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SUPERCONDUCTING UNDULATORS AND CRYOMODULES FOR X-RAY FREE-ELECTRON LASERS*

D. C. Nguyen†, G. J. Bouchard, B. M. Dunham, G. L. Gassner, Z. Huang, E. M. Kraft, P. Krejcik, M. A. Montironi, H.-D. Nuhn, T. O. Raubenheimer, Z. R. Wolf, Z. Zhang
SLAC National Accelerator Laboratory, Menlo Park, CA, USA
J. M. Byrd, J. D. Fuerst, E. Gluskin, Y. Ivanyushenkov, M. Kasa, E. R. Moog, M. F. Qian, Y. Shiroyanagi
Argonne National Laboratory, Lemont, IL, USA

Abstract

We present FEL-suitable superconducting undulator (SCU) and cryomodule (CM) designs based on previous SCU designs at Argonne National Lab. The new SCU and CM designs will allow us to connect one CM to the next to form a contiguous line of SCUs with no breaks in between the cryomodules. The SCU design will have correctors and phase shifters integrated into the main SCU magnet core, as well as external corrector magnets for trajectory corrections. There will also be a cryogenic magnetic quadrupole and a cold RF beam position monitor (BPM) inside each SCU CM. In addition to providing the usual FODO transverse focusing, the quadrupole and BPM will be used in the beam-based alignment technique that is necessary for X-ray FEL operation. In this paper, we present the conceptual design of the compact SCU CM as well as FEL simulations using three SCUs as the afterburners for the Linac Coherent Light Source (LCLS) hard X-ray undulators.

INTRODUCTION

Permanent magnet undulators (PMUs) have long been the critical components of synchrotron radiation facilities and X-ray free-electron lasers (XFELs) for generating intense monochromatic X-rays. In recent years, superconducting undulators (SCUs) have been developed and tested at the Advanced Photon Source [1] and the Angströmquelle Karlsruhe [2] synchrotron facilities. A previous R&D effort [3] was executed in 2014-2016 to develop and compare two competing planar SCU technologies for XFEL: NbTi at ANL and Nb_3Sn at LBNL. SLAC and ANL are presently collaborating in a project to design, build and test NbTi SCUs on the LCLS hard X-ray (HXR) undulator beamline. The goal is to demonstrate key features such as FEL suitable magnetic fields, thermo-mechanical properties, beam-based alignment, and FEL gains of SCUs in a working XFEL.

Worldwide Development of SCUs for XFELs

As of 2022, four FEL facilities in the world are developing SCUs for XFELs (Table 1). Besides the LCLS SCU project, the SHINE facility in Shanghai [4] and the European XFEL [5] in Hamburg are building SCUs to be driven by SRF linac. Fermilab is constructing an SCU prototype that will be considered for use in the AQUA undulator line of the SPARC_Lab laser plasma accelerator (LPA) [6].

Table 1: Parameters of SCUs for XFELs

	LCLS	SHINE	EXFEL	FNAL
SC material	**NbTi**	**NbTi**	**NbTi**	**NbTi**
Period (mm)	21	16	18	16
Vacuum gap (mm)	5	4	5	5
Magnet length (m)	2	2	2	<1.6
# magnets/CM	1	2	2	1
# CMs	3	40	5	TBD

SCU BENEFITS FOR XFEL

SCUs deliver high magnetic field, a convenient way to vary the undulator field, improved resistance to radiation induced damage, and smooth electron beam chambers with high electrical conductivity surfaces to minimize resistive wall heating [7]. The SCU resistance to radiation allows them to be driven by the large-energy-spread and divergent electron beams from an LPA [8]. The large-bore high vacuum beam chambers facilitate operation with the high repetition rate electron bunches from a superconducting

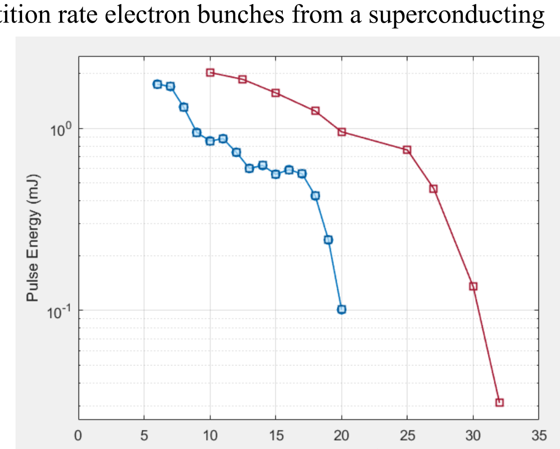

Figure 1: Expected performance of the LCLS-II-HE with 8-GeV electron beams driving the 26-mm-period HXRs (blue) and 16.5-mm-period SCUs (red).

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† dinhnguy@slac.stanford.edu

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RF linac such as the LCLS-II-HE [9]. Time-dependent FEL simulations show the 8-GeV LCLS-II-HE can produce up to 30 keV with the 16.5-mm-period SCUs, higher than the 20-keV limit of the 26-mm-period HXR undulators (Fig. 1).

Another advantage of SCUs for XFELs is the higher FEL gain if we shorten the SCU period. Figure 2 shows simulation results for a 3.9-keV FEL in the exponential gain regime. The 4-GeV electron beam from the LCLS copper linac is prebunched in seven HXR segments, followed by either three HXRs (blue dash) or three SCUs (red solid).

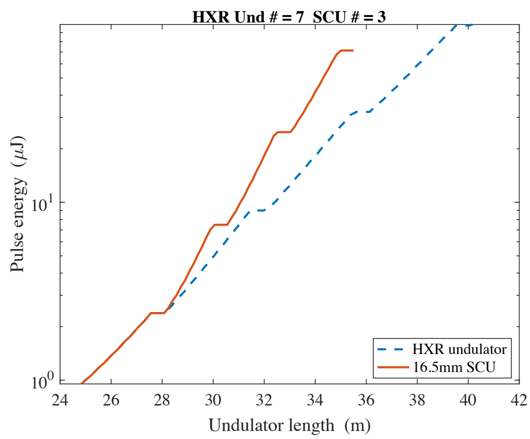

Figure 2: Calculated pulse energy in the exponential gain (linear) regime for the 26-mm-period HXRs (blue) and 16.5-mm-period SCUs (red).

SCU REQUIREMENTS FOR XFEL

The SCU magnetic requirements for XFEL operation are much more stringent than those for synchrotron facilities (see Table 2). The variation in the undulator K parameter within one SCU segment is not specified because it is related to the phase shake. The latter is defined as the standard deviation of the average phases of the radiation in different periods over the length of each SCU segment.

Table 2: Magnetic Requirements for XFELs

	Symbol	Value
K variation from one SCU to another	$\left\lvert\frac{\Delta K_{eff}}{K_{eff}}\right\rvert$	2.3×10^{-4}
1st field integral	$\left\lvert\int B_{x,y} dz\right\rvert$	$\leq 40\ \mu\mathrm{T}\cdot\mathrm{m}$
2nd field integral	$\left\lvert\iint \left(B_{x,y} dz\right) dz\right\rvert$	$\leq\ 75\ \mu\mathrm{T}\cdot\mathrm{m}^2$ Within segment $\leq 150\ \mu\mathrm{T}\cdot\mathrm{m}^2$ Between two segments
Phase shake	$\langle\Delta\phi\rangle_{rms}$	$\leq 4^{\circ}$

SCU DESIGN CALCULATIONS

Planar NbTi SCUs are fabricated with superconducting coils wound inside the shallow pockets around the iron cores that form two jaws of the SCU magnets (Fig. 3). The wound cores are then impregnated with epoxy before assembly. The SCU on-axis magnetic field can be calculated using commercial ANSYS Maxwell 2D and 3D software. Shiroyanagi has modelled the corrector coils wound on both ends of the main SCU magnet (Fig. 3) and obtained field integrals that meet the requirements in Table 2 [10]. Qian has configured the end corrector coils as an integrated phase shifter and shown the feasibility of varying the phase of the electron motion with the integrated phase shifter over a range of phase integrals [11].

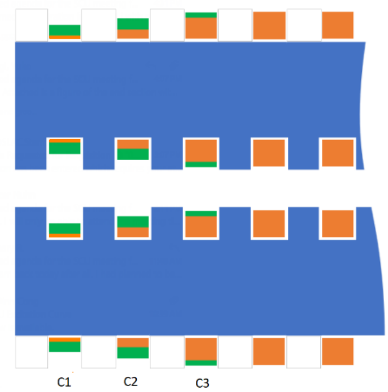

Figure 3: Schematic of one end of the SCU with corrector /phase shifter C1-C3 coils (green) and main coils (orange).

For the initial test of SCU on the HXR beamline, we chose a longer period of 21 mm to be in resonance with the HXR over a large range of beam energies. The on-axis magnetic fields at two different magnet gaps are plotted versus current in Fig. 4. For the 21-mm SCU, we estimate a maximum current of 590 A for the 0.7 mm NbTi wire [12] immersed in a 5 T magnetic field which is approximately the field on the surface of the NbTi wires at 590 A.

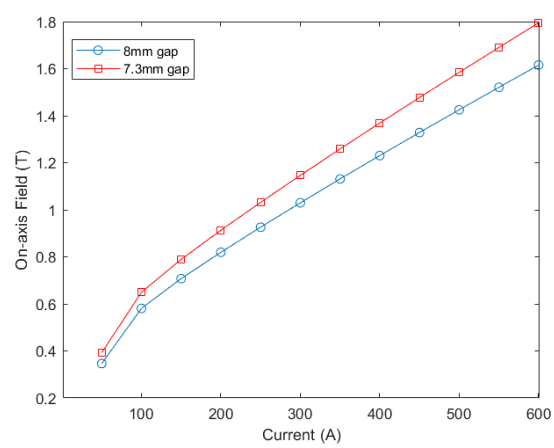

Figure 4: Excitation curve for the 21-mm-period SCU with 7.3-mm magnet gap (red) and 8-mm magnet gap (blue).

CRYOMODULE DESIGN

We have developed the conceptual design of modular SCU cryomodules (CMs) that can be connected to form a contiguous line of SCUs at the end of the HXR beamline (Fig. 5). This design will incorporate a focusing quadrupole and a BPM inside each CM. The CMs are

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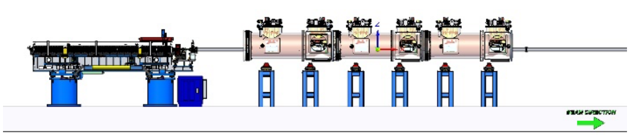

Figure 5: Schematic of three interconnected SCUs at the end of the hard X-ray (HXR) undulator line.

interconnected with no breaks between them to maximize the packing fraction, defined as the ratio of the magnet length divided by the CM total length.

A conceptual 3D engineering model has been generated for the modular SCU-CM in order to demonstrate the relative positioning and dimensions of all major components (Fig. 6). The 2-m SCU magnets are installed in a suitable strongback girder support system. Each end of the strongback girder is hung from support rods that can be adjusted externally in order to align the beamline components. The entire set of the strongback girder, SCU magnets, quadrupole and BPM move together as a rigid body.

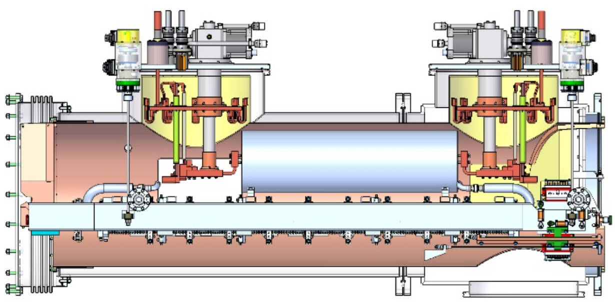

Figure 6: Engineering model of the compact and modular cryomodule design incorporating external adjustments for SCU magnet alignment with high position resolution.

CHALLENGES

Alignment

The alignment of components in the SCU CMs relative to the electron beam axis is critical to the XFEL performance. At the LCLS a well-established technique exists for installing and aligning the undulators, quadrupoles and BPMs initially to within ±50 µm, followed by beam-based alignment that reproducibly establishes a common optical axis along the entire undulator about which the quadrupoles and BPMs are centered to better than ±5 µm. This procedure must be duplicated for the same components in the SCU CMs, but with the added complication that the components are now located in the vacuum vessel and cooled to cryogenic temperatures. The SCU CM design incorporates linear actuators with sub-micron resolution and mechanical and optical diagnostics to monitor the motions of the SCU magnets during cooldown. We are testing the SCU mechanical and optical alignments using a prototype called Precision Alignment Test Stand, or PATS (Fig. 7) to demonstrate micron position accuracy and reproducibility of the entire cold mass at atmospheric pressure and under vacuum, as well as at room temperature and after cooldown to cryogenic temperature.

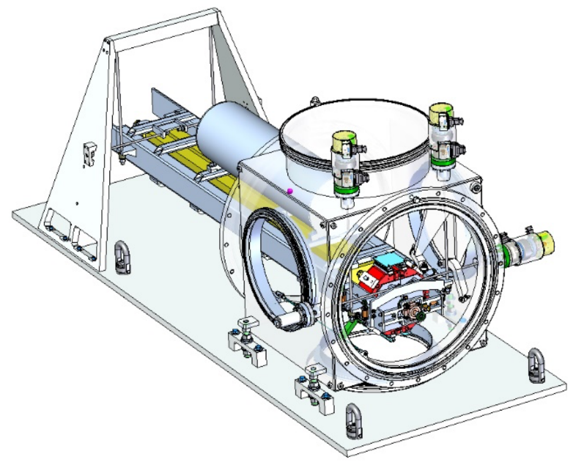

Figure 7: Model of the PATS showing the linear actuators at the quadrupole end that will be tested to demonstrate micron position accuracy and reproducibility.

Short-Period, Small-Gap SCUs

After successfully demonstrating the alignment and FEL performance on the LCLS, our next challenge is to design and fabricate short-period SCUs. The first short-period SCU will likely have 16.5-mm periods and a 7-mm magnet gap, with a vacuum beam chamber that is 5 mm wide in the narrowest dimension. The challenges of the short-period SCUs include more difficult fabrication, tighter alignment tolerances, smaller dimensions for the room-temperature Hall probe to fit inside the cold beam chamber during magnetic measurements, and more stringent cooling requirements to mitigate resistive wake heating in the chamber.

SUMMARY

SLAC and ANL are teaming to develop compact, modular SCU CMs to house 2-m NbTi magnets with integrated corrector coils, phase shifters, beam position monitors and focusing quadrupoles. The modular design allows magnetic measurements to be performed on a single SCU. The assembled module can be transported individually into the LCLS undulator hall and meets all the height and width clearance requirements to maneuver past the existing LCLS hard and soft X-ray undulators. FEL simulations show the 16.5-mm-period SCUs will have higher gain than the 26-mm-period HXR undulators.

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