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# FREE ELECTRON LASER R&D INITIATIVES AT THE SLAC NATIONAL ACCELERATOR LABORATORY

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*Abstract*

The successful lasing of the linac coherent light source in 2009 [1], the first x-ray free-electron laser (xFEL) in the world, has opened a new era for x-ray photon science. The unprecedented intensity and coherence of the LCLS photon pulses has enabled groundbreaking experiments in a wide variety of fields ranging from coherent x-ray imaging to molecular and atomic physics. Despite the success of x-ray free-electron lasers, there is a steady push to extend and improve their capabilities fueled by the users' demands for new modes of operation and more precise photon and electron diagnostics. In this article, I will review several R&D initiatives at the SLAC National Accelerator Laboratory geared towards improving the performance and extending the capabilities of x-ray FELs. In particular I will focus on the spectral manipulation of FELs and our recent development of the multibunch and multicolor x-ray FEL modes at LCLS.

## TWO-COLOR OPERATION AT LCLS

In a two color FEL, two pulses with different photon energy are generated in the undulator [2–6]. Typically the two pulses have a tunable energy separation and a tunable time delay. Two color FELs have a wide range of applications, from the imaging of bio-molecules via multiple wavelength anomalous diffraction to time resolved studies of atomic physics and warm dense matter. In response to the request of a large number of users, the several two-color schemes have been developed at LCLS .

In an FEL, the central wavelength of the emitted radiation is given by the well known formula [7]

$$\lambda_r = \lambda_w \frac{1 + \frac{K^2}{2}}{2\gamma^2} \tag{1}$$

where $\lambda_w$ is the undulator period, $K$ is the dimensionless undulator parameter (typically of order 1) and $\gamma$ is the electron beam Lorentz factor. From equation 1 follows that a free-electron laser can emit two different wavelengths if the undulator is divided in sections tuned to different $K$ values or if the electron beam is composed of two distinct energy bands (the last parameter $\lambda_w$ is typically not variable).

Figure 1 shows a schematic layout of the two-color schemes currently being used at LCLS. In the first scheme, called split undulator [2], the undulator is divided in two parts, with a magnetic chicane placed in the middle. The two undulators can be tuned to different magnetic strengths $K_{1,2}$. A single electron bunch emits radiation at two different wavelengths $\lambda_{1,2} = \lambda_w \frac{1+\frac{K_{1,2}^2}{2}}{2\gamma^2}$. The magnetic chicane between the undulatory introduces a delay between the electron bunch and the radiation emitted in the first undulator, thus inducing a time delay between the two radiation pulses. Since both x-ray pulses are emitted by the same electron bunch, the first of the two pulses cannot be amplified to saturation, since energy-spread induced by the FEL process would prevent lasing on the second color. This typically limits the radiation power to about 10% to 30% of the full saturation power. At hard x-rays, where the saturation length of the FEL is the longest, the limited number of undulators limits the two color power to less than 10% of the full saturation power. The greatest advantage of this scheme is its flexibility, since both the time delay and the energy separation of the two pulses can be varied with minimal impact on the machine tuning. At LCLS, the chicane delay can be varied in the range of 0 – 50 fs, while the relative energy difference of the two colors is limited to 3% of the central wavelength. These parameters are solely determined by the existing hardware limitations. Wider energy differences have been achieved with variable gap undulators (see e.g. [4]).

While the maximum delay of the two pulses is limited by the strength of the chicane magnets, the minimum delay has a more fundamental limitation. In fact, the exponentially growing FEL pulse has a group velocity given by $v_g = c(1 - 2\lambda_r/3\lambda_w)$ (see e.g. [8]), i.e. the FEL mode is slower than the speed of light by one third of the slippage rate. As a consequence, even for a vanishing chicane delay, the two pulses have an arrival time difference of 2/3 of the slippage time (defined as $N_w\lambda_r/c$ where $N_w$ is the number of undulator periods). While this effect is negligible for hard x-ray wavelengths, it becomes important at soft x-rays, where the minimum delay is on the order of a few femtoseconds. For many ultra-fast experiments in atomic and molecular physics this minimum delay is comparable to or larger than the pulse length.

To achieve two simultaneous x-ray pulses of different colors, a different scheme has been developed (see the second image in Fig.1). In this scheme, named gain-modulated FEL [6], the undulator is composed of many sections of alternating magnetic field strength (i.e. alternating $K$). With this configuration the two FEL pulses continuously catch up to each other and the final time delay is negligible. In this case, the energy separation is still limited by the tunability of the undulators and the performance is comparable to the split undulator in terms of peak power (since the two colors are emitted by the same bunch, the same limitation apply). The spectrum of a gain-modulated FEL can exhibit more than two peaks, due to complex spectral features arising from the interference of the radiation emitted in two consecutive resonant undulators. However, this scheme can replicate the spectral structure of the standard split undulator while achieving full simultaneity of the two x-ray pulses if the periodicity $L_p$ of the K-modulation meets the following

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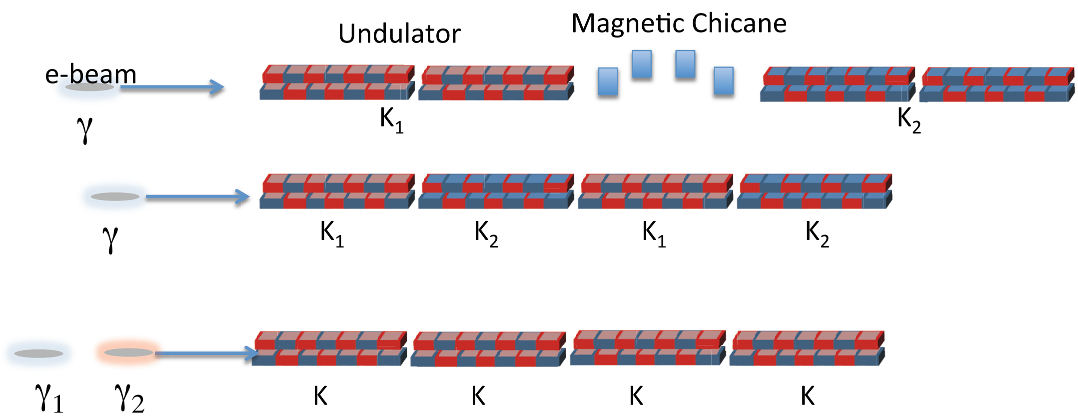


Figure 1: Layout of the two-color options at LCLS. From top to bottom: split undulator, gain-modulated FEL, double bunch FEL.

condition:

$$\frac{L_p}{\lambda_w} > 1/BW \tag{2}$$

where $BW$ is the fractional bandwidth of the FEL.

The third scheme in Fig. 1 is the so called double bunch FEL. In this case, two closely spaced electron bunches are injected in the undulator with two different energies $\gamma_{1,2}mc^2$. Each bunch emits an x-ray pulse, giving rise to a two color spectrum peaked around the two resonant wavelengths $\lambda_{1,2} = \lambda_w \frac{1+\frac{K^2}{2}}{2\gamma_{1,2}^2}$. The two bunches are generated by illuminating the injector photocathode with two laser pulses with a few ps delay. The resulting two electron bunches are accelerated and compressed in the same radio frequency bucket, resulting in two high current bunches (few kA) with a few tens of fs delay and an energy difference up to 1-2%. A detailed discussion about the energy and time separation tuning will be published elsewhere, however it should be noted that these two quantities are tunable independently, making this scheme a good candidate for x-ray pum/ x-ray probe experiments.

Note that, since the two colors are emitted by independent bunches, they can both be amplified to saturation, thus overcoming the power limitations of the previous schemes. For the LCLS, at hard x-rays, this results in a gain of a factor 20 over the split undulator scheme. Furthermore, since each color uses the entire undulator, this scheme can be combined with the recently developed two-color hard-x-ray self-seeding concept [9]. Moreover, this scheme can be modified to enable fresh bunch self-seeding by carefully tuning the two bunches to two different gain-lengths.

Finally, this scheme allows the single shot reconstruction of the temporal profile of the two-color pulse with the recently developed x-band deflector. This is a unique feature of this scheme, since in both the single-bunch schemes the x-band deflector would only allow the reconstruction of the projection of the two x-ray pulses [10] (since the x-ray profile is reconstructed by measuring the imprint of the FEL interaction on the electron's longitudinal phase-space).

## EXPERIMENTAL RESULTS

The two color modes discussed in the previous section are now transitioning into deliverable user modes. While the concepts discusses above apply over the entire energy range of the LCLS FEL (nominally between 400 eV and 10 keV) the data reported in this article refer to specific sets of parameters set by the needs of the users that have requested two color pulses to date.

The single-bunch two color schemes (split undulator and gain-modulated FEL) were both tested at soft x-rays in the short bunch regime. Figure 2 shows average spectra around a central photon energy of 850 eV for a gain-modulated FEL for different electron beam energies. The average pulse energy is 18 $\mu J$. The periodicity of the undulator modulation is given by 660 undulator periods (corresponding to 6 undulator modules in the LCLS), resulting in two clearly separated x-ray colors with minimal time delay. This corresponds to about 10% of the saturation power. The duration of the x-ray pulses was limited to about 10 fs by the use of an emittance spoiler [11].

Figure 3 shows the average x-ray spectrum as a function of central beam energy and photon energy for a split undulator experiment. This set of data was recorded during a recent user experiment at an average photon energy of 678 eV. The average pulse energy is 20 $\mu J$, over a pulse duration of 10 fs, still limited by the emittance spoiler.

The double bunch mode has been tested in the hard x-ray regime, with a photon energy of 8.4 keV. Figure 4 shows a typical double bunch phase space at full compression. While this compression setting does not optimize the extraction efficiency of the FEL, resulting in a total pulse energy of 300 $\mu J$, it yields short x-ray pulses (below 10 fs FWHM). Figure 4 illustrates the main advantage of the double bunch mode:

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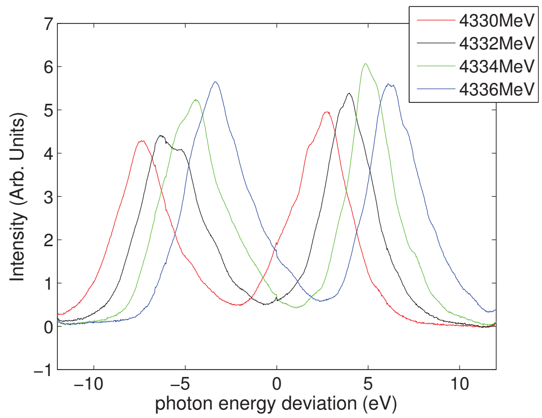


Figure 2: 2 color spectra from a gain-modulated FEL at soft x-rays.

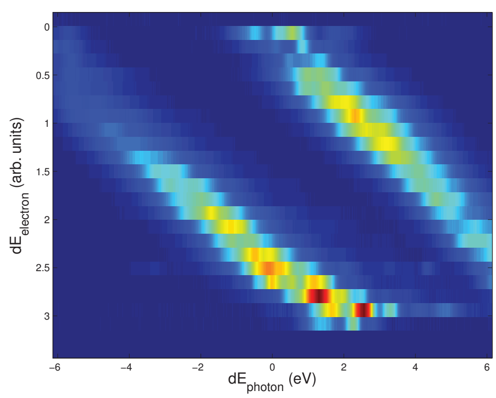


Figure 3: X-ray spectral intensity as a function of photon energy (horizontal axis) and electron beam energy (vertical axis).

which is that of achieving two-color lasing with a peak power comparable to the nominal single bunch saturation power. Pulse energies up to 1.3 mJ have been obtained with this method, running in undercompressed mode at 4 kA peak current [12]

## CONCLUSIONS

Several schemes for multicolor operation have been developed at the linac coherent light source. These schemes can meet the requirements of a large number of user experiments and have been successfully delivered during user operation. The split undulator scheme, combined with the gain-modulated FEL can deliver 2 color pulses with a tunable delay and offer the advantage of a fast tuning time. To improve the peak power performance of 2 color FELs the double bunch mode has been developed and tested at hard x-rays, yielding a performance comparable to the standard single pulse SASE mode at LCLS. In addition to high peak power, the double bunch mode can be combined to the recently developed two-color self-seeding technique, allowing

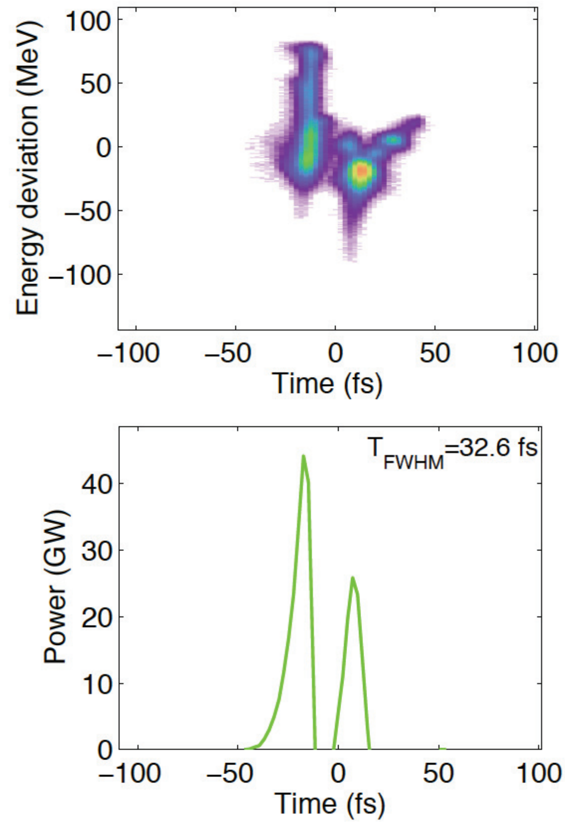


Figure 4: Top: measured longitudinal phase space for the double bunch mode at full compression. Bottom: reconstructed x-ray pulse profile.

the generation of two nearly Fourier transform limited pulses with tunable delay and energy separation.

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