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Flexible control of femtosecond pulse duration and separation using an emittance-spoiling foil in x-ray free-electron lasers

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We report experimental studies of generating and controlling femtosecond x-ray pulses in free-electron lasers (FELs) using an emittance spoiling foil. By selectively spoiling the transverse emittance of the electron beam, the output pulse duration or double-pulse separation is adjusted with a variable size single or double slotted foil. Measurements were performed with an X-band transverse deflector located downstream of the FEL undulator, from which both the FEL lasing and emittance spoiling effects are observed directly.

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X-ray free-electron lasers (FELs) provide a unique tool for ultrashort time-resolved x-ray studies in the femtosecond regime. This enables different dynamic process studies such as measuring the molecular motions in the ephemeral transition states of physical, chemical and biological systems [1]. During these studies, femtosecond time resolution is critical to resolve the dynamics of the chemical bond at the atomic level. On the other hand, it typically also requires a flexible control of the pulse duration or double pulse separation such as in the x-ray pump-probe experiments.

At present x-ray FEL facilities, for example, at the Linac Coherent Light Source (LCLS) [2], the typical pulse duration is about a few 10s to 100s of femtoseconds with a regular operating charge of 150-250 pC. To achieve shorter pulses, one can more strongly compress the electron bunch in a limited range, or additionally reduce the bunch charge to 20 pC from which less than 10 fs x-rays can be obtained [3, 4]. By changing the electron beam current or charge, the FEL gain and source point are typically affected, which requires additional accelerator tuning and x-ray optics adjustment.

Another simple way to generate and control short FEL pulses is to use an emittance-spoiling foil. This was first proposed in 2004 [5] and has been in use at the LCLS since 2010. In this scheme, an aluminum foil with slots is installed at a dispersive section of the accelerator beamline. After electrons scatter from the foil, most of the beam will not lase due to increased emittance, while the small, unspoiled fraction which passes through the slot will contribute to lasing. The pulse duration can then be controlled simply by choosing different slot sizes without any other changes to the machine configurations, while the FEL gain and pulse peak power are kept almost constant. It also has the capability to deliver two x-ray pulses using a double-slot array. The ease of operation of this scheme has been well utilized in FEL user experiments [6].

The x-ray pulse duration from the emittance-spoiling mode can be as short as a few femtoseconds [5, 7, 8] with the possibility to get down to sub-femtosecond [9]. However, experimental characterization of femtosecond x-rays is very challenging. Different methods have been explored in the past years for measuring femtosecond x-ray pulses [10]. For example, the cross-correlation scheme [11] provides a multi-shot measurement, and works well for measuring the pulse separation for the double-pulse mode at the LCLS [7]. However, it only works in the exponential gain regime and interrupts FEL operation. Another more direct measurement has been made possible recently at the LCLS with an X-band transverse deflecting cavity (XTCAV) [4, 12]. The XTCAV is used to measure the time-resolved lasing effects in the electron beam longitudinal phase space, and thus we have the capability to simultaneously characterize the electron beam spoiling effect and reconstruct the x-ray pulse duration.

Figure 1 shows a schematic of the LCLS layout from the second linac section (L2) to the beam dump. The L2 linac is set at an off-crest accelerating rf phase, so that the beam energy after L2 will be correlated with time. When the beam travels to the middle of the second bunch compressor (BC2), the time-energy correlated beam will be tilted at a large angle relative to the beam propagation axis. A 3-μm thickness aluminum foil with vertically varying size slot is placed in the path of the beam at the middle of BC2. Coulomb scattering increases the emittance of most of the beam which passes through the foil, while a very thin unspoiled slice passing through the slot still has its emittance preserved [5]. In this configuration, only the unspoiled slice contributes to lasing, and hence the x-ray pulse length can be much shorter than the electron bunch length. To flexibly control the pulse duration or separation, the foil has different available slot geometries [7], the popular ones including a variable-width single slot and two V-shape double slots with different slot widths.

For a time-energy chirped beam we define a linear chirp

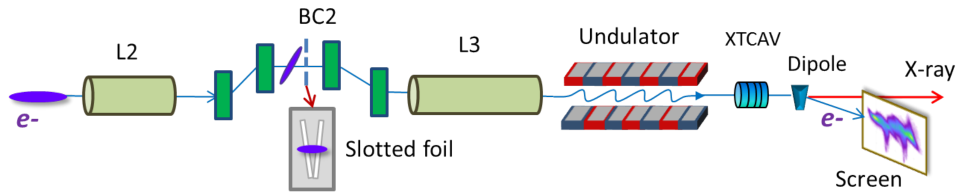

FIG. 1: A schematic of the LCLS machine layout including an emittance spoiling foil in the middle of second bunch compressor (BC2) and the XTCAV downstream of the FEL undulator. The L2 and L3 are S-band RF linac sections. A double-slotted foil array is used here for an illustration.

strength h by $\delta = hz_0$, where δ and z_0 are the electrons' relative energy spread and longitudinal coordinate before compression, respectively. After the bunch compressor with a momentum compaction factor R_{56} and a momentum dispersion η at the middle of the chicane, the centroid time separation Δt of the two pulses generated from a double slotted foil can be written as

$$\Delta t = \frac{\Delta d}{|\eta h| C_b c}, \tag{1}$$

where Δd is the centroid distance between the double slots, $C_b = 1/(1 + hR_{56})$ is the bunch compression factor for a cold beam, and c is the speed of light in vacuum. Similarly, we can also calculate the pulse duration $\Delta\tau$ from a slot with a finite width, but the uncorrelated energy spread and transverse betatron beam size have to be included, as discussed in [9]:

$$\Delta\tau \approx \frac{2.35}{|\eta h| c}\sqrt{\eta^2\sigma_{\delta_0}^2 + (\Delta x^2/12 + \sigma_{x_\beta}^2)/C_b^2}. \tag{2}$$

Here σ_{δ_0} is the initial uncorrelated relative energy spread before compression, Δx is the slot full width, and σ_{x_β} is the rms betatron beam size at the foil. The main difficulty in these calculations is accurately knowing initial beam conditions such as the chirp, uncorrelated energy spread, and betatron beam size. The collective effects and higher order optics are also hard to include in a simple fashion.

In the undulator, the FEL lasing from the unspoiled slice will induce time-dependent energy spread growth and energy loss, while lasing in other parts of the bunch is suppressed due to the largely increased emittance. This lasing "footprint" on the electron longitudinal phase space is measured directly with the XTCAV system downstream of the undulator beamline [4]. It introduces a time-dependent horizontal deflection to the electron bunch, followed by a DC vertical bending magnet. With this setup, we make absolute measurements of the beam time and energy distribution with knowledge of the deflecting cavity strength and the vertical bend angle.

Figure 2 shows two measured examples with XTCAV for electrons passing through the single slot. The electron bunch is operated at under-compression mode with a peak current of about 1100 A. The final beam energy is 4.5 GeV and the bunch charge is 180 pC. The electron longitudinal phase space with lasing off is shown in subplot (b) with the bunch at the middle part of the slot with full-width 760 μm. We can see directly the unspoiled fraction at the core part where the energy spread is much smaller with a flat energy chirp. Note that although the foil spoils the emittance rather than the energy spread, the increased beam divergence due to Coulomb scattering couples to the longitudinal dimensions through the last half of the chicane, hence the uncorrelated energy spread is increased. The FEL lasing of the unspoiled portion generates much larger slice energy spread which is shown in subplot (c). Comparing the time-dependent change of the central energy loss or energy spread between the lasing-off and lasing-on measurements, the x-ray profile is reconstructed in subplot (d). The detailed reconstruction method can be found in [4]. In this example the x-ray length is 25 fs fwhm.

Near the narrow end of the slot (slot full width about 270 μm), we see a much smaller unspoiled fraction (subplots (e) and (f)) and the resultant x-ray pulse is about 10 fs fwhm (subplot (g)). We also plot the current profiles in subplots (d) and (g). A current spike at the unspoiled area, which was predicted in [5], is directly observed. This feature is expected; scattered electrons travel with a slightly different path length through the last half of the chicane and overlap in time with the unspoiled time slice. These time-smeared electrons lead to the current spike. Although the FEL process only amplifies the cold beam core and is not affected by the time-smeared halo, this current spike still causes additional electron energy modulation from the downstream longitudinal space charge and wake fields. This is why the unspoiled beam is tilted especially with a narrow slot as clearly shown in subplot (e).

With a double-slot geometry, we can generate two pulses for x-ray pump-probe experiments. The LCLS double-slot array has a V shape (with centroid separation range 0.6-1.4 mm) to control the pulse separation, with either thin slots (slot full width ~300 μm) or thicker slots (slot full width ~430 μm) (see subplot (a) in Fig. 3). We show two measured examples in Fig. 3 with the beam at

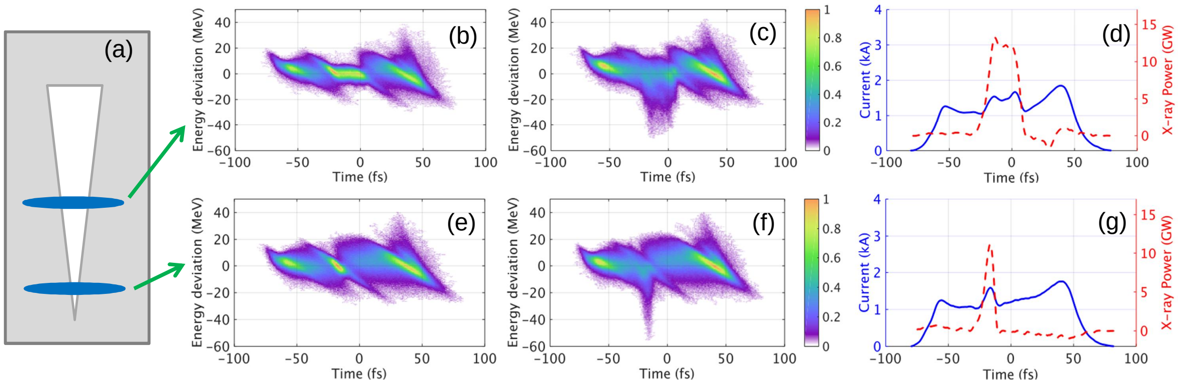

FIG. 2: Measurement examples for the single-slot foil. At two different slot widths (a), the longitudinal phase spaces with lasing-off ((b) and (e)) and lasing-on ((c) and (f)) are measured. The current profile and reconstructed x-ray power profile are shown in (d) and (g) for each slot position. The measured x-ray pulse durations are 25 fs and 10 fs fwhm, respectively. Beam parameters are listed in Table. I.

the middle of each double-slot array (the slot centroid separation is equal). We can see that the measured pulse separation is about the same as expected, but clearly the individual pulse duration in each pair is different. With this design, a flexible control of the double-pulse separation can be realized by moving the foil vertical position, with two pulse-duration options available for different user requirements.

Similar to the examples shown in Figs. 2 and 3, we systematically measured the pulse duration and separation at different single-slot widths and double-slot separations. Each point was averaged from 25 single-shot measurements. The main beam parameters are listed in Table I, which are also used for calculations with Eqs. (1) and (2). Measurement and calculation results are compared in Fig. 4. We see the pulse duration or separation are well controlled purely by adjusting the foil's vertical position, and the calculated results agree reasonably well with the measured data. At the larger double-slot separations, the measured pulse separation is slightly smaller than that from calculation. This is due to a non-uniform distribution of the beam current: the beam current near the bunch head and tail is actually higher with a double-horn profile [13], while the calculation assumes a uniform current profile which under-estimates the compression factor C_b and the chirp h near the horns. This $\sim$1 kA current level is typical for soft x-ray (<2 keV) operation at the LCLS. For hard x-ray FELs, the beam current is typically 3-4 kA with a larger chirp and compression, so that the generated pulse duration and separation are smaller. Calculated achievable pulse duration and separation at different currents can be found in [14].

Low-charge (20 pC) operation at the LCLS can produce less than 10 fs x-rays [3, 4]. In this mode the bunch is strongly compressed in BC2 to reach kA-level peak currents. Since the chirp h and compression factor C are larger, it achieves even shorter pulses if we combine the

TABLE I: Main parameters for slotted-foil measurements.

Parameter	Symbol	Value	Unit
Bunch charge	Q	180	pC
Beam energy at BC2	E	5	GeV
BC1 current	I_1	220	A
BC2 current	I_2	1100	A
Uncorrelated E-spread before BC2	σ_{δ_0}	130	keV
energy chirp before BC2	h	38	m^{-1}
Betatron beam size rms	σ_{x_β}	38	μm
Dispersion at foil location	η	0.36	m
Momentum compaction	R_{56}	-24.7	mm
Single-slot full-width	Δx	0.27-1.44	mm
Double-slot centroid separation	Δd	0.64-1.42	mm
FEL wavelength	λ	1.1	nm

foil scheme with this mode [15]. To avoid a double-horn current shape [13] during undercompression, we operate in over-compression which produces a Gaussian-like current profile but with a residual time-energy chirp. The slotted foil selects the central high-current core for lasing.

We show two measured examples in Fig. 5 for a bunch charge of 20 pC and a beam energy of 4.8 GeV. At the middle of the slot (subplot (b) - (d)), the measured pulse duration is 9 fs fwhm, and at the bottom (subplot (e) - (f)) it is 3.8 fs fwhm. The XTCAV resolution is $\sim$1 fs rms at this energy [4] which is a small effect for pulses whose durations are much longer. But for this short pulse of 3.8 fs fwhm, the actual pulse duration could be 20% shorter after subtracting resolution. However, the FEL slippage after saturation may lengthen the x-ray pulse duration. For example, the slippage length is about 1 fs with 10 m of post-saturation undulator at this energy. This slippage effect is negligible for long pulses, but it is a more significant fraction for short pulse modes and other

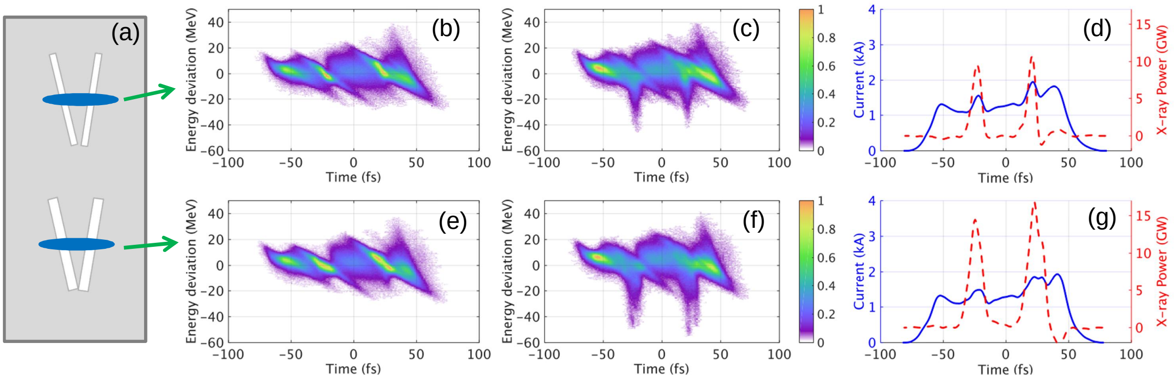

FIG. 3: Measurement examples for the double-slot foil. The examples are measured at the middle of the thin and thick double-slotted arrays. The lasing-off images are shown in ((b) and (e)), and the lasing-on images in ((c) and (f)). The current profile and reconstructed x-ray profile are shown in (d) and (g). The double-pulse separation (∼45 fs) is the same for the two sets but the pulse duration is different. Beam parameters are listed in Table I.

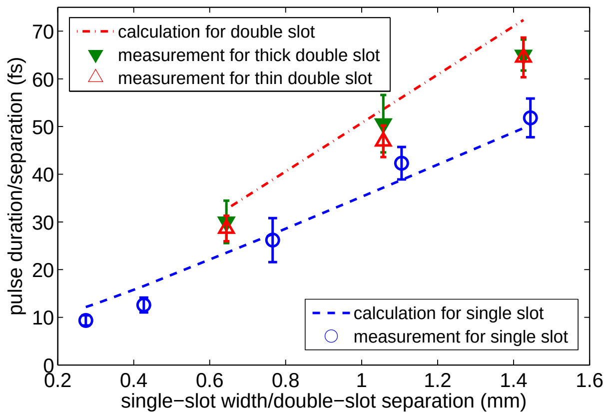

FIG. 4: Experimental measurements and calculations of the pulse duration and double-pulse separation versus foil single-slot width and double-slot separation. Each data point is averaged with 25 single-shot measurements. Beam parameters are listed in Table I.

x-ray diagnostic methods would be helpful for a benchmark once available. To generate short FEL pulses, we generally avoid operating in the deep saturation regime. Also we note that with this over-compression mode and time-energy chirped beam, we can instead generate two-color double pulses when using the double-slotted arrays.

For hard x-ray energies, as discussed earlier, the achievable pulse duration and separation can be even smaller at the required higher operating currents. On the other hand, the higher electron beam energy needed to drive hard x-ray FELs makes the XTCAV resolution lower. For example, the measured XTCAV resolution is about 4 fs rms at 9 keV [4]. For a full characterization of the slotted foil for hard x-rays, other high-resolution diagnostic techniques are desired, and a spectral domain method at the LCLS is under development [16].

In early 2015, a new set of foil geometries with much larger double-slot separation was added to the LCLS BC2 to support a twin-bunch operating mode [17], extending the flexibility for pulse tailoring over a much larger time/energy separation range, further illustrating the versatility of this emittance-spoiling foil technique.

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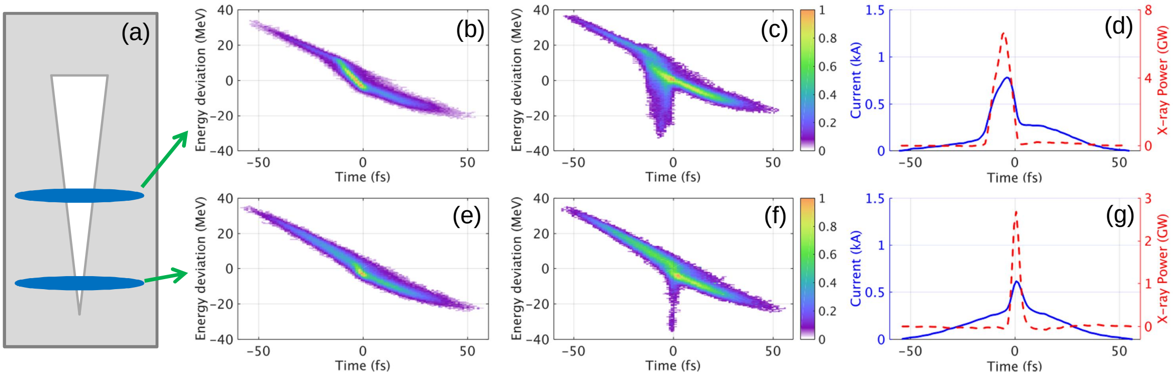

FIG. 5: Measurement examples at two slot widths for a 20 pC, 4.8 GeV beam, operated in the over-compression mode. The lasing-off images are shown in ((b) and (e)), and the lasing-on images in ((c) and (f)). The current profile and reconstructed x-ray profile are shown in (d) and (g).The pulse duration in these two examples are 9 and 3.8 fs, respectively.