R&D TOWARDS A DELTA-TYPE UNDULATOR FOR THE LCLS*

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Abstract

The 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 compact out-of-vacuum undulator design (Delta), based on a 30-cm-long in-vacuum prototype at Cornell University, is being developed and tested to add those missing properties to the LCLS undulator line. Tuning Delta undulators within tight, FEL type tolerances is a challenge due to the fact that the magnetic axis and the magnet blocks are not easily accessible for measurements and tuning in the fully assembled state. An R&D project is underway to install a 3.2-m long out-of-vacuum device in place of the last LCLS undulator, to provide controllable levels of polarized radiation and to develop measurement and tuning techniques to achieve x-ray FEL type tolerances. Presently, the installation of the device is scheduled for August 2014.

INTRODUCTION

The Linac Coherent Light Source (LCLS) has been delivering intense ultra-short x-ray beams to international users at the SLAC National Accelerator Laboratory (SLAC) since 2009 [1]. These x-ray beams are generated with fixed, canted gap hybrid permanent magnet undulators [2]. The design supports a very successful and tightly controlled alignment concept [3]. The canted poles, in connection with remote controlled undulator displacement, provide limited taper capability (up to 1% through canted pole and horizontal position adjustability). The LCLS undulator, so far, lacks full range *K* adjustability and polarization control. The latter is of great importance for soft x-ray experiments.

THE DELTA UNDULATOR

SLAC is developing a 3.2-m-long out-of-vacuum version of the Delta undulator to add polarisation control to the LCLS. The Delta undulator, which is a compact adjustable-phase device, was first developed at Cornell University [4] as a 0.3-m-long in-vacuum prototype. The SLAC version employs a vacuum beam pipe in order to keep the overall transverse size sufficiently small to allow it to replace an existing LCLS undulator segment. The Cornell prototype demonstrated that the concept produces an undulator with the required properties. The main parameters of the LCLS Delta undulator are listed in Table 1. As with the Cornell prototype, the core of the undulator consists of four parallel longitudinal structures (rows) that support arrays of magnet blocks, such that the pole tips of the magnet blocks on opposing rows face each other to form two crossed pure permanent magnet undulators. The undulators are designed in an anti-symmetric pole arrangement. The end pole design uses a 3-pole retraction technique [5]. Longitudinal position of each row can be remotely controlled. By setting the z-positions (phases) of the 4 rows, the degree of polarisation and the radiation wavelength (or on-axis magnetic field strength) can be controlled. The capabilities are similar to that of an APPLE device.

Table 1: LCLS Delta System Properties

Device Length	3.2	m
Operational *K* Parameter Range	0 – 3.37	
Period Length	32	mm
Gap Height	6.6	mm
Number of Magnet Rows	4	
Number of Magnet Blocks per Row	391	
Row Motion Range	±17	mm

CHALLENGES

Challenges that are introduced by the LCLS Delta design include (1) tighter (FEL-type) *K* reproducibility, phase shake and field integral tolerances; (2) increased mechanical reproducibility issues due to the 10 times longer device length; (3) incorporation of a vacuum chamber and (4) high precision magnetic field measurement of the fully assembled device.

Undulator Tolerances

One of development goals of the Delta undulator is to make it capable of functioning as segment in an x-ray FEL. The main requirement of x-ray FEL undulator segments is that they all operate at or can be fine tuned to the same resonant wavelength. Once installed, it is quite difficult to measure the resonant wavelength of each undulator segment to sufficient precision. It is essential that row position encoder readings can reliably predict undulator *K* values with an accuracy of $\Delta K/K<3\times10^{-4}$.

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This requires for the Delta undulator that the transverse pole separations of opposing rows (gap) must remain constant to better than a few micrometers.

Mechanical Reproducibility

Mechanical stability of the 3.2-m-long Delta is a concern with respect to both gravitational and magnetic forces. In order for the device to fit on an LCLS girder, the half height of the device needs to be less than 265 mm, which means that the device will have a large length-to-height ratio. The strong magnetic interaction of the closely spaced magnet blocks will vary over the full motion range as the four rows are shifted. In order to stabilize the transverse magnet block positions as much as possible, the design makes use of all available space as illustrated in Figure 1.

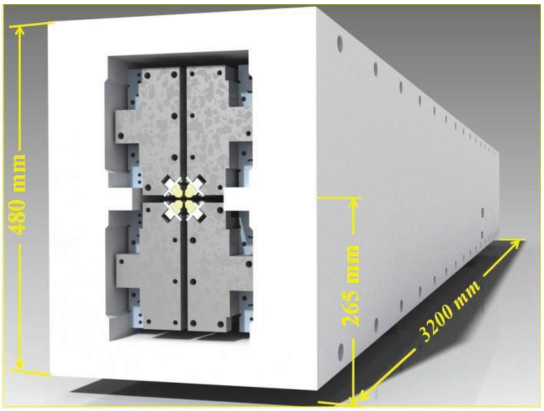

Figure 1: Layout of the 3.2-m long LCLS Delta undulator.

Vacuum Chamber

One of the main differences between the LCLS Delta and the Cornell prototype is the requirement to install a vacuum chamber on the beam axis (see Figure **2**).

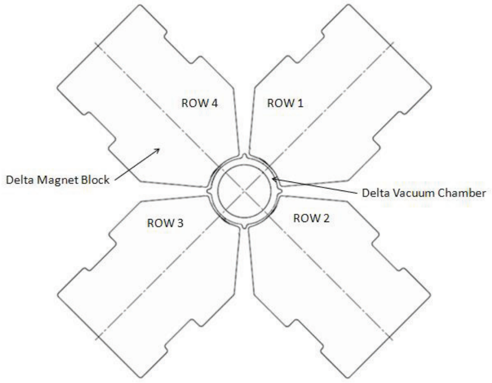

Figure 2: Arrangement of the Delta magnet blocks around the vacuum chamber, which has an ID of 5.08 mm and an OD of 6.4 mm, resulting in a 0.66 mm wall thickness.

This can only be done after the magnetic measurements on the fully assembled device are completed. The alternative of combining the four row sections around the vacuum chamber would only be possible if the magnetic measurements could be performed inside the vacuum chamber. Due to concerns about contamination during the magnetic measurement process, those measurements will actually be performed in a substitute beam pipe with similar cross section. Inserting the latter after completion of the measurements requires in situ flange welding to the extruded Al beam pipe.

Tuning and Magnetic Measurements

The final measurements will need to include Hall probe scans of the on-axis magnetic field and moving-wire field integral measurements. This will need to be done at all operational phase settings to obtain a mapping of K values vs. row phase combinations. Before the final scans can be performed it will first be necessary to correct field errors by fine-adjusting the positions of individual magnet blocks (tuning). This cannot be done after the magnet is fully assembled because of the lack of access. Instead, tuning will be done on the four individual magnet arrays, separately from each other. For this, each array will be mounted on a tuning bench with pole tips pointing upward to provide best access to the Hall probe, which will be positioned at a distance from the blocks corresponding to the beam axis in the fully assembled version. The magnetic on-axis fields of the full device can be predicted by numerically combining the measurements of the individual arrays. Before assembly, the magnet blocks are sorted [6] to compensate for field errors. During the tuning process, field errors are reduced by shimming, i.e., mechanically repositioning the individual magnet blocks by changing the thickness of shimming plates, which are incorporated in the support of each block. The tuning tolerances are listed in Table 2.

Table 2: LCLS Delta Main Tolerances

Gap Reproducibility (rms)	2	µm
$\Delta K/K$ (rms)	2.5×10^{-4}	
Phase Shake (rms)	3	degXray
Magnetic Axis Straightness	50	µm
First Field Integrals	±40	µTm
Second Field Integrals	±50	μTm^2

MEASUREMENTS

Once the undulator is fully assembled, final measurements will be performed with a combination of two 3-dimensional Hall probes, which are pulled through a copper pipe, with a diameter similar to that of the final vacuum chamber. The horizontal, vertical, and longitudinal position of the Hall probe assembly is monitored to high precision by a specially designed laser system. The horizontal and vertical position of the magnetic axis of the undulator is determined from a set of Hall probe measurements [7]. The block position repeatability measurements will be derived from magnetic field measurements over the full quadrant phase adjustment range.

SASE FEL AFTERBURNER

When installed on the last (33rd) girder of the LCLS undulator line, the Delta undulator will be operated as a SASE After-Burner (AB) [8], which will produce enhanced radiation from the micro-bunched electron beam. Micro-bunching will be generated in a SASE FEL process by the last 6 or 7 LCLS undulator segments upstream of girder 33. All other upstream undulator segments will be rolled off the beam line in order to keep the SASE-generated energy spread under control.

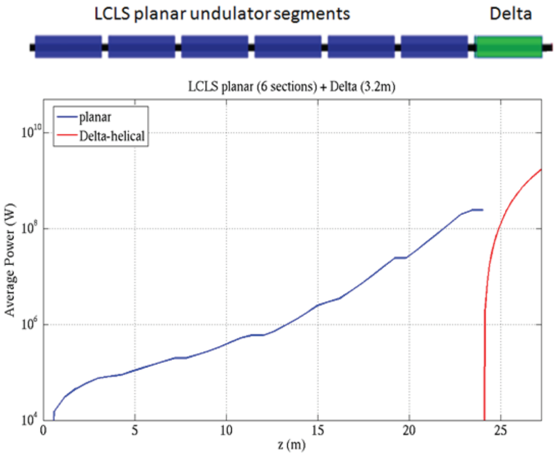

Figure 3: Genesis 3.1 simulation of Delta running as afterburner (right (red) curve, 1.7 GW) after 6 regular LCLS undulator segments (left (blue) curve, 0.24 GW).

This process has been simulated with GENESIS 1.3 [9] as shown in Figure 3 for 800 eV x-rays. The figure shows the exponential increase in average power through six LCLS undulators using the process of Self Amplified Spontaneous Emission (SASE). This process modulates the electron beam, which causes microbunching at the resonant x-ray wavelength and increases the energy spread. The latter limits the number of SASE undulators that can be used. As the micro-bunched beam enters the Delta undulator, it rapidly produces new radiation (red) with controllable polarization properties. Even though there is only one 3.2-m Delta undulator and the amount of power is modest (about 1.3 GW), it is already 7 times as high as the original SASE power. The pulse-to-pulse stability of the ratio of Delta radiation to SASE radiation is estimated to be in the few percent range. Polarization studies are presented in [10]. Adding one more Delta undulator in the future should reduce fluctuation of the polarization degree below the 1%-level and should raise the polarization degree above the 90% level. A third Delta undulator would further improve the quality of the polarized radiation component. 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 slits in front of the Delta to remove some of the diverging SASE radiation. A recent paper by Schneidmiller et al. [12] provides an even more attractive way, if verified, since it doesn't require 20-m drift space (which may degrade bunching) and slits (two sets in both x and y). The length of the LCLS Delta was chosen 20 cm shorter than a regular LCLS undulator segment to provide space for a phase shifter that will be needed if more Delta undulators are added and will be useful to test the cross polarizer scheme with one undulator.

PROJECT STATUS

A 1-m-long prototype has been completed and is currently being characterized. Initial measurements show that the device meets the expected performance requirements. Installation of the 3.2-m device is scheduled for mid 2014. More Delta undulators are likely to be added to the LCLS once the principle has been demonstrated to work.

CONCLUSION

A 3.2-m-long out-of-vacuum version of the Cornell Delta prototype is being developed at SLAC to add polarization control to the LCLS and provide compact undulators for future xray FELs. Installation is scheduled for 2014.

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