Seeded FEL with two energy level electron beam distribution at SPARC_lab

Fabio Villa[a*], David Alesini[a], Maria Pia Anania[a], Marcello Artioli[b], Alberto Bacci[c], Marco Bellaveglia[a], Mariano Carpanese[d], Michele Castellano[a], Alessandro Cianchi[e], Franco Ciocci[d], Enrica Chiadroni[a], Giuseppe Dattoli[d], Domenico Di Giovenale[a], Emanuele Di Palma[d], Giampiero Di Pirro[a], Massimo Ferrario[a], Francesco Filippi[g], Alessandro Gallo[a], Giancarlo Gatti[a], Luca Giannessi[d], Anna Giribono[g], Luca Innocenti[e], Najmeh Sada Mirian[cf], Andrea Mostacci[g], Alberto Petralia[d], Vittoria Petrillo[cf], Riccardo Pompili[a], Julietta V. Rau[h], Stefano Romeo[a], Andrea R. Rossi[c], Elio Sabia[d], Vladimir Shpakov[a], Ivan P. Spassovsky[d], Cristina Vaccarezza[a];

[a]Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati, via E. Fermi 40, 00044 Frascati (RM), Italy; [b]ENEA – Centro Ricerche Bologna, via Martiri di Monte Sole 4, 40129 Bologna, Italy; [c]Istituto Nazionale di Fisica Nucleare – Sezione Milano, via G. Celoria 16, 20133 Milano, Italy; [d]ENEA – Centro Ricerche Frascati, via E. Fermi 45, 00044 Frascati (RM), Italy; [e]Istituto Nazionale di Fisica Nucleare – Sezione Tor Vergata and Università di Roma Tor Vergata, via della Ricerca Scientifica 1, 00133 Roma, Italy; [f]Università degli Studi di Milano, via G. Celoria 16, 20133 Milano, Italy; [g]Università La Sapienza di Roma, via A. Scarpa 14, 00161 Roma, Italy; [h]ISM-CNR via del Fosso del Cavaliere 100, 00133 Roma, Italy;

ABSTRACT

We present the experimental evidence of the generation of coherent and statistically stable Free-Electron Laser (FEL) two color radiation obtained by seeding an electron double peaked beam in time and energy with a single peaked laser pulse. The FEL radiation presents two neat spectral lines, with time delay, frequency separation and relative intensity that can be accurately controlled. The analysis of the emission shows a temporal coherence and regularity in frequency significantly enhanced with respect to the Self Amplified Spontaneous Emission (SASE).

Keywords: FEL, seeded, two color

INTRODUCTION

FEL can generate an high brightness radiation in a very broad spectral region (from THz to hard x-rays) and, in particular, in x-ray region can generate coherent high peak power pulses that nowadays can't be matched by other sources. In recent times FELs have shown also the capability to generate two color pulses with tunable time and spectral separation [1-5]. Two color radiation enables a wide number of applications, ranging from time resolved analysis of atomic, surface and plasma dynamics to imaging of biomedical samples and molecules. Two color FEL experiments have been recently carried on with different methods in a wide spectral region, while many theoretical methods on two color x-ray FEL generation were investigated [6-9]. One of those methods, that uses two electron bunches to achieve two color generation, has been implemented and demonstrated in visible [2, 10, 11] and x ray [5] spectral region and, in the latter case, successfully delivered to user experiments.

This scheme is based on two closely spaced electron beamlets generated at the cathode and accelerated off-crest along the linac to two different energies. The bunch train, driven in the undulator, radiates two distinct SASE (Self Amplified Spontaneous Emission) pulses, whose relative time delay and wavelength difference can be tuned independently by changing the extraction conditions from the linac. The particular advantage of this approach is the large spectral separation, up to 1-2% [10], that can be achieved and the possibility of using the entire undulator length on both colors, thus allowing applications requiring high-intensity radiation or exploiting the activation of self-seeding processes. In previous experiments, the emission starts from noise, and, whereas the two colors can be single spiked, the radiation is affected by random shot to shot fluctuations both in the time and frequency domains and have a poor longitudinal coherence. The degree of coherence can be improved by seeding the radiation with an external field, such as that of a laser pulse.

Advances in X-ray Free-Electron Lasers Instrumentation III, edited by Sandra G. Biedron
Proc. of SPIE Vol. 9512, 95120T · © 2015 SPIE · CCC code: 0277-786X/15/$18
doi: 10.1117/12.2182160

LINAC SETUP

The experiment was performed at the SPARC_LAB facility [12], on the FEL beam line [13-15]. We used a pair of laser pulses on the photocathode to produce two electron bunches. Those two pulses were produced using a birefringent BBO crystal, employing the delay between ordinary and extraordinary propagation in the crystal, balancing the intensity of the two pulses by choosing the angle between the linear polarized laser and the birefringence axis [16]. The two pulses had a separation of 4.4 ps and a duration of few hundreds fs (Fig. 1), measured via a cross correlation with an 800 nm pulse resulting from the harmonic generation of the photocathode UV laser pulses.

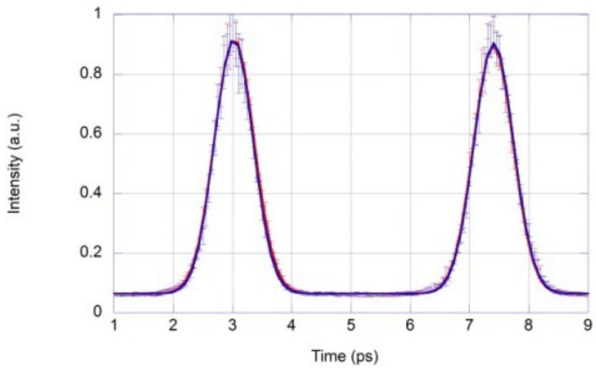


Figure 1. Cross correlation measurement of photocathode UV laser pulses.

The ps-spaced electron beam emitted from the cathode was then propagated along the linac (three S-band cavity sections) and compressed by means of the velocity bunching, a technique developed at SPARC [17-20] and consisting in the injection of the electrons into the first accelerating structure close to the zero crossing Radio Frequency (RF) field phase.

The linac RF phases were set in order to extract the electron beam near the maximum compression, when the rotation in the phase space, responsible for the energy and temporal separation of the two beams, has been completed. The final energy E was around 95MeV, a value allowing FEL emission at 800nm, an optimal condition for the availability of the seed and for the radiation diagnostics. Longitudinal phase space was projected on a screen with a FR deflector and a dipole.

Table 1. Parameters of the electron beam during the experiment.

	Total	First	Second
Mean energy (MeV)	94.8	95.3	94.3
Charge (pC)	100	50	50
Peak current (A)	180	70	110
Rms pulse duration (fs)	170	190	100
Emittance (mm mrad)	2.1		
Energy spread (MeV)	0.5	0.13	0.10

The parameters of the electron beam in the operational conditions are listed in Table 1. The experimental longitudinal phase space, Fig. 2, shows two electron beamlets with rms energy spread of 0.1MeV each, separated by 1MeV and with total rms temporal duration of 170 fs.

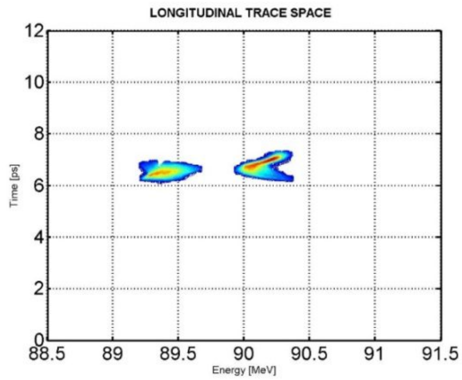


Figure 2. Longitudinal phase space of the compressed electron beam.

FEL SETUP

The electron beam was injected in the undulator system (Fig. 3), consisting of six ACCEL sections of 75 periods each, with λ_u = 2.8 cm [21], at the mean resonant wavelength

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

where K is the undulator deflecting parameter and γ is the average value of the electron Lorentz factor. The optimum matching condition of the electron beam to the undulator was found by using average values of energy and projected emittance and Twiss parameters, measured via quadrupole scan [22]. The one dimensional Pierce parameter [23] for each beamlet can be estimated as $\rho = 3\ 10^{-3}$, corresponding to a cooperation length of L_c = 11 μm. The SASE radiation was observed. The significant compression of the electron lead the system in the single spike radiation condition $L_b < 2\pi L_c$, where L_b = 51 μm is the electron beam width. We finely tune (around 1%) the gap of the last undulator section to maximize the output power.

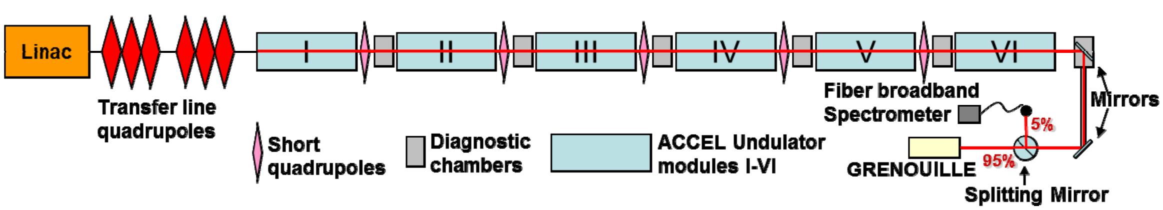


Figure 3. Scheme of the undulator sections, electron transport and diagnostics.

The seed laser system [24] consists of a Ti:Sapphire regenerative amplifier (Legend HFE by Coherent), driven by the same oscillator as the photocathode laser and can deliver up to 2.5 mJ at λ_0 = 800 nm. The seed laser pulse had a bandwidth of 7 nm FWHM and it was stretched to 1 ps FWHM duration. The scheme of attenuation, shown in Fig. 4, is composed by various steps, consisting in the coupling of a Half Wave Plate and a Polarizing beam splitter Cube. The first plate is settled at a fixed angle in order to select a fraction of the initial seed energy to 0.11 mJ. The second attenuation step is realized through a variable plate with the associated beam splitter cube. The remote rotation control of the variable plate allows to change continuously the intensity of the output polarization. The polarization at this stage is chosen vertical, since, just before the injection into the undulator, it is rotated by a periscope in order to match the horizontal polarization of the FEL radiation. The available effective seed energy at the interaction point ranges from 800 nJ to few nJ.

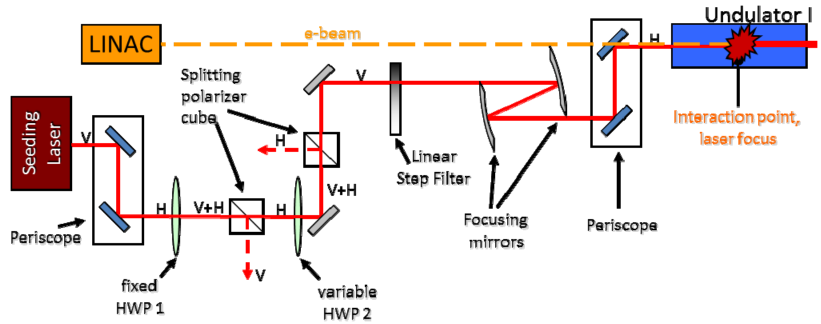
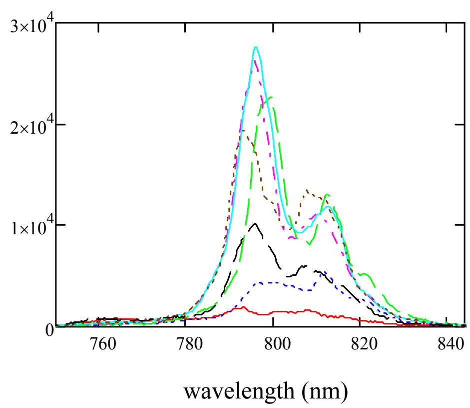


Figure 4. Scheme of the seeding laser

A single laser pulse was used to seed together the two electron bunches with two distinct energies and slightly shifted in time. The undulator was tuned at 800nm, the central wavelength of the seeding laser. In this way, the two FEL pulses generated in the undulator have their own resonance wavelengths, whose relative difference $d\lambda/\lambda = 2dE/E$ is connected to the two electron bunches energy separation. Since dE = 1MeV, the expected wavelength separation $d\lambda$ turns out to be 165 nm. The useful spectral region of the laser is the portion on the wings of the Gaussian distribution that can be estimated analytically by integrating the seed energy distribution both in time and wavelength, choosing the temporal length and spectral bandwidth as intervals of integration for each pulse. This evaluation gives an effective seed energy in the range 1-10 nJ

TWO COLOR MEASUREMENTS

A Fiber Spectrometer and a Grenouille FROG are used as diagnostics for the direct detection of the light spectrum and time distribution (Fig. 3). The FEL radiation is split in 5% to the spectrometer, 95% to the FROG so both devices can acquire at the same time.



	Seed total energy (measured)	Effective energy on each pulse (calculated)
	811 nJ	10 nJ
	707 nJ	8.5 nJ
	450 nJ	5.5 nJ
	170 nJ	2 nJ
	125 nJ	1.5 nJ
	15 nJ	0.2 nJ
	0 (SASE)	0 (SASE)

Figure 5. Spectrometer measurements at different seeding energies. On the right the seeding energies are listed.

Fig. 5 presents spectra (average on 100 shots) of the two color radiation for different value of the seed laser energy, starting from the pure SASE mode and with increasing seed. The radiation show two distinct spectral lines, whose intensity grows with increasing seed energy. Both SASE and seeded wavelength separations, 15.9 nm and 14.7 nm, are in agreement with the values deduced by the electron energy gap. The 10% difference between those two values is due to the fact that the electron measurements were done few hours before the radiation detection and that the phase space was affected by slight fluctuations. An increase in intensity by a factor about 10 and an enhancement in the visibility of the two colors from 30% to 50% between the SASE and the optimized seeded case were observed.

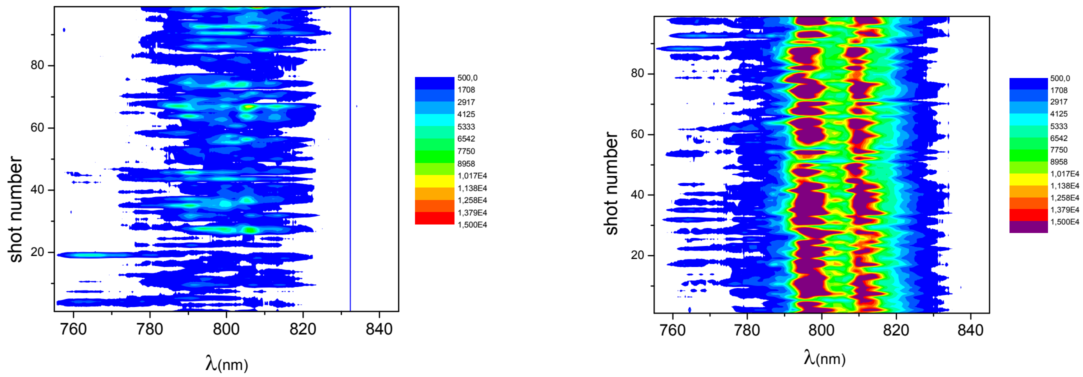


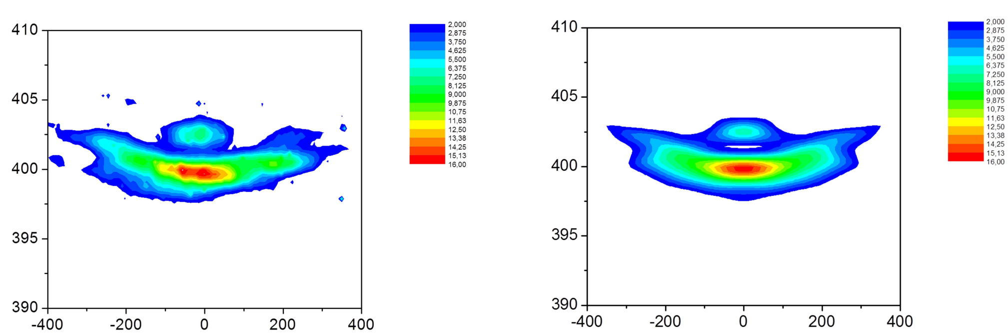
Figure 6. Spectrometer measurement of the radiation stability. On the left 100 SASE measurements are presented, on the right the same amount for seeding configuration.

Fig. 6 shows the complete sequences of 100 shots measured with the spectrometer without (left) and with seed (right). In the SASE mode, only a fraction of 66% of the shots has a double peaked configuration, while the other ones have SASE or single spike structure. In the seeded mode, instead, the double peaked shots are 99% of the total and the two pulses central wavelengths are more stable. Central wavelengths, wavelengths difference and bandwidths of the radiations are presented in Table 2.

Table 2. Averaged values of FEL two color radiation (values in nm).

	$<\lambda_1>$	$<\lambda_2>$	$<\lambda_1 - \lambda_2>$	$<bw_1>$	$<bw_2>$
SASE	790±10	808±6	17±11	9±3	7.8±1
Seeded	792.5±1.5	806.6±1.8	15.1±1.2	3.1±0.5	2.7±0.6

Measurements done with the FROG system acquire both spectral and temporal profiles. However, the FROG technique requires a radiation energy level larger than 1uJ. In the SASE case, the emission was marginally weaker with respect to this value, and only few useful FROG traces were generated, not permitting a statistical analysis. In the seeded regime, instead, 95 shots over 100 were amply above the threshold. The comparison between the two cases allowed us to quote the seeded emission energy in the order of 10 uJ. An example of the FROG trace is shown in Fig. 7. Since the radiation is composed by two pulses spectrally and temporally separated, and coming from two electron beamlets propagating in the undulator with different trajectories, the two emission pulses could enter the FROG camera with slightly different angles. The FROG traces were therefore not always perfectly symmetric with respect to time. For this reason, the FROG data were analyzed and selected also in symmetry by computing the cross correlation between the right and the left part of the raw trace. The mean separation in time is 290±70 fs, a value compatible with the temporal distance of 230 fs between the centroid positions of the two beamlets averaged on the relative current distribution.



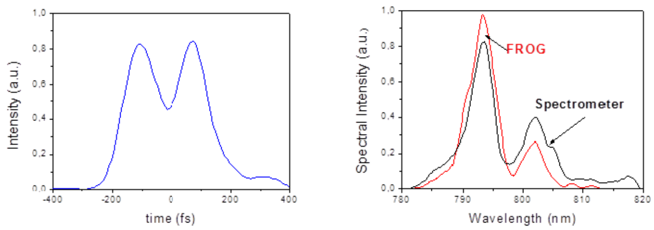


Figure 7.The top graphs are one FROG acquisition and its reconstruction. On the bottom line the time and spectral intensities are presented. The latter is compared with the spectrometer measurement.

CONCLUSIONS

In conclusion, we have presented the experimental evidence of the generation of coherent and statistically stable Free-Electron Laser two color radiation obtained by seeding electron beams double peaked in time and energy with laser pulses single spiked in frequency. This new method produces high quality light and could be extrapolated toward higher frequencies using HGHG or self-seeding techniques.

REFERENCES

[1] Lutman, A. A., et al., "Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers," Phys. Rev. Lett. 110, 134801 (2013).

[2] Petrillo, V., et al.,"Observation of time-domain modulation of free-electron-laser pulses by multipeaked electron-energy spectrum," Phys. Rev. Lett. 111, 114802 (2013).

[3] Allaria, E., et al., "Two-colour pump–probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser," Nature Communications 4, 2476 (2013).

[4] Mahieu, B., et al., "Two-colour generation in a chirped seeded free-electron laser: a close look," Optics Express 21, 22728 (2013).

[5] Marinelli, A., et al., "Two-Color Schemes at LCLS," FEL Conference 2013, WEPSO40.

[6] Freund, H. P., O'Shea, P. G., "Two-color operation in high-gain free-electron lasers," Phys. Rev. Lett. 84, 2861 (2000).

[7] Thompson, N. R., Mc Neil, B., "Mode locking in a free-electron laser amplifier," Phys. Rev. Lett. 100, 203901 (2008).

[8] Xiang, D., et al., "Enhanced tunable narrow-band THz emission from laser-modulated electron beams," Phys. Rev. ST-AB 12, 060701 (2009).

[9] Zholents, A., Penn, G., "Obtaining two attosecond pulses for X-ray stimulated Raman spectroscopy," Nucl. Instrum. Methods Phys. Res. Sect. A 612, 254 (2010).

[10] Ronsivalle, C., et al., "Large-bandwidth two-color free-electron laser driven by a comb-like electron beam," New J. Phys. 16, 033018 (2014).

[11] Chiadroni, E., et al., "Two Color FEL Driven by a Comb-like Electron Beam Distribution," Physics Procedia 52, 27 (2014).

[12] Ferrario, M., et al., "SPARC_LAB present and future," Nucl. Instrum. Methods Phys. Res. Sect. B 309, 183 (2013).

[13] Giannessi, L., et al., "High-order-harmonic generation and superradiance in a seeded free-electron laser," Phys. Rev. Lett. 108, 164801 (2012).

[14] Giannessi, L., et al., "Superradiant Cascade in a Seeded Free-Electron Laser," Phys. Rev. Lett. 110, 044801 (2013).

[15] Labat, M., et al., "High-Gain Harmonic-Generation Free-Electron Laser Seeded by Harmonics Generated in Gas," Phys. Rev. Lett. 107, 224801 (2011).

[16] Villa, F., et al., "Laser pulse shaping for multi-bunches photoinjectors," Nucl. Instrum. Methods Phys. Res. Sect. A 740, 188 (2013).

[17] Ferrario, M., et al., "Experimental demonstration of emittance compensation with velocity bunching," Phys. Rev. Lett. 104, 054801 (2010).

[18] Ferrario, M., et al., " Laser comb with velocity bunching: Preliminary results at SPARC ," Nucl. Instrum. Methods Phys. Res. Sect. A 637, S43 (2011).

[19] Giannessi, L., et al., "Self-amplified spontaneous emission free-electron laser with an energy-chirped electron beam and undulator tapering," "Phys. Rev. Lett. 106, 144801 (2011).
[20] Marcus, G., et al., "Time-domain measurement of a self-amplified spontaneous emission free-electron laser with an energy-chirped electron beam and undulator tapering," Appl. Phys. Lett. 101, 134102 (2012).
[21] Quattromini, M., et al.,"Focusing properties of linear undulators," Phys Rev. ST-AB 15,080704 (2012).
[22] Dattoli, G., et al., " Slice emittance, projected emittance and properties of the SASE FEL radiation," Nucl. Instrum. Methods Phys. Res. Sect. A 671, 51 (2012).
[23] Bonifacio, R., et al, "Collective instabilities and high-gain regime in a free electron laser," Opt. Commun. 50, 373 (1984).
[24] Vicario, C., et al., EUROFEL-Report-2007-DS4-093.