

# Demonstration of two-color X-ray FEL by photocathode laser emittance spoiler

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## ABSTRACT

Two-color is an emerging mode of operation in X-ray Free Electron Laser (FEL) having the potential to expand the pump and probe experiments toward fs temporal resolution and to site-selective spectroscopy. A novel and quick to setup method for two-color X-ray generation is presented here. The approach is experimentally demonstrated at the hard X-ray branch of Swiss FEL (Aramis) using a laser emittance spoiler (LES). A short laser pulse is overlapped at the peak of the primary photocathode laser causing a local increase of the electron bunch emittance. In this configuration, the X-ray FEL emission occurs only for the two unspoiled parts of the bunch. Due to the fact that the electron bunch acquires an energy chirp along the acceleration, the spoiled beam produces two X-ray pulses of individual duration of few tens of fs having 1% photon energy separation and a time delay controllable up to 100 fs. Different from other techniques, the present method relies on the standard FEL configuration and it does not require a dedicated accelerator and undulator setting. With the LES, we achieved high efficiency, high energy and spectral stability paired to an independent control of the duration and of the relative intensity of the two colors. The LES enables shot-to-shot switching between one and two-color FEL and further, it is compatible with high repetition-rate FELs, as it is not associated to electron beam losses such as in other two-color methods.

**Keywords:** X-Ray FEL, Two color FEL, Emittance control, photocathode laser

## 1. OVERVIEW

X-ray free electron lasers (FELs) are large scale facilities aiming to forefront researches in biology, femto-chemistry, physics and material science. With the typical femtosecond pulse length, FELs extend X-ray techniques to unprecedented ultrafast timescale [1-5]. The time-resolved experiments are usually carried out by combining a conventional laser pump pulse with an X-ray FEL probe. For such studies, the reduction of the temporal jitter between the pump and the probe pulses down to fs-level remains a persistent challenge [6]. With two-color FEL, X-ray pump, X-ray probe experiments have the potential to drastically decrease the time jitter while enabling site-selective spectroscopy [7, 8]. Typically, a two-color FEL output structure can be obtained by setting two sections of the undulator to two resonances or by the manipulation of the electron bunch properties, see references in [9]. Both approaches are implemented with a dedicated FEL setting which is often not optimized for high energy FEL output and, in addition, requires a long preparation time.

### 1.1 Experimental setup

A novel approach for the generation of a two-color FEL by a laser emittance spoiler pulse (LES) is here reported [9]. Different from other techniques, for the present method the two-color X-rays is reached with the optimal FEL settings as a dedicated machine retuning is not required. In this way, the preparation time is minimized making best use of the beam-time for the user experiment. Shot-to-shot switching between two and single color is enabled by the LES. This method is directly applicable to high-average power x-ray FELs because it is not associated to the electron beam losses such for other approaches. The laser emittance spoiler concept is sketched in Figure 1. A ps LES pulse is overlapped on the longer photocathode (PC) laser. The excess of charge generated by the LES, spoils locally the electron beam emittance, preventing this part to contribute to the FEL amplification. The portion of the bunch not interacting with the laser spoiler still produces FEL emission at two wavelengths due to the energy chirp that can be accumulated along the linear accelerator.

The two-color FEL by LES is demonstrated at the hard X-ray branch of SwissFEL (Aramis) [1]. SwissFEL delivers up to mJ pulses at photon energy of 2-12 keV. To drive the FEL, 200 pC electron bunches at 100 Hz are typically generated from a Cs<sub>2</sub>Te photocathode in an electron gun. The beam energy is boosted up to 6 GeV and compressed down to a few tens of fs before the Aramis undulator. In table I, the main parameters of the PC and LES at the photocathode are reported. Both the lasers consist of a low-noise Yb-based oscillator and a diode-pumped Yb:CaF<sub>2</sub> regenerative amplifier running at 100 Hz [10].

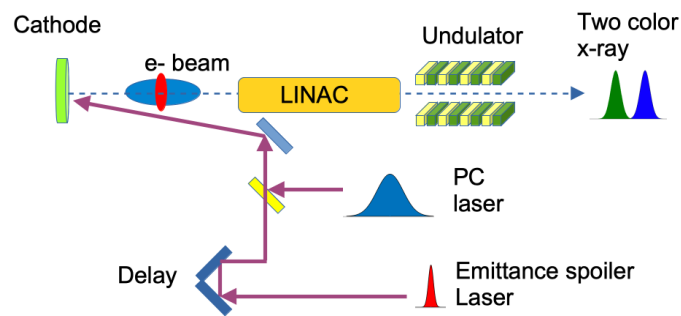


Figure 1. Layout of the two-color FEL scheme based on the LES.

The fundamental wavelength is frequency quadrupled in the deep-UV at a photon energy above the Cs<sub>2</sub>Te photocathode work function. The timing jitter between the two lasers is below 20 fs rms [11]. The deep-UV laser pulses of the two systems are stretched in time with transmissive diffraction gratings. The stretcher is bypassed for the spoiler laser to keep pulse duration below 1 ps. The LES pulse can in principle be picked up from the PC laser in front of the stretcher. However, for the present experiment, for more flexibility a second laser is used. In this configuration, the LES can be triggered on a shot-to-shot basis, and it can be easily delayed and controlled in energy.

Table 1. Specification of the photocathode laser (PC) and the laser emittance spoiler (LES).

Parameters	PC laser	LES
Wavelength	260 nm	260 nm
Pulse duration	6.6 ps	0.95 ps
Beam radius	1 mm	2 mm
Generated Charge	200 pC	11-34 pC

At SwissFEL, an emittance of several hundred nm is required for the full bunch to radiate at the shortest wavelength (1 Å) [1]. With the ps-laser, the emittance can be spoiled at the center of the bunch well beyond this limit preventing the FEL emission. In this way, only the front and the end of the bunch having low emittance will produce two short X-ray pulses of two-colors.

## 2. EXPERIMENTAL RESULTS

### 2.1 Slice emittance

The effect of the LES on the slice emittance of the nominal 200 pC electron beam was measured at the injector and upstream the undulator, Figure 2. The dashed lines indicate the temporal overlap between the PC and the LES. When the LES is off (black curve), the slice emittance at low energy (left plot) stays constant in the central part of the bunch with a value slightly higher than the standard SwissFEL emittance of 200 nm [12] well below the emittance limit for the FEL emission. When the spoiler generates a charge of 19 pC (red curve) the emittance increases locally enough to prevent the lasing. The emittance peak is preserved to the undulator entrance as shown in the right plot of Figure 2. The temporal structure of the two-color FEL can be estimated by the slice emittance at the undulator (right plot). The FEL emission occurs at the minima of the emittance in two few tens of femtosecond long pulses separated by about 40 fs.

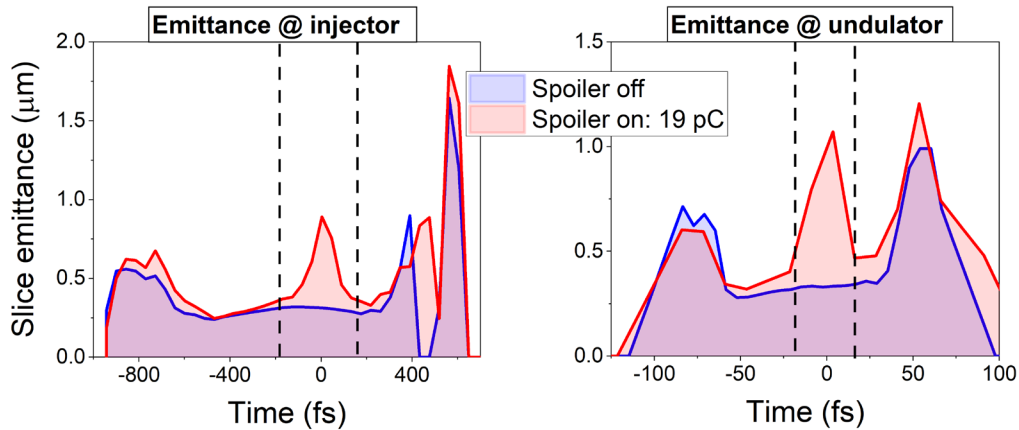


Figure 2. Slice emittance at the injector (left) and at the undulator entrance (right) when the LES is off (black curves) and on (red curves).

## 2.2 Spectrum of the two-color FEL

Stable two color FEL is achieved with the LES. The left plot of Figure 3 displays in fact 6000 consecutive spectra at 11.2 keV with relative photon energy separation of 0.5%. The grey area and the red curve indicate the overall FEL spectra and their average. Two-color spectrum with well-separated peaks can be reached for all the FEL pulses and maintained over extended time. The present two-color scheme is applicable to all the photon energies of the Swiss FEL. With larger energy spread a maximum relative wavelength separation up to 2% can be expected [13].

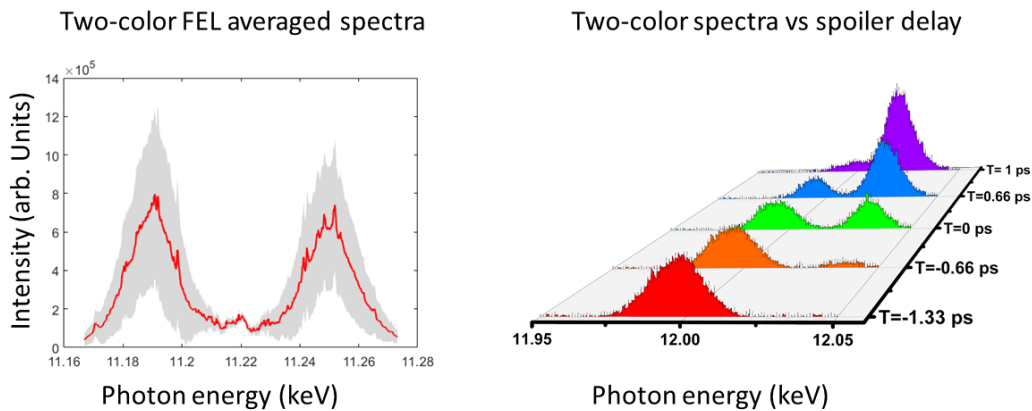


Figure 3. Two-color FEL spectra at 11.2 keV (left). The grey area and the red curve show 6000 consecutive FEL spectra and their average. By changing the delay between of the LES it is possible to unbalance the intensity of the two X-ray colors (right).

## 2.3 Temporal and spectral shaping of the two-color FEL

By changing the relative delay  $T$  between the LES and the PC laser, the relative intensity, the spectral width and the duration of the two individual colors can be adjusted. The averaged FEL spectra around 12 keV for different  $T$  are shown in Figure 3 (right plot). When the LES pulse overlaps with the centroid of the PC laser pulse, at  $T = 0$ , two X-ray colors having the same intensity are obtained. The FWHM the durations of the longer and shorter wavelength color as a function of the spoiler delay  $T$  were calculated by fitting the second order spectral correlation function with the model derived in [14]. The duration of the two colors at  $T = 0$  ps, are calculated to be 7 and 11.3 fs for the high and low photon energy. These pulse durations are consistent with the slice emittance obtained in the same experimental conditions

reported in Figure 2, right plot. For  $T = \pm 0.66$  ps, the two-color spectrum can be drastically unbalanced towards the high or low energy color and the pulse duration change accordingly [9]. These uneven spectra may be useful to generate X-ray pump and the X-ray probe pulses in time-resolved experiments. With delays of the spoiler pulse larger  $\pm 1$  ps the single spectral line FEL is recovered. Adjusting the spoiler delay, the duration of the two FEL colors is significantly unbalanced and can be reduced to a minimum value of 6 and 9 fs FWHM for the long and short wavelength pulses [9].

## 2.4 Temporal structure of the two-color FEL measured with passive wakefield streaker

The temporal structure of the two-color X-ray pulse was also measured. The power profile of the FEL pulse versus time is obtained with the recently-developed passive wakefield streaker diagnostics [15]. The indirect measurement of the FEL power temporal profile is based on detecting the change in the final longitudinal phase space (LPS) of the electron beam induced by the FEL process [16]. In fact, the slice energy spread after the undulators is increased when the FEL is enabled. The LPS is obtained from the transverse electron distribution on a beam monitor located in a dispersive section after the passive streaker. The time coordinates are retrieved by inverting the nonlinear wakefield streaking in horizontal direction through an iterative algorithm. The energy coordinates can be easily accessed due to the linear lattice dispersion in the vertical plane.

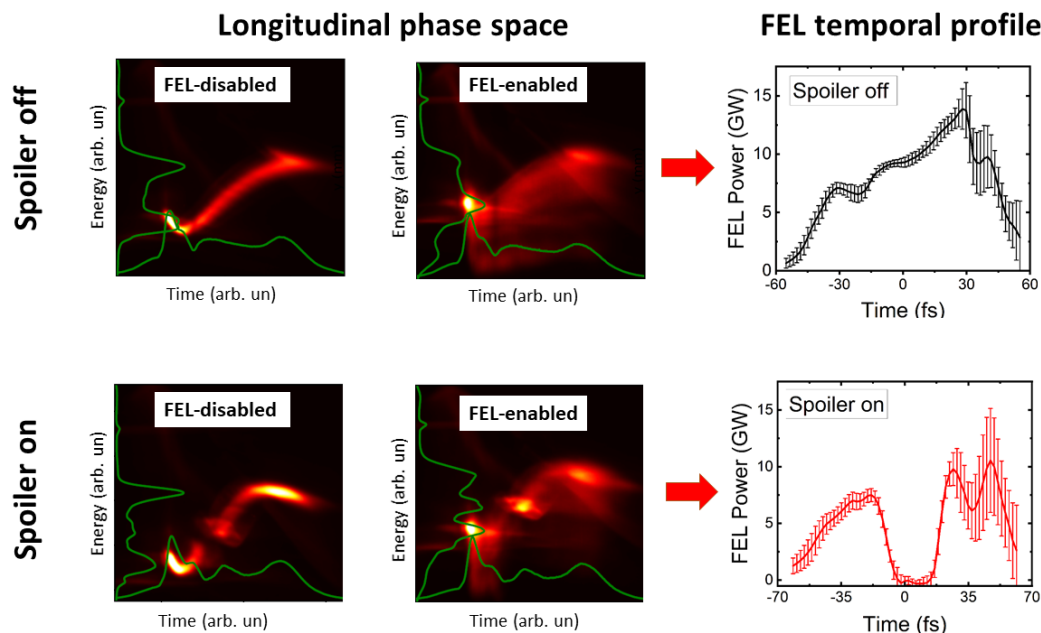


Figure 4. FEL temporal profiles for spoiler off (top row) and on (bottom) reconstructed using the passive wakefield streaker [13]. The four left figures show the electron beam longitudinal phase space when the FEL is disabled and enabled. The one and two color FEL temporal profile is shown on the right graphs.

Figure 4 displays the LPS and power profiles of the FEL operated at 6.6 keV. The LPS, both with the LES off (up) and on (down), when the FEL is disabled, are shown in the left column. The effect of the LES is observable in the defocused part of the beam distribution. The corresponding LPS with the FEL enabled are presented in the middle column. The retrieved temporal profile of the FEL emission is illustrated on the right plots for one (top) and two-color emission (low).

A total energy of 604  $\mu\text{J}$  is carried by the two-color FEL pulse when a charge of 6 pC is generated by the LES, resulting in two colors well-separated in time. This accounts for around 67% of the energy detected for the standard SASE single X-ray color (900  $\mu\text{J}$ ). Increasing the intensity of the LES restricts the emission from a larger portion of the beam, resulting in a greater temporal separation of the two colors but a slightly smaller total energy. The energy fluctuations for single and two-color FEL are comparable, confirming the robustness of the LES scheme.

## 2.5 Temporal reconstruction with THz streaking

A direct measurement of the photon temporal distribution of the two-color FEL was carried out using the photon arrival and length monitor (PALM) [17]. This diagnostic technique utilizes THz streaking generated from the experimental optical pump laser to determine both the arrival time and pulse distribution of the incoming X-ray FEL pulses. The measurement was performed while switching between one and two colors on a shot-to-shot basis by triggering the LES at half of the FEL repetition rate (50 Hz) and measuring only the two-color pulses. Figure 5 displays the corresponding streaking trace, where the photon energy is plotted on the vertical axis, exhibiting two well-separated wavelengths. The temporal structure of the photon emission and the temporal separation of the two colors can be deduced from the analysis of the sinusoidal THz waveform along the horizontal axis. The streaking trace confirms the existence of two FEL wavelengths that are delayed in time (Figure 5) which are visualized as two THz fields shifted in time.

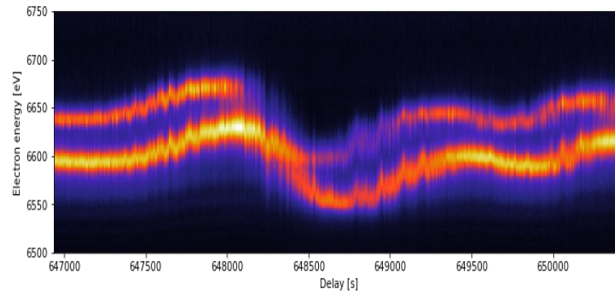


Figure 5. THz streaking measurement of the two-color FEL. The vertical and the horizontal axes reports the photon energy and the time scale. Two wavelengths delayed in time are clearly visible in the figure.

## 3. CONCLUSION

A straightforward and robust method for creating a two-color hard X-ray FEL based on a laser emittance spoiler is presented. Notably, no specific tuning of the machine is required for this operation mode, rendering the method highly efficient. Energy in the two-color mode of up to 67% of the nominal FEL were demonstrated with comparable energy stability. The setup time of the FEL for the two-color mode is negligible, and it can be activated on a shot-to-shot basis. The range of accessible wavelengths, colors, and temporal separation of the two pulses is solely dependent on the electron bunch energy, chirp, and duration. This method is well-suited for high-repetition rate X-ray FEL applications since electron beam losses are negligible. The dependability of the method and the ease of its setup make it an attractive option for the FEL scientific community seeking lower-risk two-color configurations for advanced X-ray pump and X-ray probe experiments.

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