Superconducting Undulators and Cryomodules for X-ray Free-Electron Lasers

NAPAC Paper THYE3

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)

J.M. Byrd, J.D. Fuerst, E. Gluskin, Y. Ivanyushenkov, M. Kasa, E.R. Moog, M.F. Qian, Y. Shiroyanagi (ANL)

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Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

- Why Superconducting Undulators for X-ray FELs?
- Worldwide development of SCUs for X-ray FELs
- SCU magnetic requirements
- SCU magnet designs
- SCU cryomodule designs
- Challenges

Why Superconducting Undulators for X-ray FELs?

Strong Magnetic Field

SCUs produce stronger field than IVUs and CPMUs for periods > 15 mm, same vacuum gap.

Convenient Tunability

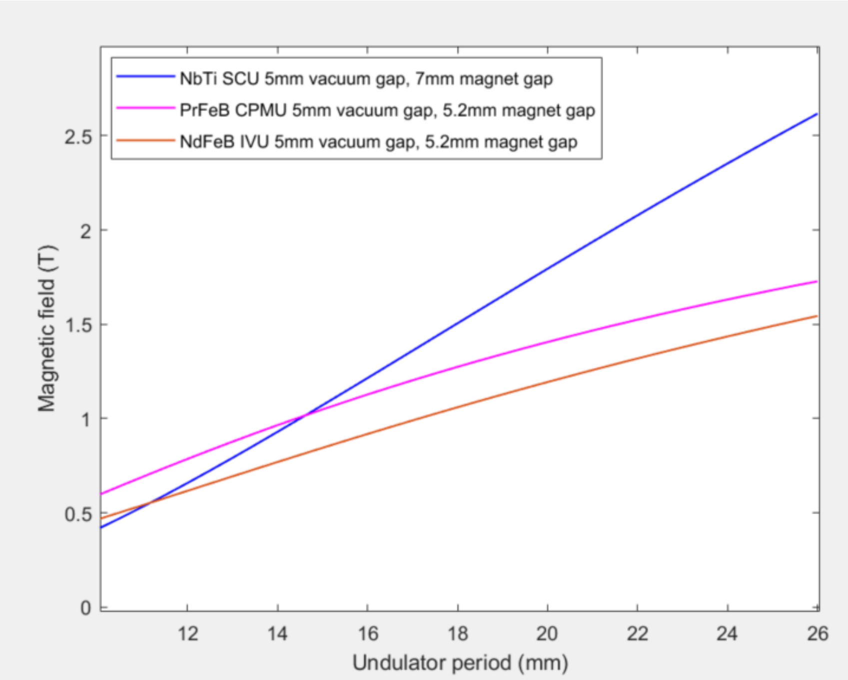
SCUs offer a convenient way to adjust the undulator magnetic field (for wavelength tuning, tapering) by varying the current in the SCU coils.

Resistance to Radiation Damage

Being resistant to demagnetization, SCU can be driven by the high-energy-spread electron beams from a Laser Plasma Accelerator.

Cryogenically Cooled Beam Chambers

The cold beam chambers provide smooth, high electrical conductivity surfaces that are suitable for high-repetition-rate X-ray FELs.

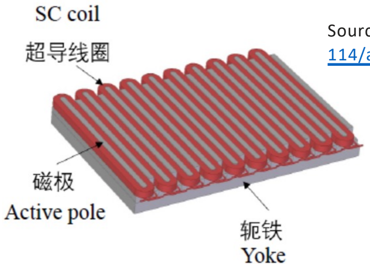


References:
1. J. Bahrdt and E. Gluskin. Cryogenic permanent magnet and superconducting undulators, Nuclear Inst. and Methods in Physics Research, A, Volume 907, p. 149-168 (2018).
2. E.R. Moog, R.J. Dejus, and S. Sasaki. Comparison of achievable magnetic fields with superconducting and cryogenic permanent magnet undulators – A Comprehensive Study of Computed and Measured Values, Light Source Notes, ANL/APS/LS-348.

Worldwide Development of SCUs for X-ray FELs

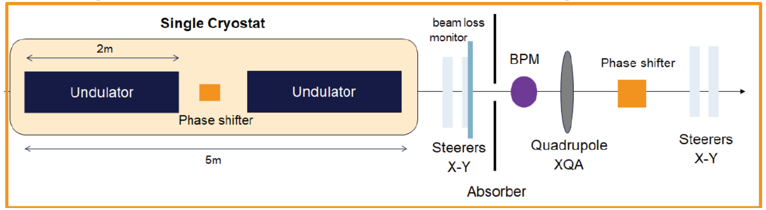
Parameters	LCLS	SHINE	Euro-XFEL	FNAL
SC material	NbTi	NbTi	NbTi	NbTi
Period (mm)	21	16	18	16
Vacuum gap (mm)	5	4	5	5
Magnet length (m)	2	2	2	<1.6
# of magnets per cryomodule	1	2	2	1
# of cryomodule	3	40	5	TBD

SHINE (SARI, China)



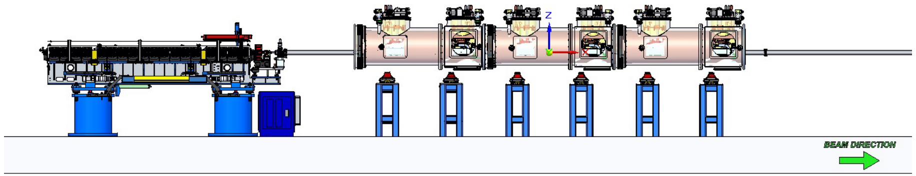
Source: https://indico.desy.de/event/28501/contributions/99114/attachments/65299/80635/SCU%20workshop_zhou.pdf

European XFEL (DESY, Germany)



B. Marchetti et al., Study of the Tolerances for Superconducting Undulators at the European XFEL, IPAC 2021, Campinas SP Brazil, Paper THPAB035

LCLS (SLAC, USA)



SCU after-burners at the end of the LCLS Hard X-ray undulators

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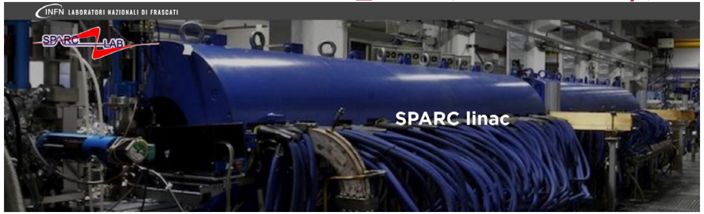
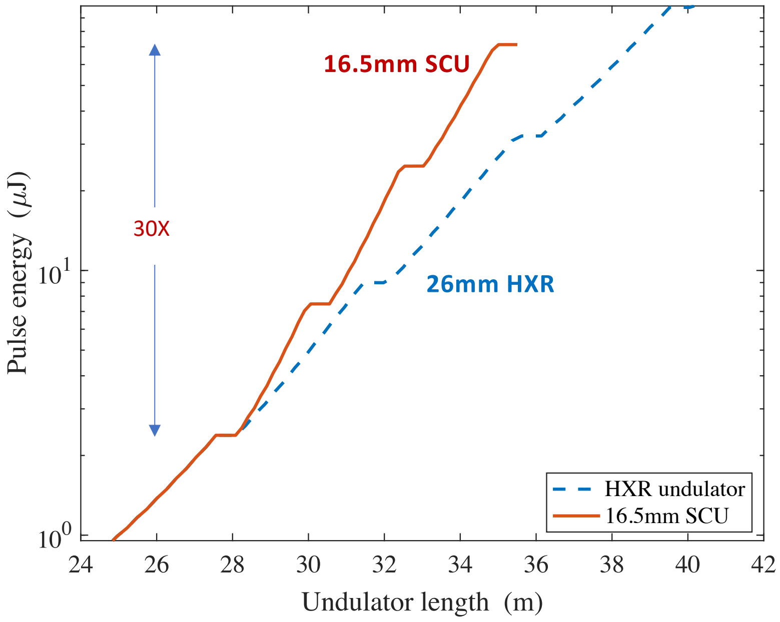


Expected Performance with LCLS and LCLS-II-HE Beams

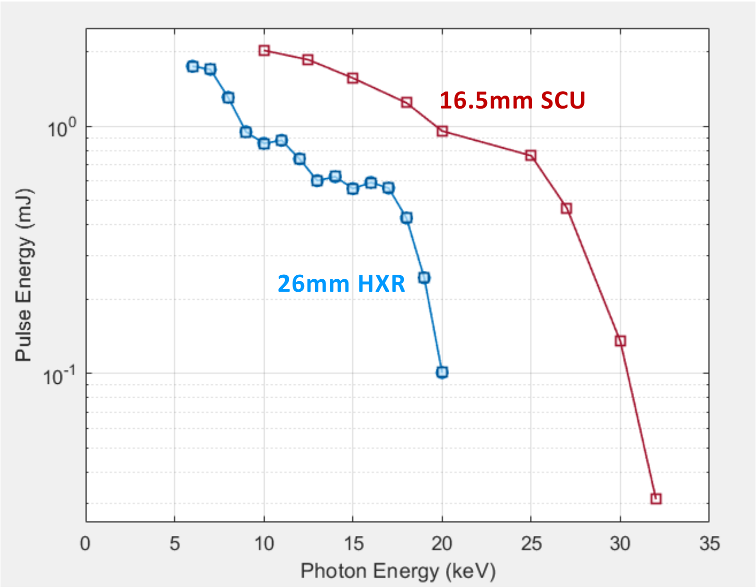
Higher Gain with Short-period SCUs

LCLS 4-GeV beam with seven HXR undulators as prebunchers



Higher Pulse Energy and Photon Energy

LCLS-II-HE 8-GeV beam with the low-emittance injector



Simulations performed by Zhen Zhang (SCU) and David Cesar (HXR)

SCU Magnetic Requirements for X-ray FEL

Undulator *K* tolerances

Segment-to-segment delta_K

$$\left|\frac{\Delta K_{eff}}{K_{eff}}\right| = 2.3 \times 10^{-4}$$

Field integrals

First field integral

$$\left|\int B_{x,y} dz\right| \leq 40\mu T \cdot m$$

Second field integral

$$\left|\iint (B_{x,y} dz) dz\right| \leq 75\mu T \cdot m^2 \quad \text{Within segment}$$

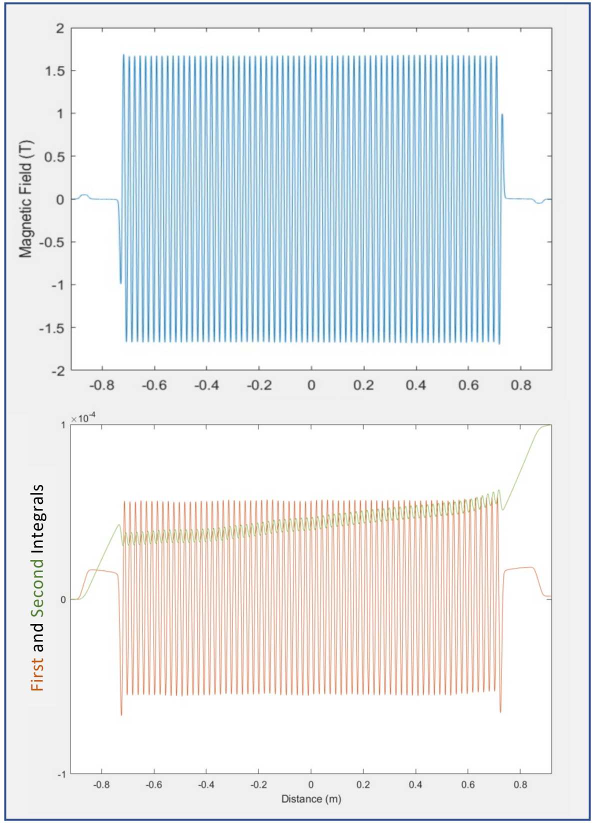
$$\leq 150\mu T \cdot m^2 \quad \text{Between segments}$$

Phase shake

$$\langle \Delta\phi \rangle_{rms} = \left(\langle \phi \rangle_{\lambda_u}(z) - \left\langle \langle \phi \rangle_{\lambda_u}(z) \right\rangle \right)_{rms}$$

$$\langle \Delta\phi \rangle_{rms} \leq 4^{\circ}$$

FEL SCU magnetic requirements established by Heinz-Dieter Nuhn



Reference: LCLS SCU Magnetic Performance Data, Y. Ivanyushenkov, LCLS SCU Close-out, March 2016, ANL.

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Superconducting Undulator Design

SCU as an HXR afterburner

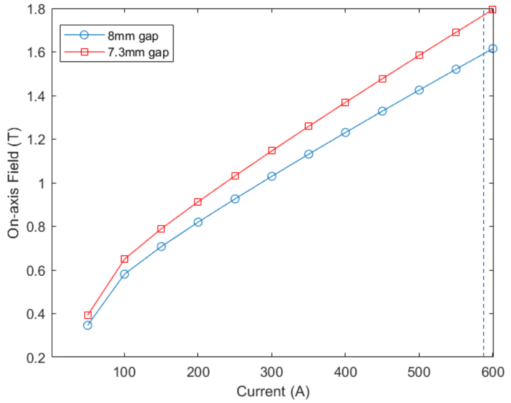
Parameter	HXR	21mm SCU	16.5mm SCU
Period length (mm)	26	21	16.5
Magnet length (m)	3.38	1.89	1.89
$\mathbf{K_{max}}$	2.54	3.0	3.4
$\mathbf{B_{max}}$ **(T)**	1.05	1.5	2.2

Matching resonant FEL wavelength

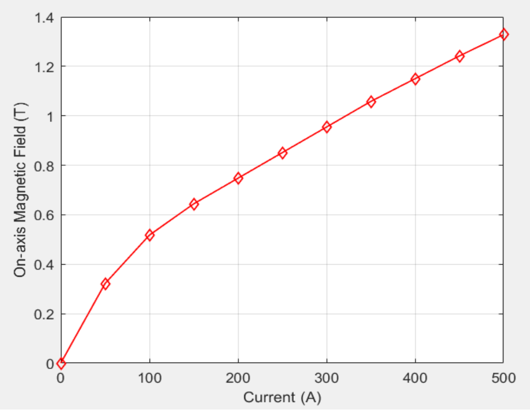
$$\frac{2 + K^2_{max,SCU}}{2 + K^2_{max,HXR}} = \frac{\lambda_{u,HXR}}{\lambda_{u,SCU}}$$

$$B_{max} = \frac{K_{max}}{.0934\ \lambda_u} (T - mm)$$

Excitation curves for 21mm NbTi SCU at 7.3mm and 8mm gap

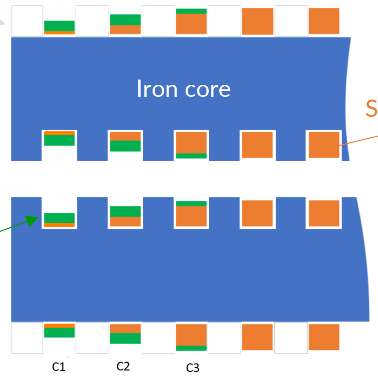


Excitation curves for 16.5mm period, 7.3mm gap NbTi

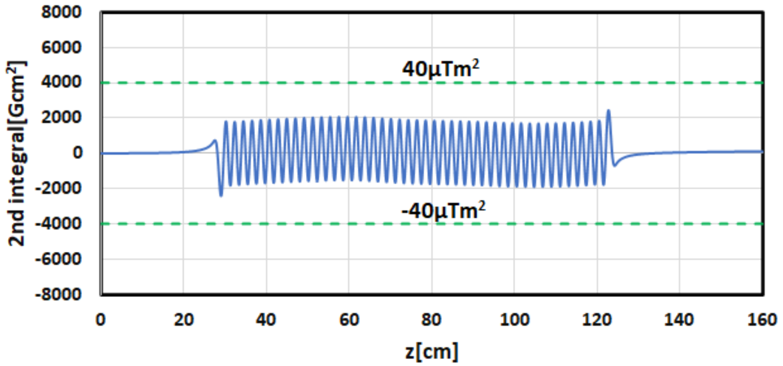


End Corrector & Phase Shifter Designs

Integrated correctors & phase shifter



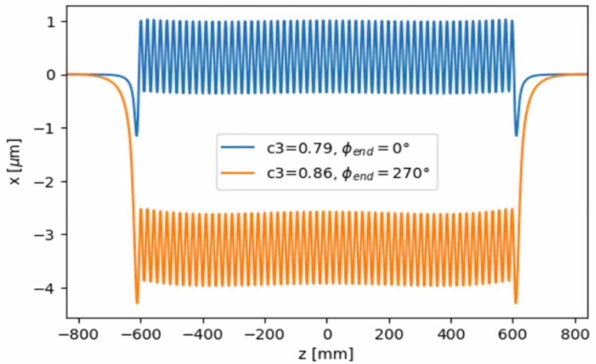
End corrector magnetic modelling performed by Yuko Shiroyanagi



Magnetic Field Calculation of Superconducting Undulators for FEL Using Maxwell 3D
Y. Shiroyanagi, M. Kasa, and Y. Ivanyushenkov (ANL), NAPAC 2022 Poster TUPA33

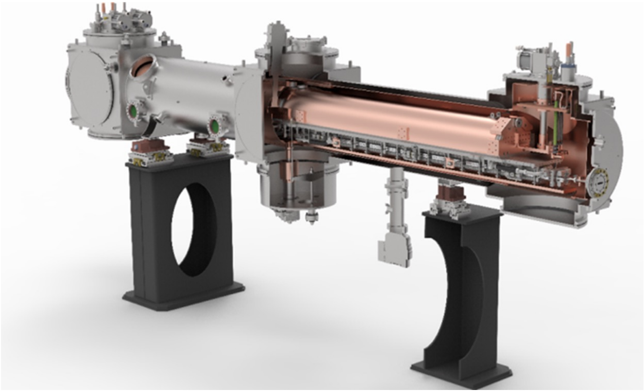
Phase shifter design calculations performed by Maofei Qian

Superconducting Undulator End Coils Configured as a
Phase Shifter, M. Qian (ANL), NAPAC 2022 Poster TUPA32

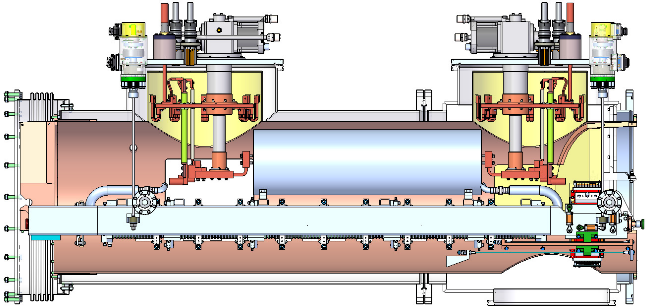


Cryomodule Designs

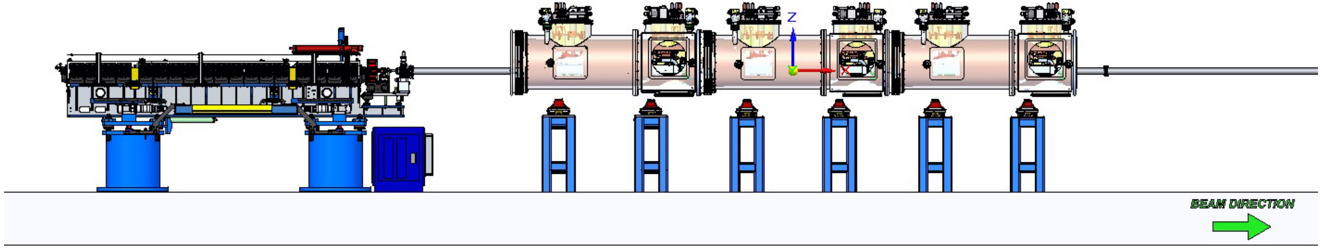
Standalone Cryomodules



Interconnected Cryomodules



$$Packing\ Fraction = \frac{Magnet\ Length}{Total\ CM\ Length}$$

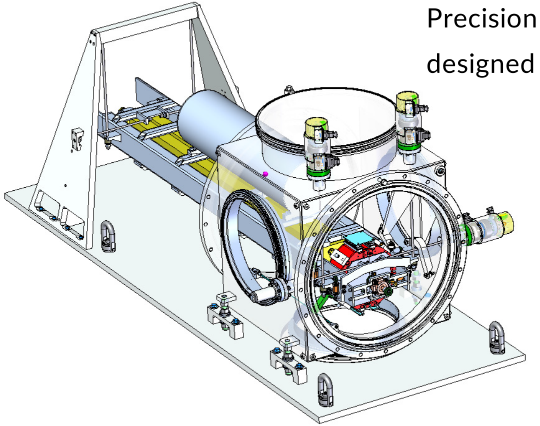


The interconnected cryomodule design will be tested on the HXR undulator line

Alignment is key to SCU operation in an X-ray FEL

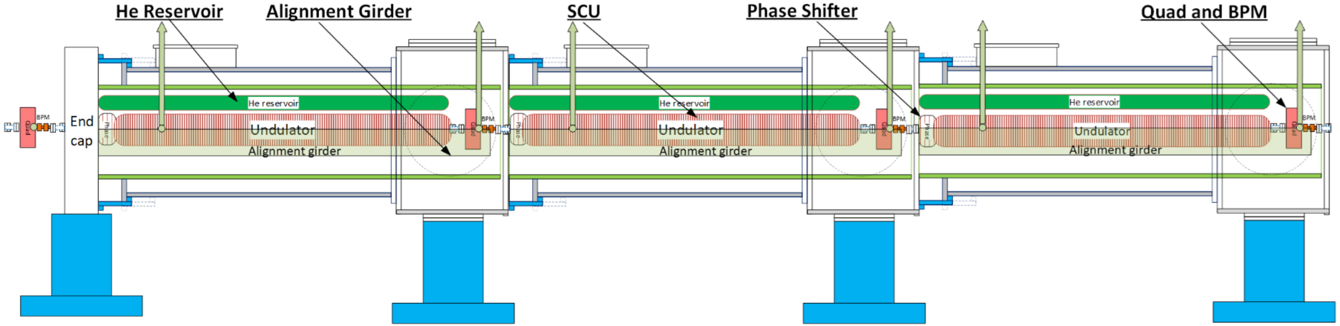
Mechanical & optical alignment

A set of SCU magnets, quad and BPM are mounted on the same strongback inside each cryomodule and move together as a rigid body. Mechanical & optical alignments will be tested to demonstrate micron position resolution and reproducibility on the Precision Alignment Test Stand.



Precision Alignment Test Stand designed by Gary Bouchard

Beam-based alignment



Multi-SCU alignment concept by Patrick Krejcik and others

Short-period, high-field SCUs

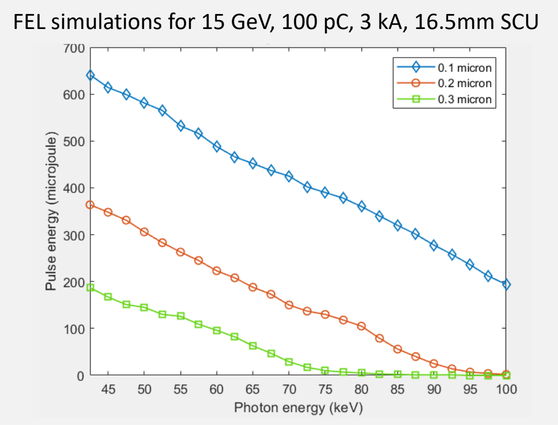
Benefits of short-period SCUs

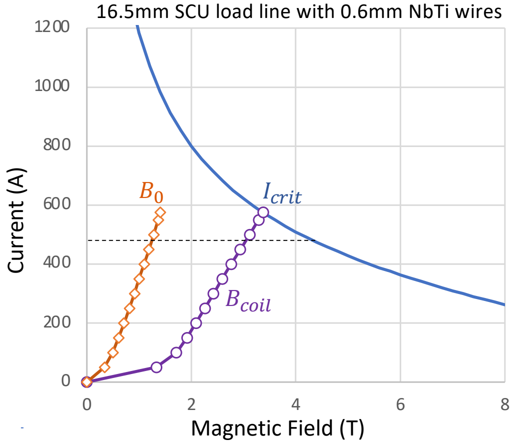
- Shorter saturation length (with low emittance)
- Higher photon energy (same electron beam energy)
- Lower electron beam energy (same photon energy)

Challenges of short-period SCUs

- Superconductor critical current (J_c and size of SC wire)
- Manufacturing challenges*
- Tighter alignment tolerances

* The Design and Manufacturing of Superconducting Undulator Magnets for the APS Upgrade
E. Anliker et al. (ANL), Mech. Eng. Design of Synchrotron Radiat. Equip. and Instrum., Chicago IL (2020)





Acknowledgments

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Thank you for your attention!

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