65 fs was observed. For the FROG measurement with a detuned e-beam, the seed laser and the amplified FEL were measured simultaneously and the shorter FEL pulse compared with the seed laser was observed. We will explore the superradiance for HGHG FEL in the future.

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