GENERATION OF A TRAIN OF SHORT PULSES BY MEANS OF FEL EMISSION OF A COMBED ELECTRON BEAM

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Abstract

We present the experimental demonstration of a novel scheme for the generation of ultrashort pulse trains based on the FEL lasing from a multi-peaked eletron energy distribution. At SPARC we generated two electron beamlets with relative energy difference larger than the FEL parameter ρ by illuminating the cathode with a combed laser, followed by a manipulation of the longitudinal phase space by velocity bunching in the linac. The SASE FEL radiation obtained by sending such beam in the undulator is analyzed by a FROG diagnostic revealing the double-peaked spectrum and temporally modulated pulse structure.

INTRODUCTION

Radiation pulse trains with atto-femtosecond time spacing represent a real possibility for a breakthrough in science and technology, permitting unprecedented insights into the atomic, multielectron and nuclear dynamics [1,2,3]. Since attosecond electronic motion is relevant to chemical processes leading to the formation of new materials and to chemical/biological transformations, the studies of time-resolved electron and nuclear rearrangements could lead to significant advances in understanding of intermolecular processes, chemical bond breaking and formation, and interaction of photoactivated molecules with their environment.

The ultrafast electron dynamics can be studied in atomic and molecular systems by using trains of ultrashort pulses, that allow not only the ultrafast electron imaging in atomic and molecular systems [4] or the investigation of the electronic response accompanying collective electron motion in nanomaterials, but find further applications in other technical fields as the enhancement of transmission or reflectivity in materials, the resonant inelastic X ray scattering, or the ab-initio phasing of nanocrystals. Sequences of spikes have been so far synthesized by means of the High Harmonic Generation driven by lasers in gases [HGHG] and regularly used in experiments, but with the intrinsic frequency limitations of this kind of sources.

The Free Electron Laser, in the self-amplified spontaneous emission (SASE) mode of operation, generates radiation with limited temporal coherence, time duration of the order of the electron bunch length and structured in a chaotic succession of random peaks. Several techniques have been explored to increase longitudinal coherence and stability and shorten the time scale towards the attosecond domain, and the progresses along this route have allowed the systematic generation of femtosecond EUV/x-ray pulses at the Fourier limit. The amplification of one single SASE spike has been demonstrated by compressing the electron beam below the radiation coherence length [5-6], by using a chirped bunch energy combined with a negative undulator taper [7-9], or by spoiling the whole electron beam except a limited fraction [10,11], a technique that has also been implemented to produce double pulse two color radiation for pump and probe experiments [12]. UV or soft X-ray short single or multiple pulses have been also produced in seeded or cascaded FELs [13], guaranteeing phase stability and coherence from shot to shot.

Another technique [14,15], relying on concepts adapted to FELs from mode-locked cavity lasers, has been proposed for reducing the duration of X-ray pulses generated by SASE FELs to less than the atomic unit of time and foresees the generation of trains of high peak coherent power flashes with large contrast ratio. Such scheme provides a comb of longitudinal modes by applying a series of spatiotemporal shifts between the co-propagating radiation and electron bunch, and is foreseen operating in the X-ray range of wavelength.

In this paper we present the experimental demonstration of a novel scheme for the generation of a regular short FEL pulse sequence [16] based on lasing from a multipeaked electron energy distribution.

DESCRIPTION OF THE METHOD

The experiment was carried out at the SPARC FEL facility in the IR-optical frequency range. The electron

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beam, constituted by two balanced and short bunches, is extracted from the linac at the maximum compression when, during the longitudinal phase space rotation, the two beamlets are temporary superimposed but split in energy, so that each of them is characterized by a different value of the Lorentz factor γ [17]. When driven in the FEL undulator, they emit two separate spectral lines, according to the FEL resonance condition

$$\lambda = \lambda_u \frac{(1+K^2/2)}{2\gamma_i^{\ 2}} \tag{1}$$

where K and λ_u are respectively the deflection parameter and the period of the undulator. If the electron beam width L_b is shorter than 2π times the cooperation length L_c, then the emission is constituted by two single-spiked bursts growing from noise. The two pulses, when temporary superimposed, interfere and, if the wavelengths satisfy the condition

$$|\lambda_1 - \lambda_2|/\lambda > 2\rho, \tag{2}$$

beating fringes are produced in the time-domain. A train of regular pulses with constant spacing can therefore be obtained, without any limitation in frequency, with the perspective of reaching the attosecond domain in the X-ray regime. The Fourier analysis of a double peaked pulse radiation permits to write the relation between the time separation of the fringes ΔT and the separation in energy of the bunches $\Delta\gamma = |\gamma_1 - \gamma_2|$, which results to be given by:

$$\Delta T = \frac{\lambda^2}{c(\lambda_1 - \lambda_2)} = \frac{\lambda_u(1+K^2)}{4c\gamma\Delta\gamma} \tag{3}$$

with λ and γ average values of wavelength and Lorentz factor. Fig. 1 presents the trend of the fringe separation with the energy of the electron beam, the shape of spectrum and pulse for a number N of spectral lines respectively equal to 2 and 4. As can be seen, the width of the fringes scales as 1/N, due to a sort of grating-like effect.

EXPERIMENTAL DETAILS

The experiment was performed at the SPARC FEL [18] operated at λ =800 nm, during two shifts in different compression conditions of the electron beam, summarized in Table 1 columns A and B. The experimental procedure started with the generation of a combed laser beam [19] characterized by two short (hundreds of fs) pulses spaced by a few ps, produced by enlightening a birefringent α-BBO crystal. The laser primary pulse was decomposed in two orthogonally polarized pulses with a time separation proportional to the crystal length; changing the birefringent glass, the distance between the two output packets could be ruled. Once that the electron beam was properly modulated, it was driven in the accelerating system and compressed by means of the velocity bunching method. The velocity bunching consists in the injection of the electron beam along the accelerating structure close to the zero crossing RF field phase [20]. Since the injection takes place at low energies, where the beam velocity is much lower than the phase velocity of the RF wave, the electrons slip back to phases where the field is accelerating, being chirped and compressed at the same time.

Table 1: Electron Beam Parameters

	Beam A	Beam B
Energy(MeV)	93+0.6	90+0.1
Charge(pC)	150	165
Emit-x(mmmrad)	1.56+0.1	1.68+0.18
Emit.-y(mmmrad)	1.7+0.12	1.81+0.15
Energy spread (MeV)	0.62+0.01	0.59+0.01
En. spread single beamlet (MeV)	0.3+0.01	0.27+0.1
Time duration (ps)	0.63+0.03	0.30+0.01
3D FEL parameter	5 10-4	1.510-3
Cooperation length(μm)	36	12.5

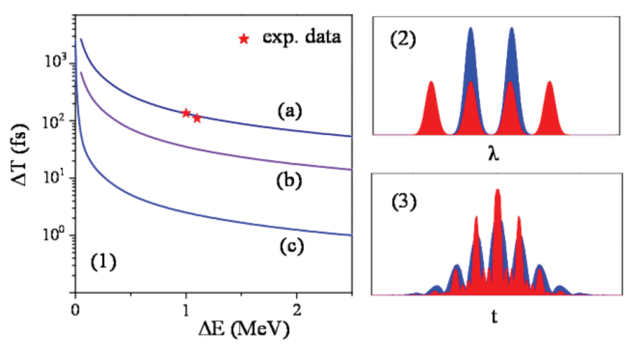

Figure 1: (1) Dependence of the fringe separation on the energy distance between the electron packets for (a) SPARC case, λ=800 nm, (b) λ=30nm, (c) λ=0.15 nm. Sketch of the spectrum (2) and temporal shape (3) of the pulse for N=2 electron packets (blue curve) and N=4 (red curve). The width of the fringes scales as 1/N.

In the first experimental condition (Table 1A) the linac radiofrequency phases were set in such a way to extract the electron beam before the condition of maximum compression, when the rotation in the phase space, responsible for approach of the peaks and increasing spatial overlapping of the two beams, was not completed. The experimental longitudinal electron phase space is presented in Fig. 2, first row, panel (a). The partial current profiles of both beams are shown together with the total one in panel (b). The beam was characterized by a peak current of about 110 A , with width of 650 fs at energies of 90 MeV . The charge was almost equally shared between the two bunches, the peak currents of the single beams being 65 and 90 A with energy spreads of about 0.3 MeV.

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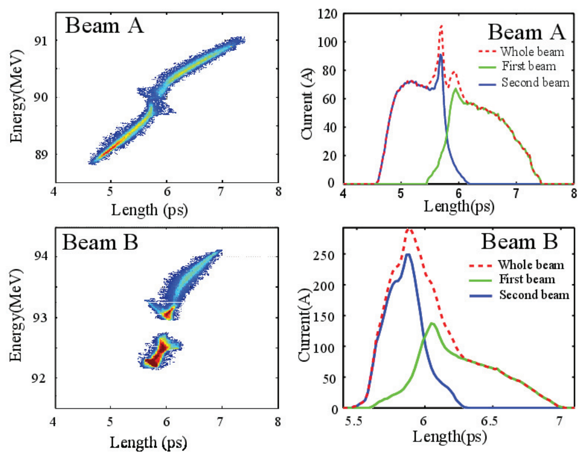

Figure 2: First row: Experimental electron phase space (1A) and electron current (2A) in the case of beam (A). Second row: the same for beam (B).

With these parameters, the 1D Pierce parameter was about $\rho=10^{-3}$, corrected by the 3D and energy spread effects in $\rho=5.5\ 10^{-4}$, with a corresponding cooperation length $L_c=57\mu m$. The condition for operating in single spike regime was therefore fulfilled.

Subsequently, the electron beam was injected in the undulator system, consisting of six sections of 75 periods each, with $\lambda_u=2.8cm$ [21], at the resonant wavelength $\lambda=800$ nm. The optimum matching condition of the electron beam to the undulator was found by using average values of energy and Twiss parameters.

The diagnostics used for characterizing the radiation were a Joulemeter, a spectrometer in fiber, and a Grenouille FROG for the direct detection of the time domain pulse structure. The observation of strong signals on all the instruments, as well as a double spectral peak structure on spectrometer and FROG in a large fraction of the shots were the demonstration that both electron beams were lasing contemporaneously.

EXPERIMENTAL DATA

An example of spectral measurements is shown in the first row of Fig. 3, panel (1), where the spectrometer (blue curve) and the FROG (red curve) signals are presented. In 90% of the shots, the spectrum observed with the spectrometer is double peaked with a preponderance of the power in the larger wavelength band, that sometimes presents SASE structures and with an interdistance $\Delta\lambda=21.5$ nm, corresponding to a mean value $\Delta E=1.2$ MeV. The analysis of the FROG traces reveals two neat spectral lines in 36% of the shots, while in other 36% the spectrum is single spiked. The remaining 28% cannot be clearly classified. A mean distance $\Delta\lambda=21.5$ nm was observed, corresponding to an energy gap mean value of $\Delta E=1.2$ MeV. The data were compared with start to end simulations by T-step [22] and GENESIS 1.3 [23]. The temporal structure of the pulse as given by the FROG set up is shown in the first row of Fig. 3, red curve of panel (2), together with GENESIS 1.3 simulation (dotted black curve), showing a good agreement. The interference structure does not develop on the whole time domain, because the beam was not at the maximum compression. In the left part of the pulse, whose r.m.s total temporal duration is T=232.5 fs , however, four regular fringes can be recognized, with width $\delta T_{f,rms}=26.7$ fs and interdistance $\Delta T=112$ fs.

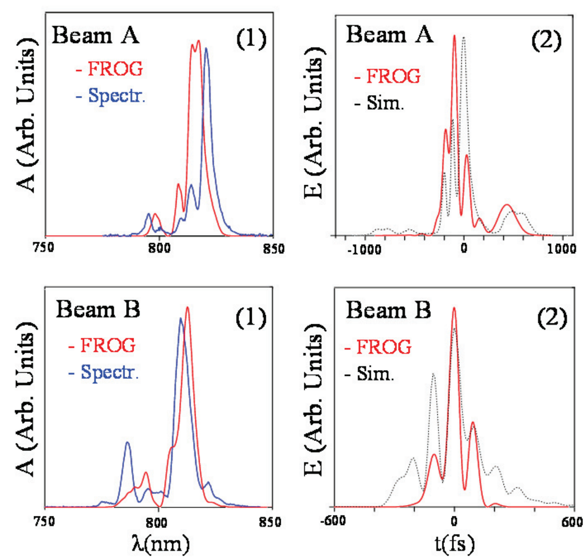

Figure 3: First row, beam A: panel (1) spectrometer signal (blue curve, abscissa on the top scale) and FROG spectral signal A (red curve, abscissa on the bottom scale). Panel (2): temporal pulse E from FROG (blue curve) and start to end simulation by Tstep and GENESIS 1.3 (black dotted curve). Second row: the same but for beam B.

In the second experimental session, the electron beam (Table 1, column B) was extracted at the maximum compression. The phase space is shown in Fig. 2, second row, panel (1) together with the currents (2). The space charge effects cause the indentation of the phase space. Also in this case, almost all spectrometer shots are double-peaked, with a mean separation of 26 nm. 57 % of the FROG data are characterized by a neat two color spectrum with $\Delta\lambda=16.6$ nm, corresponding to a mean value $\Delta E=0.98$ MeV, with total r.m.s. bandwidth of $\delta\lambda=6.9$ nm and spectral depth of the single lines $\Delta\lambda_{1,2}=3.2$ nm. Regular temporal fringes in the time domain were detected with average width of $\delta T=31.4$ fs, the rms time duration of the whole pulse being T=76.9 fs. The remaining 43% of the shots presented two close spectral lines that do not satisfy condition (2), leading to a single spiked shape in the time domain. One of the spectrometer data is presented in Fig. 3, second row, together with the spectral trace of the FROG (panel (1)). The temporal structure of the pulse as given by the FROG set up is

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shown in Fig. 3, second row (panel (2)) together with Genesis 1.3 simulation.

The experimental averaged values of the fringe separation ΔT are compared with the analytical previsions in Fig. 1 fully confirming the trend of process.

CONCLUSIONS

In this paper, the first realization of a train of FEL pulses is presented. The method, which has been applied to the SPARC FEL for the generation of IR radiation pulse trains, can be extrapolated to the production of attosecond pulses in the X-rays range. The electron beam with two beamlets could be also used in the Thomson source to provide two color X rays. Moreover, if a larger number N of electron bunches is used, then the rms width of the radiation pulses should become shorter due to grating effect. The development of such schemes is of significant importance since it opens a promising avenue for the femto- attosecond science and nanotechnology, providing the tools to record a 'molecular movie' as a dynamic real-space imaging.

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