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DEVELOPMENT OF THE VERTICALLY POLARIZING HARD X-RAY UNDULATOR SEGMENTS FOR THE LINEAR COHERENT LIGHT SOURCE UPGRADE (LCLS-II) PROJECT*

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Abstract

The Linear Coherent Light Source II (LCLS-II) is a free electron laser facility currently in its final construction stage at Stanford Linear Accelerator Center. The project includes two variable-gap, hybrid-permanent-magnet undulator lines: A soft x-ray undulator line with 21 undulator segments optimized for a photon energy range from 0.2 keV to 1.3 keV and a hard x-ray undulator line with 32 undulator segments designed for a photon energy range from 1.0 keV to 25.0 keV. This paper focuses on the development of the hard x-ray undulator line which utilizes uniquely-developed, vertically-polarizing undulators. To fully compensate the magnetic force throughout the entire gap range these devices incorporate non-linear spring systems which permit the construction of relatively compact undulators. However, significant magnetic field repeatability challenges have been encountered during prototyping of this novel design. The paper describes some of the innovative design improvements that were implemented which lead to reaching the LCLS-II required performance. These final design solutions can also be advantageous improving the operation of any future undulator design.

INTRODUCTION

LCLS-II

Stanford Linear Accelerator Laboratory (SLAC) is currently constructing the Linear Coherent Light Source II (LCLS-II), a free-electron laser (FEL) which will deliver x-rays at an energy range between 0.2 keV and 5 keV at high repetition rate of up to ~1 MHz (929 kHz) using a new 4 GeV superconducting (SC) RF linac [1, 2]. To cover the full photon energy range, LCLS-II includes two new, variable-gap, hybrid-permanent-magnet undulator lines: A soft x-ray undulator (SXR) line optimized for a photon energy range from 0.2 keV to 1.3 keV and a hard x-ray undulator (HXR) line designed for a photon energy range from 1.0 keV to 5.0 keV. The hard x-ray undulator can also be fed by an existing, 2.5 to 15 GeV, normal-conducting (NC), low-repetition-rate (100 Hz) linac generating 1 to 25 keV photons.

Hard X-Ray Undulators

This paper focuses on the description of unique details of the LCLS-II hard x-ray undulator segments. Figure 1 displays an elevation view of the hard x-ray undulator line which consists of 4.4 m long repeating lattice cells containing the 3.4 m long undulator segments with a 26 mm magnet period. A lattice cell also includes a break (or interspace) section mounted on the undulator girder which consists of a focusing quadrupole, a beam position monitor, a phase shifter, a collimator, vacuum pumping equipment, a gate valve, and a beamloss monitor. The hard x-ray undulator line includes a total of 32 undulator segments, two cells set aside for x-ray self-seeding, and four empty cells for future expansion.

As a novel capability the LCLS-II hard x-ray undulator line will provide vertically polarized x-rays to users. This polarization direction is preferred for several experimental setups at LCLS-II [3]. For instance, x-ray photon correlation spectroscopy utilizes a sizable and heavy detector arm designed to operate in the horizontal plane through large angles. For such a setup an up to five-fold signal increase [1] can be achieved by using vertically polarized x-rays. Beam splitting monochromators also benefit from vertically polarized x-rays.

Alternative Force Compensation Schemes

Conventional undulator designs as developed for XFEL [4] or the LCLS-II soft x-ray line [5] utilize large aluminum strongbacks and powerful drive systems to counteract the strong (several tons) magnetic force in the undulator gap. Due to the strongback size these planar undulators are operated in a vertical gap configuration providing horizontally polarized x-rays. It is not practical to rotate these devices by 90 degrees due to their large size.

Several laboratories have developed undulator prototype structures utilizing alternate means of magnetic force compensation with the goal to eliminate the need for large mechanical I-beam structures. This would permit more compact undulator designs.

The magnetic force in an undulator decreases exponentially with increasing gap (see for instance Fig. 4). Special magnetic [6, 7], hydraulic [8], or mechanical spring [9, 10] compensation schemes have been designed to mirror such exponential force behavior. However, the stringent undulator

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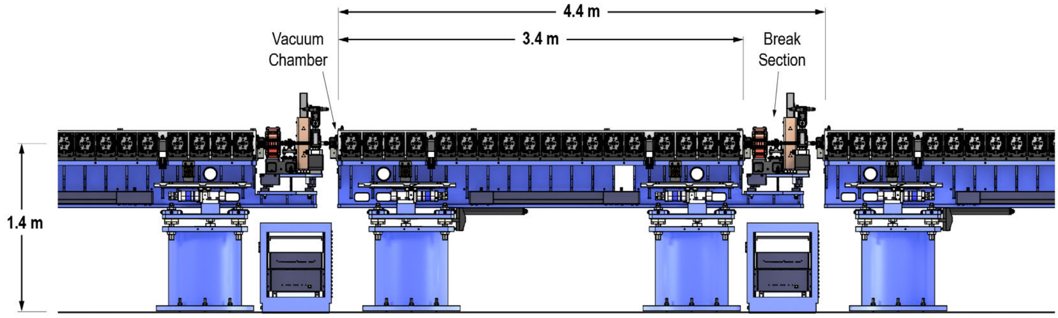

Figure 1: Elevation view of the LCLS-II hard x-ray undulator line which consists of 4.4 m long, repeating lattice cells.

magnetic field and gap straightness requirements demand excellent force compensation. Therefore, such devices have not yet been widely utilized.

Argonne National Laboratory (ANL) has previously developed a fully functional undulator prototype [10,11] which relies on conical springs to counteract the magnetic forces. The undulator width has been reduced to minimize the overall transverse size (to ~1 m). The goal was to permit installation of such undulators inside the existing LCLS tunnel in parallel to the soft x-ray line. Due to the compact size the undulator design allows operation in a horizontal gap configuration producing vertically polarized photons (hence the tongue-twisting acronym: Horizontal Gap Vertically Polarizing Undulator, HGVPU).

Due to their ability to deliver vertically polarized photon beams HGVPUs have been implemented in the LCLS-II project in January 2016, which was fairly late in the project. The HGVPU design was transferred to Lawrence Berkeley National Laboratory (LBNL) to mass-produce the undulators for LCLS-II construction. LBNL has independently developed advanced magnet module configurations [12] which reduce tuning effort while significantly enhancing gap-dependent field correction capabilities. Therefore, the project decided to utilize the HGVPU mechanical structure while implementing the LBNL high-performance magnet module design.

HGVPU DESIGN DETAILS

Figure 2 illustrates the main components of the horizontal-gap, vertically-polarizing undulator (HGVPU) design. The magnet modules are mounted on thin aluminum strongbacks. Eighteen spring cages which compensate the magnetic gap forces are mounted on each side. The strongbacks are supported by linear bearings attached and precision-aligned to an aluminum girder which also holds the spring cages. The overall configuration is quite compact. For instance, the entire undulator can be assembled on a coordinate-measuring machine (CMM) granite table which simplifies overall precision alignment. Table 1 lists the main parameters as well as magnetic field tuning requirements for the HGVPUs [13].

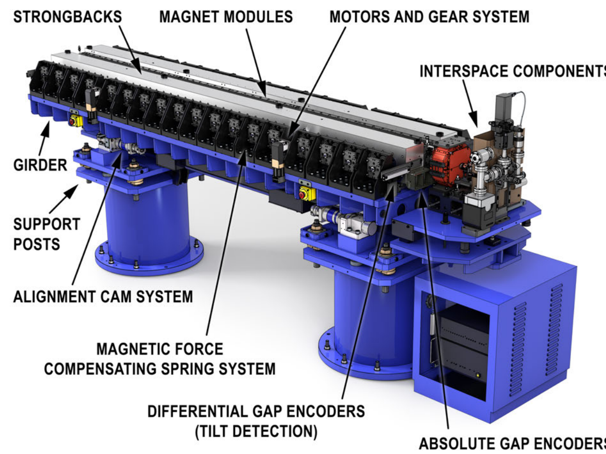

Figure 2: HGVPU main components.

Table 1: Important HGVPU Parameters [13]

Parameter	Requirement
Undulator Segment Parameters	
Undulator Type	Planar PM Hybrid
X-Ray Polarization Direction	Vertical
Photon Energy Range (SC Linac)	1.0 - 5.0 keV
Photon Energy Range (NC Linac)	1.0 - 25.0 keV
Undulator Period Length (λ_u)	26 mm
Min. Operational Magnet Gap	7.2 mm
Max. Operational Magnet Gap	20 mm
B_{eff} at Min. Operational Gap	> 1.01 T
Undulator Length	3.4 m
Periods per Segment (incl. Ends)	130
Essential Field Tuning Requirements	
Field Tolerance $\Delta K_{eff}/K_{eff}$	$\pm$ 2.3×10^{-4}
RMS Phase Shake	± 4.0°
Thermal Cycle Repeatability	± 15 °C
First Field Int. of $B_{x,\,y}$	< 40 µTm
Second Field Int. of $B_{x,\,y}$	< 150 µTm^2

HGVPU Magnet Module

Figure 3 shows a schematic picture and a photo of the HGVPU magnet module configuration. LCLS-II relies on

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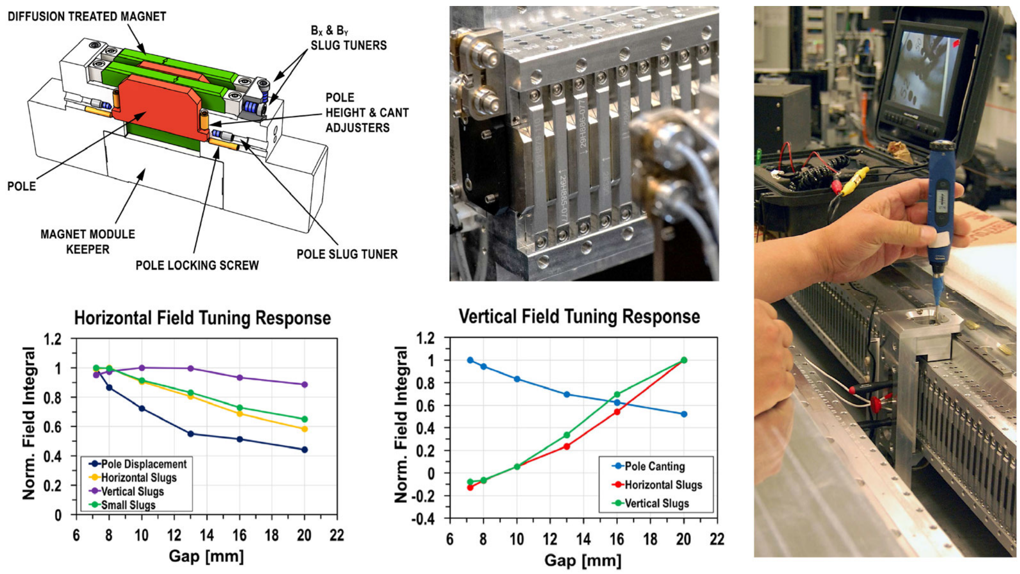

Figure 3: The LCLS-II undulator magnet modules incorporate specially designed tuning features which provide a range of gap-dependent error correction responses. The rightmost photo illustrates the use of a tuning fixture which automates pole adjustments within the undulator vertical gap. A single undulator can be tuned within only two days.

undulators with stringent field quality requirements across a large operational gap range. Therefore, the magnet modules incorporate several tuning options: The poles can be moved in and out of the gap and can also be canted. Positioning of the poles is achieved by set screw adjusters in combination with locking screws. Small cylindrical magnet slugs can be inserted at different positions providing varying magnetization directions. These tuning options exhibit individualized and gap-dependent field responses as shown in the graphs of Fig. 3.

To speed up and more consistently perform the tuning of each device the normalized magnetic field error correction responses were implemented into an automated computer software [12] which evaluates undulator field integral measurement results. The software suggests appropriate correction elements along the undulator magnet modules. The rightmost photo in Fig. 3 illustrates the use of a specially designed tuning fixture which automates pole adjustments within the undulator vertical gap in an ergonomic manner. A single undulator can be tuned within only two days.

HGVPU Spring System

Figure 4 illustrates the mechanical interaction between the magnet modules mounted on the undulator strongbacks and the spring cages. The undulator operational full gap extends from 7.2 mm to 20 mm. Each strongback moves half that distance (6.4 mm). As for instance shown in the left bottom graph in Fig. 4, a single spring cage provides an exponential force increase from almost zero force to 1800 N within this 6.4 mm movement range. All eighteen spring cages on each side of the undulator provide a total magnetic force compensation of up to 32.4 kN (~7,300 lbf).

A single spring cage incorporates four conical springs which are shown in a photo in Fig. 4. A combination of two soft and two strong springs was chosen to best match the force curve developed by the magnet modules. Contrary to linear springs the force of a conical spring grows exponentially as individual revolutions start to short out with increasing compression. The ANL developed prototype [10] was the first undulator utilizing such spring types and provided remarkably good magnetic field compensation.

For LCLS-II mass production LBNL developed an automated spring cage calibration routine: Individual springs were first calibrated utilizing a commercial spring tester as shown in the photos of Fig. 4. The force curves were fed into a computer sorting algorithm. The software chose four springs for each spring cage assembly by minimizing the deviation from the ideal magnetic force dependence. Results of this sorting process are shown in the bottom graphs of Fig. 4. Finally, for each fully assembled spring cage a calibration curve is recorded in a custom-made spring cage tester. The results are subsequently utilized to optimize selection of spring cages for each undulator assembly, and the data are recorded in the travelers for each device.

The spring cage sorting process minimizes force deviations from the ideal magnetic force curve to less than 2% (~40 N at max. force) as shown in Fig. 4. Such force variation corresponds to approx. 10 µm strongback deflection. However, taking advantage of the spring cage calibration data the assembly for each undulator can be optimized to develop a close-to-straight strongback at the smallest gap while allowing greater deflections at large gaps where phase errors are less critical. This is a delicate balancing act and requires tight control on the work procedures. For LCLS-II we were able to successfully transfer the whole process to our industrial suppliers.

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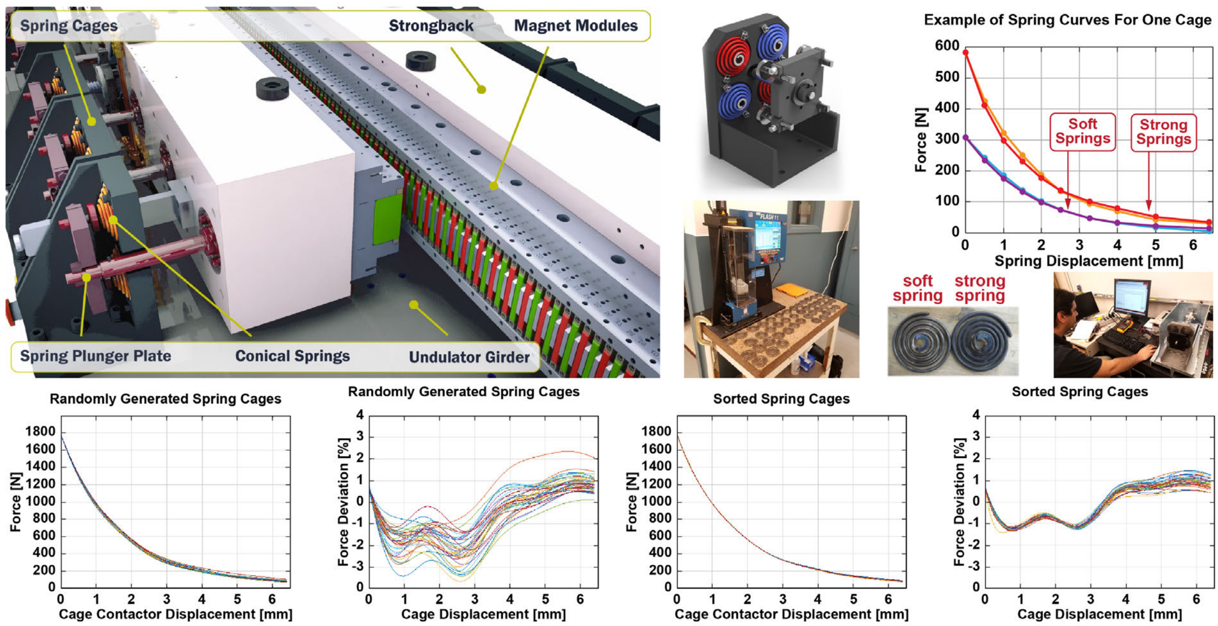

Figure 4: Schematic illustration of the interaction between magnet modules, strongbacks, and the spring-cage force-compensation system. Conical springs provide an exponential force dependence which can be well matched to the gap magnetic force. A computer program is utilized to sort and pair individual springs minimizing the deviation from the ideal force curve to less than 2%. The undulations in the force deviation curves correspond to the conical spring revolutions sequentially bottoming out as compression increases.

HGVPU Design Challenges

HGVPUs were implemented into the LCLS-II baseline design late in the project supported by results obtained with an early undulator prototype [10, 11] and based on the expectation that the HGVPU design was fully developed and only needed to be optimized for production. However, more extensive and thorough repeatability tests at LBNL revealed that the undulator design had serious repeatability issues. The strongbacks deformed by more than 20 µm from one day to the next without obvious cause and clear pattern. This behavior rendered them unusable since strongback distortions have to be kept a magnitude smaller.

After a systematic testing program, it rapidly became clear that the HGVPU suffered from a fundamental design oversight. In principle, the magnetic force compensation worked remarkably well. The primary prospect of force compensation is the possibility to reduce magnet module strongback thickness and therefore overall undulator size. The left photo of Fig. 5 displays the HGVPU strongback dimensions. At a significant length of 3.4 m the strongback is only 15.5 cm wide. At such dimensions the strongbacks - although they do not experience significant magnetic forces - are extremely sensitive to any mechanical imperfection or thermal imbalance. We identified two main contributors to the observed strongback deformations which we separated into "global deformations" and "local deformations" which had to be addressed in the mechanical design of the undulator.

(1) Global Deformations: Extensive thermal tests on two undulators were performed by heating the devices to +35°Celsius and cooling to +10°Celsius. Magnet module, strongback, and girder temperatures were continually monitored. Although all subcomponents are fabricated out of aluminum the girder changed temperature more rapidly than the strongbacks due to it's significantly larger surface area. This created a several mm length difference between girder and strongbacks at the maximum temperature difference. In the original design the strongbacks were fixed to linear bearings mounted on the girder. Therefore, the interface had to resist huge forces developed by the differential contraction. This led to frictional bolt slippage not recoverable once the undulator settled back to its operating temperature resulting in varying strongback bend. For the same reason, even small temperature variations which can typically occur in an assembly area resulted in strongback bending. These deformations appeared random since they were caused by slippage across a frictional boundary.

Figure 5 displays some of the design solutions developed to eliminate global deformations. A kinematic flexure joint was inserted between the strongback and the girder linear bearing assembly. This flexure permits longitudinal contraction and expansion without loosing strongback alignment. Since the strongback is now allowed to expand and contract independent from the girder we also had to implement a flexure mount for the motor drive screw to permit following the strongback. The mentioned design solutions successfully eliminated the distortion effect caused by the different thermal response of girder and strongbacks.

(2) Local Deformations: A more serious problem caused by the weak strongbacks is their sensitivity to any mechani-

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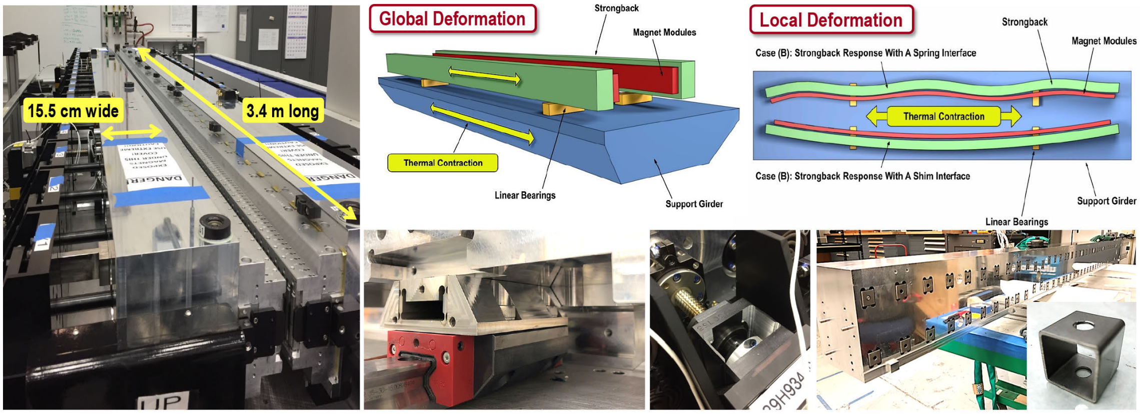

Figure 5: At a sizable length of 3.4 m the HGVPU strongback is only 15.5 cm wide. At such dimensions the strongbacks - although they do not experience significant magnetic forces - are extremely sensitive to any mechanical imperfection or thermal imbalance. Specially designed flexures have been incorporated between the girder and strongbacks as well as magnet modules and strongbacks to decouple differential movement which could otherwise lead to frictional slippage and unpredictable hysteresis in strongback deformation.

cal imperfection on a local scale. For instance, during testing we found out that tightening just a single bolt on the backside of the girder resulted in a 6 µm strongback bend (caused by the strain in the threads). In addition, magnet modules and strongbacks are made from aluminum but different alloys (5000 and 6000 series). The slightly different metallic composition resulted in too much thermal differential contraction and expansion. For traditionally designed undulators which incorporate larger I-beam structures this would never become an issue. However, on the HGVPUs the magnet module to strongback assembly became a bi-metallic strip which bent too much exceeding requirements even within the 0.1°Celsius tunnel temperature control range.

The HGVPU design suffers from too soft strongbacks which should ideally be strengthened - perhaps a task for a next generation of such devices. Since the LCLS-II project schedule did not permit a major redesign it became necessary to find a solution making the existing undulator configuration resilient against local deformations. Tests revealed that the magnet modules needed to be decoupled from the strongbacks using fully kinematic joints. However, magnet modules for a single undulator require small flexures for close to 200 bolt locations. Producing flexures in such large quantities is prohibitively expensive. Instead - as shown in Fig. 5 - we found a simple design solution utilizing cut square stainless steel profiles inserted at each magnet module bolt location. These profiles provide sufficient flexibility and are cheap to mass-manufacture. After the new flexure installation we did not observe significant residual strongback deformations anymore after thermal excursions.

At last, in the fully assembled undulator any minute but remaining frictional sources at the ends of each strongback were removed to further reduce remaining hysteresis in the bend behavior. Dust wipers on the main linear bearings as well as dust protections on the encoders were eliminated. As shown in Fig. 6 the gap straightness of the undulator can now be maintained to astonishing precision considering the dimensions and setup of the HGVPU device.

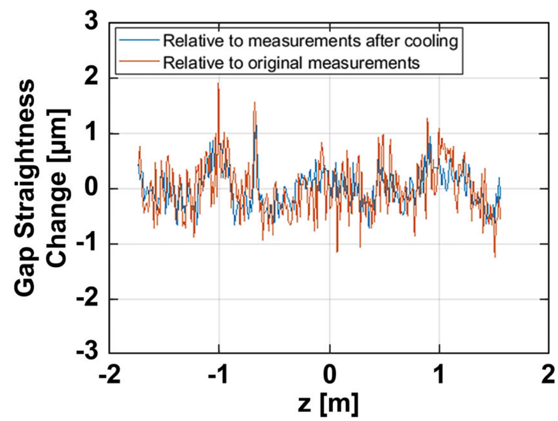

Figure 6: The LCLS-II HGVPUs are able to maintain gap straightness during shipping, storage, or significant temperature excursions (orange: after heating, blue: after cooling).

SUMMARY

This paper highlighted key design features of the LCLS-II hard x-ray undulators. LCLS-II is the first major research facility to implement spring-compensated undulators with the primary benefit of operating in a horizontal gap configuration delivering vertically polarized photon beams. The spring compensation scheme is labor intensive to implement on an industrial scale but works reliably. Unfortunately, the overall undulator configuration is not rigid enough and could benefit from more development. For LCLS-II the existing design was augmented with a series of kinematic flexures commonly developed for high-precision, micro-fabrication assemblies. The upgraded HGVPU design can maintain gap straightness to within a few µm withstanding signifi-

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cant temperature excursions or rough transport and handling procedures. The design solutions briefly described in the paper could also benefit future more conventional undulator developments.

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