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Superconducting Undulators (SCU) R&D for World Leading X-ray FEL Capabilities

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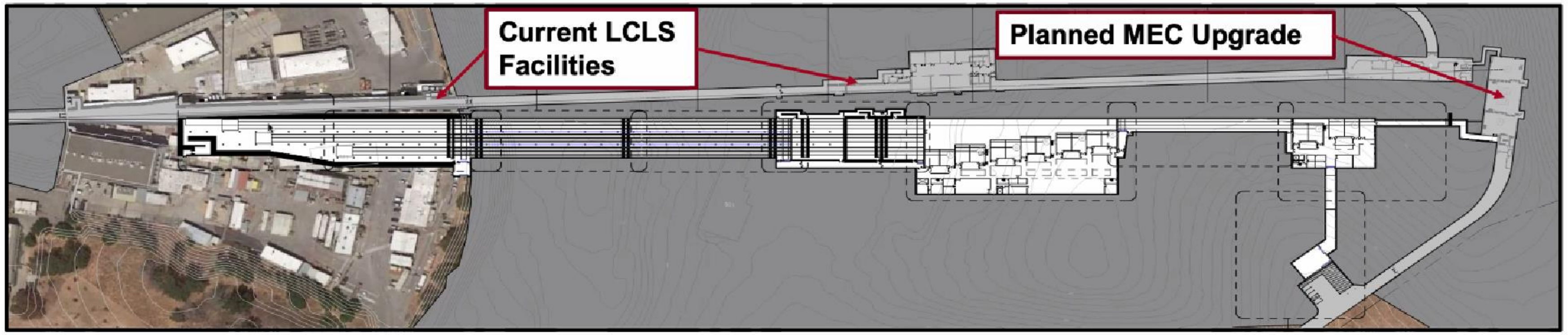
In Collaboration with Argonne National Laboratory

Motivation

- More powerful magnetic fields can be achieved with SC undulators than PM counterparts
  - Stronger fields and shorter period length translate into shorter wavelength and higher power at X-ray FELs
  - Shorter gain length results in more compact beamlines
- Additional benefits
  - Tunability
  - Radiation hardness
- Applications include
  - Multiple X-ray FEL beamlines at XFEL facilities such as the SLAC LCLS
  - Commercial application to FEL-based lithography machines

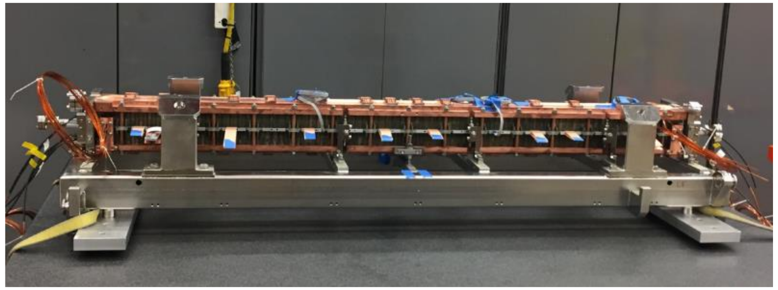
LCLS long-term plans include multiple FEL beamlines

- How to maximize the number of new, user beamlines?
  - Compact SCUs are the answer!



SCU State-of-the-Art in US storage ring light sources

- NbTi SCUs have been installed and tested on the APS
  - Two planar, one helical SCUs are being used
- Nb_3Sn SCUs have been built at LBNL and ANL
- A Nb_3Sn SCU has been tested on the APS



LBNL Nb_3Sn SCU

ANL APS-U SCU CM

- In 2015, ANL built a 1.5m NbTi SCU that met all requirements except for the kicks at entrance and exit
- ANL is building NbTi SCUs up to 1.9m in magnetic length for the APS-U project.

What does it take to integrate SCUs into an XFEL?

- Many undulators must now be installed on one contiguous beamline
  - Together with focusing quadrupoles, phase shifters, and Beam Position Monitors
- High packing fraction for components to achieve compact beamline layout
- Optical alignment along the entire length to within a few microns to reach peak performance
  - Achieved with remotely adjustable Beam-Based Alignment
  - And make sure undulator end-fields are completely corrected

Research Project Identification & Description

- **Project Title**: Superconducting Undulators for World Leading X-ray FEL Capabilities
- **Research Project Period**: August 2021 to August 2025
- **Research Project Brief Description**:

SLAC and Argonne are teaming to develop a modular, FEL-suitable SCU design with precision alignments, phase shifters, beam diagnostics and quadrupole magnets all integrated inside the cryomodule. The modular cryomodule design allows assembly and testing of individual SCUs prior to installation. The SCU modules can be transported individually into the LCLS Undulator Hall and bolted together at the end of the Hard X-ray Undulator (HXR) beamline. We plan to integrate three SCUs into the existing HXR beamline at LCLS in order to:

- Demonstrate the micron-precision beam-based alignment that is needed for XFEL
- Measure the FEL gain in the SCUs using the long HXR undulator as the electron beam prebuncher.

These demonstrations pave the way to the eventual integration of a full SCU FEL beamline at LCLS. The design of the SCU magnets and cryomodule therefore must allow connections of multiple SCUs to form a contiguous line of SCUs for the XFEL.

Collaborators/Institutions

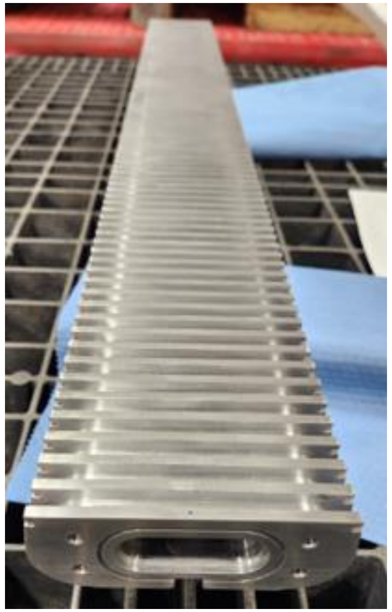
- **SLAC**
  - P. Krejcik PI
  - D. Cesar Co-PI
  - G. Bouchard, D. Caltabiano, G. Gassner, Z. Huang, E. Kraft, A. Haase, B. Lam, A.M. Montironi, C. Nantista, D.C. Nguyen, H-D. Nuhn, X. Permanyer, Z. Wolf, Z. Zhang,
- **ANL**
  - E. Gluskin PI
  - E. Antliker, J. Byrd, J. Fuerst, Y. Ivanyushenkov, M. Kasa, I. Kesgin, M. Qian, Y. Shiroyanagi, J. Xu

Progress in the following areas

- SC undulator magnet fabrication and testing
- Phase shifter magnetic design
- Modular cryomodule design
- Precision Alignment Test Stand
- Cryogenic Beam Position Monitor
- LCLS beamline installation plan

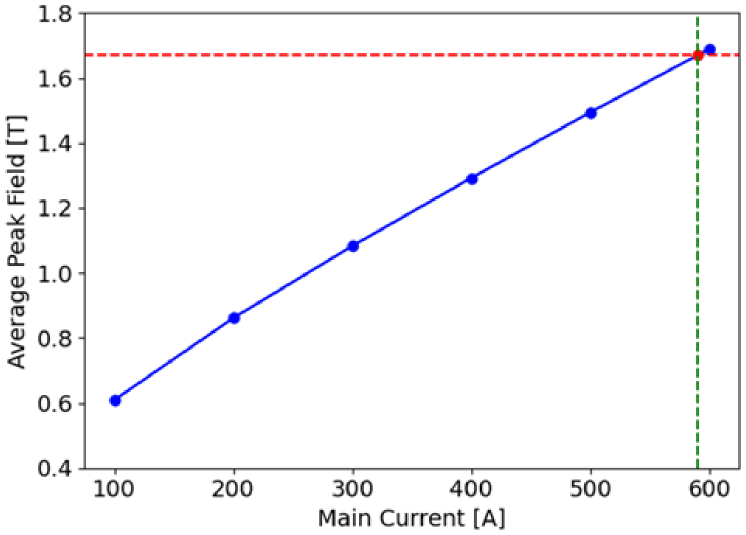
Magnet Prototype Fabrication & Characterization

1-m long magnet prototype was fabricated and tested in a vertical LHe-bath cryostat equipped with a movable Hall probe

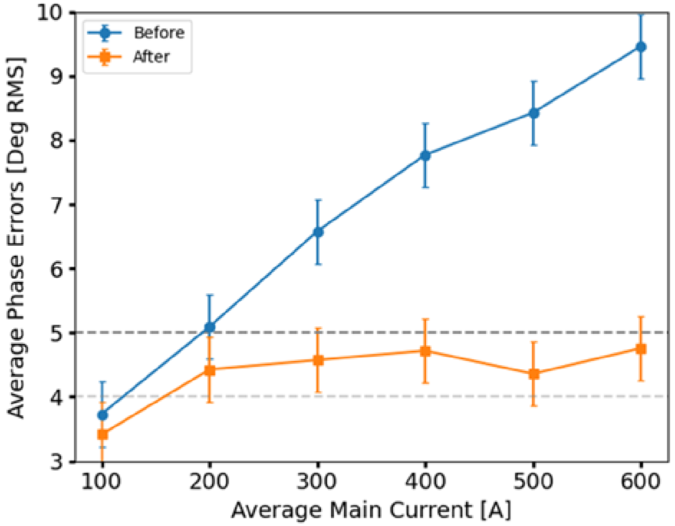


Machined core

Wound core



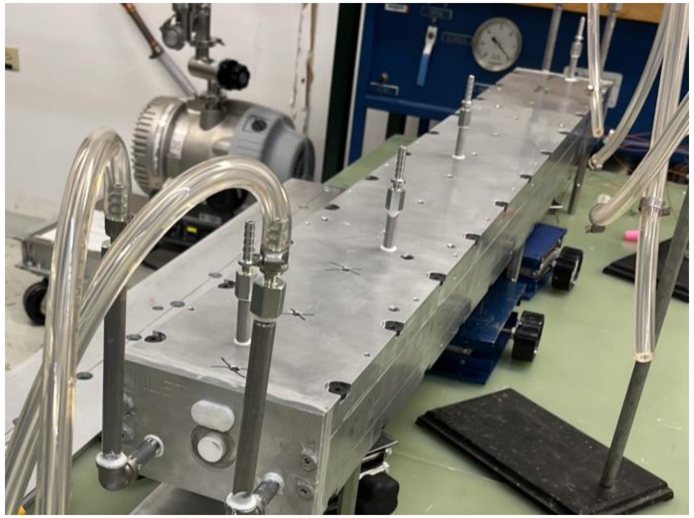
The measured magnetic field at 590 A current and 8 mm gap is 1.67 T corresponding to K of 3.26 (meeting FEL specifications).

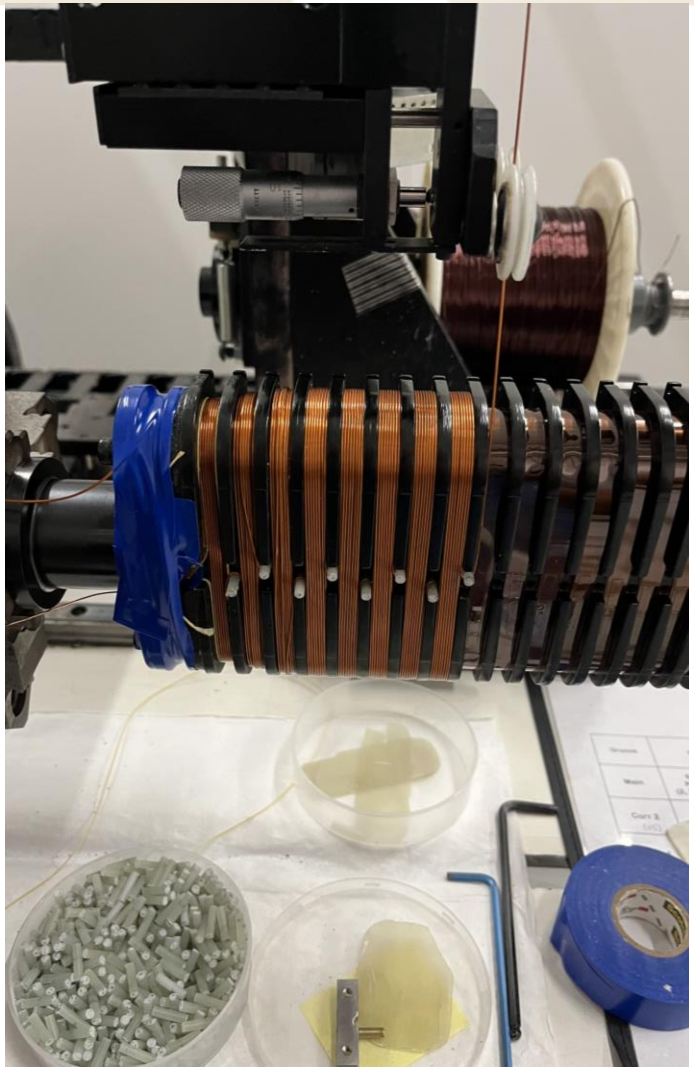


The phase error is less than 5 degrees rms (meeting specifications) after magnetic gap corrections (orange curve).

Features of this undulator magnet design

- Monolithic core without detachable pole pieces
- Application of insulating e-coating
- ANL winding technology and epoxy impregnation with windings under compression



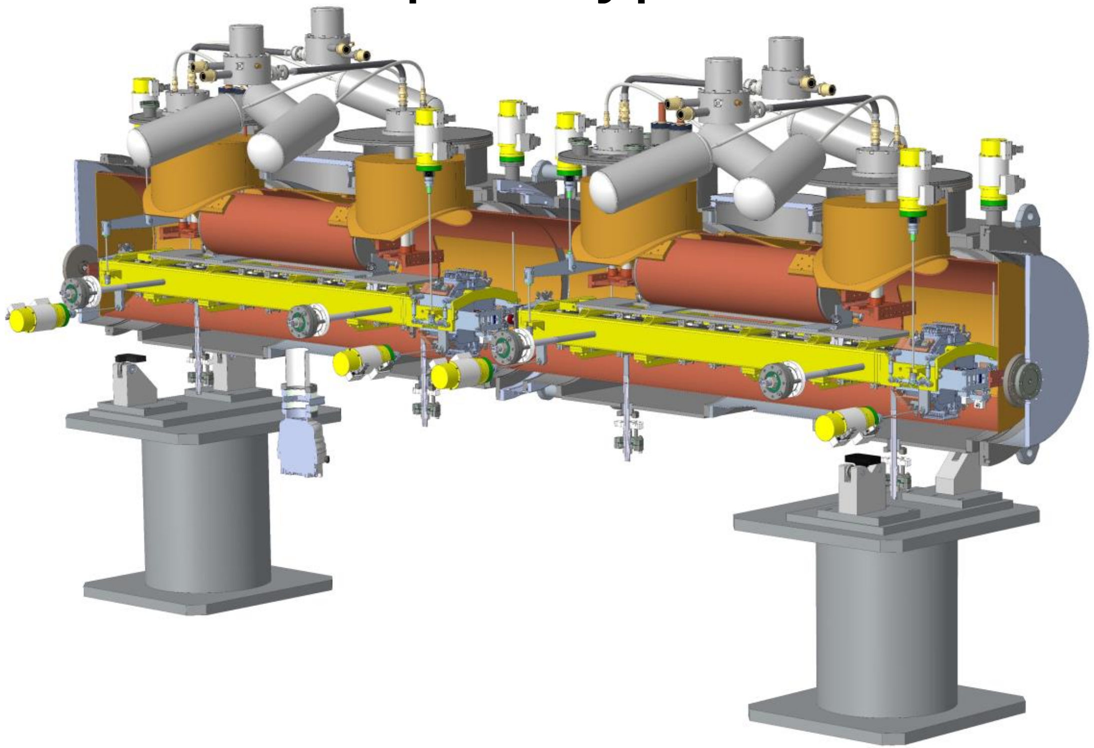


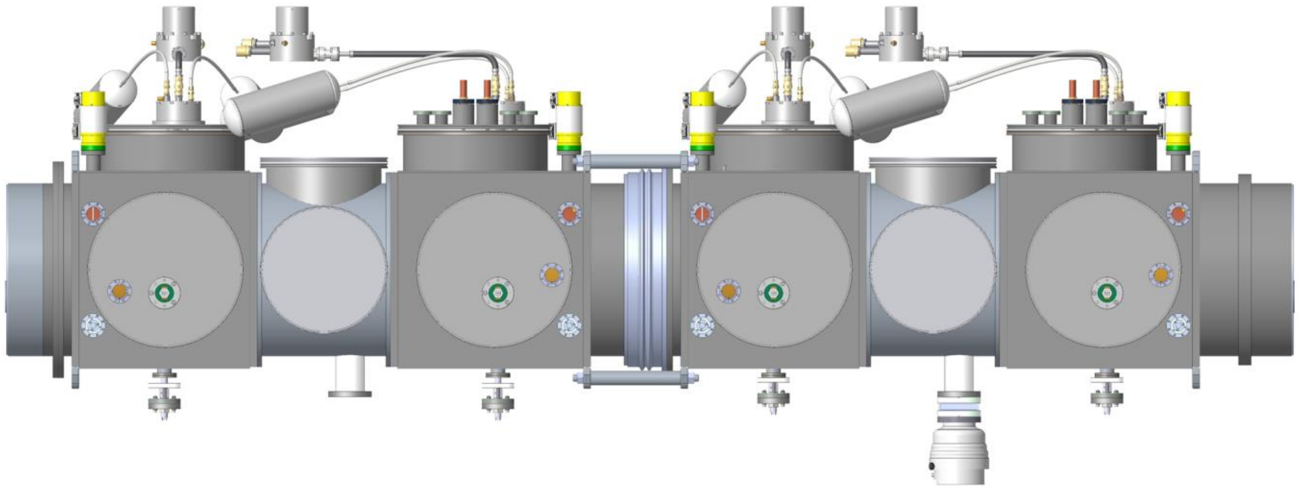
Late breaking news

- Although magnetic measurements in the vertical cryostat met the requirements
- Testing in the APS-U cryostat failed reliability testing
  - Ground faults developed between the core and the SC winding
- Some of the new core machining innovations in this design will be dropped in favor of older, proven techniques.
- ANL SCU magnet delivery could be delayed ~12 months

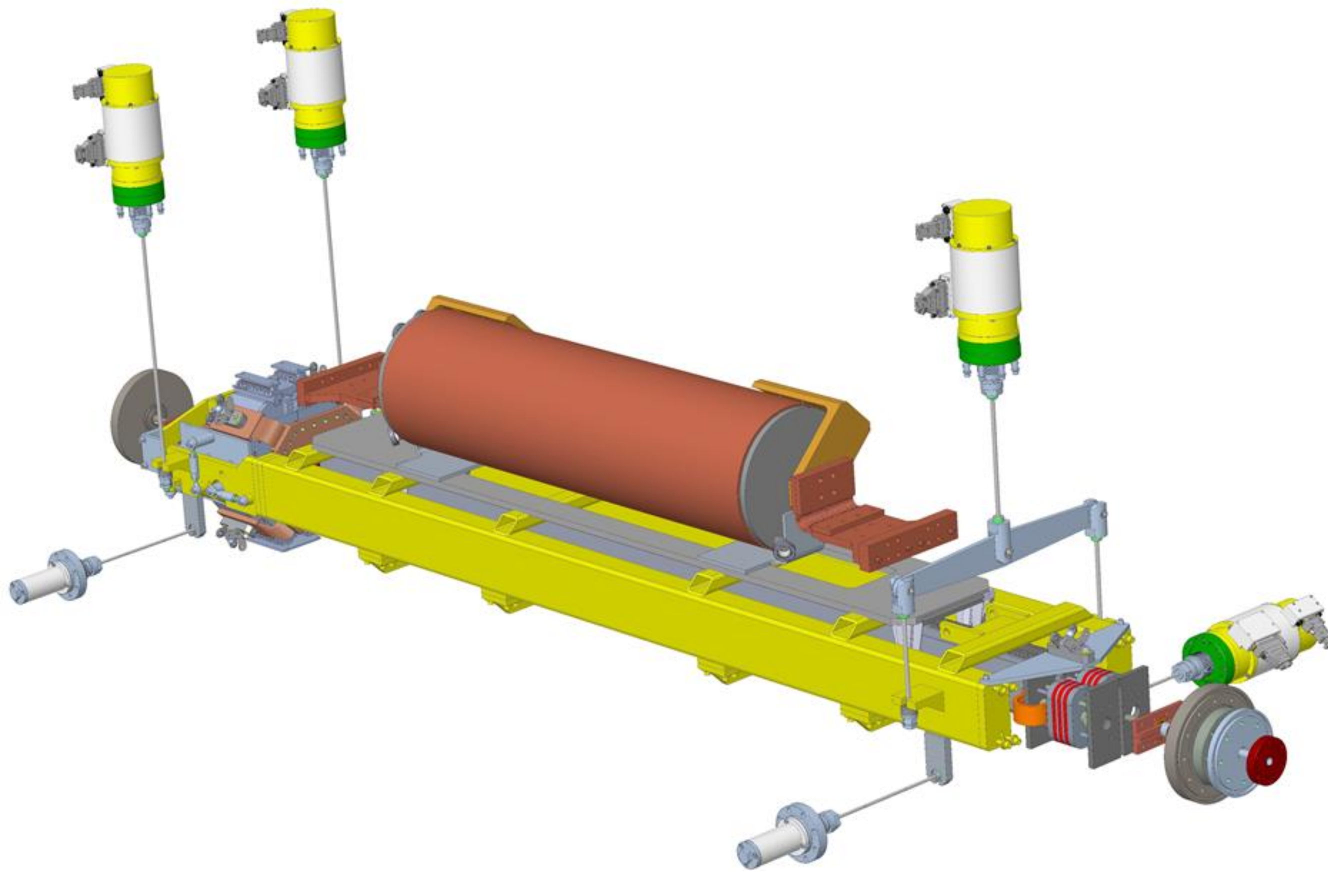
Key features of the cryomodule design

- Modular design approach with a high packing fraction
- Adjacent modules are bolted together with a common shield vacuum (same as the SLAC SC linac)
- The prototype is cooled with cryocoolers





Key features



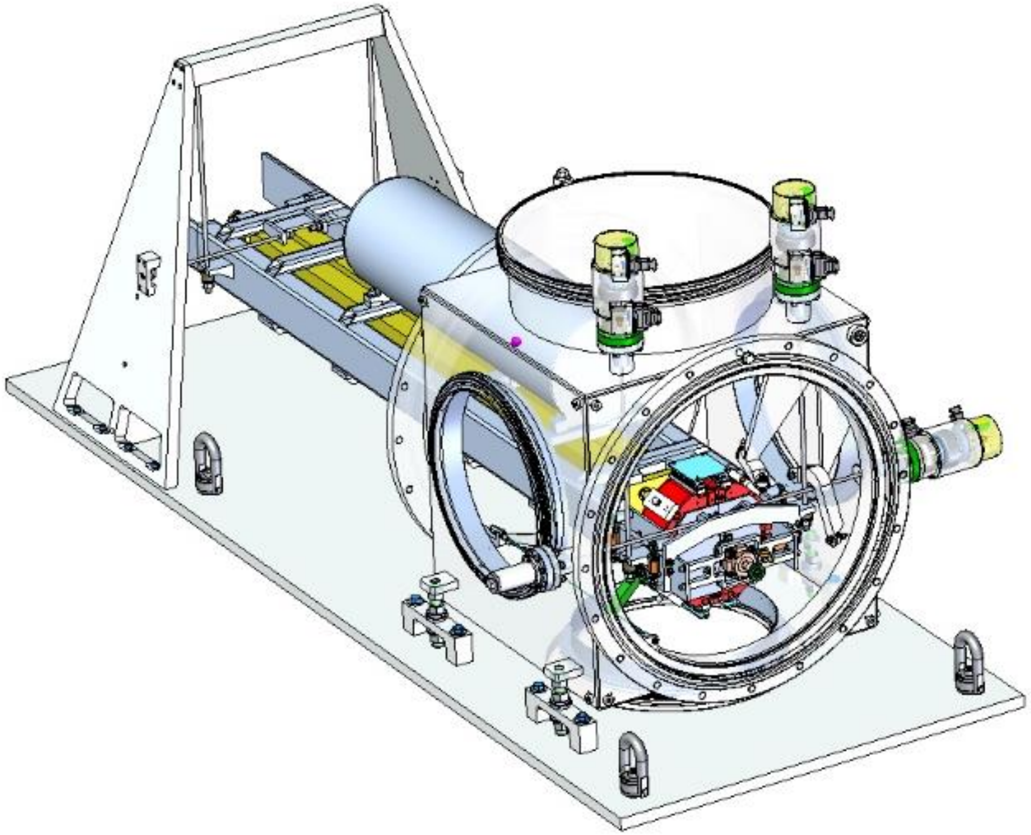
- Each module contains an SCU, phase shifter, quadrupole, and Beam Position Monitor.
- They are mounted on an internal strongback girder
- Which can be externally aligned during operation with micron adjusters

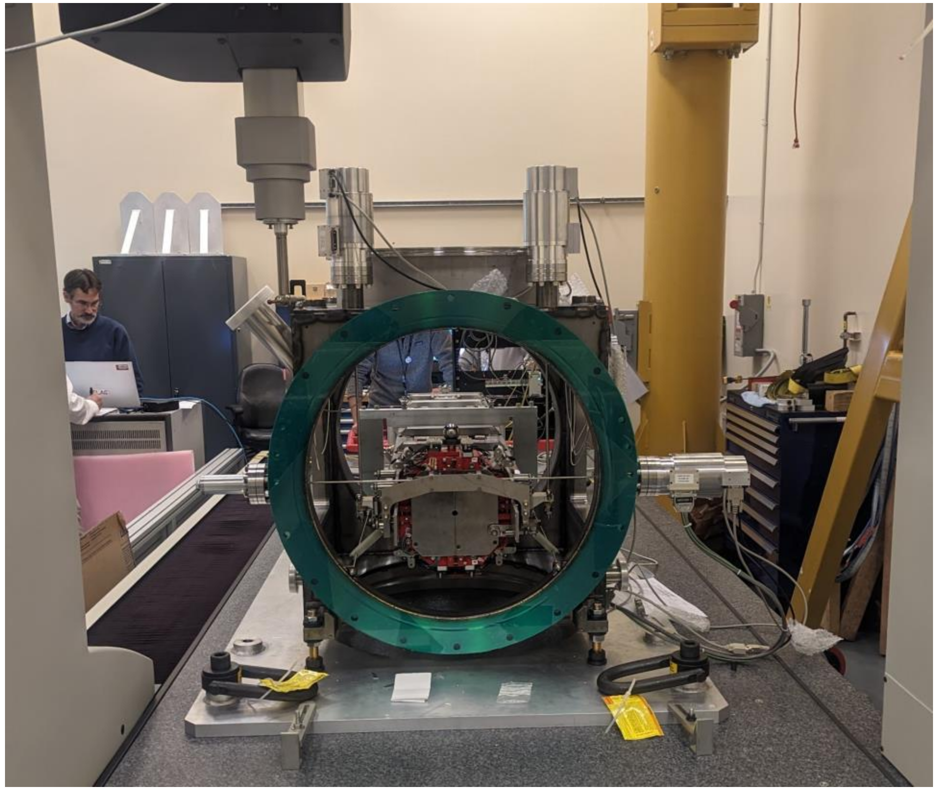
PATS, Precision Alignment Test Stand

- Beam-Based Alignment of the undulator beamline, to micron precision is critical to the performance of an X-ray FEL
- The new challenge is that now the components are inside a cryomodule and the internal support girder must be remotely and reproducibly adjusted with micron precision
- The engineering solution is undergoing testing at PATS

Phase 1 testing at the PATS

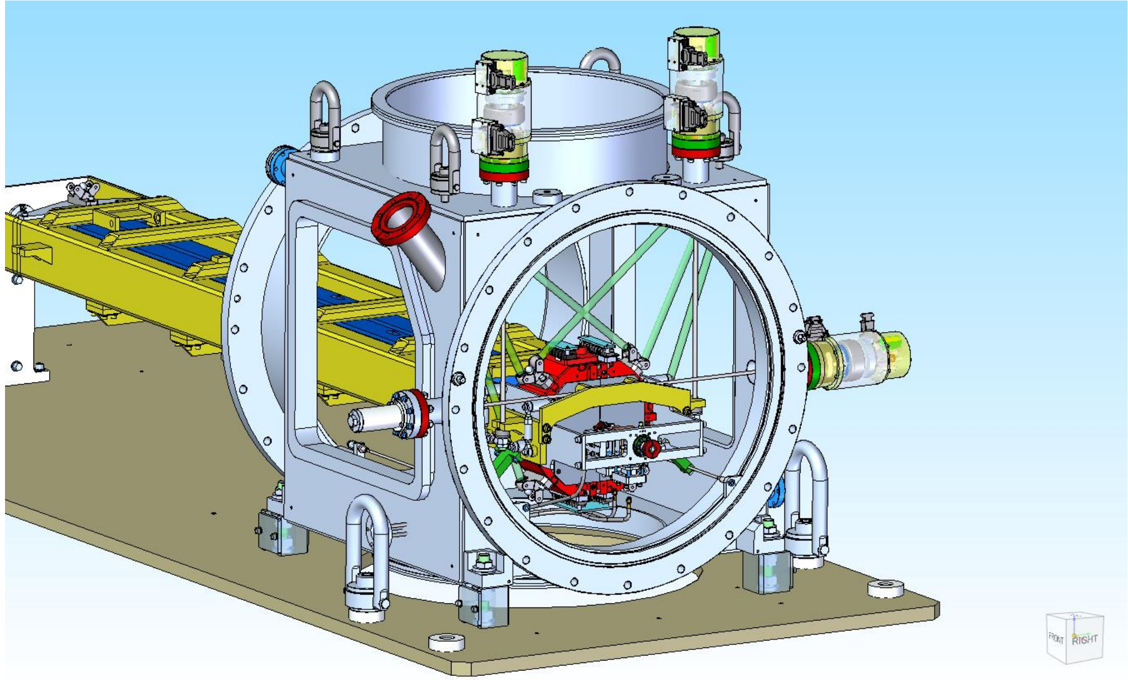
- Precision and reproducibility of linear actuators is confirmed on a Coordinate Measuring Machine, CMM





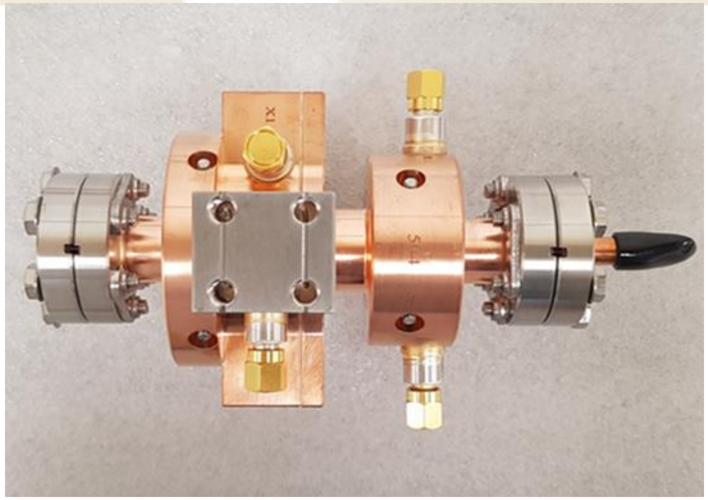
PATS Testing

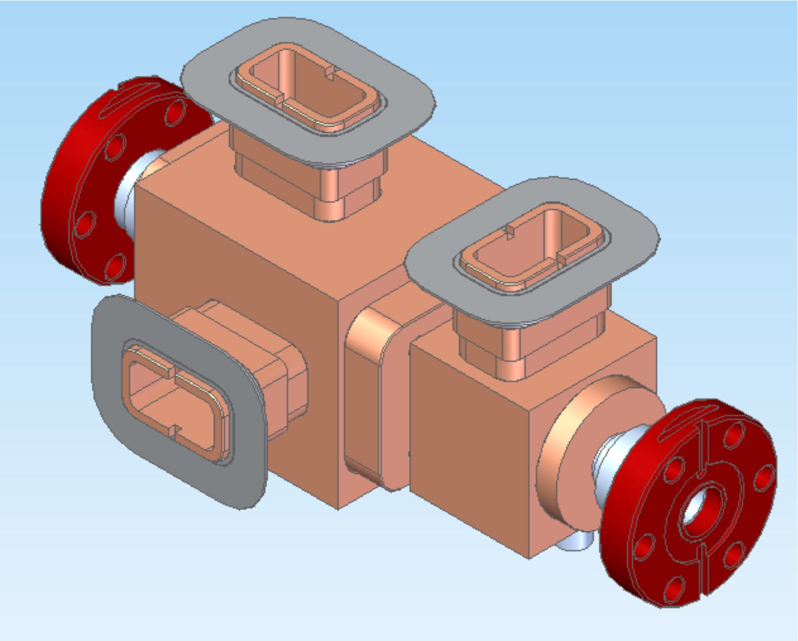
- Backlash and shaft wobble were revealed and corrected at the 10-micron level.
- Thanks in part to the commissioning of the internal optical interferometer measuring system
- The system is now being prepared for vacuum and cryogenic cooling tests

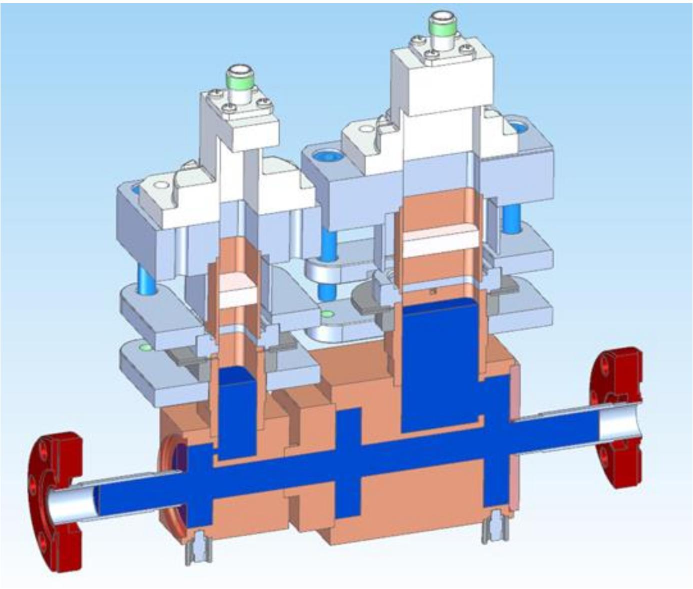


Cryogenic RF Cavity Beam Position Monitor

- Design based on the successful X-band RF cavity BPM used on the present LCLS undulator beamline
- Now engineered to withstand the temperature swings when cooled to 4.2K

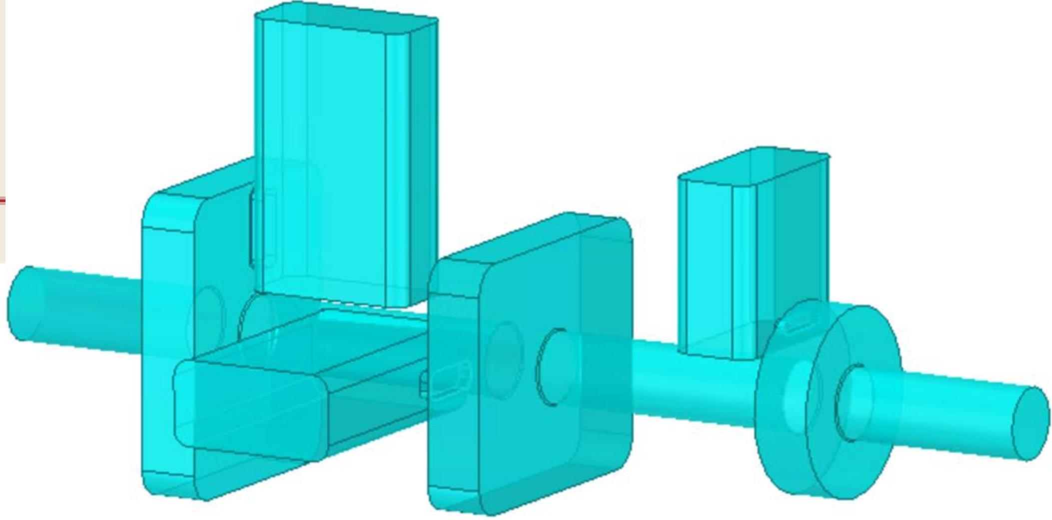


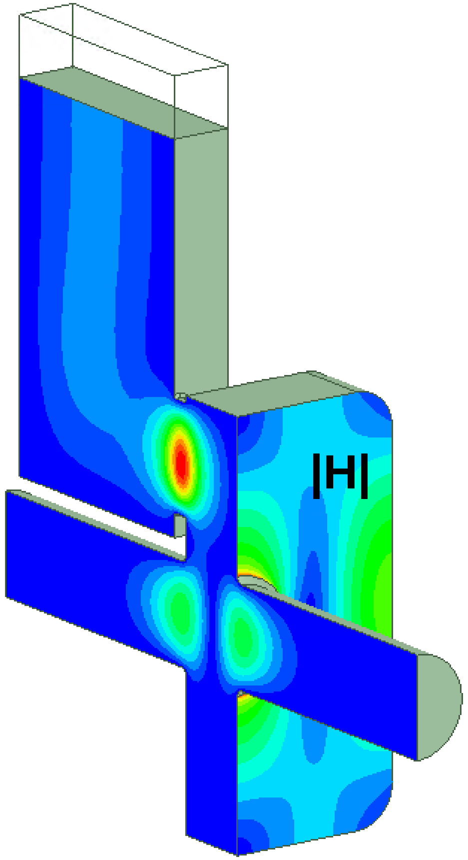




Position Cavity

- Separate, orthogonal X & Y cavities
- Degeneracy of diagnostic mode removed.
- Magnetically slot-coupled to a single waveguide.
- Coupling set for desired loaded Q and thus time constant τ.





$(R/Q)_\perp = (V/m)^2/(\omega U) =$ 3.63 Ω /mm² *
Q_0 (20K) = 50,772 (uncoupled)
$\rightarrow R_{s\perp}$ = 184 kΩ /mm² (uncoupled)

w/ ~20K Cu loss

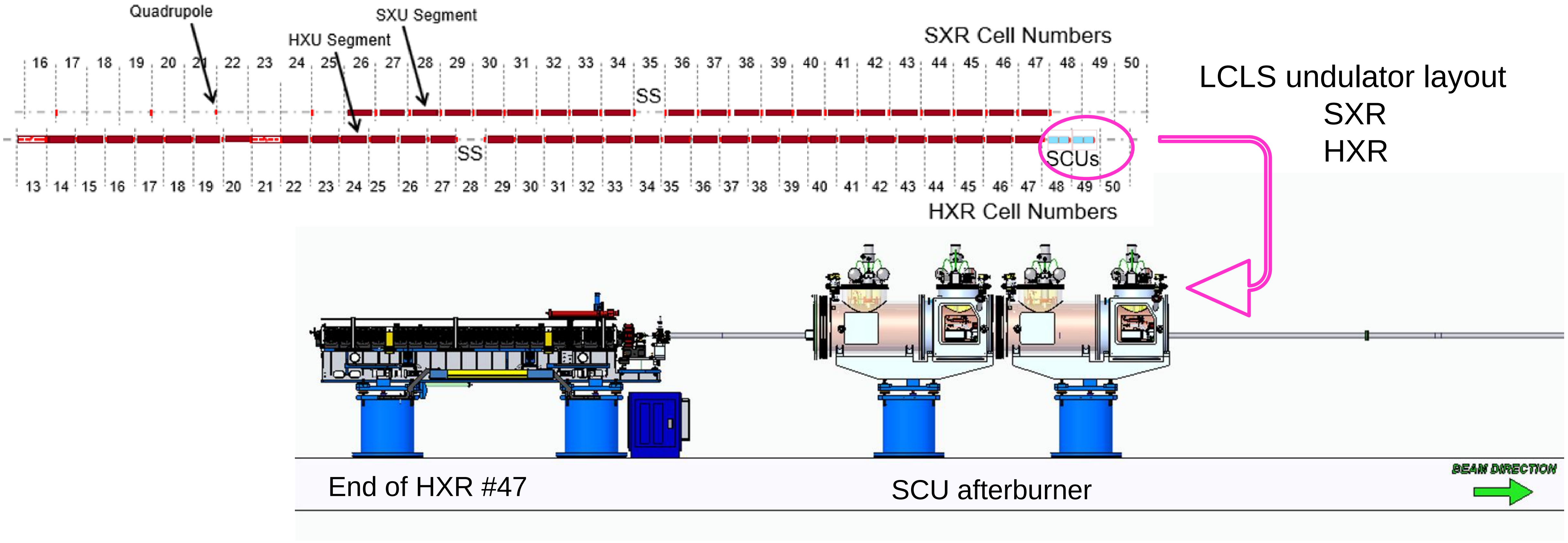
Q_0

Frequency (GHz)	Q
11.4239 +j 0.000112502	50772.1

Q_L

Frequency (GHz)	Q
11.4240 +j 0.00256930	2223.17

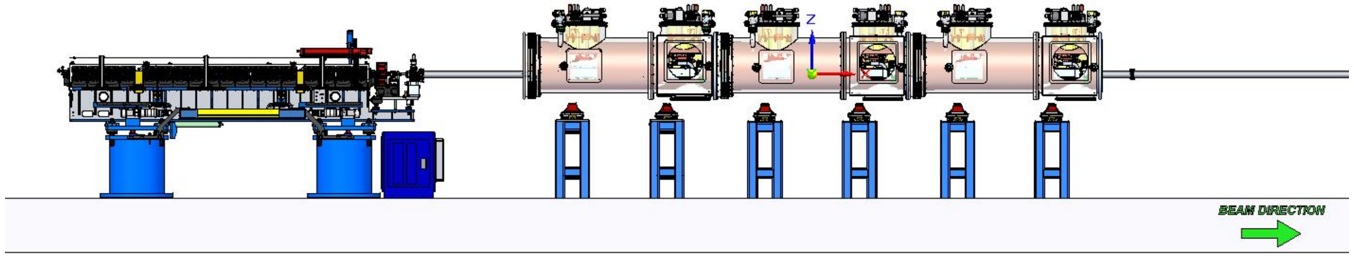
SCU Prototype Installation at end of LCLS HXR

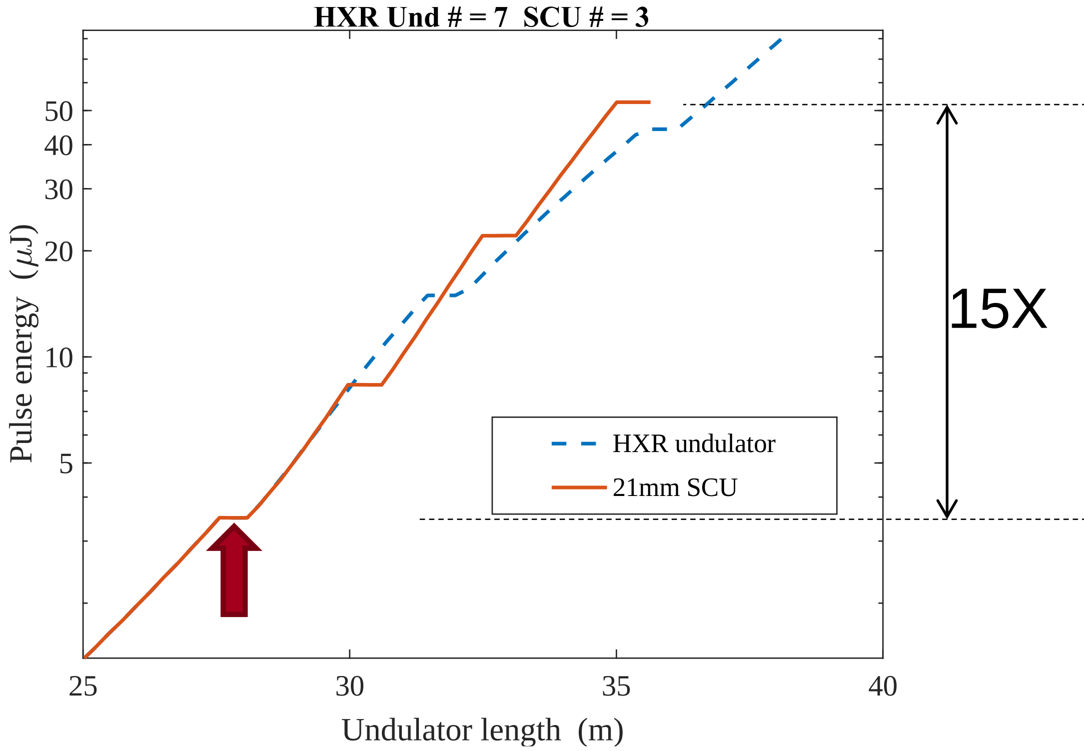


- SCU parameters chosen to match FEL resonance of existing HXR undulators
- Cryomodule design will be extendable into a full-length FEL beamline

Expected FEL Gains in Three SCU Modules

- Simulations show SCUs provide 15X FEL gains at 4.2 keV with seven HXR as pre-bunchers





Budget data

- BES Funding (used to pay for shop labor & materials):
  - FY21: $998.4k ($502.4k for SLAC; **$496k for ANL materials only**)
  - FY22: $1,103k (Spending of BES funds started in FY22)
  - FY23: $1,403k (Remaining balance = $150k)
  - FY24: $1,103k (to be received in August 2024)
- Total received: $3,504.4k
- Total BES funds: $4,607.4k
- SLAC PD Funding (used to pay for SLAC staff):
  - FY22: $650k
  - FY23: $400k
  - FY24: $500k (remaining balance = 200k?)
- Total SLAC PD funds: $1,550k

Proposed Schedule

FY22	FY23	FY24	FY25	FY26	FY27
PATS Design	PATS Fabrication	PATS Testing & CM Design Verification			
SCU Prototype Physics Design	SCU Prototype Engineering Design & Fab.	SCU Prototype Magnetic Characterization	SCU Magnet Fabrication	SCU Magnet Magnetic Characterization	
SCU-CM Conceptual Design	SCU-CM Engineering Design	SCU-CM Engineering Design	SCU-CM Fabrication & Assembly	Integrate SCU Magnets & Diag. into SCU-CM	
Physics Requirements	CDR	PDR Engineering Req.	FDR	Accelerator Readiness Review	
SCU FEL Physics Calculations					Installation on LCLS HXR Line
					BBA & FEL Gain Demo

Summary

- The SCU development program is a major initiative to keep US facilities at the forefront of X-ray FEL performance.
- SCUs will enhance the power and wavelength reach at LCLS, and provide the technology for compact, multiple FEL beamlines.
- The SCU prototype will demonstrate beam-based alignment and FEL gain measurement in a realistic FEL environment in 2026.
- SCU magnets are being developed and tested at ANL
- A modular cryomodule has been designed, suitable for a FEL
- Testing is underway on the PATS for the internal alignment control of the cold mass in the cryomodule, together with the cryogenic BPM

Other international SCU R&D

EuXFEL plans to develop the technology of SCUs as part of its facility development program

- an SCU afterburner is planned to increase the photon energy range of SASE2 towards harder X-rays and covering the present photon energy range by running with 8 GeV (CW upgrade)
- the first module, has been specified, the contract assigned to Bilfinger Noell GmbH, the TDR received and production has started
- two test facilities to characterize SCU coils and SCU undulators are under development
- R&D on advanced SCU coils

European XFEL