COMMISSIONING OF THE DELTA POLARIZING UNDULATOR AT LCLS*

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Abstract

The Linac Coherent Light Source (LCLS) generates linearly polarized, intense, high brightness x-ray pulses from planar fixed-gap undulators. While the fixed-gap design supports a very successful and tightly controlled alignment concept, it provides only limited taper capability (up to 1% through canted pole and horizontal position adjustability) and lacks polarization control. The latter is of great importance for soft x-ray experiments. A new 3.2-m-long compact undulator (based on the Cornell University Delta design [1]) has been developed and installed in place of the last LCLS undulator segment (U33) in October 2014. This undulator provides full control of the polarization degree and *K* value. Used on its own, it produces fully polarized radiation in the selected state (linear, circular or elliptical) but at low intensity. To increase the output power by orders of magnitude, the electron beam is micro-bunched by several (~10) of the upstream LCLS undulator segments operated in the linear FEL regime. As unavoidable by-product, this micro-bunching process produces moderate amounts of horizontally linear polarized radiation which mixes with the radiation produced by the Delta undulator. This unwanted radiation component has been greatly reduced by the reverse taper configuration, as suggested by E. Schneidmiller and M. Yurkov [2]. Full elimination of the linear polarized component was achieved through spatial separation combined with transverse collimation. The paper describes these and other methods tested during commissioning, It also presents results of polarization measurements showing high degrees of circular polarization in the soft x-ray wavelength range (500 eV-1500 eV).

INTRODUCTION

The design and measurement plans for the first 3.2-m-long Delta undulator for the LCLS were described in an FEL2013 paper [3]. Since then, these plans have been implemented close to the original schedule; the parameters listed in Table 1 of the FEL2013 paper all apply. Installation occurred in October 2014. (Figure 1) Beam based commissioning took place from October 2014 to May 2015. During this period operational techniques were developed that allowed to operate the Delta undulator at performance levels significantly exceeding expectations. Beam based commissioning was followed by the first user experiments in June 2015. The following will discuss quadrant tuning, magnet field mapping, and beam based commissioning. Tuning and magnetic field mapping made use of experience obtained in the course of construction and testing of the 0.3-m model at Cornell and the 1-m long prototype at SLAC.

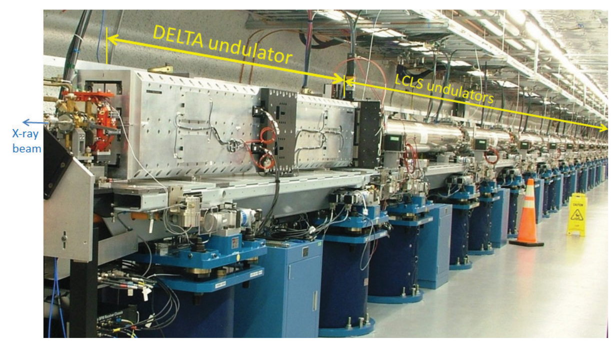

Figure 1: 3.2-m long LCLS Delta undulator installed at the end of the LCLS undulator line.

MAGNET BLOCKS

Each of the four rows of the Delta undulator contains 391 magnet blocks, four per period, arranged as Halbach array [4]. The first and last three blocks in each row are mounted at larger distances to the beam axis to accomplish end-field matching. Each magnet block is glued to an Al holder (Figure 2), which has been designed to also secure the magnet, mechanically, in case of glue

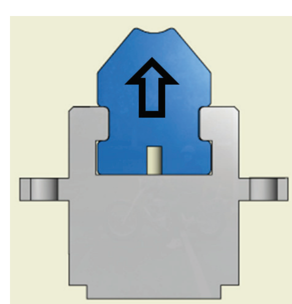

Figure 2: Ni coated PM blocks epoxied to Al holders. (Design by T. Montagne, SLAC)

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failure. 2000 regular mounted magnet block units and 60 individual blocks were purchased from AA International, Inc.

Block Sorting

After all blocks had been labelled, the amplitude and direction of their individual magnetic moments were measured with a Helmholtz coil at SLAC. The magnetic moment information was used to sort the blocks [5] before mounting them onto the carriers. The mounting fixture was designed to allow adjusting the position (distance to beam axis (y) and perpendicular direction (x)) of individual magnet blocks to enable virtual tuning (change of transverse magnet positions). Tuning was done separately for each quadrant.

Quadrant Tuning

For quadrant tuning, one of the two strongbacks was used as a support structure. For each quadrant the three carriers where mounted to the same location of the support strongback. The assembly was rotated such that the virtual beamline was positioned above the magnets (Figure 3).

Figure 3: Delta quadrant on the tuning bench.

A 2-sensor Sentron Hall probe was used to measure the magnetic field at the virtual beam axis as a function of the longitudinal (z) location. The mechanical positions of the magnets were measured and were used as constraints during virtual tuning to leave enough clearance for insertion of the vacuum chamber after the undulator was assembled (Figure 4).

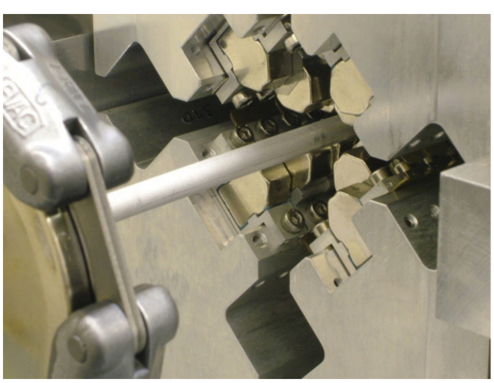

Figure 4: Delta undulator with vacuum chamber.

The measured fields of the four quadrants after tuning were combined numerically to a complete undulator and evaluated. The field integrals and phase shake values came out close to the tolerances in Table 2 of [3]. Errors due to mechanical tolerances and deformations of the strongbacks were introduced during final assembly because quadrants were mounted at strong back locations different from the ones used during tuning. These errors caused a significant increase in phase shake.

BENCH CHARACTERIZATION

After the Delta undulator was fully assembled (Figure 5), a number of measurements, both mechanical and magnetic, were performed to characterize the device and produce magnetic field maps vs. row positions.

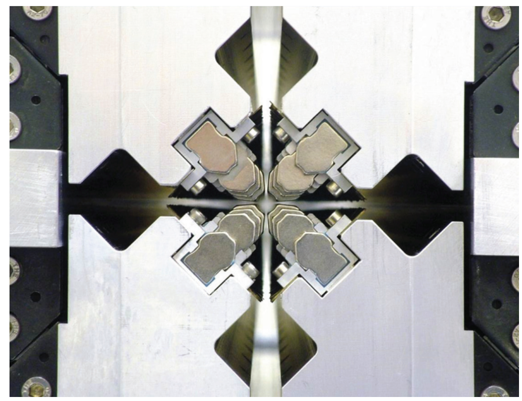

Figure 5: Front view of the fully assembled Delta undulator. Visible are the Al magnet block carriers and part of the precision rail system [6].

Mechanical Deformation Measurements

Dimensional changes of the strongback as function of row positions (different force directions) were measured with a coordinate measuring machine with relative position errors of less than 1 µm. As a result, the width and height of the Delta undulator change by about ±1.5 µm when changing the transverse forces (vertical or horizontal) between their extreme negative and positive amplitudes by adjusting row positions. This agrees well with the results of finite element modelling shown in Figure 6.

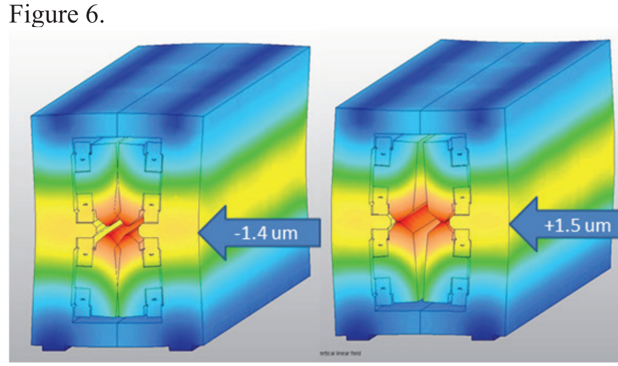

Figure 6: Shape deforming of Delta due to the transverse magnetic forces of ±15,000 N, according to finite element modeling.

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Quadrant Moving and Position Control

The four magnet arrays shown in Figure 5 generate longitudinal forces of up to ±18,000 N between the quadrants depending on the relative longitudinal positions of all quadrants. Each quadrant can be moved independently in the longitudinal direction via so called drive units. Each of the four drive units consists of one spindle, roller nut, reduction gear and DC servo motor. The longitudinal position of the quadrants is measured relative to the common strongback using four inductive position sensors which feature a resolution of ±0.1 µm. The changing longitudinal force on the quadrants generates elastic deformations of the drive unit components, such as spindle, roller nut and bearings of up to ±75 µm for each quadrant. This effect is compensated by the position control system, which iterates the quadrant position setting by moving the four quadrants simultaneously until the four quadrant position readouts are matched with the demanded values. Operation experience has shown that quadrant position setting and control works reproducible within ±0.75 µm over the entire moving range of ±16 mm per quadrant and for all operated Delta configurations. The longitudinal elongation or contraction of the 3.2-meter-long magnet arrays due to the changing coupling forces was measured as ≤3.0 µm. One of the reasons that this small value is achievable comes from the fact that the drive units are positioned in the middle of Delta, which means one half of the magnet arrays is compressed while the other half is elongated at the same time. The drive unit position can be seen as the black part in the middle of Delta in Figure 7.

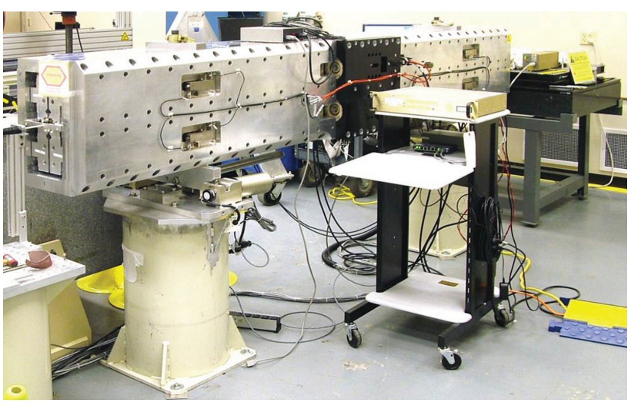

Figure 7: Delta undulator on the field mapping stand.

Magnetic Field Measurements

Magnetic field measurements were performed with a specially designed configuration of 6 Hall sensors packed as two 3-axis probes [3, 7, 8, 9]. Probe 1 was mounted close to the beam axis while probe 2 was transversely displaced by 200 µm, to allow estimates of the magnetic axis. The Hall probes were mounted at the end of a long carbon fiber tube which was guided through the device in an Al tube similar to the vacuum pipe used during operations. Figure 8 and Figure 9 show examples of B_x and B_y field measurements by probe 1 for the four main configurations (linear horizontal (LH), linear vertical (LV), circular left (CL) and circular right (CR)) at full strength.

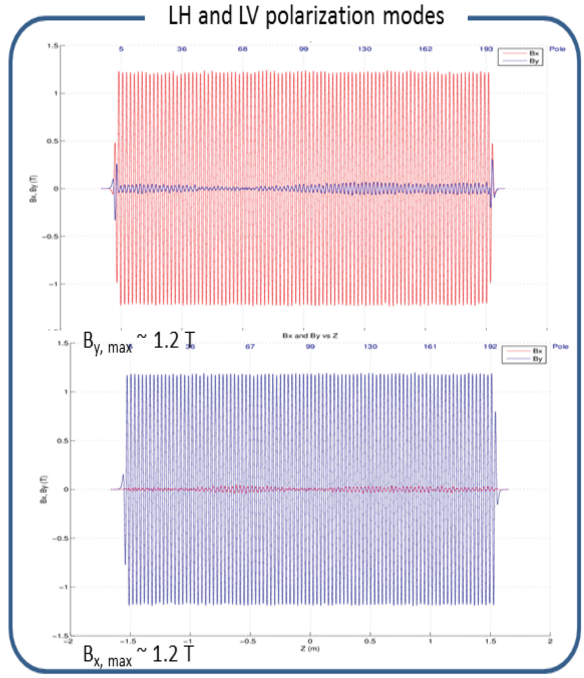

Figure 8: Undulator magnetic fields (red: $\boldsymbol{B_x}$, blue: $\boldsymbol{B_y}$) for the linear horizontal (LH) and linear vertical (LV) polarization modes at maximum *K* value.

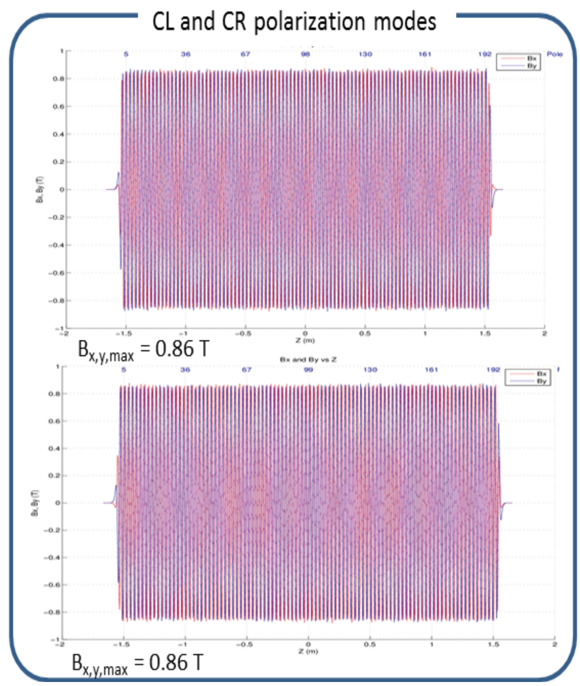

Figure 9: Undulator magnetic fields (red: $\boldsymbol{B_x}$, blue: $\boldsymbol{B_y}$) for the circular left (CL) and circular right (CR) polarization modes at maximum *K* value.

Field Integral Measurements

Field integral measurements were performed with a moving wire. The measurements were done for a number of row configurations. The information is used to

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determine the change in beam steering. The dominant component comes from the environmental field (Earth field), which has not been corrected in this first version. Future versions will incorporate a correction coil or mu-metal shielding along the device to compensate these effects.

Magnetic Multipoles

In addition to field integrals, the moving wire was used to measure the quadrupole and skew quadrupole components in the Delta undulator.

While the quadrupole component came out close to expected, an unexpectedly large, first order skew quadrupole component was measured (0.55 T integrated gradient). Both components show only small dependence on *K* and polarization modes.

AFTERBURNER OPERATION

The spontaneous radiation that the Delta undulator produces from a regular electron bunch is quite small. It can be enhanced by several orders of magnitude by first micro-bunching the electrons at the optical wavelength in a SASE FEL process by regular LCLS undulator segments. This configuration of an undulator (micro-bunching undulator) operating in the linear regime followed by another undulator (in this case the Delta undulator) producing radiation with different characteristic is called afterburner configuration.

In this configuration, the Delta undulator produces significantly enhanced radiation amplitudes from the micro-bunched electron beam compared to the spontaneous radiation from the unmodified bunch.

Examples of different radiation characteristics used in afterburners are harmonics, i.e., the second undulator is tuned to a harmonic of the SASE undulator [10], and polarization, i.e., the second undulator produces a different polarization state than the SASE undulator segments. Different characteristics can be mixed.

In the afterburner configuration, the radiation produced by the micro-bunching undulator is often considered undesirable background when only the micro-bunching is needed to enhance the performance of the second undulator.

For the Delta undulator running to produce circular polarized radiation, schemes have been developed to minimize this background component. Those schemes include crossed polarized undulators, reverse taper, and beam splitting. They are explained in some detail, below.

Regular Afterburner

The Regular Afterburner scheme was the first scheme proposed for the Delta undulator. In all afterburner schemes, it is necessary to adjust the number of micro-bunching undulators, in order to balance the micro-bunching output and energy spread generated during the SASE process. (Figure 10 shows ten LCLS undulator segments being used in this example). A fine adjustment can be achieved by slightly detuning the first of those micro-bunching undulators. A minimum taper is applied (Figure 10) just enough to compensate for energy loss from spontaneous radiation and wakefields.

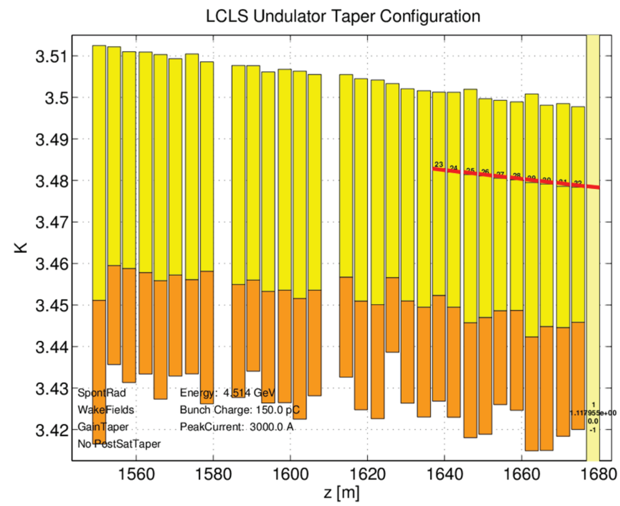

Figure 10: *K* values of the LCLS micro-bunching undulators segments for Delta operation in regular afterburner mode.

The efficiency of an afterburner configuration can be tested using a *K* resonance scan in which the *K* value of the Delta undulator is changed while the polarization mode is kept constant (Figure 11).

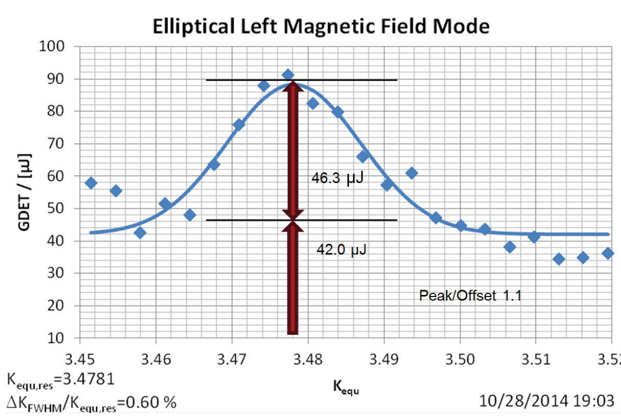

Figure 11: Delta resonance scan in elliptical left magnetic field mode (elliptical right polarization) in regular afterburner configuration.

In the scan, the x-ray intensity, measured by the gas detector or Direct Imager, is plotted against the *K* value, as derived through row positions using field mapping data. The scan results can be fitted by a Gaussian sitting on top of a slowly varying background. The ratio of the amplitude of the fitted Gaussian to the average amplitude of the background is called the contrast ratio.

Contrast ratios between 1 and 2.5 were achieved in this mode, depending on photon energy. The resonance scans also help determining the *K* values at which the Delta undulator is resonant to the micro-bunching undulators.

The degree of polarization can also be improved, following a proposal by Geloni et al. [11], by introducing a large (~20 m) spacing between the SASE and the Delta undulators and inserting slits in front of the Delta to

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remove some of the diverging SASE radiation. This has not yet been tested on the Delta due to resource limitations and damage concerns.

Crossed Polarized Undulators

The crossed polarized undulator scheme produces circular polarized radiation by superposing the horizontally linear polarized radiation of the micro-bunching undulators with the radiation produced by the Delta undulator running in vertically linear polarization mode [12]. In this scheme, the radiation produced in the micro-bunching process is not considered undesirable background but is utilized. It is important to adjust the number of micro-bunching undulators to equalize the strength of their radiation and that produced by the micro-bunched electron beam in the Delta undulator.

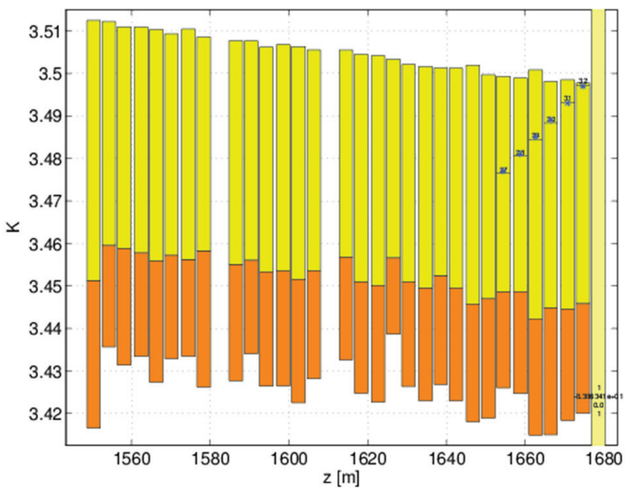

Figure 12: *K* values of the LCLS micro-bunching undulators segments for Delta operation in reverse taper mode.

A phase shifter in front of the Delta undulator is needed to adjust the phase between the two radiation components and thus the polarization mode (right circular, left circular, elliptical). A permanent magnet phase shifter was developed as part of the Delta project and installed just in front of the Delta undulator. It has been used to control the phase between the two radiation components (i.e., radiation of the micro-bunching undulator vs. radiation from the Delta undulator).

In the crossed polarized undulator scheme, the vertical polarized light produced from the spiky micro-bunching structure of the electron beam in the Delta undulator needs to be combined with the light produced during the micro-bunching process. Even though the total intensity of the horizontal and vertical components are about the same in the experiment, the time-dependent x-ray profiles can be quite different from horizontal to vertical since some parts of the bunch reach saturation much faster than other parts. As the experiment is conducted in the SASE mode, different time slices of the x-ray pulse will have different degrees of circular polarization. Due to the lack of any phase relationship among SASE spikes. The varying degrees of polarization along the SASE pulses will cause unpolarised radiation. Preliminary studies show that only relatively low intensity levels and low polarization degrees have been obtained with the cross undulator scheme with the Delta undulator. The degree of polarization in this scheme can be improved with a more-uniform electron bunch and increased temporal coherence [13].

Reverse Taper

The reverse taper scheme suggested by E. Schneidmiller and M. Yurkov [2] is an improvement of the afterburner scheme. By reversing the sign of the taper, i.e. by increasing the *K* values of the undulator segments instead of decreasing them along the undulator line (Figure 12), micro-bunching can built up with significantly reduced radiation amplitude. This method, which is described in more detail by MacArthur et al. [14] is more dependent on beam energy spread than the regular afterburner mode. Figure 13 shows the image of the 710 eV x-ray pulse produced with the reverse taper method. The image was taken with the Direct Imager, which is located about 88 m downstream of Delta undulator. It shows the combination of circular polarized Delta radiation (480 uJ) and linearly polarized radiation from the micro-bunching undulator segments (30 uJ).

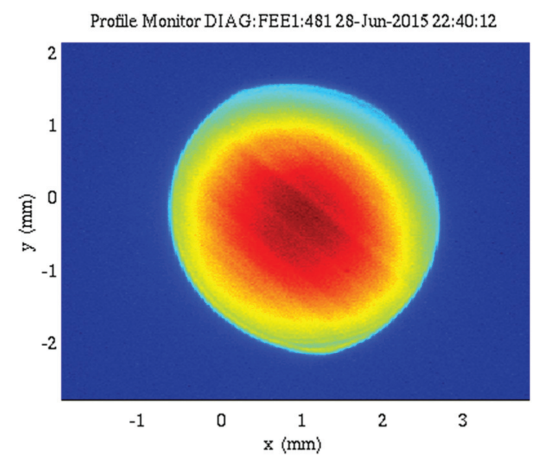

Figure 13: X-ray pulse image at 710 eV on Direct Imager in reverse taper contribution.

Beam Splitting

Beam splitting is a way of supressing the background component from the micro-bunching process. It is done by kicking the electron beam before entering the Delta undulator causing the electron beam and the background radiation beam to enter the Delta undulator under different angles. This beam kicking is controlled by the regular vertical corrector that is integrated in the quadrupole located at the end of the previous girder. The Delta undulator is detuned to be resonant to the off-axis component of the background radiation that still overlaps with it (Figure 14). Since there are about two gain lengths in the Delta undulator in the soft x-ray regime, simulations show that the micro-bunching orientation is readjusted to produce coherent radiation in the kicked direction. Detailed discussions of this method will be published elsewhere.

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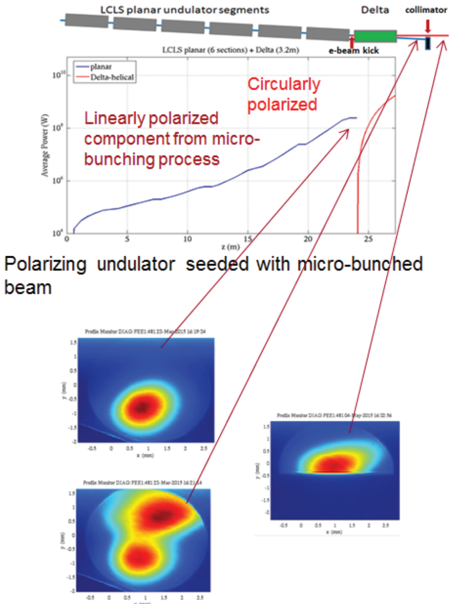

Figure 14: Beam splitting and collimation pushes degree of circular polarization close to 100 %.

POLARIMETER

The first measurements of the polarization degree of the radiation produced by the Delta undulator were done with a polarimeter developed at DESY [15], which is based on an array of 16 independently working time-of-flight spectrometers (TOF) aligned perpendicular to the plane of light propagation. The device measures the degree of linear polarization

$$P_{lin} \propto \sqrt{\frac{s_1^2 + s_2^2}{s_0^2}} \tag{1}$$

on a shot-by-shot basis. The equation is written in terms of the Stokes parameters, which are defined as

$$\begin{aligned} s_0 &= I_x + I_y \\ s_1 &= I_x - I_y \\ s_2 &= I_{45°} - I_{-45°} \\ s_3 &= I_{RCP} - I_{LCP} \end{aligned} \tag{2}$$

with

$$s_0^2 \geq s_1^2 + s_2^2 + s_{3.}^2 \tag{3}$$

The equal sign applies if the light is fully polarized. Only in this case can the degree of circular polarization be deduced from P_{lin}

$$P_{circ} = \frac{|s_3|}{s_0} = \sqrt{1 - \frac{s_1^2 + s_2^2}{s_0^2}} = \sqrt{1 - {P_{lin}}^2}. \tag{4}$$

The assumption that that the pulse is fully polarized is expected to be quite accurate in the beam splitting scheme. In the crossed polarized scheme, the unpolarized component can be quite significant, as has been measured in this experiment, and the degree of circular polarization cannot be deduced from the measured degree of linear polarization according to equation (3).

The TOF polarimeter was used to measure the circular dichroism of sidebands in molecular oxygen in a two color scheme, allowing the direct measurement of a high degree of circular polarization for the regular and reverse taper schemes [16].

Table 1: Performance Overview over Afterburner Schemes

Scheme	E_{circ}/E_{lin}	P_{lin}	P_{circ}	E_{xray} (μJ)
Crossed Polarization			low	50
Regular Afterburner		0.5	0.87	50
Reverse Taper		0.3	0.96	480
Split Beams	≳100		~1	220

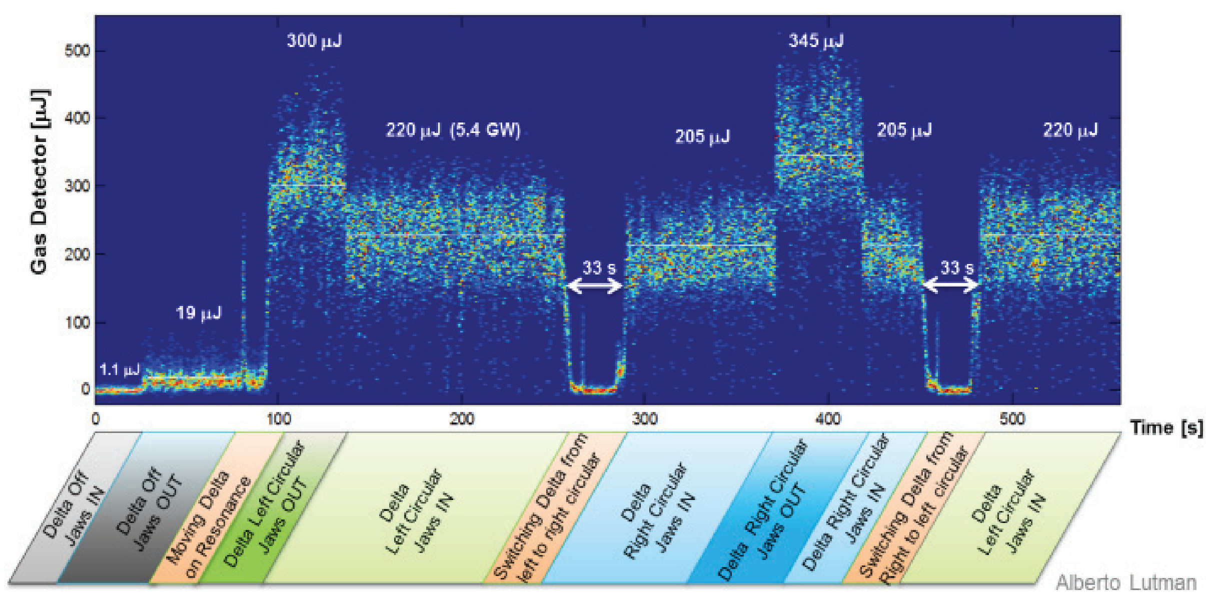

Figure 15: Delta polarization switching during operation.

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USER EXPERIMENTS

The first user experiments were carried out in June 2015 in split beams mode [17, 18]. The effects of the difference between right and left circular polarized radiation produced by the Delta undulator using the beam splitting scheme was measured by x-ray magnetic circular dichroism (XMCD). It was confirmed that the degree of circular polarization is very close to 100%. Figure 15 shows the intensity during polarization switching as a function of time. The first part shows the background at 1.1 uJ with the collimators (Jaws) inserted. The next part shows the linear polarized radiation produced by the micro-bunching undulators at 19 uJ with the reverse taper scheme. When the Delta undulator is turned to resonance in left circular mode it adds 281 uJ to a total of 300 uJ. When the collimator jaws are inserted to remove the linear polarized component some of the circular polarized Delta light is cut in the process as well. The intensity drops to 220 uJ. Switching the Delta undulator from left to right circular polarization mode takes 33 s and generates a quite similar intensity (205 uJ). Later, switching back to left circular polarization mode takes the same time and reproduces the intensity quite well.

LESSONS LEARNED

Quadrants should not be moved to different support structures after tuning. Earth field compensation coils or mu-metal shielding along the Delta undulator should be included into the design. A small correctional skew quadrupole should be added in line with the Delta undulator.

FUTURE PLANS

Different beam modes have been tested when operating the Delta undulator. For example, two pulses with different color and polarization (for instance linear and circular) arriving with adjustable time delay have been created and will be reported in a separate publication. SLAC is developing a stronger version of the Delta undulator to be operated in the LCLS-II SXR beamline. The present plan is to produce up to three Delta undulators to be installed at the end of the SXR line.

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