Development of the Vertically Polarizing Hard X-Ray Undulator Segments for the Linear Coherent Light Source Upgrade (LCLS-II)

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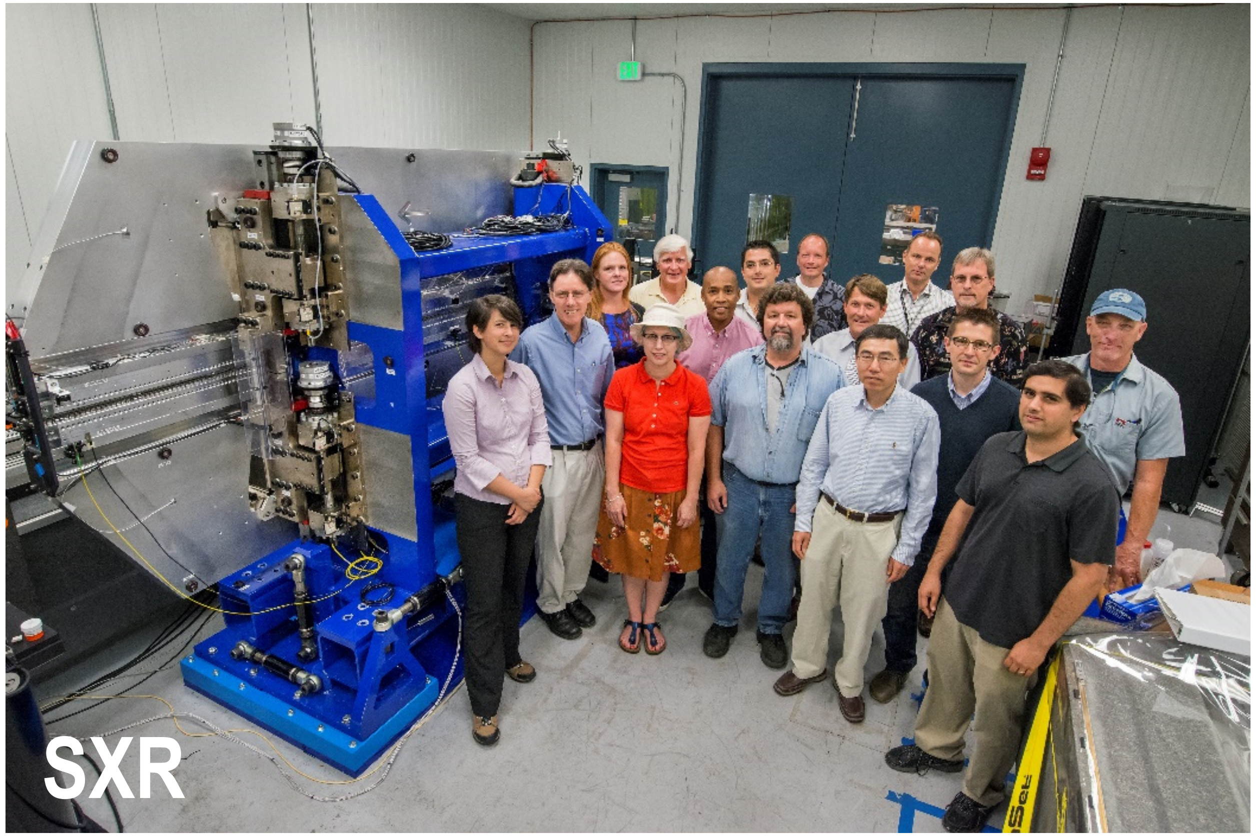
Outline

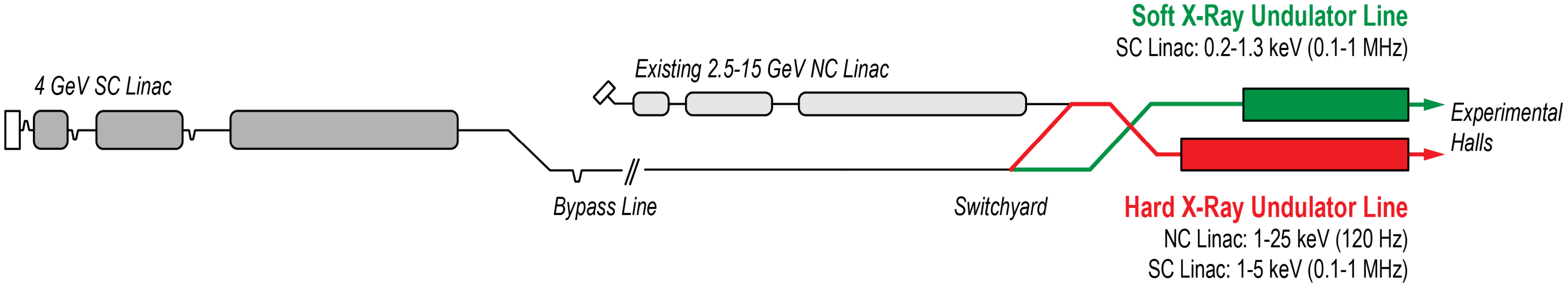
- LCLS-II Introduction and Requirements
- Undulator Lines (Soft X-Ray And Hard X-Ray)
- Novel Horizontal-Gap, Vertically-Polarizing Undulator Line
  - Concept
  - Technical Realization and Challenges
  - Performance Data
- Summary

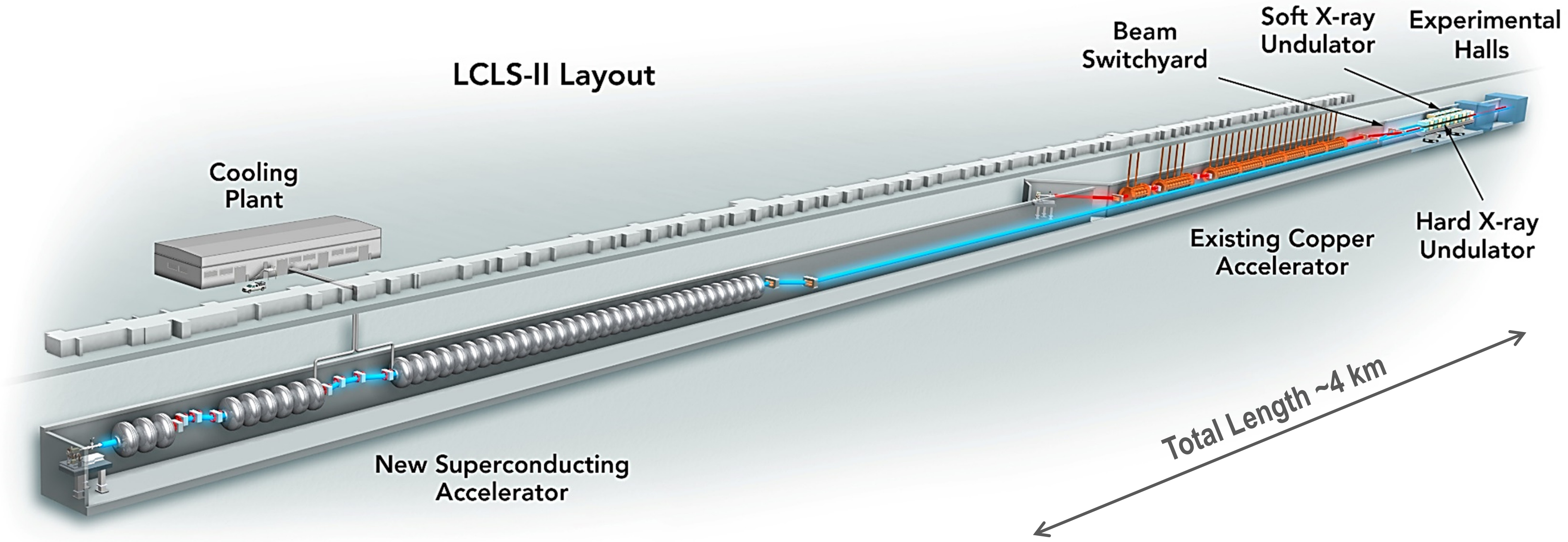
LBNL LCLS-II Undulator Team



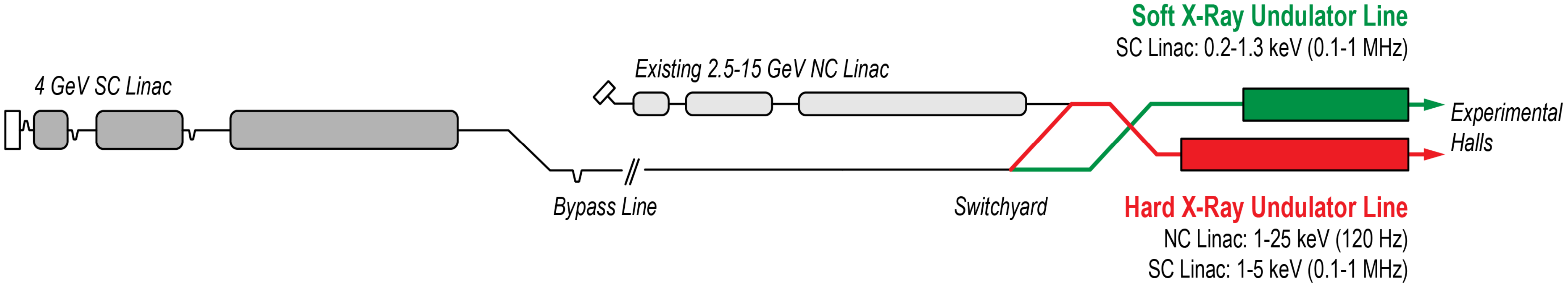
Katherine Ray, Allan DeMello, Dawn Munson, Dave Plate, Dianna Jacobs, Adam Brown, Kyle McCombs, Matthaeus Leitner, John Pucci, Ross Schlueter, Erik Wallen, Steve Marks, Arnaud Madur, Jin-Young Jung, Diego Arbelaez, Jim Dougherty, Davide Bianculli, Tom Miller, Dave Yeagli, Daniel Sadlier, Jiani Niu, Daniela Leitner, John Corlett

LCLS-II Free Electron Laser

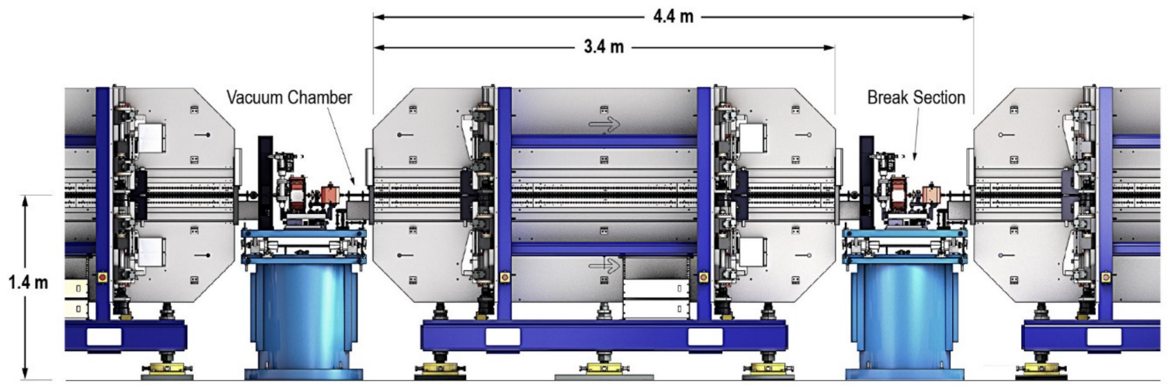




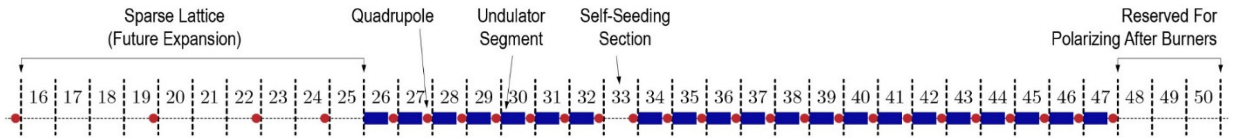
LCLS-II Free Electron Laser



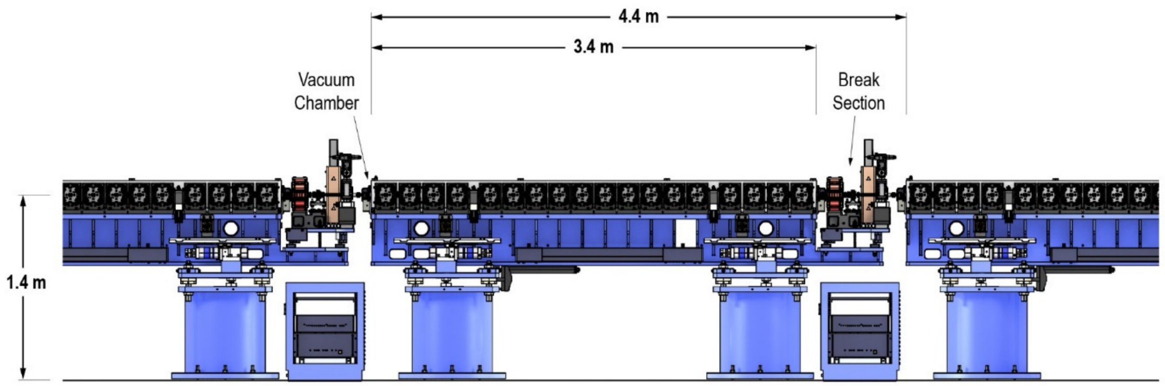
LBNL Supplies 21 (+ 1 Spare) Soft X-Ray And 32 (+ 1 Spare) Hard X-Ray Production Undulator Segments To LCLS-II



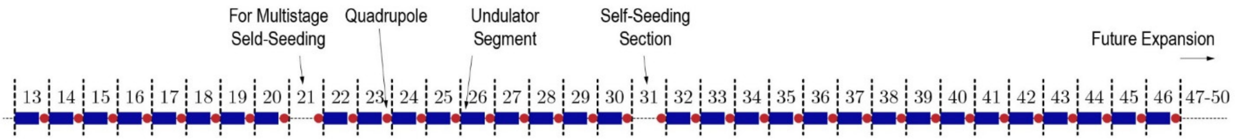
2(a) *LCLS-II Soft X-Ray Undulator Line - Elevation View*



2(b) *LCLS-II Soft X-Ray Undulator Line - Schematic Tunnel Layout*



2(a) *LCLS-II Hard X-Ray Undulator Line - Elevation View*



2(b) *LCLS-II Hard X-Ray Undulator Line - Schematic Tunnel Configuration*

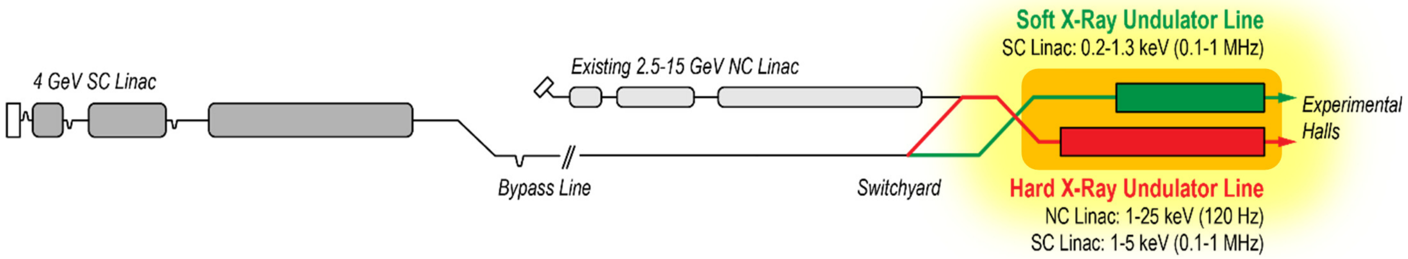
Soft X-Ray Line

21 Undulators + 1 spare

Horizontally Polarizing

Total Cost ~$19M

Production: Mar. 2016 To Feb. 2019



Hard X-Ray Line

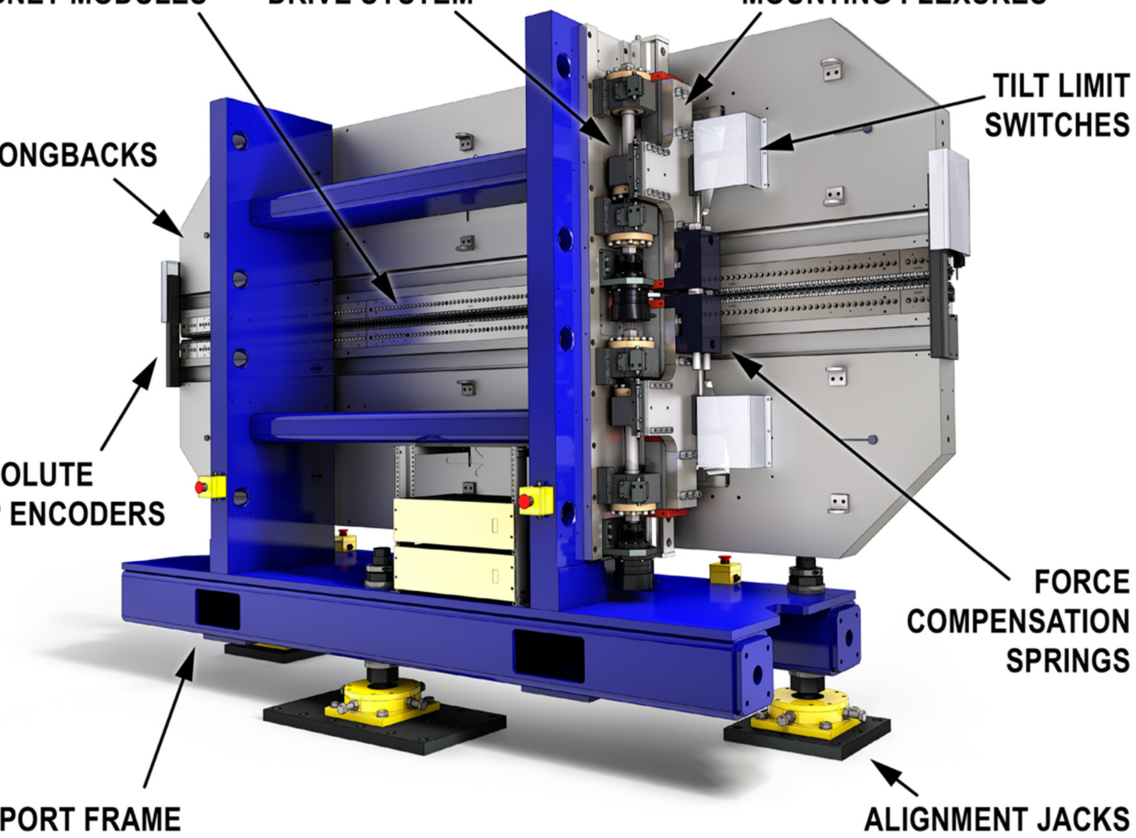
32 Undulators + 1 spare

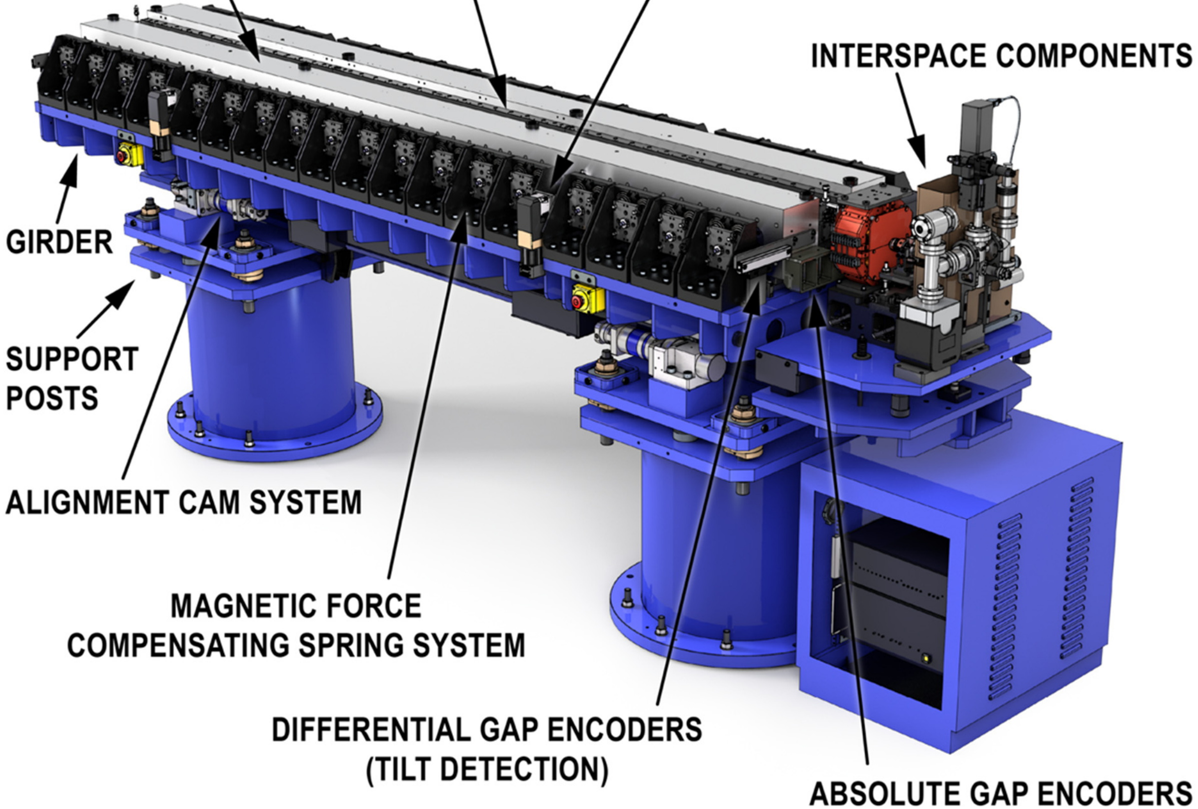
Vertically Polarizing

Total Cost ~$21M

Production: Aug. 2016 To Oct. 2019

LBNL Supplies 21 (+ 1 Spare) Soft X-Ray And 32 (+ 1 Spare) Hard X-Ray Production Undulator Segments To LCLS-II





VAC VACUUMSCHMELZE — Magnet Module Vendor

KTC — Mechanical System And Integration Vendor

neorem magnets — Magnet Module Vendor

KTC, MOTION SOLUTIONS — Mechanical System And Integration Vendor

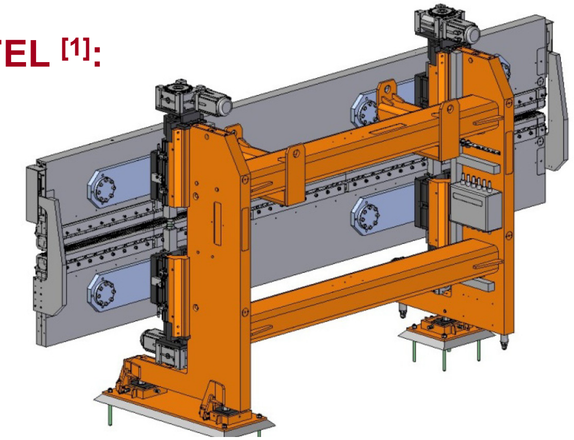
Main LCLS-II Undulator Segment Parameters

Parameter	Soft X-Ray Line (SXR)	Hard X-Ray Line (HXR)
Undulator Type	Planar PM Hybrid	Planar PM Hybrid
Magnet Material	NdFeB (Diffusion Treated)	NdFeB (Diffusion Treated)
Gap Type	Variable	Variable
X-Ray Polarization Direction	Horizontal	Vertical
Photon Energy Range	0.2 – 1.3 keV (SC Linac)	1.0 – 5.0 keV (SC Linac)
Undulator Period Length (λ_u)	39 mm	26 mm
Minimum Operational Magnet Gap	7.2 mm	7.2 mm
Maximum Operational Magnetic Gap	22 mm	20 mm
On-Axis Vertical Eff. Field B_{eff} at Min. Operational Gap	> 1.49 T	> 1.01 T
Undulator Parameter K_{eff} at Min. Operational Gap	> 5.43	> 2.44
Minimum Operational Undulator Parameter K	1.24	0.44
Minimum Full Open Gap	100 mm	100 mm
Individual Undulator Segment Length	3.4 m	3.4 m
Magnetic Field Symmetry	Anti-Symmetric	Anti-Symmetric
Number of Periods per Segment (incl. Undulator Ends)	87	130
Number of Poles per Segment (incl. Undulator Ends)	174	260
Number of Magnets per Segment (incl. Ends)	173	259

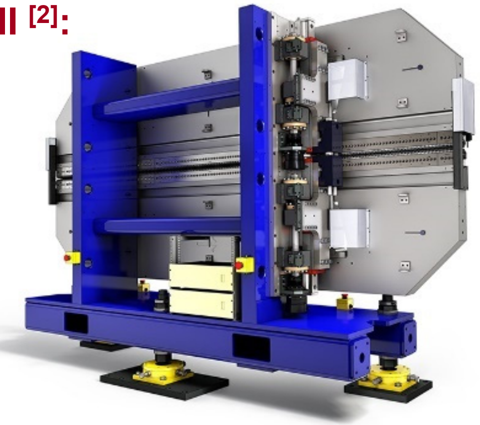
Undulator Prototypes Incorporating Magnetic Force Compensation Promise More Compact Insertion Devices: LCLS-II Will Be The First Research Facility To Implement Force-Compensated Production Undulators On A Larger Scale

- Variable gap undulators: Force between two rows of magnets increases exponentially as the operational gap decreases. This force is usually managed by implementing large strongbacks and powerful gap drives. Example: XFEL[1] and LCLS-II SXR Undulators[2]
- Compact undulators: Magnetic attractive forces can be compensated by implementing counteracting force schemes. Such arrangements permit a significant reduction of strongback and drive system sizes.
- **(A) Magnetic Force Compensation:** Proof-of Principle Setup at SLAC[3] and <u>In-Vacuum Undulator</u> Prototype at RIKEN Spring-8[4]
- **(B) Hydraulic Force Compensation:** Proof-of-Principle Setup at Cornell[5]
- **(C) Spring Force Compensation:** Wiggler with partial force compensation at SOLEIL[6] <u>Vertically Polarizing Undulator</u> Prototype at ANL[7]

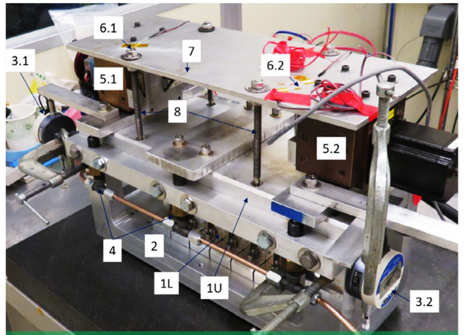
XFEL [1]:



LCLS-II [2]:

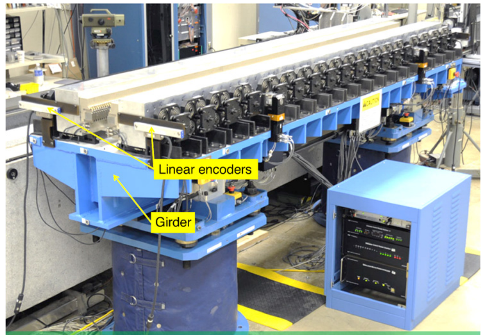


SLAC [3]



Cornell [5]

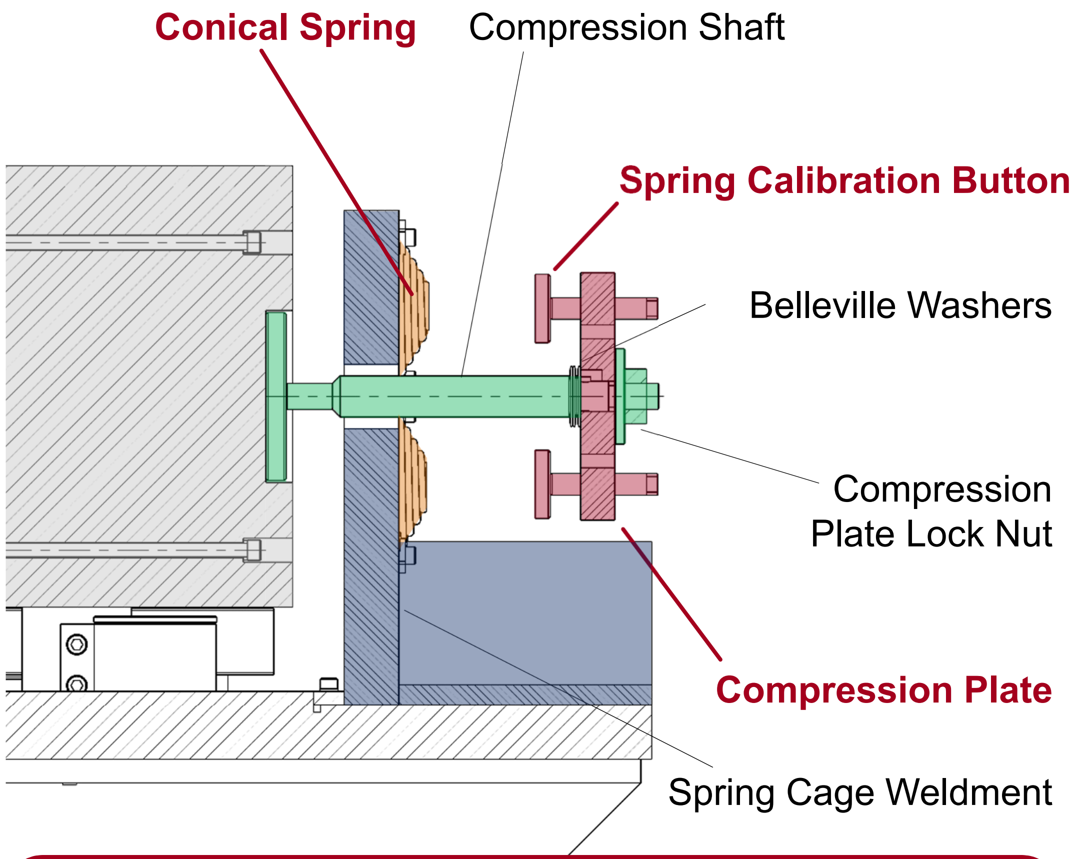
RIKEN Spring-8 [4]

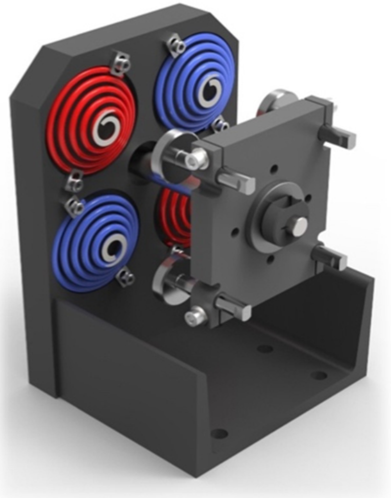


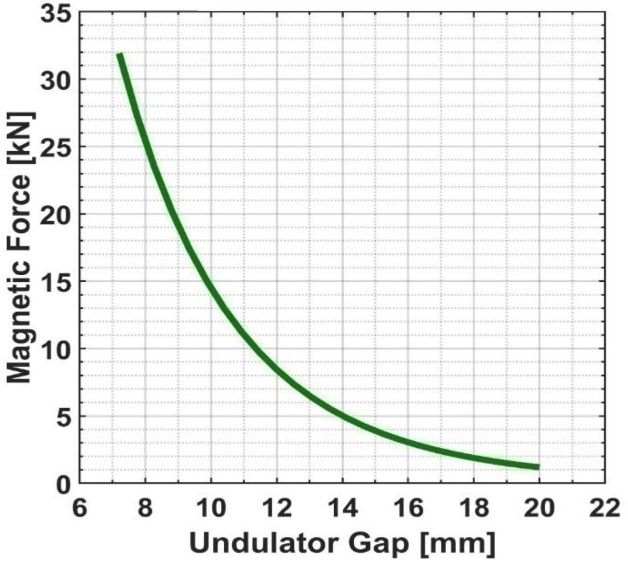
ANL APS [7]

[1] J. Pflueger *et al.*, "Status of the Undulator Systems for the European X-ray Free Electron Laser", *Proc. 35th Int. Free Electron Laser Conf. (FEL'13)*, New York, NY, USA, Aug. 2013, paper TUPSO60, pp. 367-371
[2] M. Leitner *et al.*, "Hard X-Ray and Soft X-Ray Undulator Segments for the Linear Coherent Light Source Upgrade (LCLS-II) Project", *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 1605-1608
[3] R. Carr, "Magnetic counterforce for insertion devices," *J. Synchrotron Radiation*, vol. 10, no. 3, pp. 269–271, May 2003
[4] R. Kinjo *et al.*, "Lightweight-compact variable-gap undulator with force cancellation system based on multipole monolithic magnets," *Rev. Sci. Instrum.*, vol. 88, no. 7, p. 073302, Jul. 2017
[5] A. Temnykh, I. Temnykh, and E. Banta, "Hydraulic-assist driver for compact insertion devices," *Nucl. Instruments Methods Phys. Res. Sect. A*, vol. 917, pp. 18–24, Feb. 2019
[6] O. Marcouillé et al., "An In Vacuum Wiggler WSV50 for Producing Hard X-rays at SOLEIL", in Proc. 11th European Particle Accelerator Conf. (EPAC'08), Genoa, Italy, Jun. 2008, paper WEPC120, pp. 2288-2290
[7] N. Strelnikov *et al.*, "Vertically polarizing undulator with dynamic compensation of magnetic forces," *Phys. Rev. Accel. Beams*, vol. 20, no. 1, 2017

A Horizontal Gap Undulator Requires Innovative Magnetic Force Compensation: Two Pairs Of Conical Springs Provide Counteracting And Exponentially Increasing Force [1]



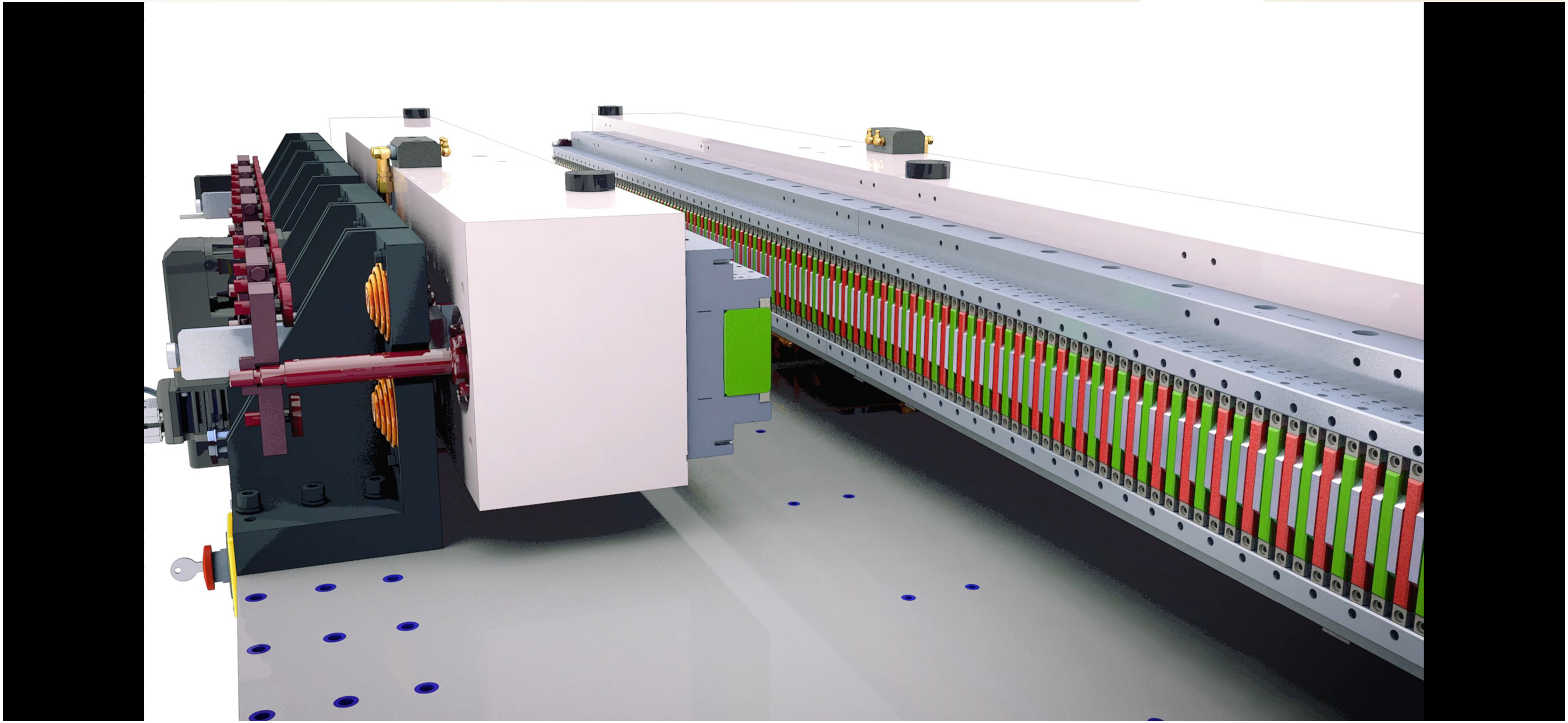




[1] N. Strelnikov et al., “Vertically polarizing undulator with dynamic compensation of magnetic forces,” Phys. Rev. Accel. Beams, vol. 20, no. 1, 2017

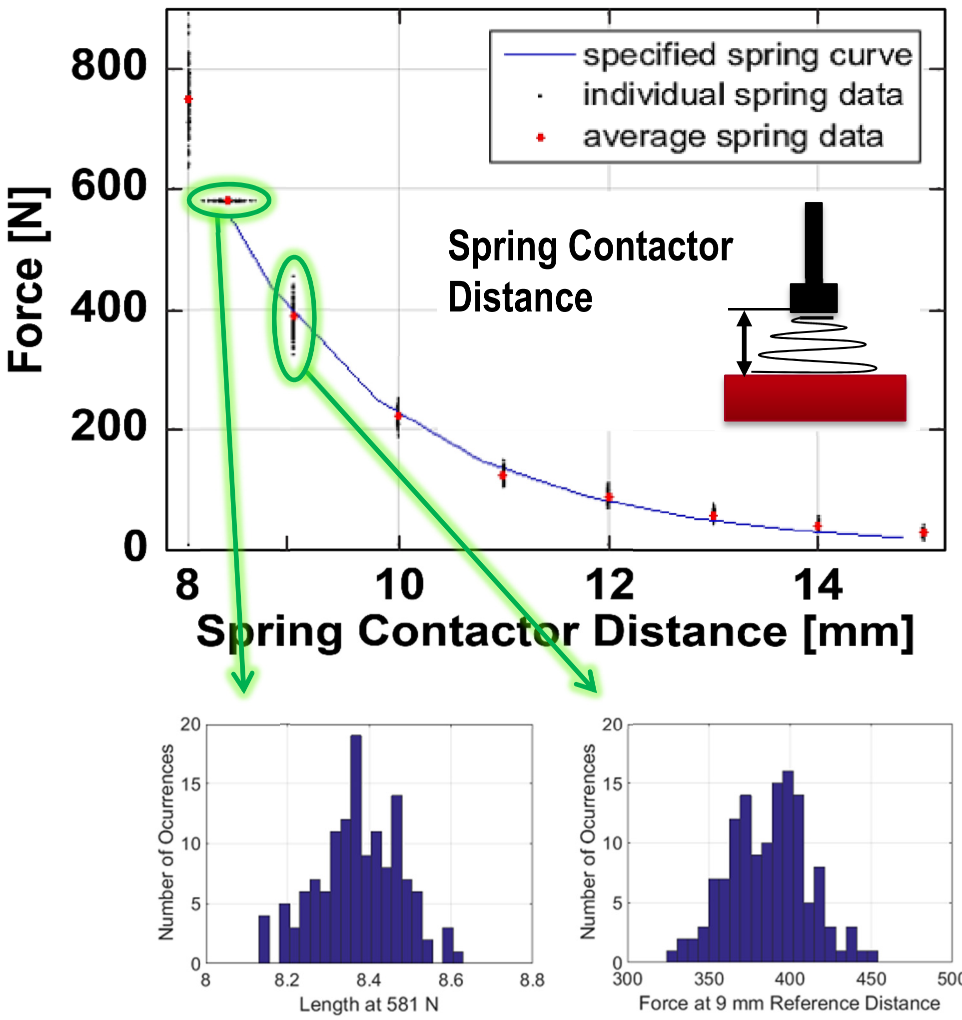
[2] O. A. Schmidt et al., “Horizontal-Gap Vertically-Polarizing Undulator (HGVPU) Design Challenges and Resolutions”, in Proc. 9th Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation Int. Conf. (MEDSI'16), Barcelona, Spain, Sep. 2016, pp. 288-292

A Horizontal Gap Undulator Requires Innovative Magnetic Force Compensation: Two Pairs Of Conical Springs Provide Counteracting And Exponentially Increasing Force [2]

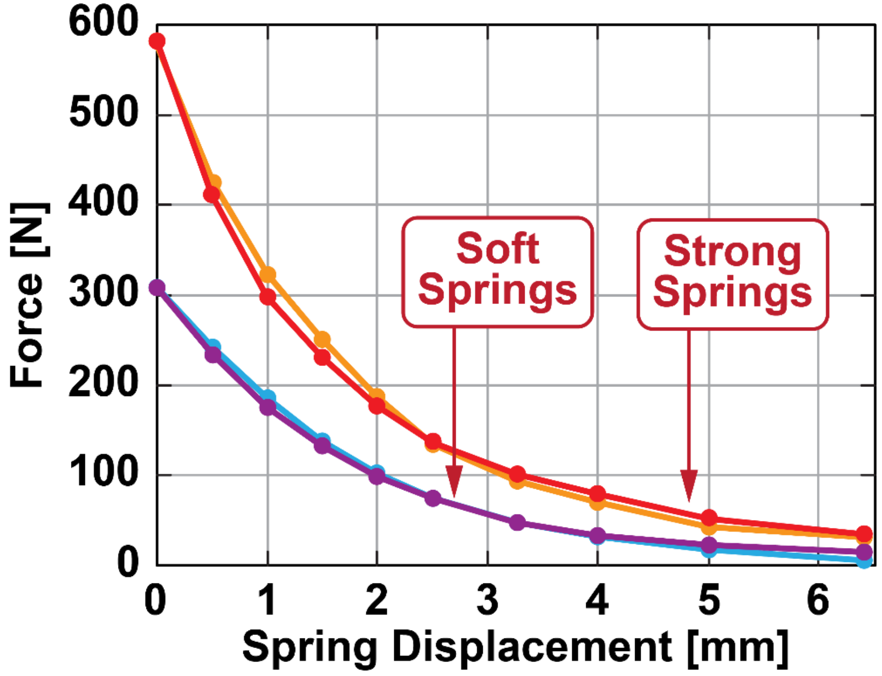


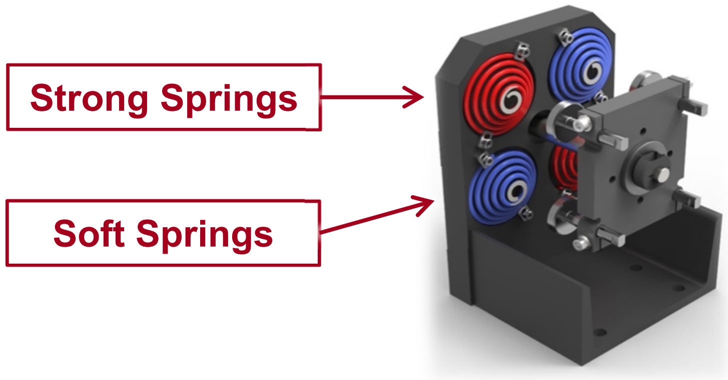
A Horizontal Gap Undulator Requires Innovative Magnetic Force Compensation: Two Pairs Of Conical Springs Provide Counteracting And Exponentially Increasing Force [3]

Spring Curve (Spring Base Reference)



Example of Spring Curves For One Cage

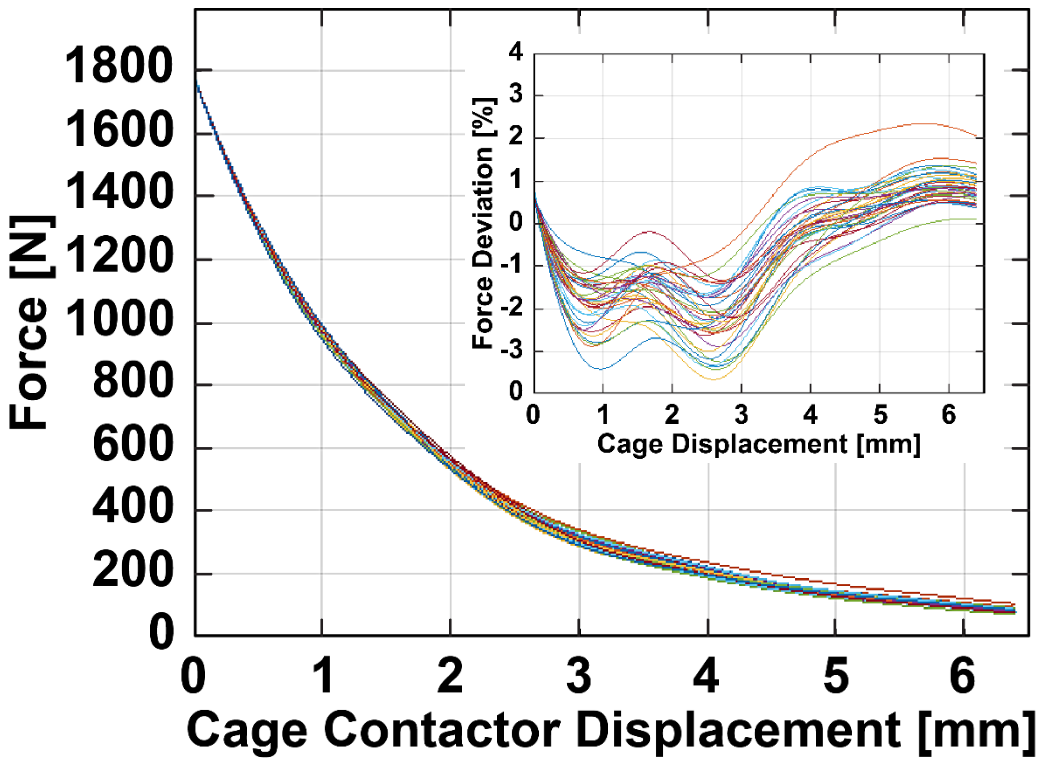




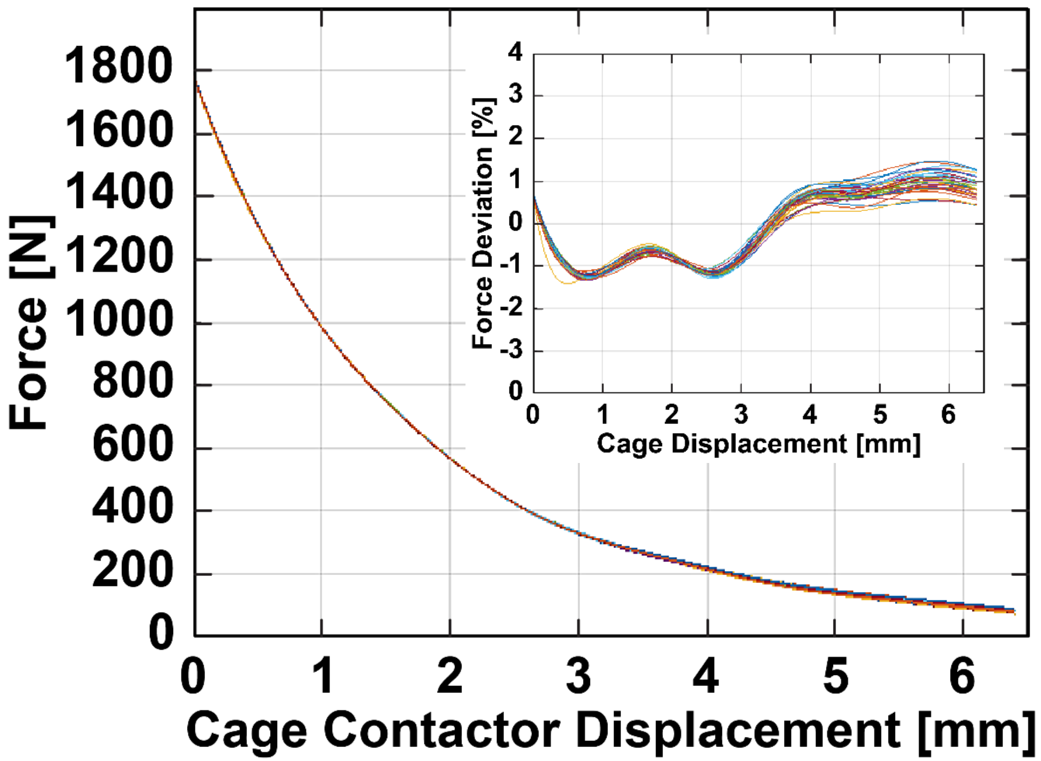
A Horizontal Gap Undulator Requires Innovative Magnetic Force Compensation: Two Pairs Of Conical Springs Provide Counteracting And Exponentially Increasing Force [4]

- Random error can be reduced
- Overall effectiveness is limited by systematic errors
- All cages have similar force curves after sorting
- Number of conical revolutions reflected in force curves
- 18 spring cages each side = 32.4 kN (7,300 lbf) total magnetic force

Randomly Generated Spring Cages



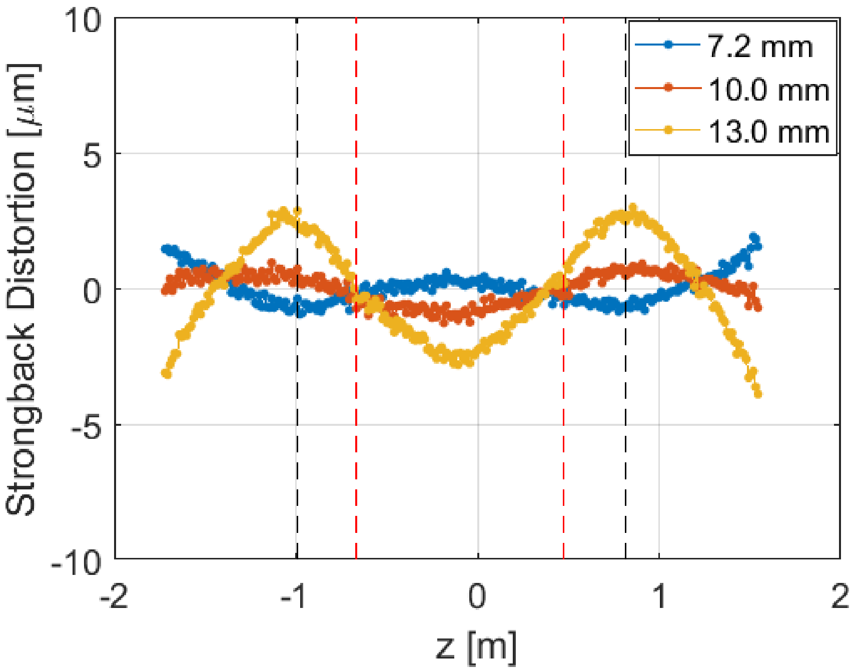
Sorted Spring Cages



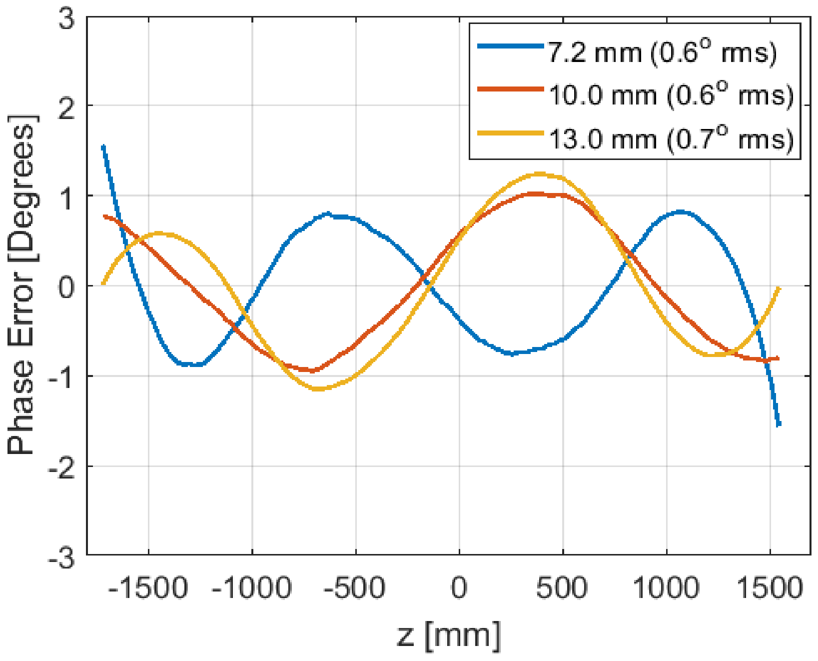
Taking Advantage Of The Spring Cage Calibration Data The Assembly For Each Undulator Can Be Optimized To Develop A Close-To-Straight Strongback At The Smallest Gap While Allowing Greater Deflections At Large Gaps Where Phase Errors Are Less Critical

- Phase error is reasonably small due to gap distortion
- Phase error is minimized for a tuning gap of 8.0 mm
- Moving two spring cages by 100 μm each corresponds to a ~40 lbf change
- ~50 lbf applied in center results in ~ 10 μm strongback deformation
- A computer program has been developed facilitating strongback straightness tuning for vendors

Gap Distortion (SB distortion x 2)



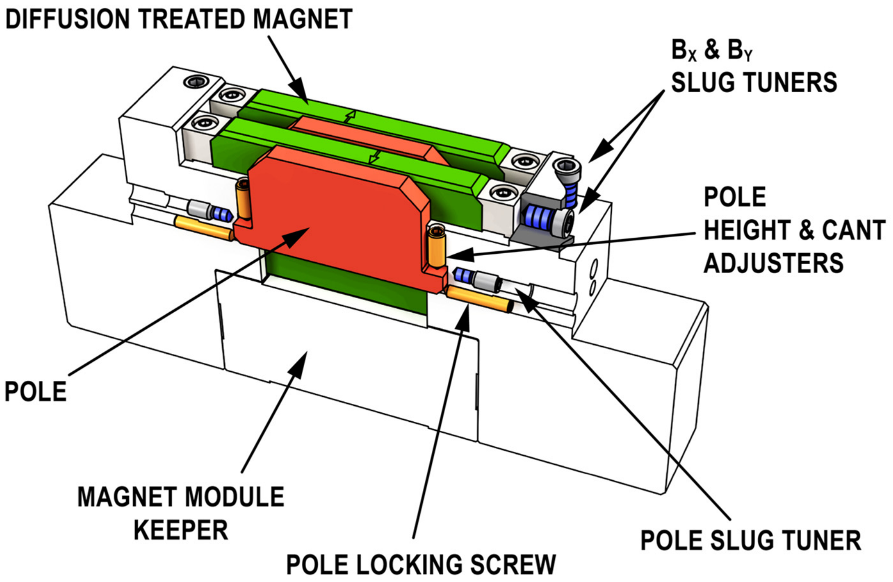
Phase Error

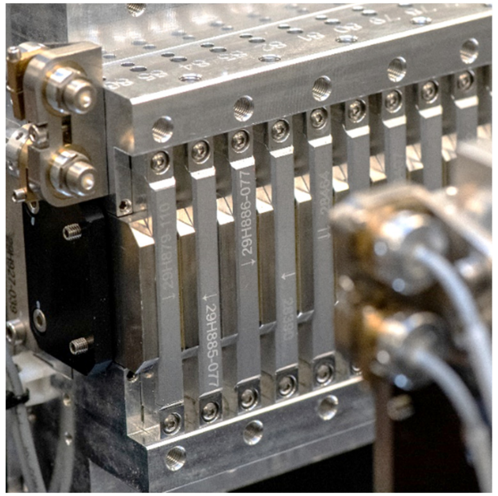


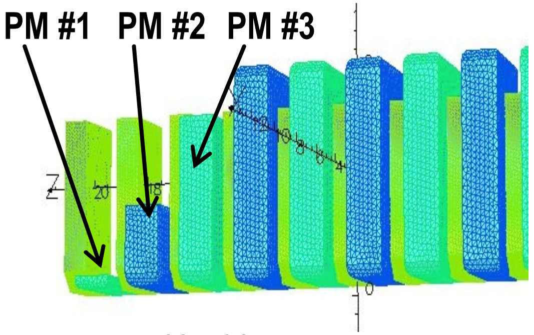
- Undulator spring cage adjustment is a delicate balancing act and requires tight control on the work procedures
- For LCLS-II we were able to successfully transfer the whole process to our industrial suppliers

HGVPU Production Unit In Undulator Magnet Measurement Facility

LCLS-II Undulators Incorporate Advanced Magnet Module Error Correction Features Developed At LBNL: Enable Rapid Undulator Tuning During Production Phase

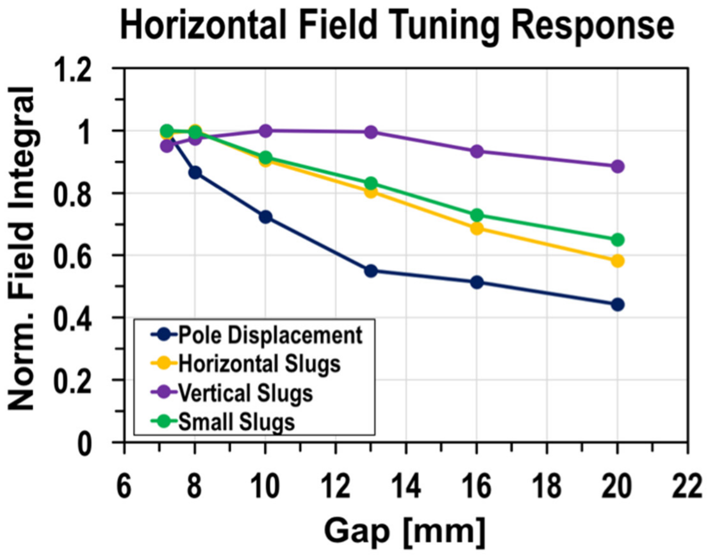


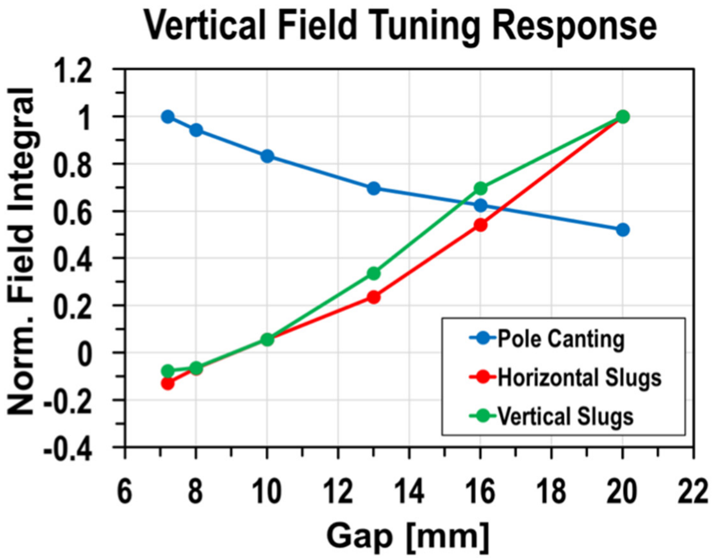




$A \approx 0, +\frac{1}{4}, -\frac{3}{4}, +1, -1, \ldots$

End Design Minimizes Second Field Integral





Magnet Properties

B_r = 1.3 *T*, H_c = 12.2 *kOe*

Diffusion Treatment: H_{cj} > 26 *kOe*

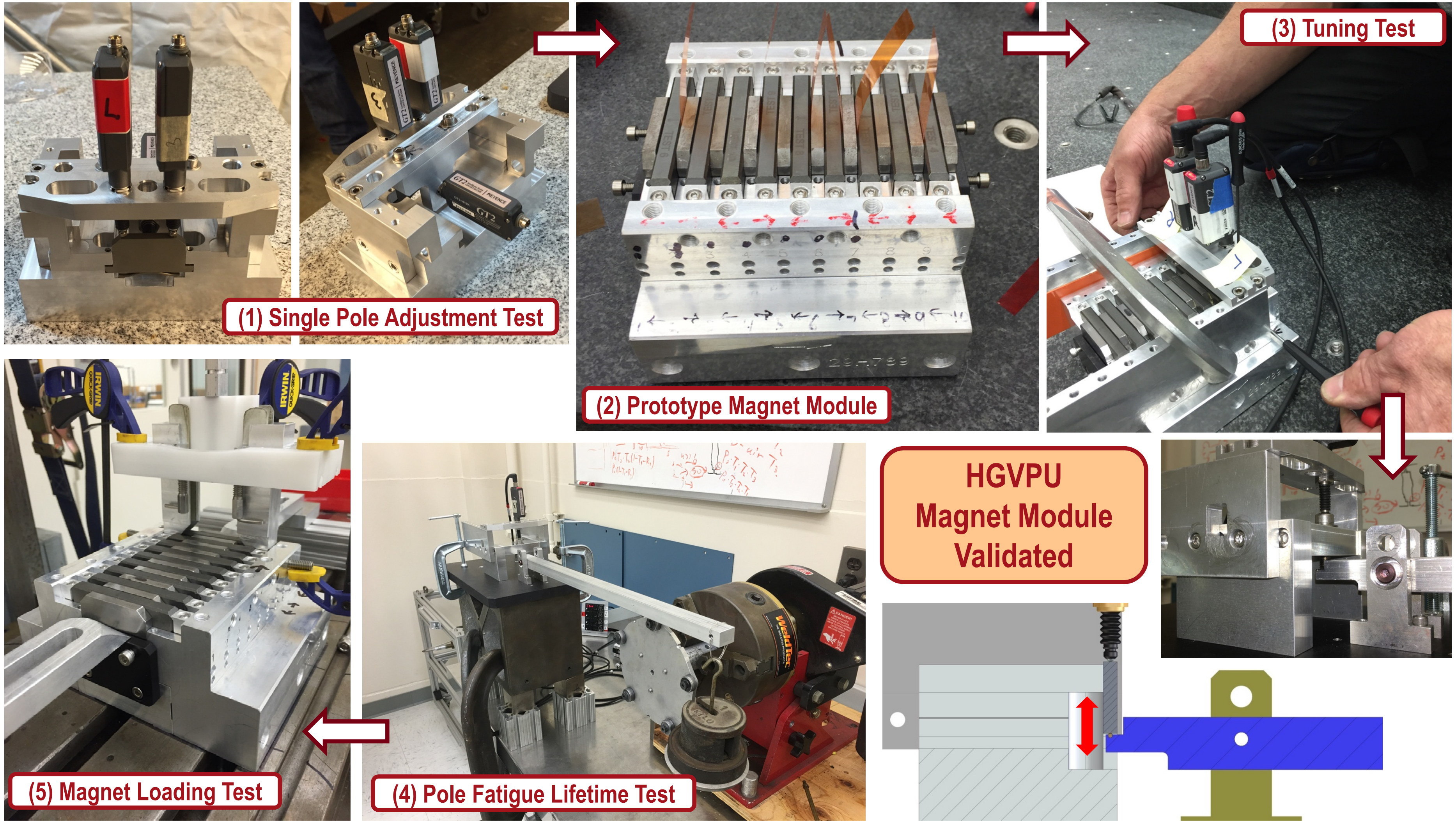
λ_u = 26 *mm*, th_{magnet} = 7.85 *mm*

B_{eff} = 1.03 *T* (Simulation)

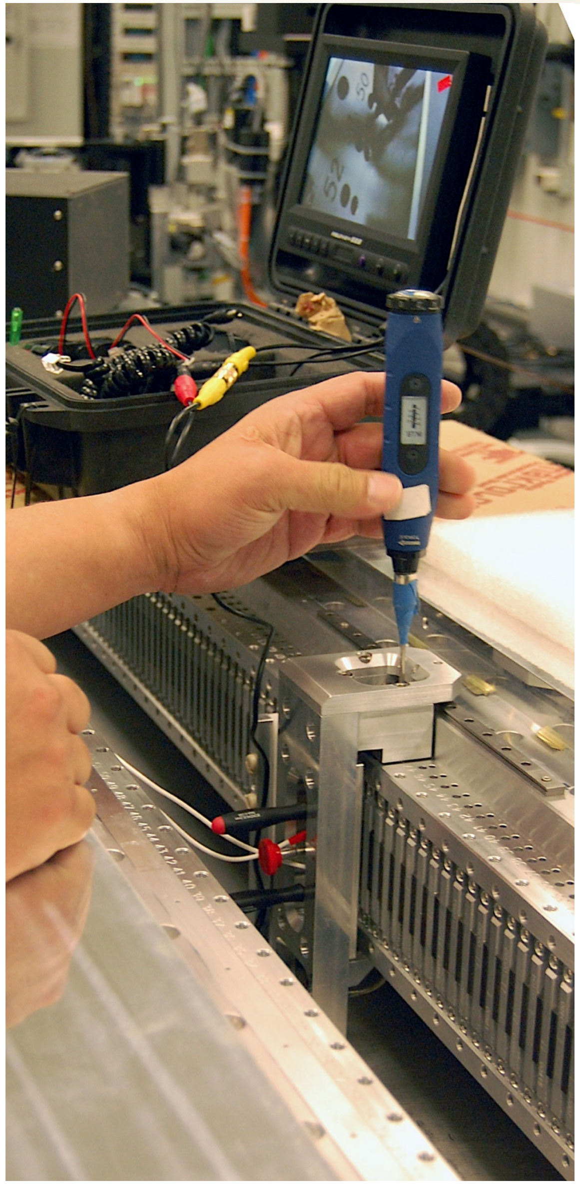
B_{eff} = ~1.07 *T* (Actual)

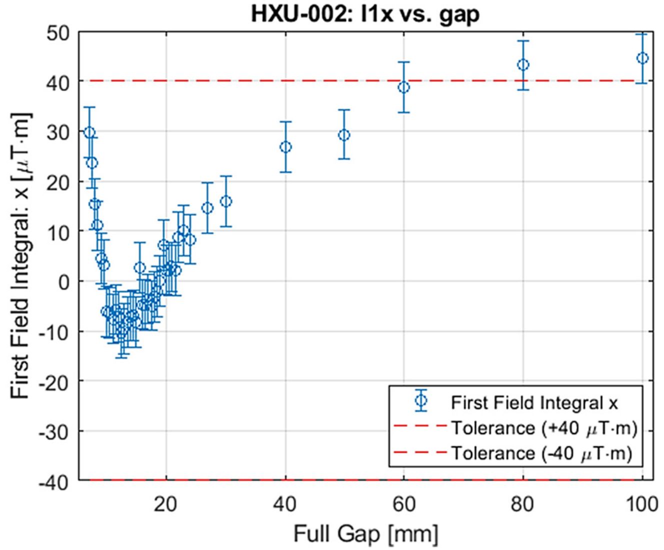
[1] D. Arbelaez et al., "Magnetic Field Correction Methods for Hybrid Permanent Magnet and Superconducting Undulators," Synchrotron Radiation News, vol. 31, no. 3, pp. 9–13, May 2018

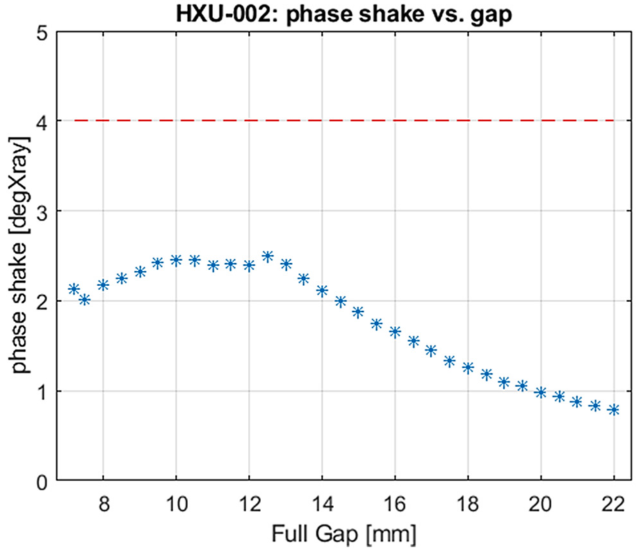
Several Prototypes Have Been Built To Validate Magnet Module Design Features And Long-Term Stability

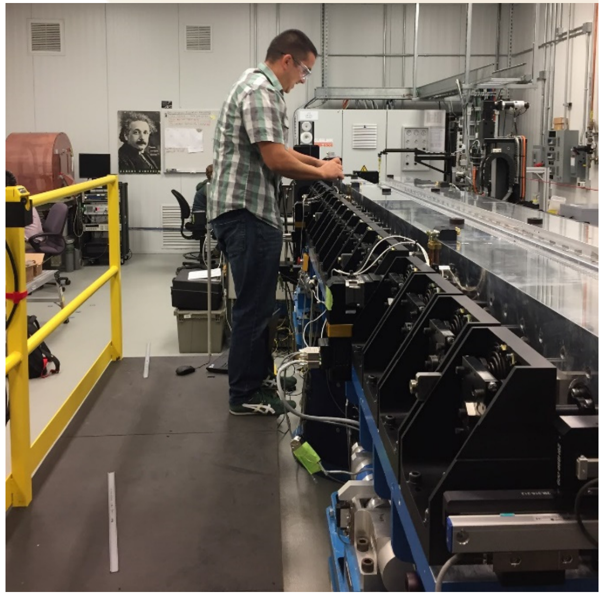


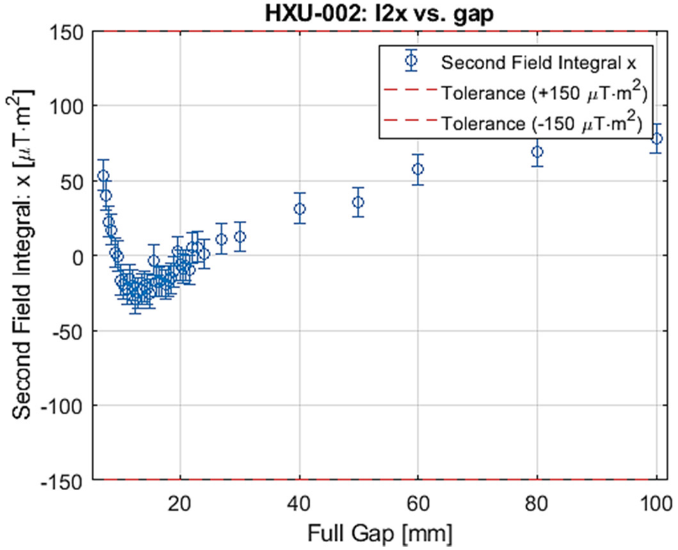
HGVPU Tuning Can Be Achieved Within Days: Typical Undulator Tuning Results

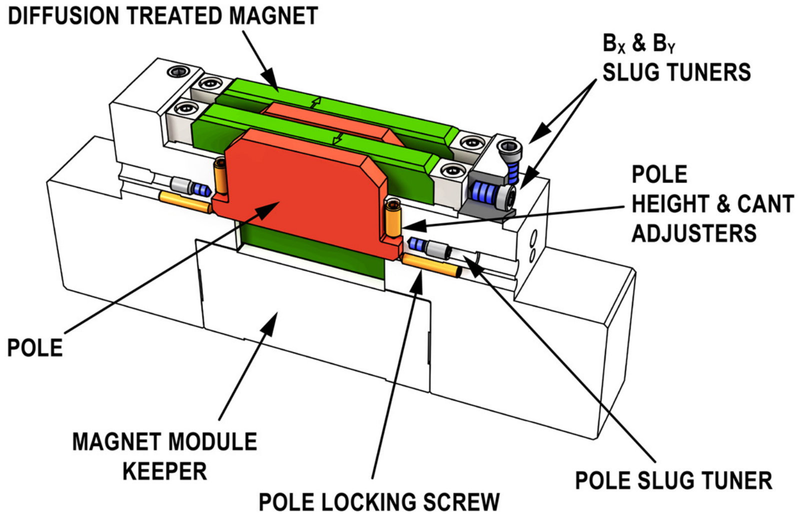


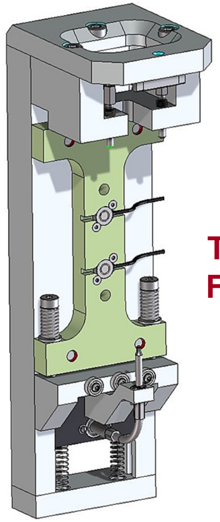












Tuning Fixture

HGVPU Undulator Field Requirements Have Been Achieved, But Field Repeatability Target Could Not Be Maintained

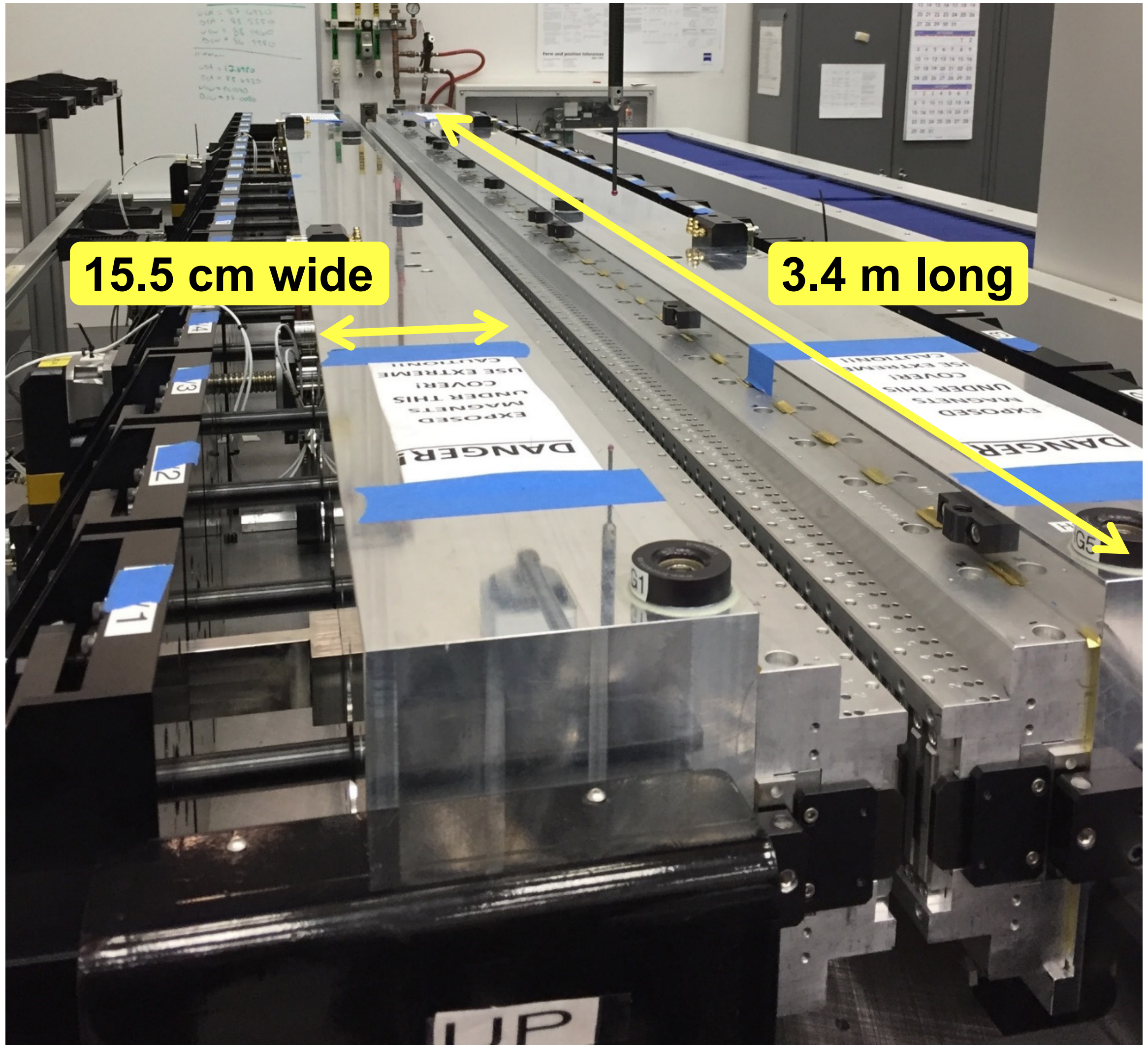
	HGVPU Undulator
Period Length	26 mm
B_{eff} @ 7.2 mm Gap	> 1.01 T
ΔB/B Repeatability	± 2.3 ×10^{-4}
Field Roll-Off (ΔK/K @ x=0.4mm)	< 1.1 ×10^{-4}
$\lvert\int B_{x,y} dz\rvert$	< 40 μTm
$\lvert\iint B_{x,y} dz^2\rvert$	< 150 μTm^2
Phase Shake (rms)	< 4°
Thermal Cycle Repeatability	± 15°C

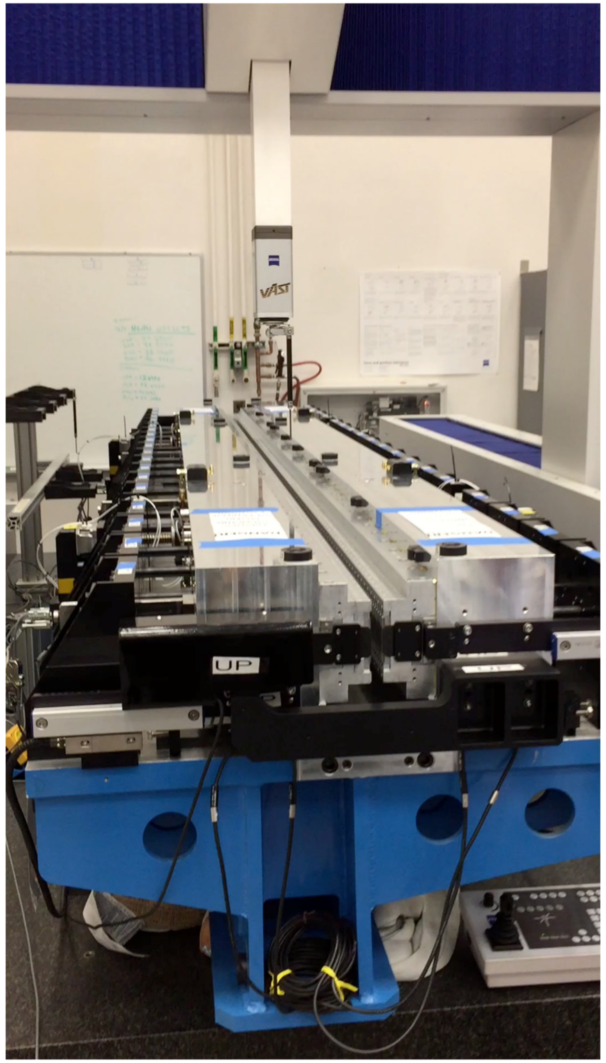
Undulator Must Maintain Field Accuracy After Thermal Cycles (Storage, Assembly)

[1] H.-D. Nuhn, "Undulator System Physics Requirements", unpublished, LCLS-II Tech. Rep. (2016), LCLSII-3.2-PR-0038-R

Slim Strongback Is Highly Sensitive To Small Residual Deflection

($\Delta B/B < \pm 2.3 \times 10^{-4}$ Repeatability Requirement Necessitates Strongback To Maintain Shape Within ±1 μm)





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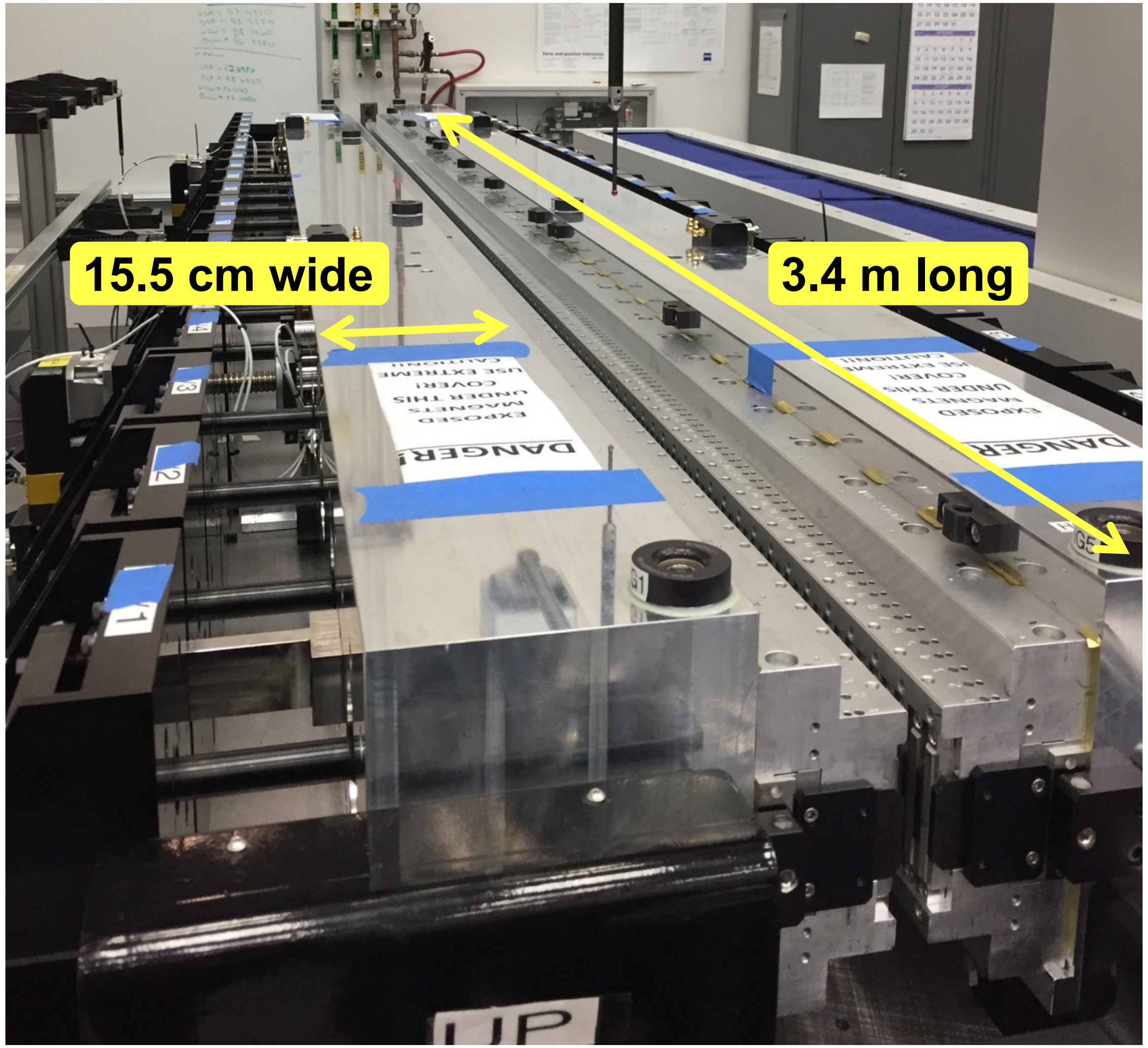
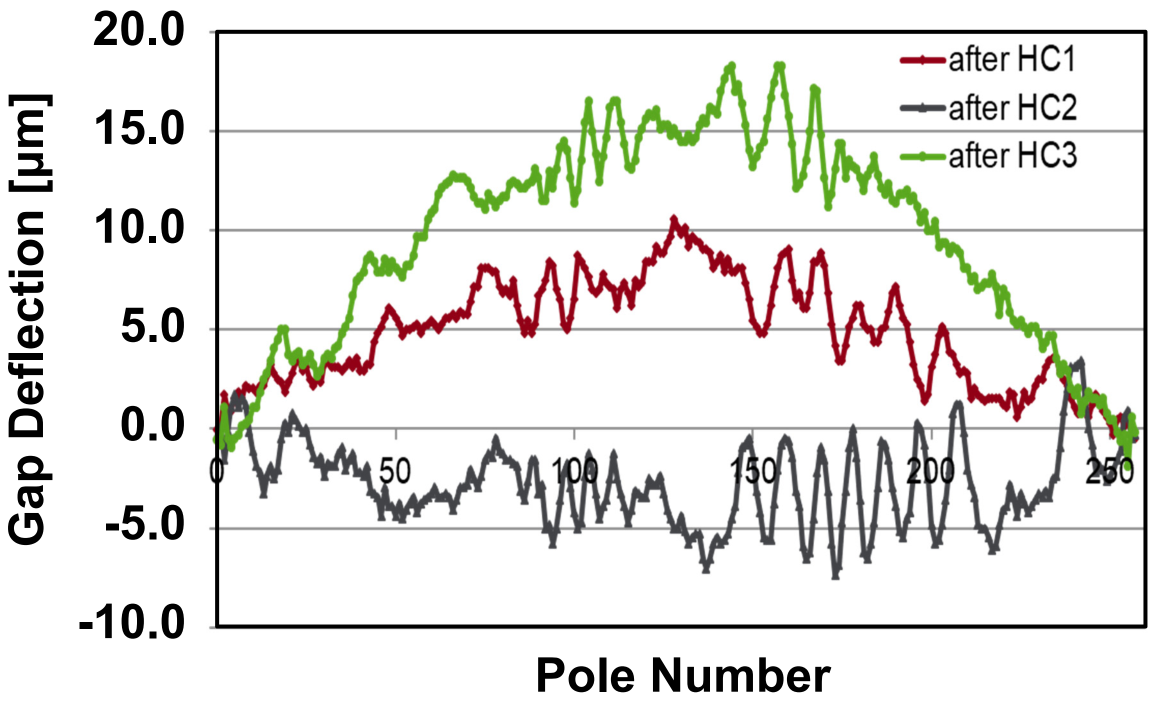
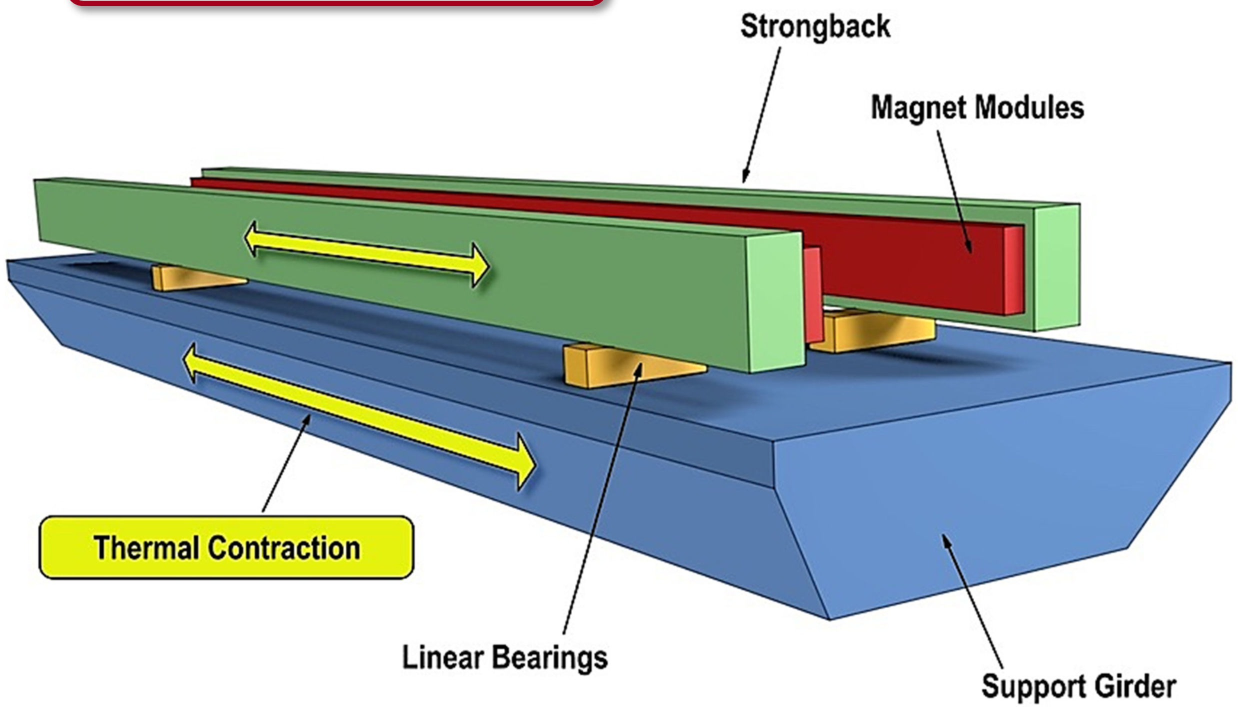




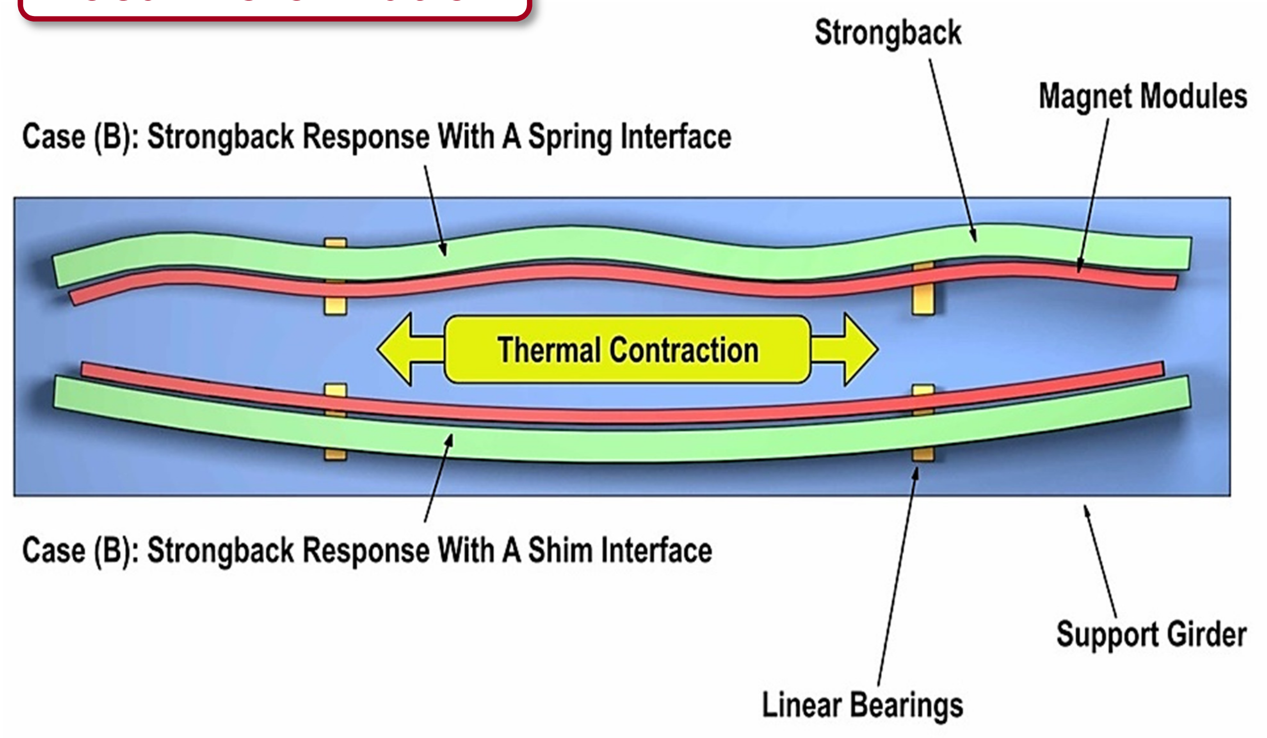
- HGVPUs were implemented into the LCLS-II baseline late in the project based on the expectation that the HGVPU design was fully developed and only needed to be optimized for production.
- Extensive repeatability tests at LBNL revealed that the undulator design had serious repeatability issues.

Slim Strongback Is Highly Sensitive To Small Residual Deflection: Not Resilient To Thermal Excursions and Mechanical Imperfections

Global Deformation

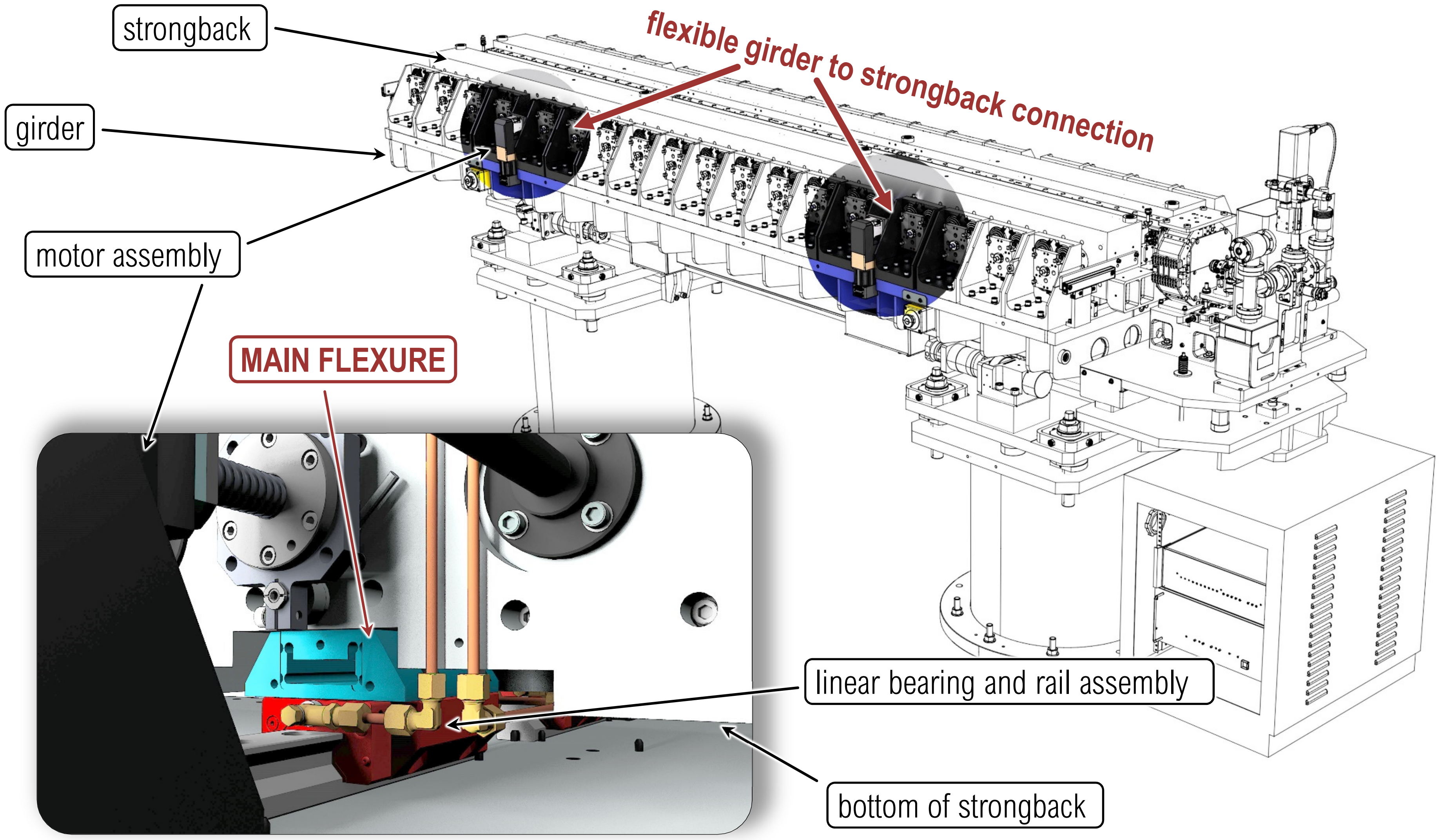


Local Deformation



- **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.**

Main Flexure Addresses Global Strongback Bending



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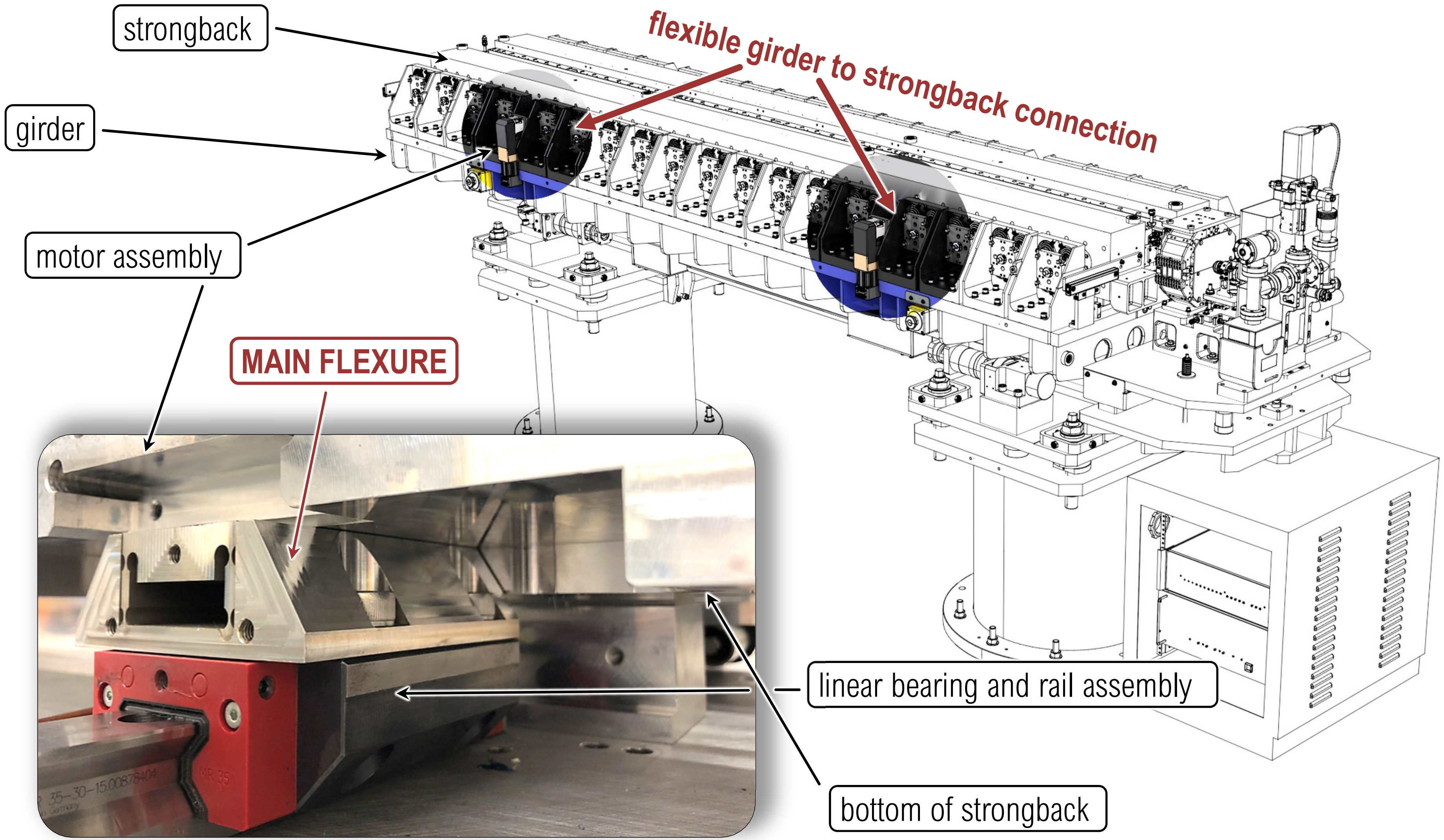
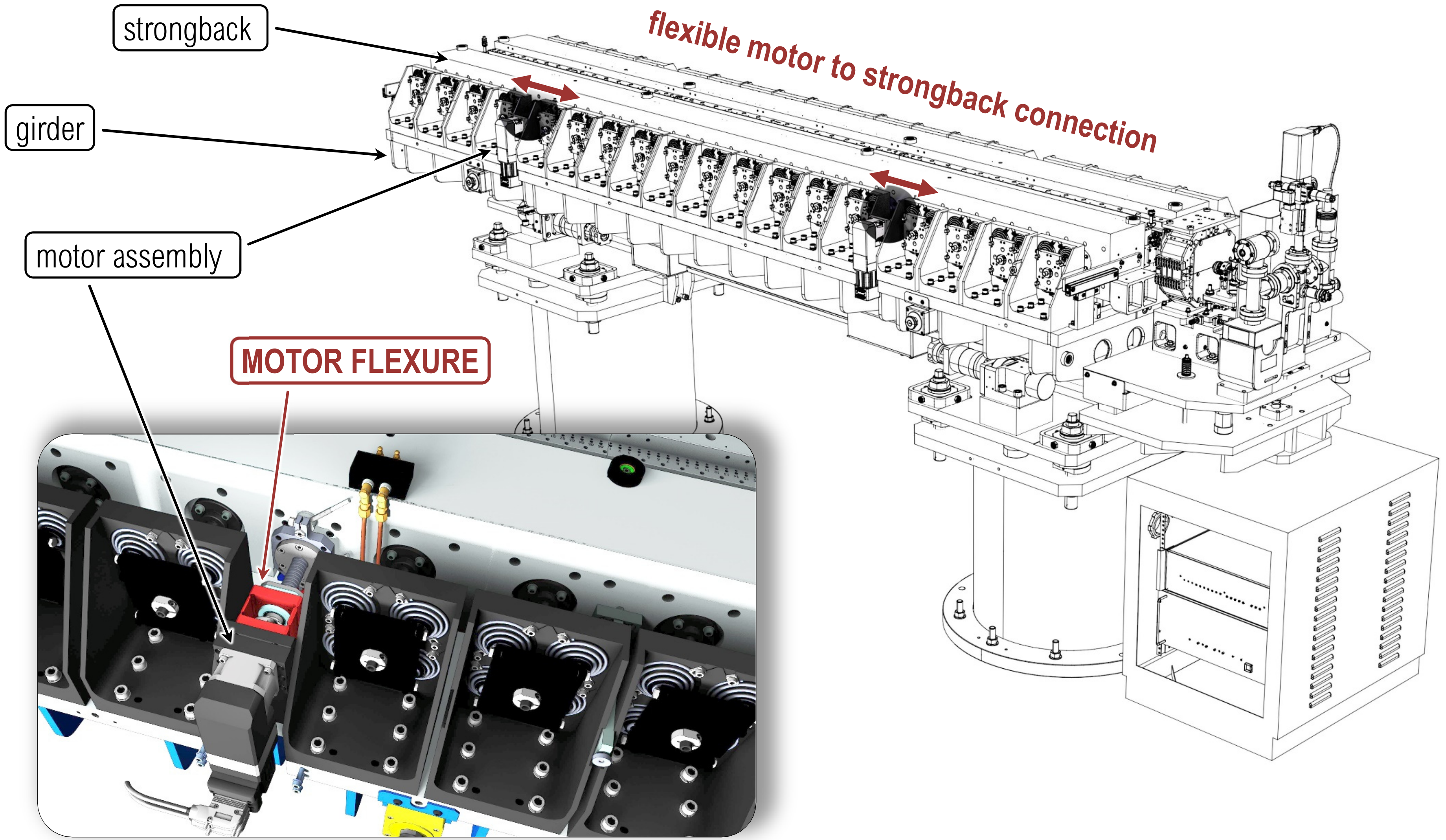
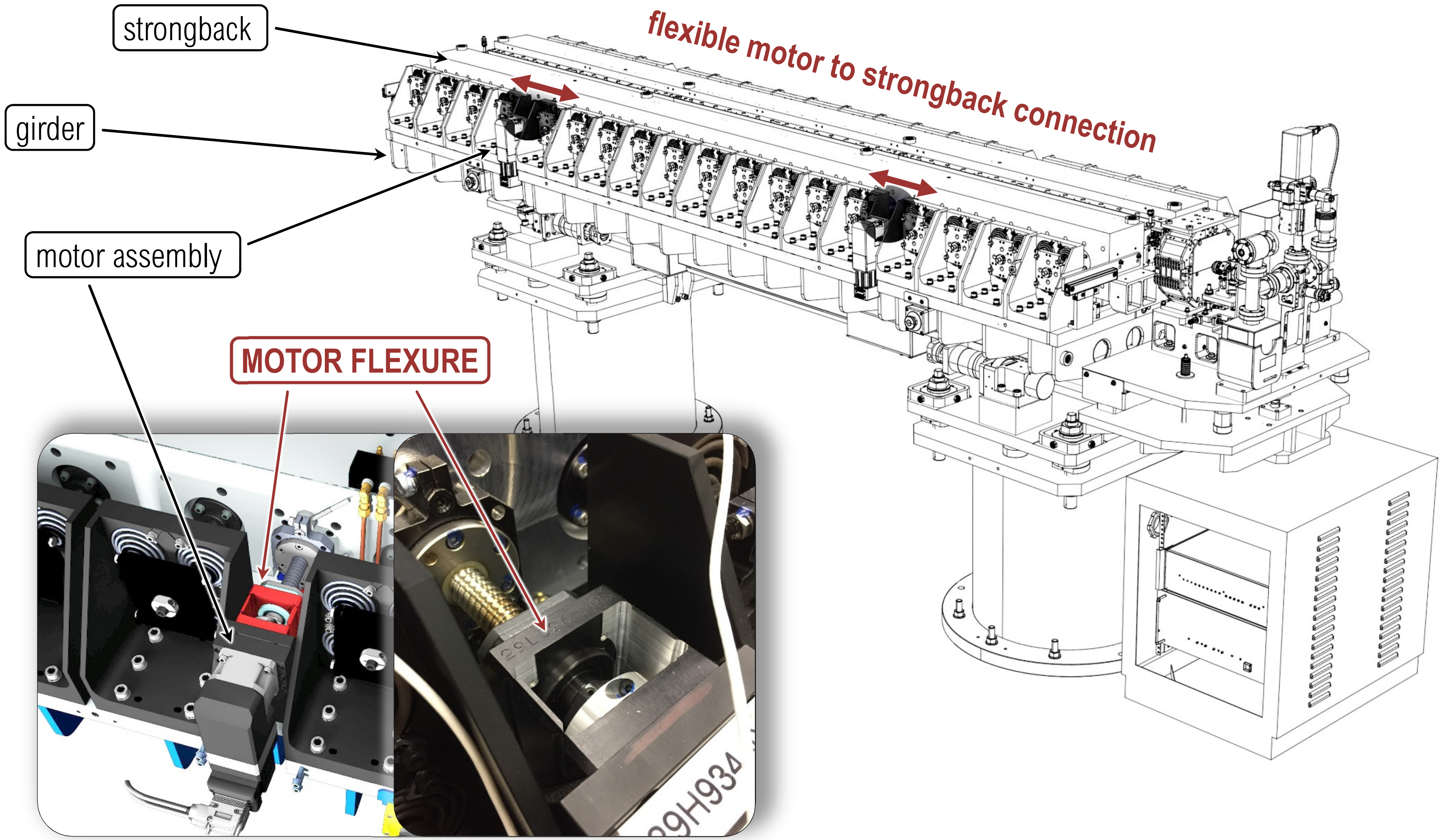


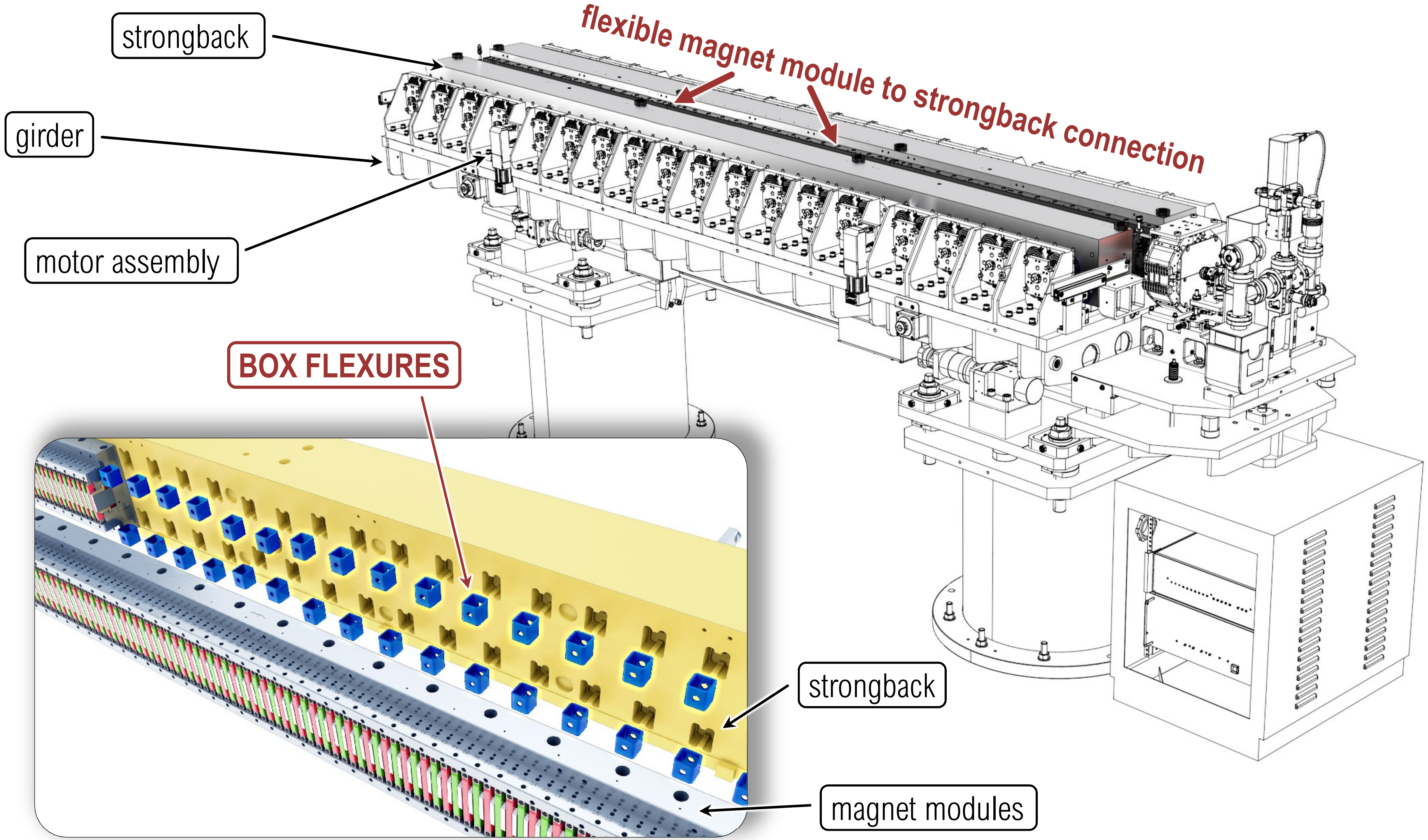
Motor Flexure Permits Strongback Movement



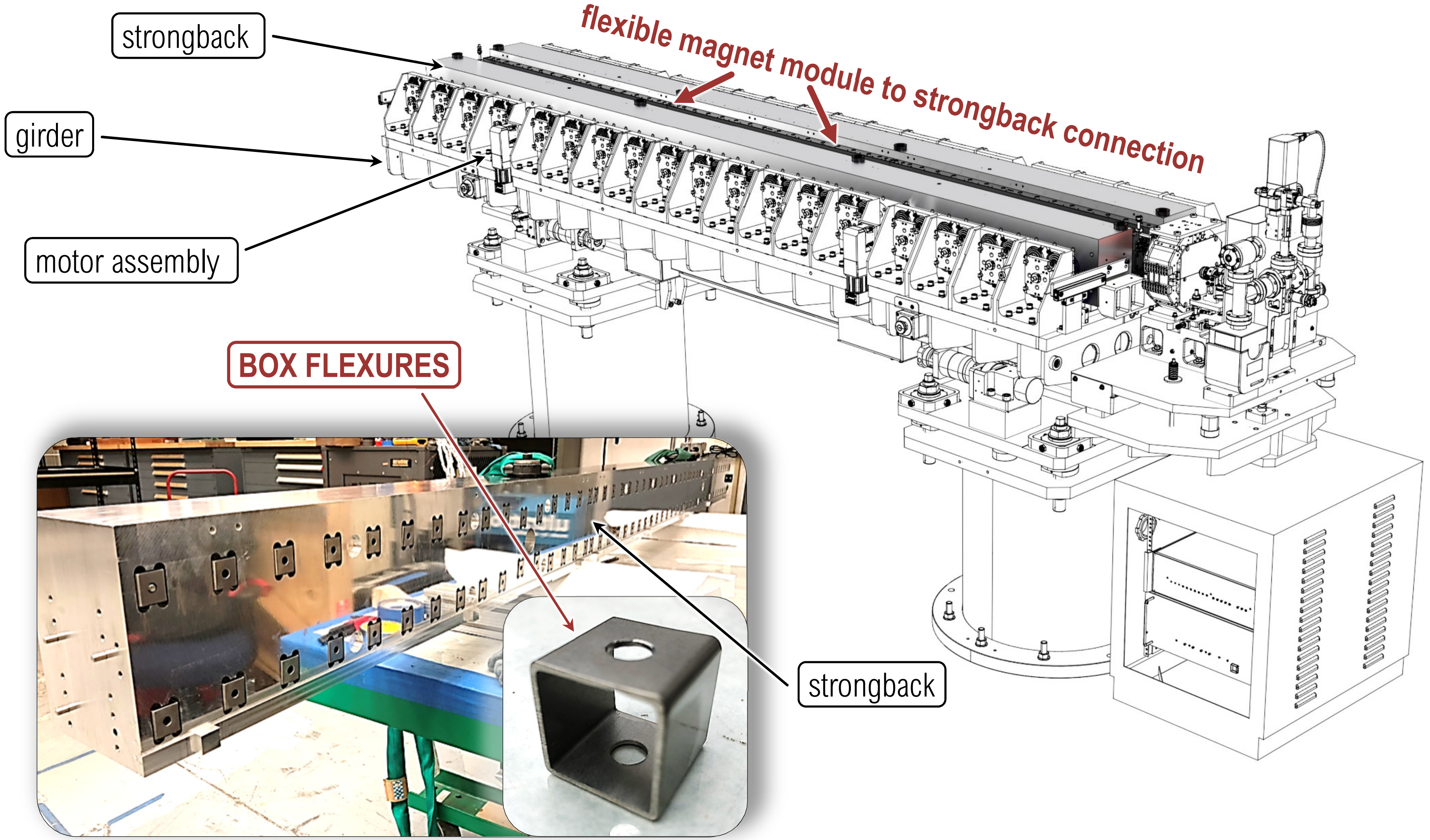
Motor Flexure Permits Strongback Movement



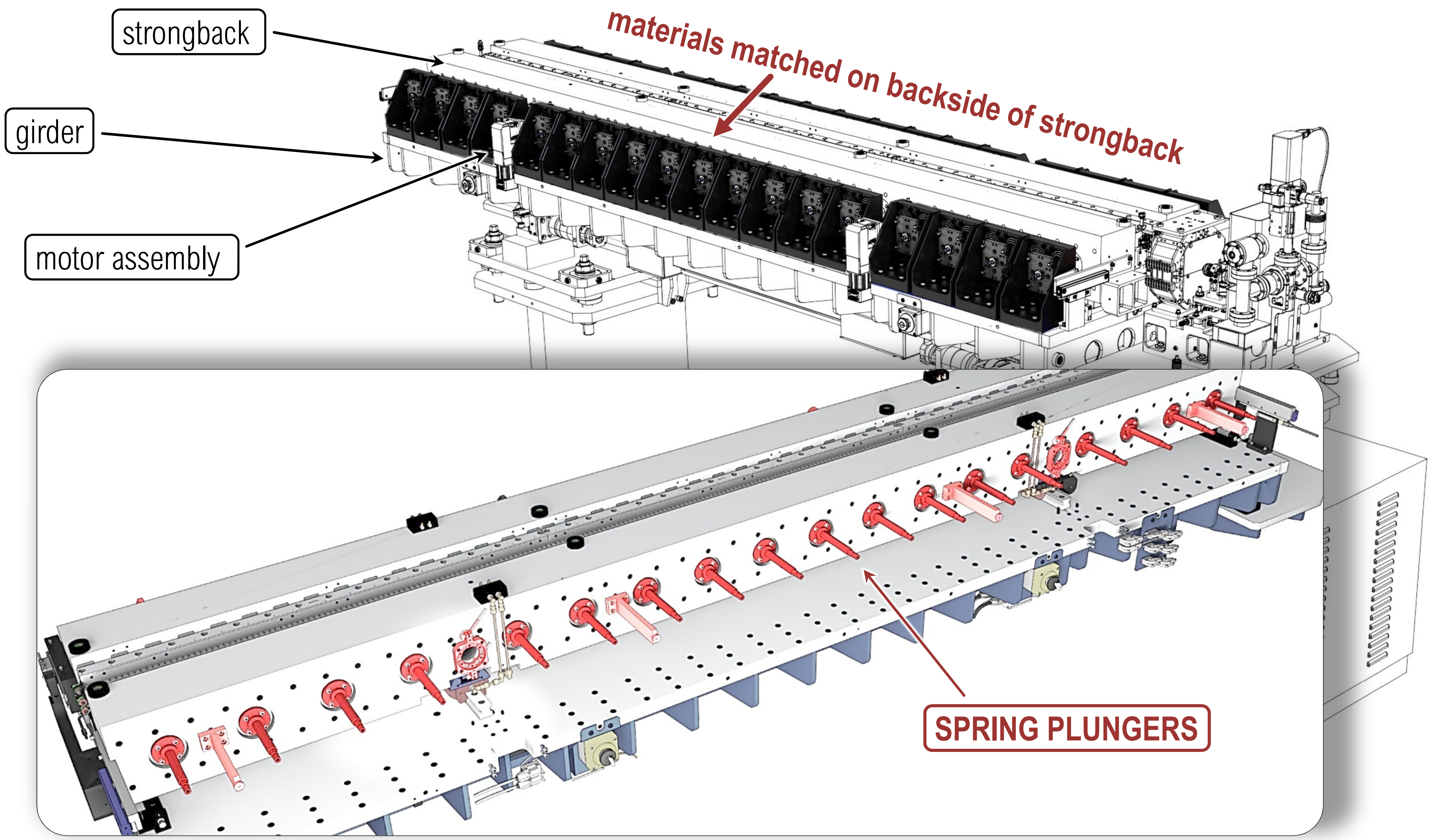
Magnet Module Box Flexures Eliminate Non-Linear Interface Forces and CTE Mismatch



Magnet Module Box Flexures Eliminate Non-Linear Interface Forces and CTE Mismatch



Spring Plunger Material Was Changed To Aluminum And Strongback Shimming Sequence Was Updated



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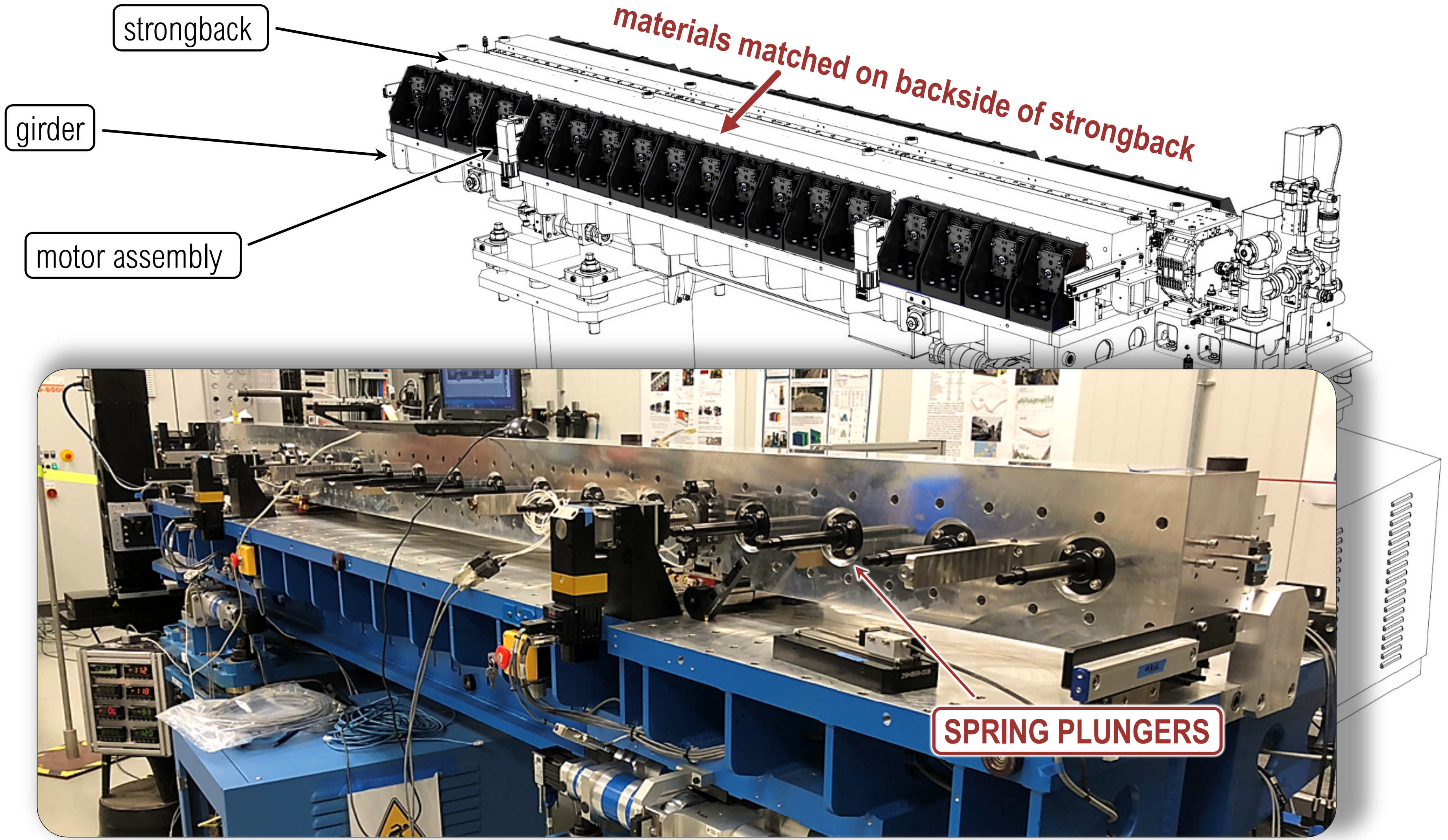
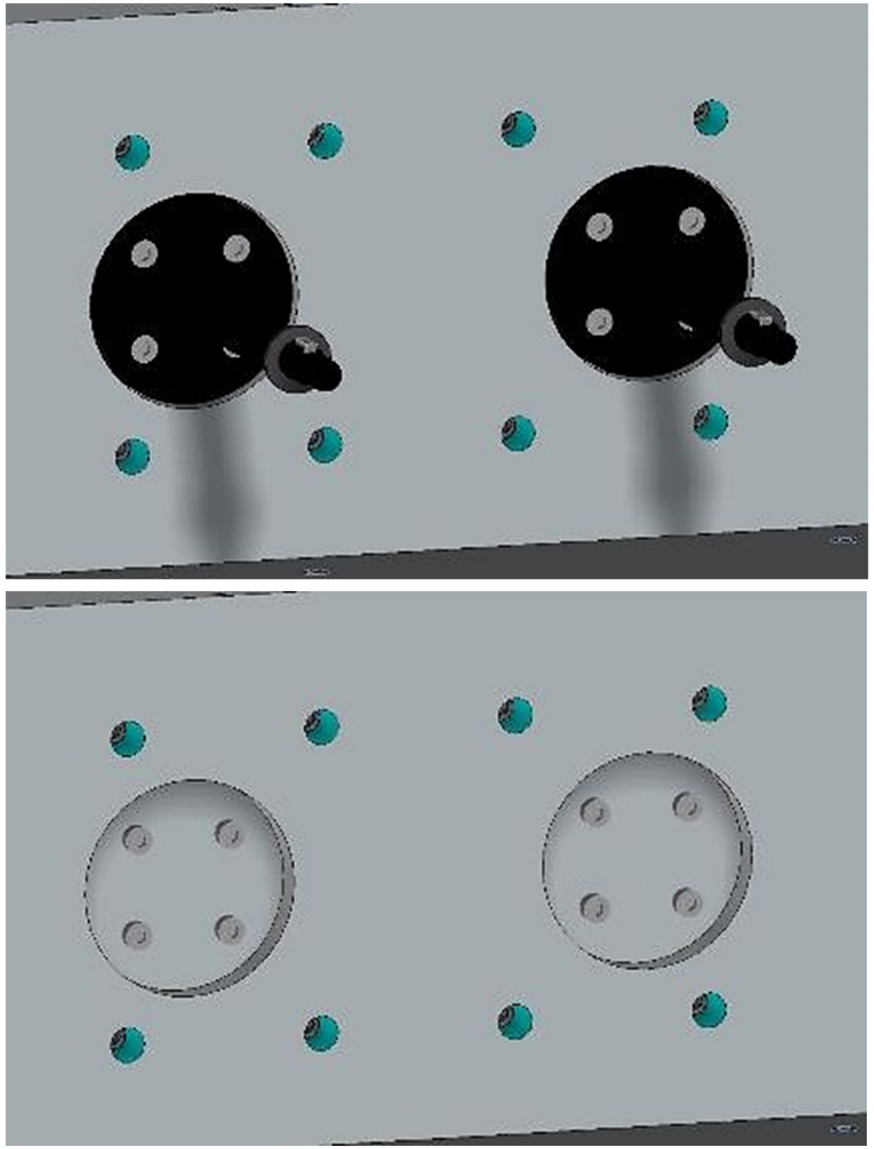
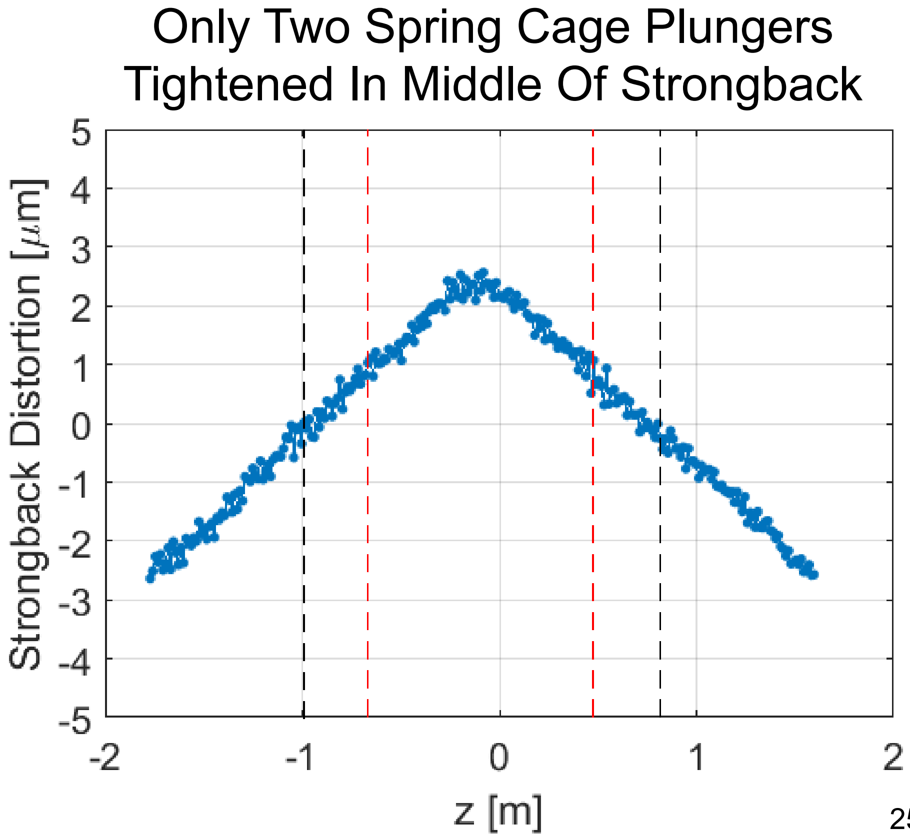


Strongback Deflection Due To Screws Tensioning



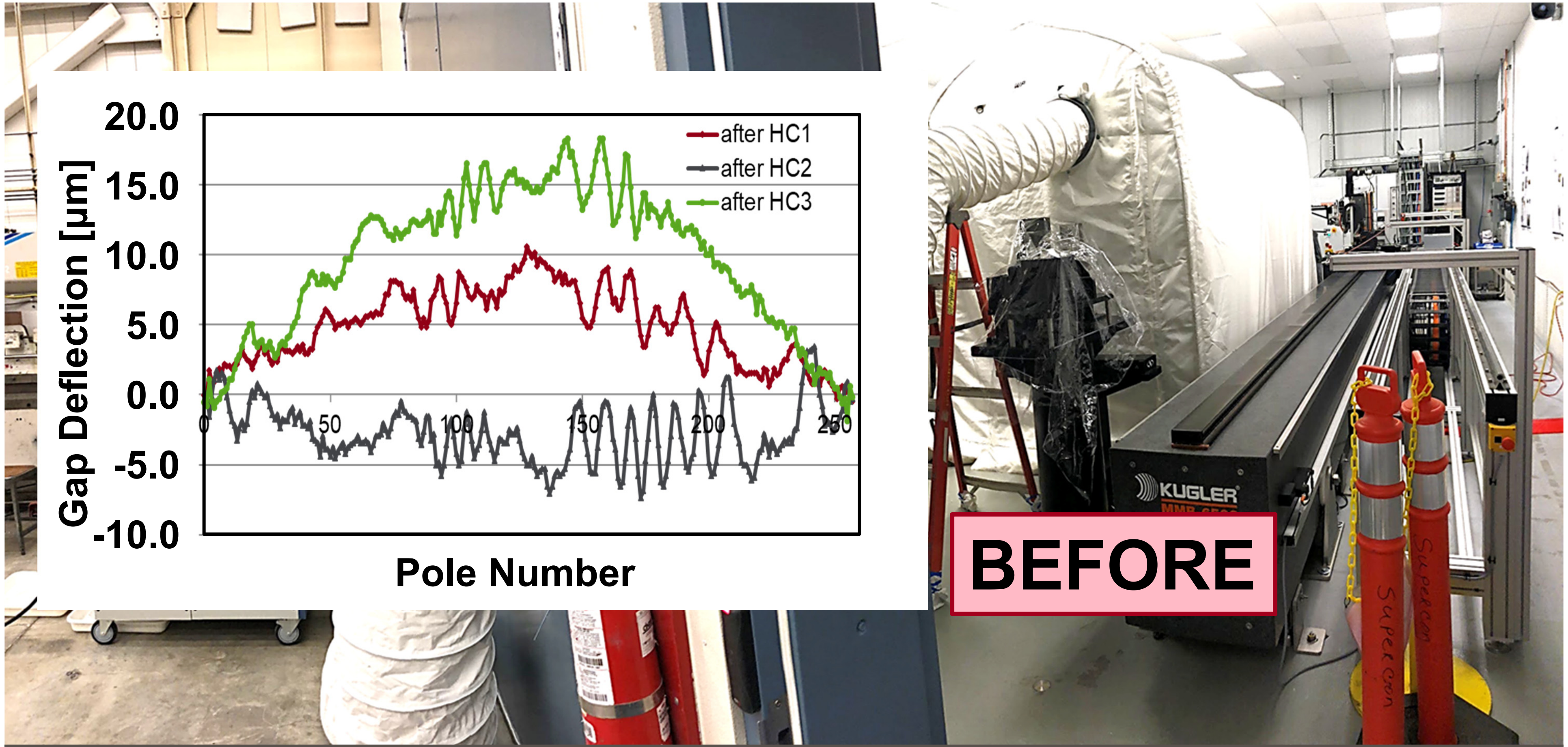
- Results were the similar with or without plungers (i.e. screws only)
- Torque used was 60 in-lbs.



Extensive Environmental Testing Demonstrates Robustness of New Undulator Mechanical System

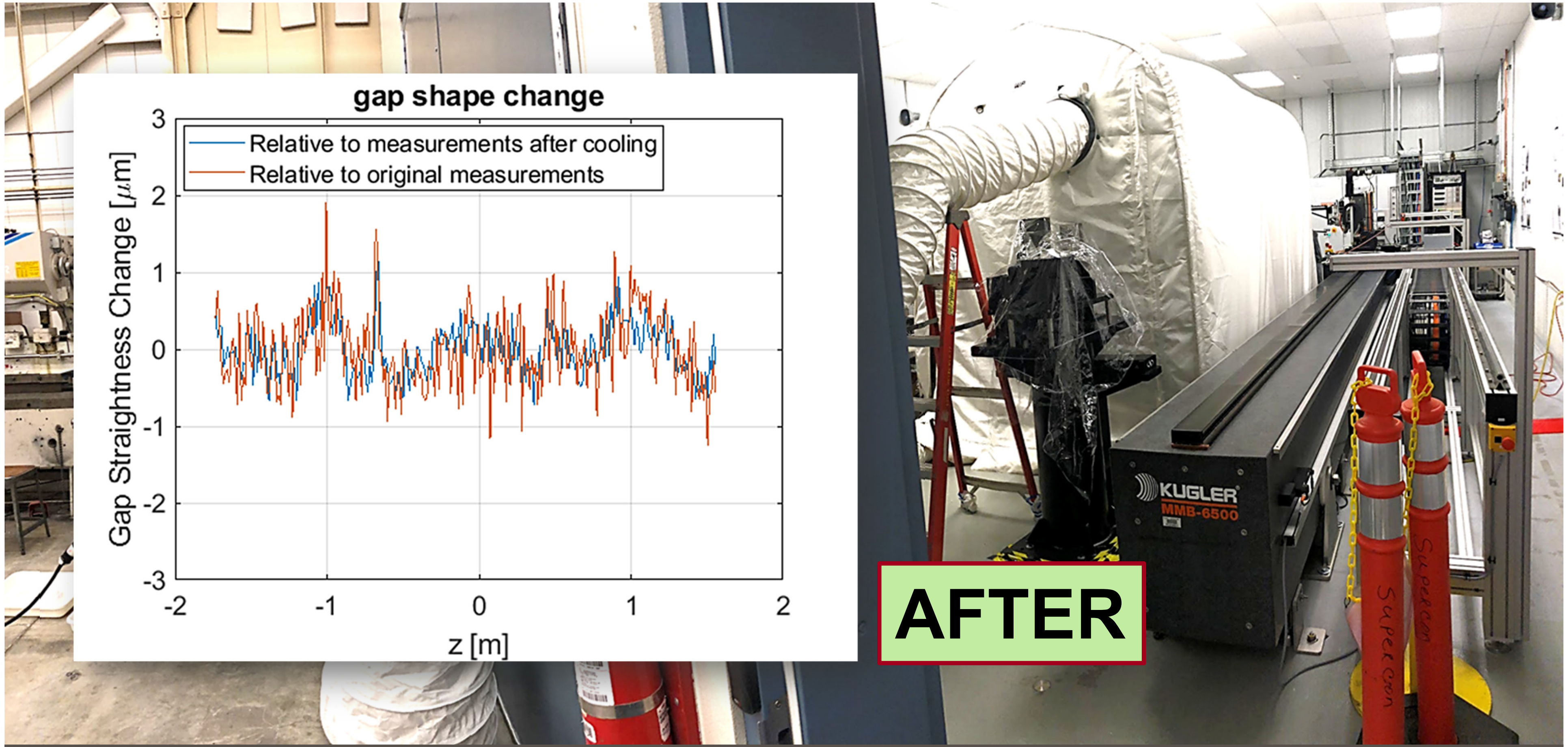
LBNL Undulator Environmental Test Setup (Temperature = 10 ºC to 35 ºC)

Extensive Environmental Testing Demonstrates Robustness of New Undulator Mechanical System



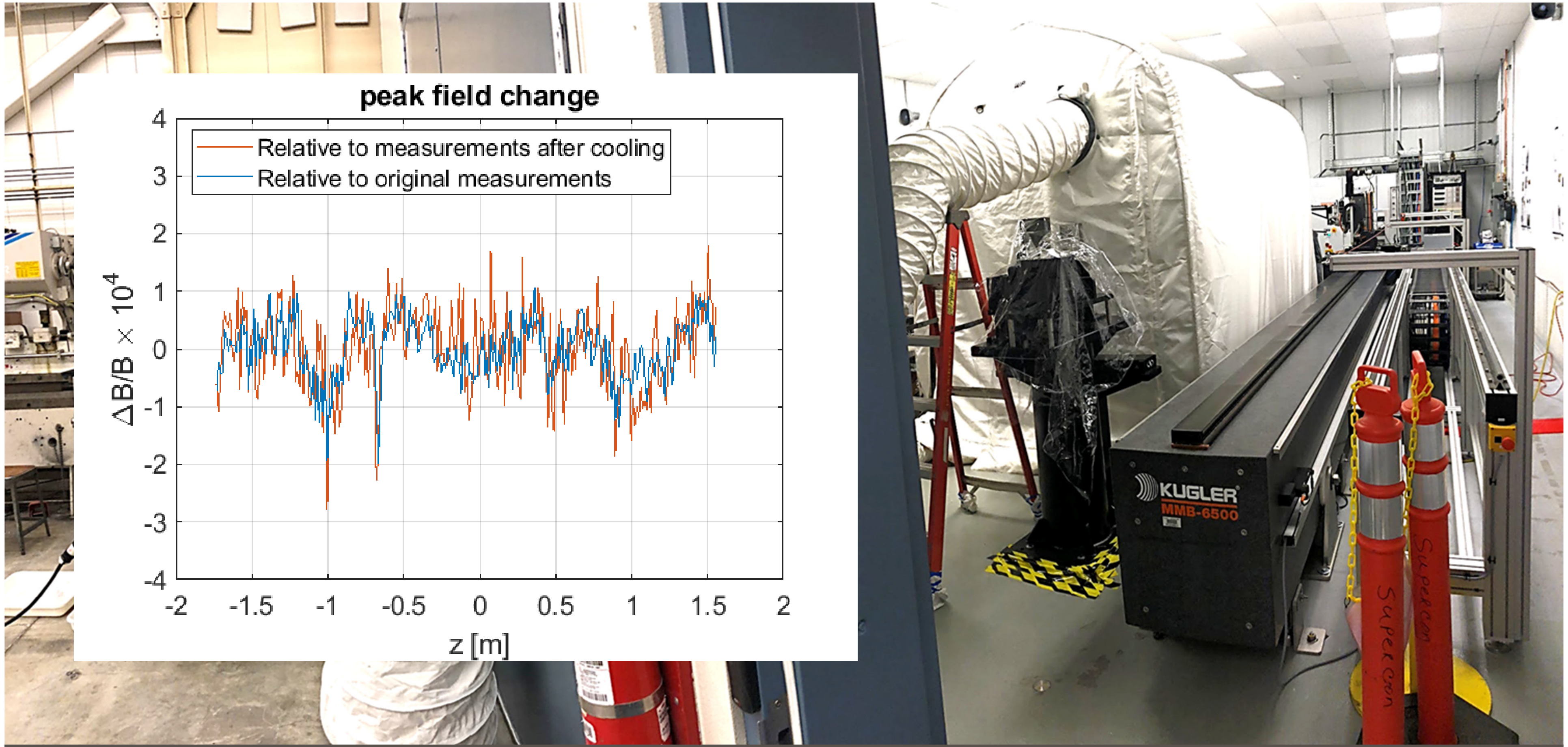
LBNL Undulator Environmental Test Setup (Temperature = 10 ºC to 35 ºC)

Extensive Environmental Testing Demonstrates Robustness of New Undulator Mechanical System



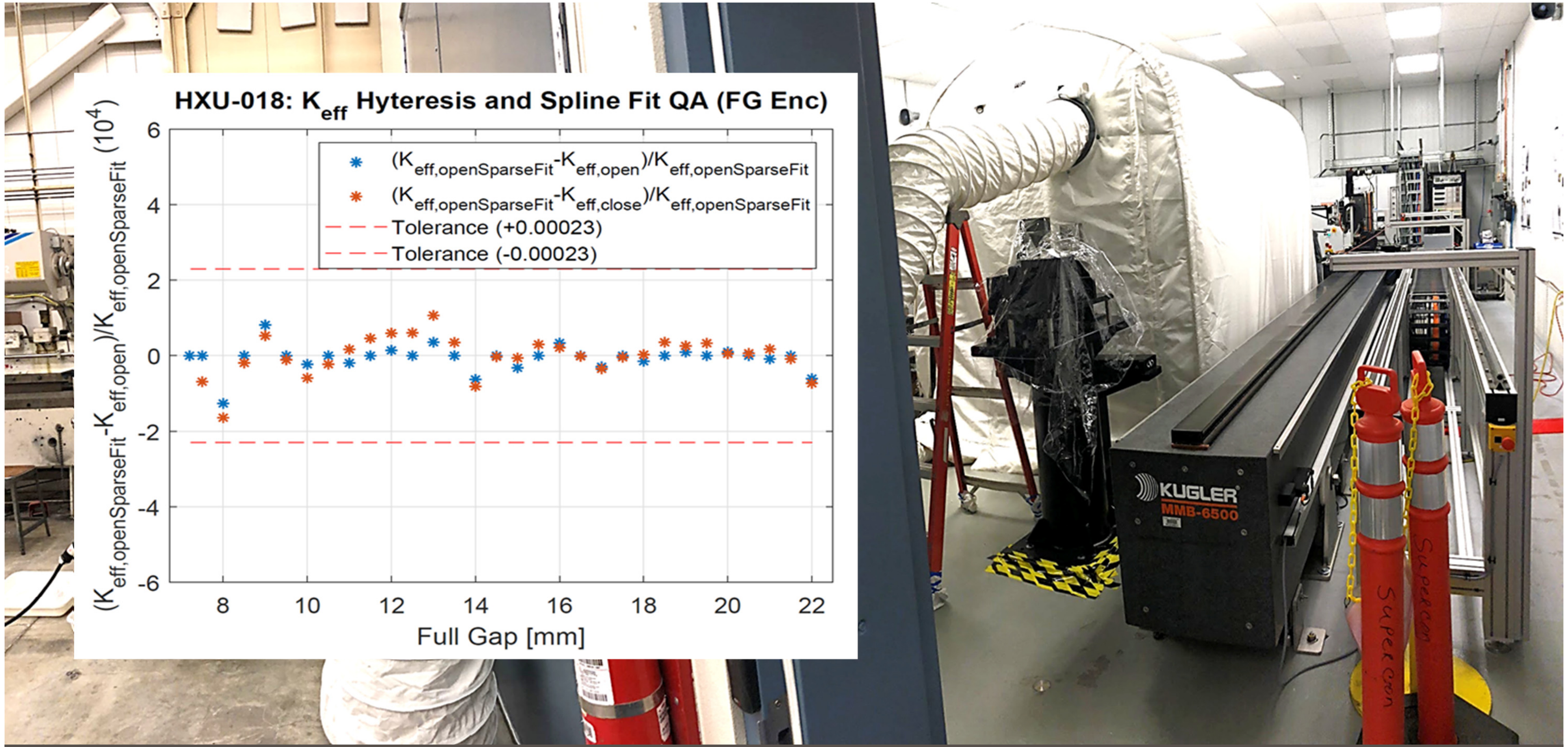
LBNL Undulator Environmental Test Setup (Temperature = 10 ºC to 35 ºC)

Extensive Environmental Testing Demonstrates Robustness of New Undulator Mechanical System



LBNL Undulator Environmental Test Setup (Temperature = 10 ºC to 35 ºC)

HGVPU Achieves Field Repeatability Requirement Independent Of Direction Of Gap Movement



LBNL Undulator Environmental Test Setup (Temperature = 10 ºC to 35 ºC)

Summary

- LCLS-II free electron laser project includes a 0.7 MeV VHF injector gun, 4 GeV superconducting linac, two 4 kW (@ 2K) cryoplants, and two variable gap undulator lines.
- Undulator installation will be completed by end of 2019.
- LCLS-II first light: Spring 2021.
- LBNL has completed the fabrication of all 22 soft-x-ray (SXR) undulator segments. SXR undulators are horizontally polarizing, hybrid permanent magnet undulator structures.
- LBNL is currently producing 33 hard x-ray (HGVPU) undulator segments. HGVPU undulators are vertically polarizing, hybrid permanent magnet undulator structures with novel magnetic force compensation.
- HGVPU technical development was difficult due to a challenging undulator design. However, vertically polarized radiation is preferred by experimental systems.
- LBNL undulator manufacturing was optimized for mass production using external vendors with a rigorous quality program and successful manufacturing and procurement oversight.

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