ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEXPLM1

XFEL OPERATIONAL FLEXIBILITY DUE TO THE DECHIRPER SYSTEM

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Abstract

The RadiaBeam/SLAC dechirper was installed to demonstrate the concept of using wakefields from a corrugated structure to change the energy profile along an electron bunch. Since installation, the system has allowed a large number of additional XFEL operating modes including fresh-slice two-color or three color operation, fresh-slice seeding, passive streaking, etc. This talk will discuss the results from using the dechirper system and possible implementation issues related to the high-rate LCLS-II.

INTRODUCTION

X-ray Free-Electron Lasers (XFEL) are the brightest sources of x rays for scientific applications [1]. Several schemes and insertion devices have been designed and installed to provide x ray pulses with tailored temporal profiles, spectra and polarization, as required from the experimental needs. For producing narrow bandwidth x-ray pulses a high brightness electron bunch with a flat temporal energy profile is required at the undulator entrance. An energy chirp would increase the produced FEL bandwidth.

A dechirper system [2] was designed [3] to control the temporal energy profile of the electron bunch. The system comprises two modules one vertical and one horizontal located upstream of the undulator line entrance. Each module has two corrugated aluminum plates with parameters specified in Table 1. The beam passing in the device is subject to the longitudinal and transverse wakefields. The longitudinal wakefields impress an approximately linear time-dependent energy chirp on the electorn bunch, useful to remove the existing energy chirp, from this the name of *dechirper*. As typically unwanted effect, longitudinal wakefields increase also the uncorrelated energy spread of the beam, affecting in a stronger way the bunch slices toward the bunch tail. The transverse wakefield impress a time-dependent kick on the electron bunch, approximately parabolic in shape, kicking the electrons toward the metal jaw when the bunch travels off-axis. Transverse wakefield also defocus the beam in the direction of the transverse kick. While initially designed to control the bunch energy chirp, the dechirper proved a very versatile device, enabling the Fresh-slice technique [4] with impact on several FEL schemes.

ENERGY CHIRP CONTROL

To control the electron bunch energy chirp the dechirper gap is closed and the electron bunch travels on the axis

Table 1: RadiaBeam/SLAC Dechirper Parameters

Parameter	Value	Units
Half gap	0.5 – 12.5	mm
Corrugation period	0.5	mm
Corrugation depth	0.5	mm
Corrugation Longitudinal gap	0.25	mm
Corrugation plate width	12	mm
Structure length	2	m

structure. The passive device can only cause the bunch tail to lose energy, therefore it is effective to remove the electron bunch chirp only when the bunch head is at lower energy than the bunch tail. Alignment procedures have been devised to align the dechirper jaws so that the beam travels on the axis of the device. A first alignment technique sets a fixed dechirper gap and then scans the dechirper offset recording the electron bunch trajectory on the first downstream Beam Position Monitor (BPM) [5]. The central position is calculated by fitting the experimental data. This technique does not take advantage of the possibility of tilting each dechirper jaw, which stays uncorrected, and also the retrieved center is far from the measurements with large transverse displacement. Another study [6] showed that offset scans with parallel plates can hardly distinguish between a tilt of a corrugated plate or a different structure offset, and that scanning the jaw tilt in a single-jaw measurement is a more reliable way of measuring the bunch distance from the beam and to remove the jaw tilt. In practice due to the limited amount of time available for setup, rather than performing full scans, the device is typically aligned by turning off the transverse orbit feedbacks downstream of the device, closing the dechirper gap and then adjusting each plate individually, both in offset and tilt, so that the beam stays on-axis on the accurate Radio-Frequency (RF) BPM of the undulator line.

At the LCLS, operating in under-compression mode, the electron bunch presents typically a small energy chirp, with the head at higher energy. Therefore the dechirper device increases the energy chirp and therefore the FEL bandwidth. Measurements of the FEL bandwidth for different gaps have been previously reported [7] and demonstrate the possibility of increasing the FEL bandwidth, or to minimize it, in the less common LCLS case of an electron bunch with the head at lower energy than the bunch tail.

When operating the dechirper to control the energy chirp, the time-dependent defocusing effect can prevent the bunch tail and core from lasing. Defocusing can be canceled by

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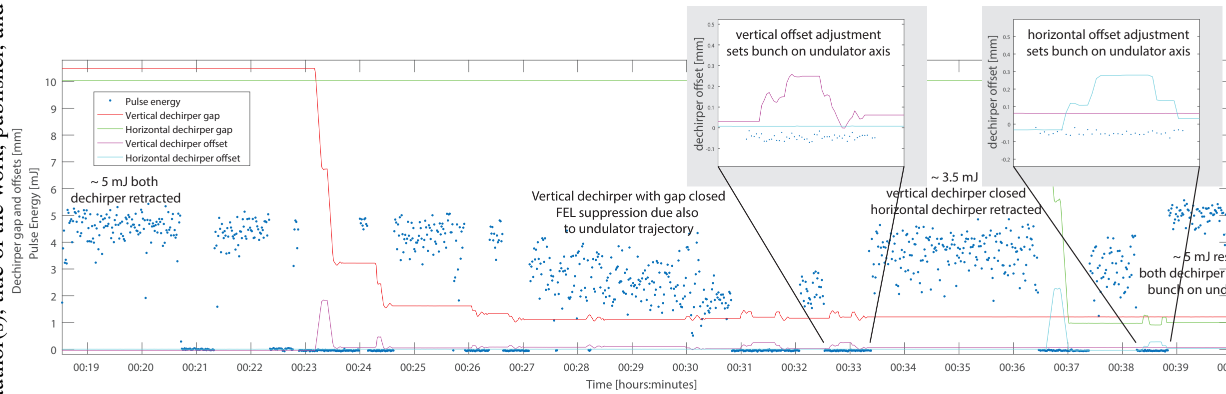

Figure 1: Impact on the FEL pulse energy from the movement of the dechirper corrugated jaws. When the vertical dechirper gap is closed, and after offset correction the pulse energy drops from ~ 5 mJ to ~ 3.5 mJ. The full pulse energy is restored when the horizontal dechirper is closed as well and its offset is set to have the electron bunch travelling on the undulator axis.

using both modules, horizontal and vertical set at proper gap. The focusing effect depends, besides on gap, on the beam transverse size at the dechirper location and to cancel the effect, dechirper gaps may need different settings in the vertiacal and horizontal direction. When the first dechirper is inserted with a small gap, the FEL energy decreases, even when the bunch orbit is carefully kept on the undulator axis with feedbacks turned off. The effect is also visible on the time-resolved bunch phase space at the beam dump [8]. The focusing effect is well canceled when inserting the second dechirper the total FEL intensity is restored. Figure 1 shows the FEL pulse energy as function of time and the position of the dechirper jaws. With both dechirper retracted, the FEL intensity is ~ 5 mJ. Then the vertical dechirper gap is closed. When the jaws are in proximity of the bunch the pulse energy drops; it is a combined effect of focusing effect and kicked trajectory in the undulator line. After the vertical offset adjustment, the bunch travel on axis in the undulator line and the pulse energy is of ~ 3.5 mJ. Closing the gap of the horizontal dechirper can cancel the time-dependent quadrupole effect, and careful setting of the dechirper offset to control the orbit in the undulator line allows restoring the full initial ~ 5 mJ of pulse energy.

FRESH-SLICE CONTROL

During the dechirper commissioning it was observed that when the dechirper gap was closed, the energy produced by the FEL was decreasing. The time-resolved phase spaces revealed particularly that the beam was first lasing on the head, and shortly later on the bunch core (see Fig. 2). Since the dechirper was not well aligned, when the gap was closed the beam received also a time-dependent kick, negligible on the bunch head that was still lasing. However shortly after the transverse feedbacks were setting the bunch orbit on axis, and therefore the slice in the bunch core was lasing. This observation lead to the demonstration of the Fresh-slice lasing technique [4] allowing to control which electron bunch slice is lasing in each undulator section.

A dechirper jaw is moved close to the electron bunch to give the time-dependent kick, with the downstream feedbacks turned off. The bunch head is unaffected, stays on the former orbit, and lases in the undulator line. The bunch slices toward the head travel on increasing oscillating orbit in the strong focusing lattice and do not lase in the undulator line. Since the energy spread in the lasing-suppressed slices does not increase they remain *fresh* and can be used for lasing in a downstream undulator section or in another undulator line.

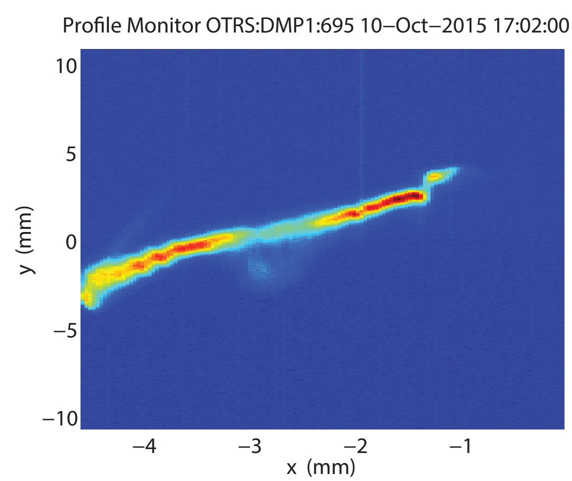

Figure 2: Time-resolved phase space of the electron bunch at the beam dump with a dechirper inserted with closed gap. The vertical axis is proportional to bunch energy and the horizontal coordinate represents time.

In the condition with only the head of the electron bunch lasing, the head lasing orbit is recorded. The lasing slice is then controlled by adjusting the orbit correctors upstream of the undulator line so that the desired bunch slice travels on axis. Keeping the same slice on-axis in the whole undulator line is a viable way to control the FEL pulse duration down to few femtoseconds. The pulse can be made shorter either by inserting the metallic jaw closer to the beam, or

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by pushing the lasing slice farther toward the bunch tail [9], and femtosecond pulses have been demonstrated in the hard X-rays by manipulating the first corrector after the dechirper device [10].

Alternatively the Fresh-slice scheme can be enabled by using the transverse focusing effect of the dechirper [11, 12]. Both dechirper corrugated plates of a single module are used in a closed gap configuration with the bunch passing on axis. In this configuration, the beam is not kicked transversely (as it occours also in the dispersion-based Fresh-slice [13]), instead, it is time-dependent focused so that only the head of the bunch is still matched to the undulator line lattice. Mismatched slices do not lase, and thus remain fresh. For the time-dependent focusing effect to be sufficient for impacting the lasing process, a quadrupole matching section is used to manipulate the transverse phase space at the dechirper location. A second matching section, downstream of the dechirper, is used to select which temporal slice within the bunch lases by matching it to the undulator lattice. The matching-based Fresh-slice presents the advantage of avoiding large transverse orbits for the electrons and it may be better suitable for high repetition rate operation as in the LCLS-II, or the European XFEL.

FRESH-SLICE MULTI-COLOR OPERATION

Multi-color Fresh-slice FEL x ray pulses are produced by setting different temporal slices to lase in cascaded undulator sections, overcoming the limitations of the split undulator scheme [14]: the minimum intrinsic delay and the pre-saturation power level. The minimum intrinsic delay is due to the group velocity of the X-ray pulse being higher than the speed of the electrons, causing the X-ray pulse produced in the upstream undulator section arriving always earlier than the pulse produced in the downstream one. By using the Fresh-slice technique, if the tail slices are used to produce the x-rays in the first section and the head slices are used to produce the x-rays in the second section, the pulse produced in the second sections arrive first on the sample. A magnetic chicane located between the two undulator sections allows scanning smoothly through zero delay the two pulses. The power level limitation of the split undulator scheme is due to the uncorrelated energy spread increase occurring in the lasing process. When the pulse produced in the first section approaches saturation, it will prevent lasing in the second section. By using the Fresh-slice technique, different bunch slices produce each x-ray pulse, and therefore both can saturate and a suitable post-saturation undulator taper can be applied. Typical performance in the soft X-rays present pulses with duration from few to 20 fs and a power of ten to few tens of gigawatts. The typical delay ranges from an advance of 15 fs for the x-ray pulse on the bunch head to a delay of 1 picosecond [4].

Three color operation has also been demonstrated with powers of 10 GW per pulse, and the polarization of the pulse produced in the last section has been controlled by using the variable polarization Delta undulator with the beam diverting technique [15] enabled by the microbunching rotation [16].

Adjusting the slice matching within the undulator line, requires more space than correcting the bunch orbit and in general it is easier and faster to control the bunch trajectory than its transverse phase space. For this reason, multi-color operation based on matching has yet to be demonstrated and standard operation relies on time-dependent orbits to deliver beam for the experimental users [17].

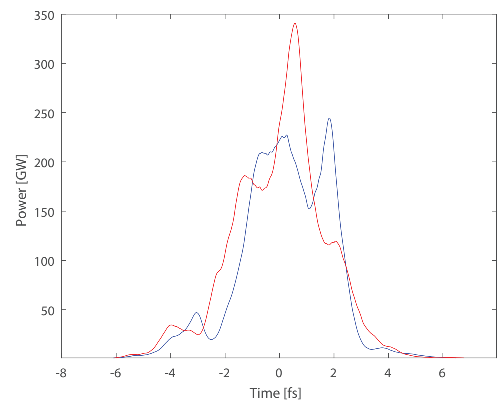

Figure 3: Simulated temporal profiles for three-stage cascaded Fresh-slice amplification matching the demonstrated experimental condition

FRESH-SLICE MULTI-STAGE AMPLIFICATION

The Fresh-slice technique has been used to produce high power ultra-short XFEL pulses in the soft x-rays, by amplifying an ultra short X-ray pulse produced on the bunch tail in subsequent cascaded stages using fresh electrons. Simulations showed the possibility of producing TW few femtosecond pulses in 10 cascaded stages [18]. At the LCLS, the machine layout allows to implement three cascaded stages since there are only two chicanes available to overlap the X-ray pulse with fresh electrons. The experiment performed at the LCLS demonstrated the possibility of producing ultra-short X-ray pulses in the soft X-rays with an average pulse energy of 300 μJ and peaks above 700 μJ with a reliable rate of single-spike of about 13% [19]. A simulation framework has been developed to study the Fresh-slice modes of delivery. The code Elegant [20] has been used for the beam transport, including time-dependent kick and focusing effects from the dechirper device. Genesis version 4 [21] has been used as FEL code. The simulation has been validated reproducing the experimental results of the multi-stage amplification experiment in terms of spikes energy, bandwidth and statistics, using the same undulator line configuration and an electron bunch with parameters close to the one of the experiment. Figure 3 shows simulated shots temporal profiles produced in such configuration with a peak power of few hundreds of gigawatts.

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FRESH-SLICE SELF-SEEDING MODES

The Fresh-slice technique can enhance the performance of self-seeding modes in terms of power. In a first section a SASE pulse is produced on a bunch temporal slice and is monochromatized in a device located within an electron magnetic chicane. The monochromatized beam seeds the lasing process being amplified in the downstream section [22–24]. In Fresh-slice self-seeding the SASE pulse is typically produced on a tail slice (although this isn't necessary, as both the monochromatized seed and the electrons are delayed), and is amplified on a different bunch slice. The scheme presents two advantages over regular implementation. Larger seed power is allowed because the pulse in the first stage can reach saturation and the fresh-slice used for amplification in the second stage presents lower initial energy spread. The scheme was demonstrated in the hard x-rays achieving a pulse power a factor 2 larger compared to the regular implementation [25], and better performance may be achievable with proper dechirper defocusing compensation.

More advanced schemes combining self-seeding and three stage amplification are applicable in the soft X-rays because the undulator line effectively longer in terms of gain-lengths. In typical operation of soft x-ray self-seeding, using a post-saturation taper has proven difficult because it amplifies frequencies outside the narrow seeded bandwidth, produced by the SASE process starting in the second section and by microbunching instability driven pedestal [26]. Using a three stage scheme, the monochromatized seed can be amplified either on the same bunch slice or on a different one up to the second chicane, reaching ∼ 1 GW power while maintaining a clean narrow bandwidth spectral structure. After the second chicane the X-rays seed a Fresh-slice of the bunch, reaching saturation in the space of 1 or 2 undulator modules and then a strong post-saturation taper is applied to further amplify the clean spectrum.

A similar concept has been applied to amplify the narrow-bandwidth seeded x-ray pulse in the Delta undulator located ∼ 60m downstream of the monochromator. Previous experimental attempts of preserving the long coherence time microbunching structure up to end of the undulator line and amplifying it in the Delta undulator failed. Rather than trying to preserve the microbunching on the electrons for a long distance, by using three stages and Fresh-slice, the gigawatt level amplified seed is picked up by fresh-electrons in proximity of the Delta undulator. Figure 4 shows the average spectra collected with the Delta undulator set on resonance in circular polarization and out of resonance, demonstrating amplification in the variable polarization undulator. In this particular case, the seed was picked up by fresh electrons 5 undulator segments upstream of the Delta.

PASSIVE STREAKING

The time-correlated transverse kick imparted by the transverse wakefield on the electron bunch to enable the Fresh-slice modes of operation can be also useful for electron bunch diagnostic purposes. Passive streaking for diagnostic

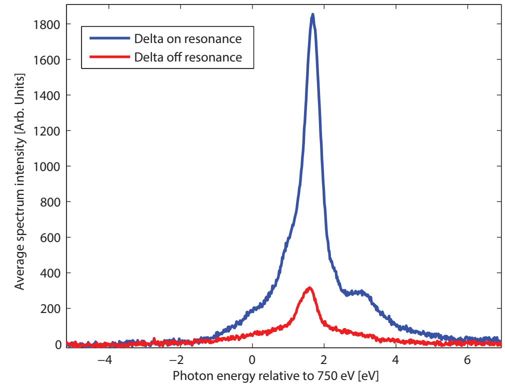

Figure 4: Average spectra measured with the Delta undulator set on resonance in circular polarization and off resonance, in a fresh-slice three stage scheme designed to produce narrow-bandwidth x-ray pulses with polarization control.

purposes has been demonstrated and studied earlier, operating at lower bunch energies [27]. However the true potential of passive streaking is in the operation at high electron bunch energies [10, 28]. While streaking an electron bunch with a transverse deflecting cavity becomes harder when the electron's energy increases, in the case of a passive structure, the increased beam rigidity allows the beam to travel closer to the corrugated plates, thus exciting stronger transverse wakefields that are still suitable to streak the electron bunch. Passive streaking does not need RF power and is beam synchronous by design, but cannot resolve the bunch head that is unaffected by the wakefield. Extracting time-resolved information is more difficult because of the non-linearity of the process and particular cares have to been taken to limit the quadrupole effect [29].

Since the dechirper devices are located upstream of the undulator line passive streaking is not routinely used at the LCLS as it would interfere with beam delivery, unless it is specifically used for x-ray production.

CONCLUSION

We showed that the installation of the dechirper system enabled several novel schemes, besides the longitudinal beam phase space manipulations for which it had been designed. The transverse wakefield dipole and quadrupole components, considered essentially harmful in the design process [3], enabled the Fresh-slice modes of operation [4] that largely increased the capability of the LCLS machine, in terms of multi-color operation, production of high-power femtosecond pulses, self-seeding schemes, thus allowing novel scientific experiments to be performed.

ACKNOWLEDGMENTS

This work was supported by the U.S.Department of Energy, Office of Science, Laboratory Directed Research and Development (LDRD) program at SLAC National Accelerator Laboratory, under Contract No. DE-AC02-76SF00515.

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