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FEL PULSE SHORTENING BY SUPERRADIANCE AT FERMI

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Abstract

Explorations of saturated superradiant regime is one of the methods that could be used to reduce the duration of the pulses delivered by FERMI. Here we present simulation studies that show the possible application of a superradiant cascade leading to a minimum pulse duration below 8 fs and to a peak power exceeding the GW level in both FEL lines FEL-1 and FEL-2.

INTRODUCTION

FERMI is an externally seeded free electron laser (FEL) user facility producing photons in extreme-ultraviolet and soft x-ray spectral region, with a high degree of coherence and spectral stability [1]. FERMI hosts two FEL lines, FEL-1, which covers the wavelength range between 100 and 17 nm and FEL-2 in the range between 17 and 4 nm. The shortest pulses delivered by the FELs are expected to be in the ranges 40-90 fs on FEL-1 [2] and 20-40 fs on FEL-2, according to the seed duration and the final wavelength [1,3]. The FERMI FELs have already been exploited in fast time resolution studies, however a shorter-duration pulse, in the few femtoseconds regime, would allow resolving very fast processes as electronic rearrangements, and would increase the number of targeted experiments. One of the remarks about the implementation of ultrashort-ultraintense pulses in structural studies is that it should be possible to outrun radiation damage while collecting single-shot diffraction images with high spatial resolution [4–7].

Several techniques were proposed to obtain shorter FEL pulses at FERMI, as the chirped pulse amplification (CPA) method [8] or the manipulation of electron beam energy spread at the laser heater to longitudinally reduce the lasing portion of the beam itself [9, 10]. The method we investigate in this contribution relays on the exploration of superradiant regime in a cascaded FEL [11–16] to reduce the pulse length below the cooperation length, while preserving or even enhancing the FEL peak power beyond the saturation level ($P_{\text{sat}} \approx \rho P_{\text{beam}}$).

According to the theory [16–18], when the seed duration L_{seed} is comparable or shorter than slippage distance over a synchrotron period, slippage itself, combined with the saturation process, can shorten the pulse pushing it forward into fresh, unmodulated electrons. In this regime the pulse energy continues to grow at the expense of the electron energy and the peak power increases as $P \propto z^2$; the pulse duration δs is related to the peak power and scales as the slippage distance in half synchrotron oscillation period $2\pi/\omega_s$, i.e. proportionally to the root of the optical field amplitude, $\delta s \propto z^{-1/2}$.

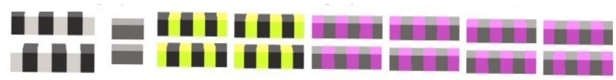

Figure 1: Layout of FERMI FEL-1. The modulator (period length of λ_m = 10 cm) is tuned to the seed wavelength (λ_s = 232 nm). The amplifier is composed of two parts. Two undulators are resonant with the 5th harmonic of the seed (λ_1 = 46 nm) and the last four undulators are tuned to the 10th (λ_f = 23.2 nm) or 15th (λ_f = 15.6 nm) harmonics of the seed.

The FEL pulse is therefore temporally compressed and may become significantly shorter than the input seed.

The initial pulse formation may be induced by an external seed or may be the result of an equivalent density modulation of the electron current. In a cascaded undulator configuration, the power growth is indeed proportional to the profile of the bunching ($G(z,s) \propto b(z,s)$) at the resonant frequency in each stage of the cascade. This configuration, based on a sequence of FEL amplifiers, allows to seed an undulator at optical frequencies while inducing the growth of a superradiant pulse in the VUV range of the spectrum [16]. The scheme was investigated at SPARC, where the transition in a two stages cascade with frequency doubling at optical frequencies was studied [13]. A similar setup in the frame of the FERMI FEL-1 or FEL-2 allowing an undulator cascade made by three or four stages should enable reaching with the final wavelength the VUV or even the soft X-ray spectral range.

In this contribution we have studied via Genesis simulations [20], the applications of superradiance at FERMI FEL-1 and FEL-2 as a method to achieve extremely short pulses.

FERMI FEL-1

The superradiant cascade may be configured at FERMI by tuning the variable gap undulators defining different undulator segments resonant a the different wavelengths. The undulator line of FERMI FEL-1 is composed by a modulator resonant with the UV seed laser and a sequence of six radiators amplifying the desired harmonic order in the VUV, with harmonics typically in the range of 3-15. A superradiant cascade may be configured by tuning the undulator resonances of FEL-1 as shown in Fig. 1.

The electron beam energy at FERMI can be adjusted in the range 0.9 to 1.5 GeV. Table 1 summarizes typical electron beam parameters from the FERMI LINAC, which were used in the simulation. The electron beam profiles were retrieved

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Table 1: Main Parameters of the Electron Beam

Electron beam energy	1.3 GeV
Energy spread	120 keV
Current	750 A
Normalized emittance	1.2 µm.rad
Beam size in x	0.0675 mm
Beam size in y	0.0675 mm
α_x	0.1235
α_y	0.1825

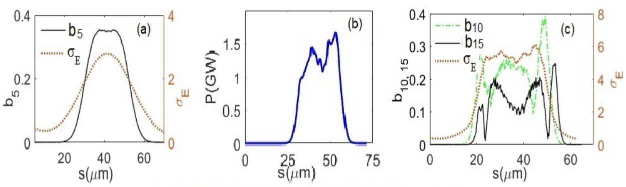

Figure 2: (a) Longitudinal distribution of the energy spread and the bunching profile at the 5th harmonic of the seed, at the entrance of the first segment of radiators tuned at $\lambda_1 = 46$ nm. (b) Pulse temporal profile of the 46-nm pulse. (c) Beam energy spread and bunching profile at the 10th and 15th harmonics, at the entrance of the third radiator.

from an Elegant beam dynamic simulation in the accelerator line [23, 24].

A UV seed laser pulse (FWHM 70 fs) imprints a periodic energy modulation on the relativistic electron beam in the modulator. This energy modulation is then converted into a current density modulation by the dispersive section ($R_{56} =$ 22.5 µm). This microbunched electron beam emits coherent light at λ/n in the XUV to x-ray region as the electrons traverse through the periodic magnetic field of the radiators. The evolution of the bunching factors and field temporal distributions through the cascade is shown in Fig. 2.

The bunching factor at harmonic 10, or alternatively 15, at the exit of the two radiators tuned to the 5th harmonic shows a multipeak structure with the front peak slipping forward toward a region with a lower energy spread. The front peak is therefore amplified in the final radiator stage, tuned at harmonic 10 or 15 as shown in Fig. 3. In 3(a) a peak power of 3 GW, is reached in a pulse of 8 fs FWHM duration at 23.2 nm. The inset shows the pulse spectrum of width 0.094 nm (FWHM). Similarly, 3(b) shows the behavior of the cascade when the last radiator is tuned to harmonic 15. In this case the final power is reduced to about 800 MW in a pulse of 6.3 fs FWHM duration at 15.4 nm. The spectral width is 0.064 nm (FWHM).

FERMI FEL-2

This configuration of FEL-1 can be thought as a double stage cascade implementing the fresh bunch injection technique [25] via the natural slippage of radiation over the electron pulse. A similar setup may be implemented on FERMI FEL-2, which was originally designed to implement the fresh bunch injection technique, with the longitudinal

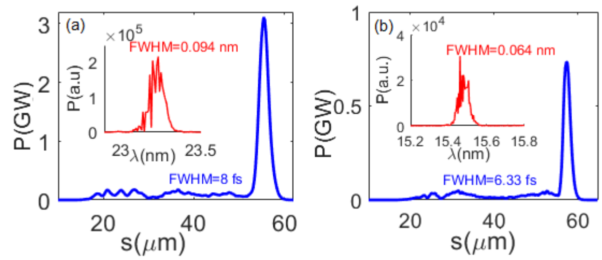

Figure 3: Pulse output power and spectrum in case of the 10th harmonic (a), or 15th harmonic (b).

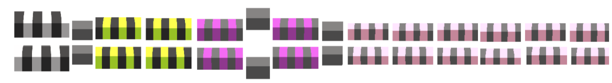
Figure 4: Layout of FERMI FEL-2 in superradiant cascade mode. Similarly to the case of FEL-1, the first modulator and two radiators of the first stage are used to prepare a modulated beam with the features shown in Fig. 2 at harmonic 5. The last radiator of the first stage and the modulator of the second stage are tuned to harmonic 10 while the entire final radiator is tuned to harmonic 30 to reach the final wavelength of $\lambda = 7.7$ nm.

slippage enhanced by the delay line magnetic chicane. When operated in double stage HGHG configuration, FEL-2 is made up by a first stage similar to FEL-1 with a reduced number of radiators (three instead of six), and a second stage composed by a second modulator physically identical to the radiators of the first stage, and a final amplifier composed by six radiators with a shorter period ($\lambda_m = 3.5$ cm). The two stages are separated by the dispersive delay line used to shift the light emitted in the first stage onto fresh electrons in the second stage, to implement the fresh bunch injection technique. This large delay is not used in the superradiant cascaded configuration and the separation in different stages was rearranged as shown in Fig. 4.

Figure 5 shows the profile of the energy spread and bunching factor at harmonic 30, at the entrance of the last amplification stage. Similarly to the case analyzed on FEL-1, we have a complicated peaks structure with two narrow peaks in the head and tail region of the pulse. The energy spread in front of the trailing peak is higher than 1.3 MeV while the energy spread at the position of the leading edge peak is less than 0.51 MeV.

The slippage distance in the last amplifier is about 10 fs and the leading edge pulse has the possibility to shift over fresh electrons where the energy spread is even lower (120 keV, see Table 1). Figure 6 shows the output power and spectrum profile of the 30th harmonic. The result is that in the final amplifier this front pulse is the one giving the main contribution reaching a peak power of about 1 GW. The output pulse duration from the simulation is about 5.2 fs (FWHM) and the corresponding spectral width is 0.016 nm (FWHM).

At the end, three narrow pulses in harmonics 5, 10 and 30 with a fixed delay of few hundred are extracted. Hence this

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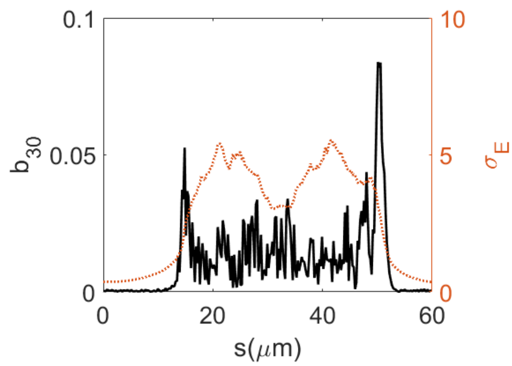

Figure 5: Bunching factor at harmonic 30 (black solid line) and energy spread (brown dotted line), vs. the longitudinal position along the electron bunch.

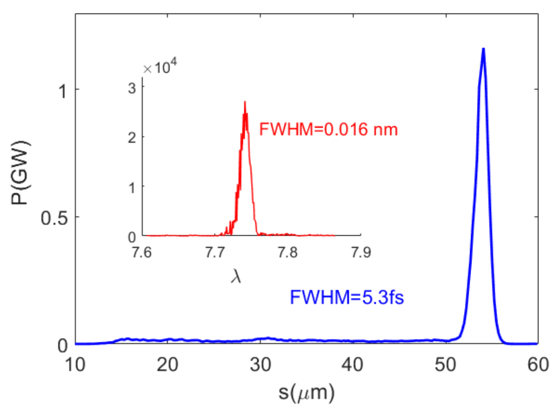

Figure 6: Pulse temporal profile and spectrum.

configuration can help to drive time resolved experiments requiring multiple ultrashort VUV pulses [26].

In Fig. 7, we show the evolution of the peak power at 7.7 nm in the final amplifier of FEL-2. In the first part of the undulator the growth is driven by the bunching factor and is quadratic. In the second part, in the last three radiators, the growth is still quadratic, but with the intensity at the saturation level the pulse is longitudinally focused as shown in the inserted plot.

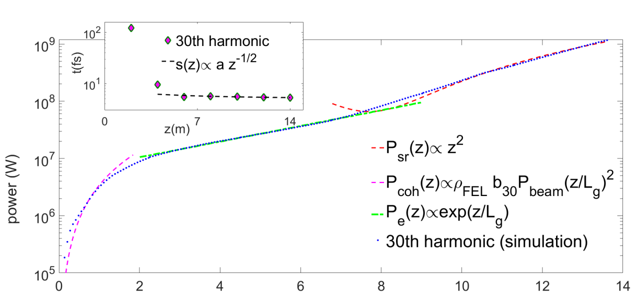

Figure 7: Growth of peak power as function of electron beam position (z) through the last radiators of the FEL-2 at the 30th harmonic radiation in different phases. Inserted plot: Evolution of time duration of the radiation pulse.

CONCLUSION

We have shown the possibility to drive the two FERMI FELs (FEL-1 and FEL-2) into a superradiant cascade regime in the VUV spectral region, leading to short pulses with duration well below 10 fs and peak power exceeding the GW level. In the specific case of FEL-2 this configuration does not require the large dispersion in the delay line between the first and second stage and therefore the region of beam used to generate the pulse has a limited extension of the order of 150 fs. The implication is that also on FEL 2 it would be possible to generate multiple pulses with a fixed delay of few hundreds of fs, to drive time resolved pump and probe experiments requiring multiple ultrashort VUV pulses. As a last remark, we remind that the presented analysis is based on the assumption of a seed duration of 70 fs, which is the shortest seed presently available at FERMI. This configuration may benefit of future developments where a reduction of the seed pulse duration to the 40-50-fs level is foreseen.

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