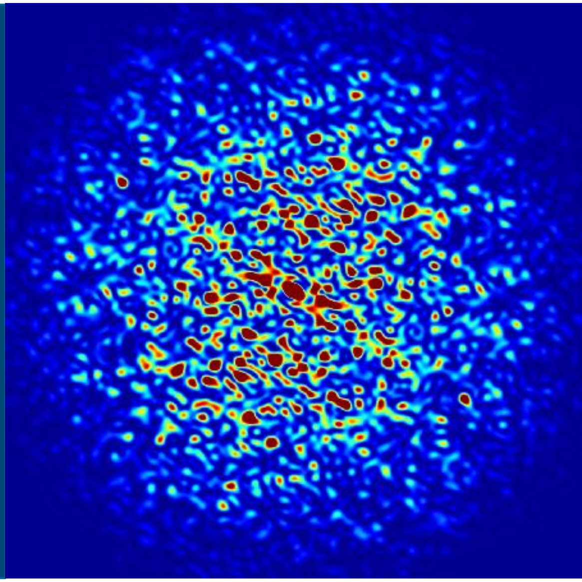
# MAGNETIC MEASUREMENTS AT THE ADVANCED PHOTON SOURCE*



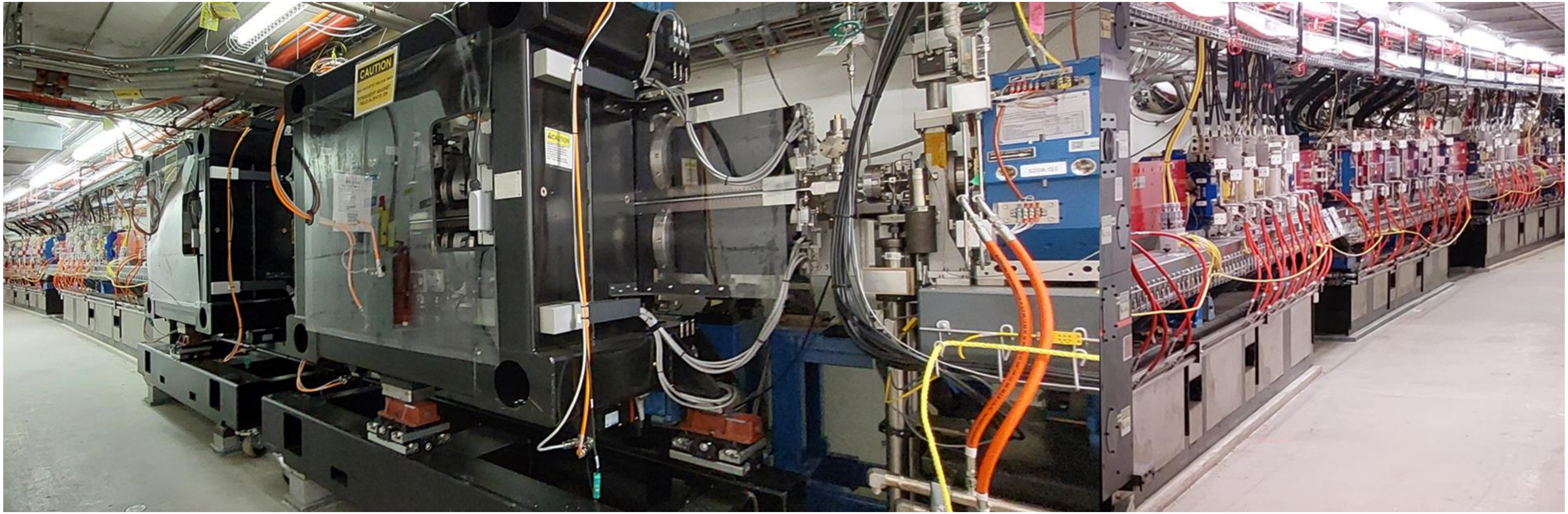
**Joseph Z. Xu**
On behalf of the APS magnetic measurement team
Argonne National Laboratory

IMMW #23, Parkhotel Bad Zurzach, Switzerland, Oct. 6 – 11, 2024
*Work supported by the U.S. DOE under Contract No. DE-AC02-06CH11357

# Outline

- Introduction
- Storage ring magnet measurement
- Permanent magnet undulator measurement
- Superconducting undulator measurement
- Summary

# Introduction



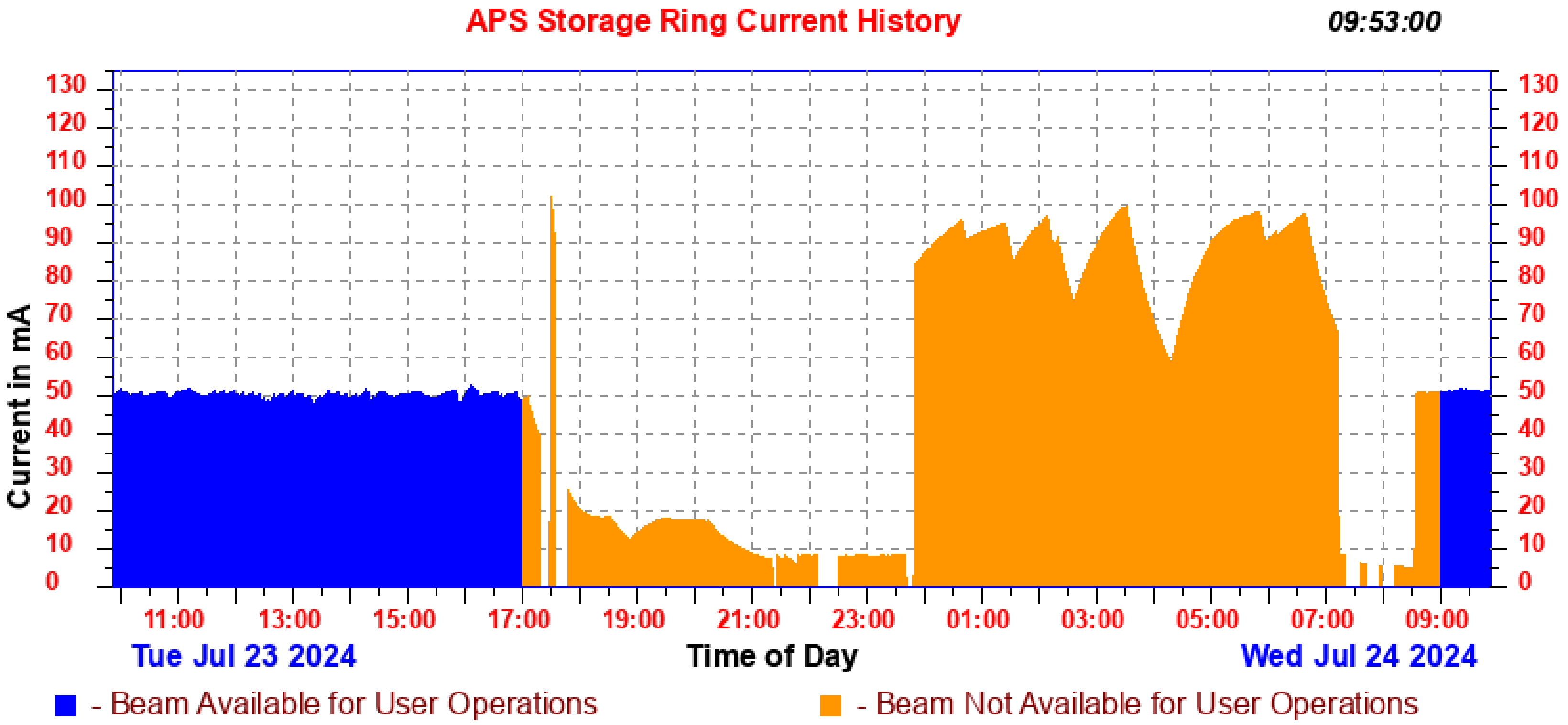

Section of the APS-U storage ring

The APS Upgrade (APS-U) project has installed and commissioned a 7 forward and 6 reverse multi-bend achromat (MBA) lattice operating at 6.0-GeV beam energy, replacing the legacy double bend achromat APS storage ring lattice that operated at 7.0 GeV.

# APS-U storage ring status

**Beam Current: 51.39 mA**
**Operations Status: Delivered Beam**
**Operations Messages:**

**Swapout in Progress**
**Beamlines Operating: 3**
Fill Number : 40




*Last Update : July 24, 2024 09:53:18* *https://www3.aps.anl.gov/aod/blops/status/srStatus.html*

# APS magnetic measurement teams

## Magnet measurement:

**Animesh Jain** (Physicist, the mastermind behind all the systems and procedures.)

**Charles Doose** (Engineer, implemented the systems and carried out the measurements.)

## Undulator measurement:

**Isaac Vasserman** (Physicist, the mastermind behind the systems and procedures.)

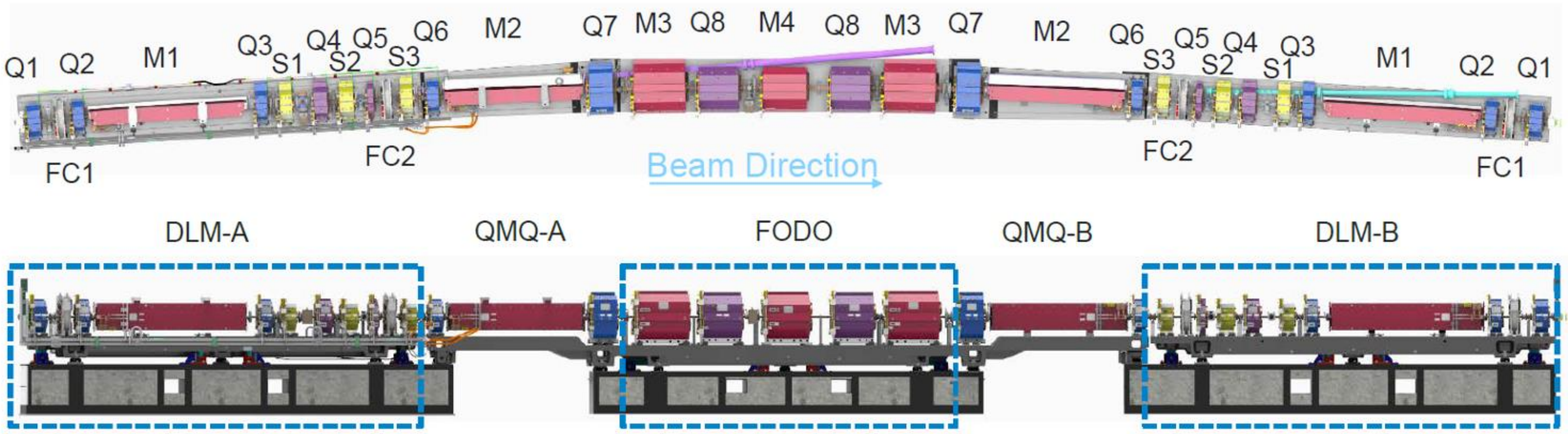
**Maofei Qian** (Physicist, upgraded the systems and the procedures.)

**Yinghu Piao** (Engineer, implemented the procedures and carried out the tuning and measurements.)

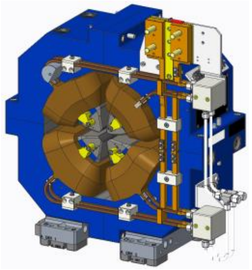
## SCU measurement:

**Matthew Kasa** (Engineer, the mastermind behind all the systems and procedures; implemented the systems and carried out the measurements.)

# APS-U storage ring magnets



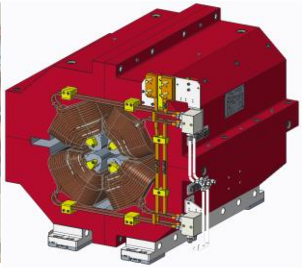

| APSU SR Mag | Types | Pole material | Qty req | Qty order |
|---|---|---|---|---|
| M1 | Longitudinal gradient dipole | steel | 80 | 82 |
| M2 | Longitudinal gradient dipole | steel | 80 | 82 |
| M3 | Transverse gradient dipole | VP | 80 | 82 |
| M4 | Transverse gradient dipole | VP | 40 | 42 |
| Q1 | Quadrupole | VP | 80 | 82 |
| Q2 | Quadrupole | steel | 79 | 81 |
| Q3 | Quadrupole | steel | 81 | 83 |
| Q4 | Reverse bend Quadrupole | VP | 80 | 82 |
| Q5 | Reverse bend Quadrupole | steel | 80 | 82 |
| Q6 | Quadrupole | steel | 80 | 82 |
| Q7 | Quadrupole | VP | 80 | 82 |
| Q8 | Reverse bend Quadrupole | VP | 80 | 82 |
| S1 and S3 | Sextupole | steel | 160 | 164 |
| S2 | Sextupole | VP | 80 | 82 |
| FC1 and FC2 | Fast corrector | Lamination | 161 | 165 |
| Total | | | 1321 | 1355 |


Q1

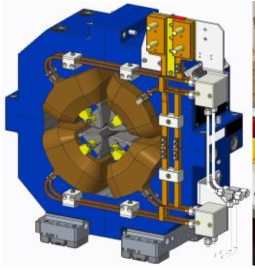

Q3

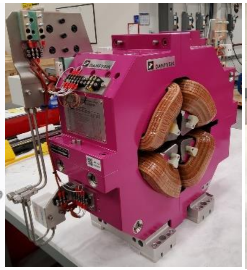

Q5

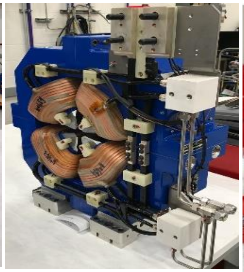

Q7

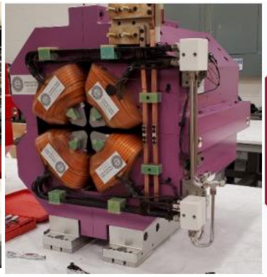

M3

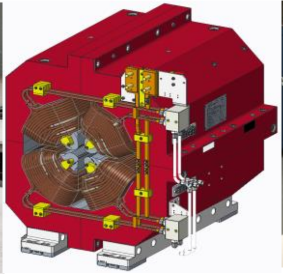

M1


Q2


Q4

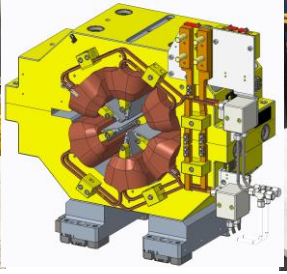

Q6


Q8


M4


M2


S1/S3


S2


FC

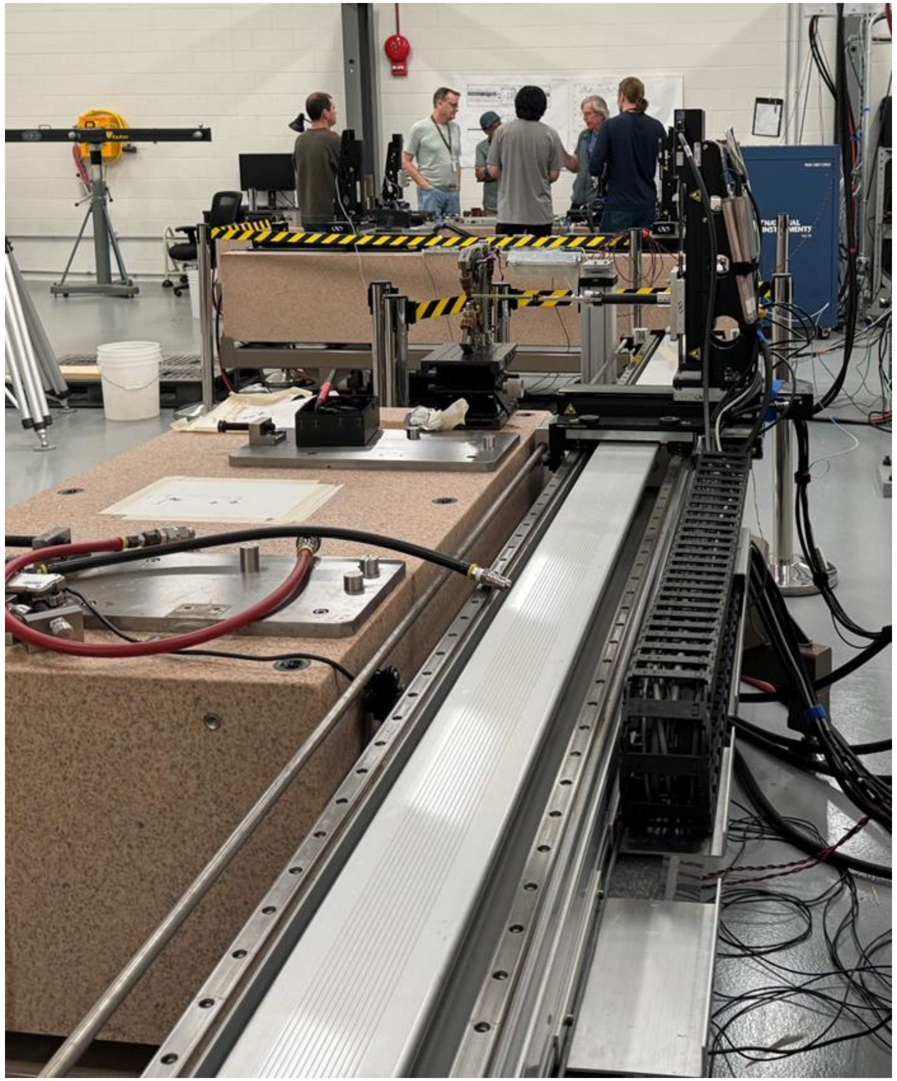
# Field quality and alignment requirements

- Maximum field deviation in terms of integrated field harmonics is $\pm 10\times10^{-4}$ (10 "unit") relative to the nominal field, at 10-mm radius about the designed orbit position. (*APS-U Accelerator Functional Requirements Document*)
  - The random errors specifications are more stringent (*APS-U Preliminary Design Report*)
  - Goal is to measure field harmonics with a resolution of well below $1\times10^{-4}$ of the main field (1 "unit") at a reference radius of 10 mm (< 0.1 unit is achievable with current state-of-the-art equipment).

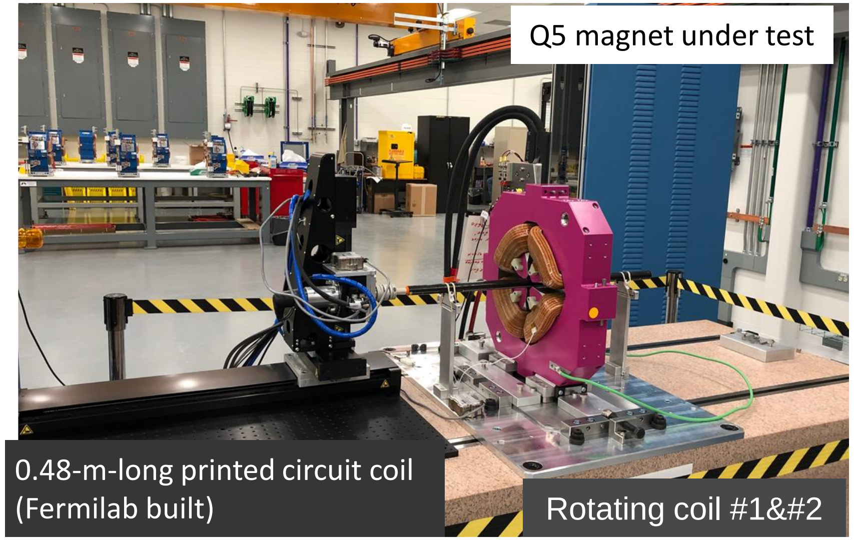
- Alignment requirements (*APS-U Accelerator Functional Requirements Document*):

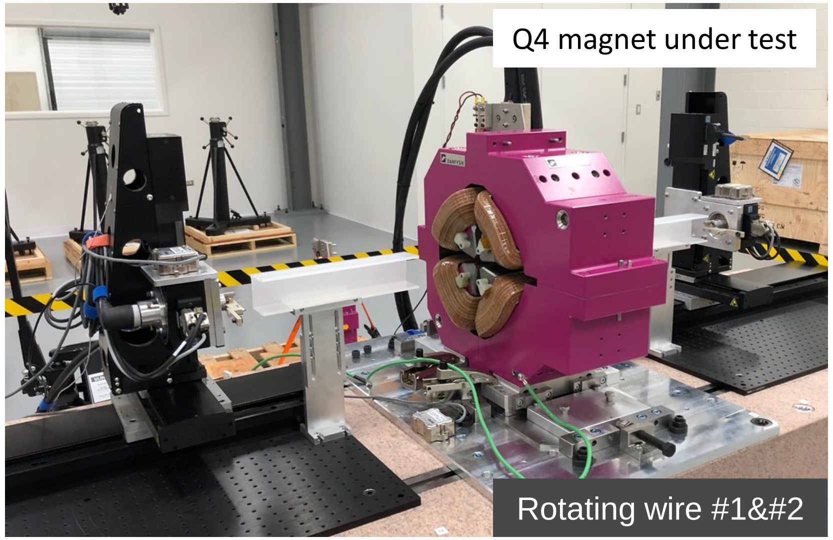
| | | | |
|---|---|---|---|
| **Girder to girder alignment** | | | |
| DLM to FODO; 1 sigma cutoff | μm rms | 100 | (by survey) |
| QMQ to DLM or FODO; 1.5 sigma cutoff | μm rms | 50 | (by survey) |
| **Elements within a girder** | | | |
| Magnet to magnet (2 sigma cutoff) | μm rms | 30 | (magnetic + survey) |
| Dipole roll | mrad | 0.4 | (survey of poles + mechanical) |
| Quadrupole roll | mrad | 0.4 | (magnetic + mechanical) |
| Sextupole roll | mrad | 0.4 | (magnetic + mechanical) |

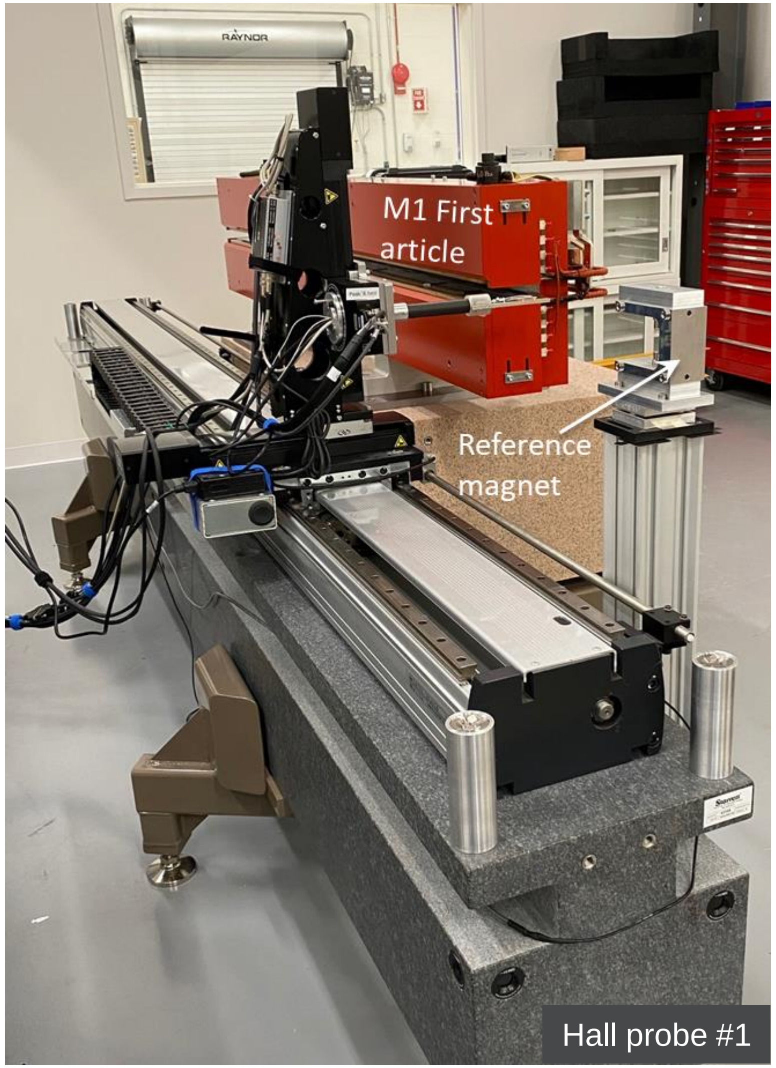
# Storage ring magnet measurement lab

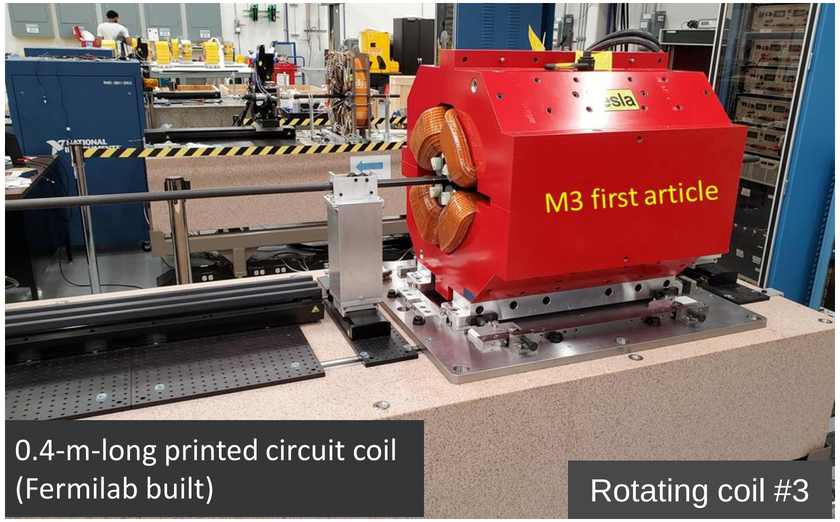



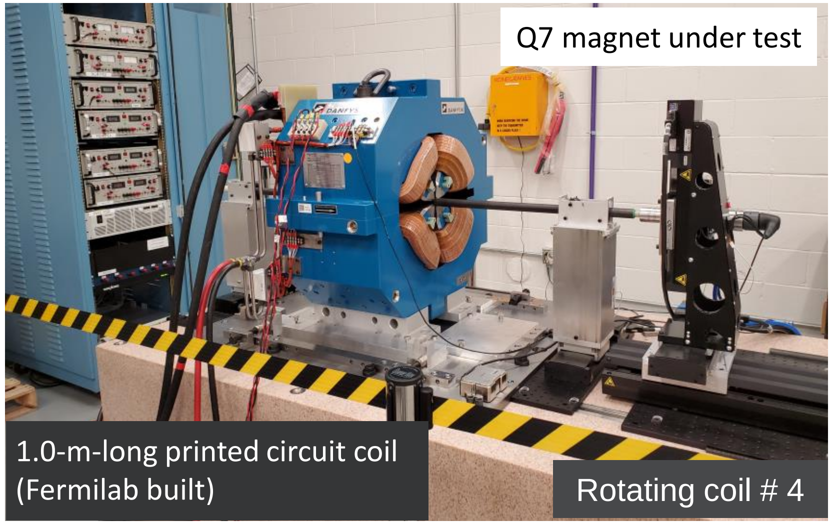
# Storage ring magnet measurement benches

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# Magnetic measurement methods employed

- **For field quality measurements (main field strength, field roll angle, harmonics):**
  - Rotating coils are the most established and accurate tools to measure harmonics.
  - Accurate measurement of absolute strength requires a one-time calibration, but it is very repeatable over long periods of time.
  - The coil consists of a system of wire loops that are rotated in the field to generate a signal. This gives azimuthal dependence of field, which is used to derive the field harmonics.
  - All coils for APS-U used printed circuit boards with dipole and quadrupole bucking and were built by Fermilab. One bench had sextupole bucking as well.
- **For fiducialization of magnetic center:**
  - Several wire-based techniques are suitable for this. APS-U used the *Rotating Wire* method, which works very similar to the rotating coil measurements and so uses very similar software.
- **For 3D field maps in longitudinal gradient dipoles:**
  - Hall probe bench with a 3-axis Hall probe and two NMR probes for in-situ calibration.

# Magnet measurements on different benches

| Bench | Type | Magnet | Quantity | Date completed |
|---|---|---|---|---|
| RC#1 | Rotating coil | Q1-Q6 | 492 | June 28, 2021 |
| RC#2 | Rotating coil | S1-S3 | 411 | May 25, 2022 |
| RC#3 | Rotating coil | M3, M4 | 124 | July 7, 2022 |
| RC#4 | Rotating coil | Q7, Q8 | 164 | June 1, 2023 |
| RW#1 | Rotating wire | Q1-Q5, S1-S3 | 656 | August 6, 2021 |
| RW#2 | Rotating wire | Q6, Q7, Q8, M3, M4 | 370 | June 6, 2023 |
| HP#1 | Hall probe | M1, M2 | 164 | August 9, 2022 |
| Total number of measurements/duration | | | 2,545 | 47 [months] |
| Note: Two magnets of each type were also 3-D mapped using a Hall probe by converting the rotating wire benches into a Hall probe bench. These are not included in the list above. | | | | |

# Permanent magnet undulators (PMUs)


APS

| ID | Qty |
|---|---|
| APS85 | 2 |
| APS55 | 1 |
| APS36 | 1 |
| APS35 | 1 |
| APS/U33 | 37 |
| APS30 | 8 |
| APS27 | 7 |
| APS23 | 3 |
| U18 | 1 |
| APS17.2 | 3 |
| Total | 64 |

APS-U

| ID | Qty |
|---|---|
| APS85 | 2 |
| APS55 | 1 |
| APS36 | 1 |
| APS35 | 1 |
| APS/U33 | 37 |
| APS30 | 8 |
| APS28 | 13 |
| APS27 | 7 |
| APS25 | 12 |
| APS23 | 3 |
| APS21 | 15 |
| U18 | 1 |
| APS17.2 | 3 |
| APS14 | 2 |
| APS13.5 | 3 |
| Total | 109 |

Note: Number of magnetic structure sets. Green are newly built (45) IDs, yellow are reconditioned legacy IDs, and grey are surpluses.

CAUTION
CAUTION
STRONG
MAGNETIC
FIELDS
DANGER
CAUTION
WARNING
SHELTER
USE ONLY

# APS-U ID specifications

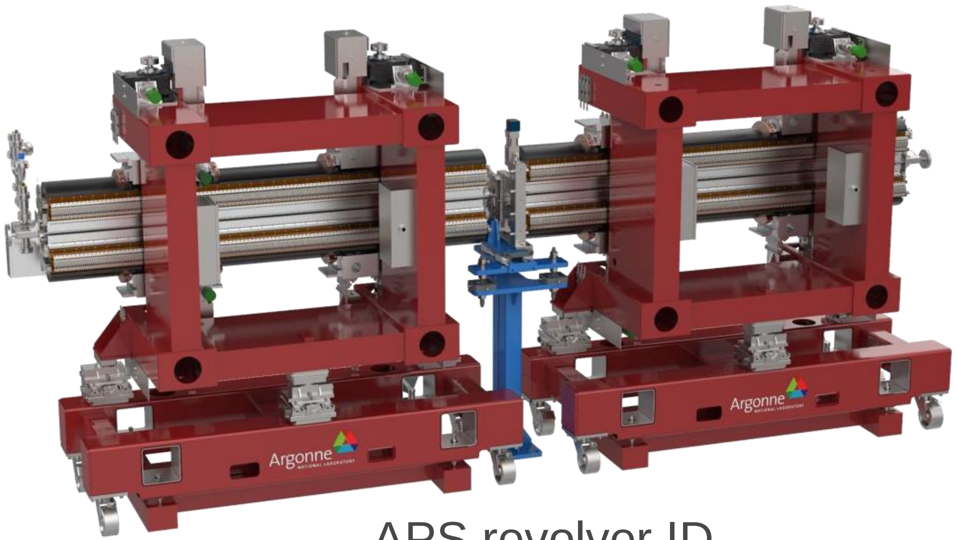

APS planar ID

### ID Global Specifications

| Parameter | Value | Unit |
|---|---|---|
| Number of ID straights | 35 | |
| Insertion device maximum length | 4.8 | m |
| Vertical magnetic gap | ≥8.5 | mm |
| ID chamber vertical aperture | ≥6.3 | mm |
| Maximum canting angle | 1 | mrad |
| Vacuum chamber straightness in plane with small magnetic gap | 50 | µm |
| ID rms phase error for any operational gap [1)] | ~3 | degree |

### ID Drive System Specifications

| Parameter | Value | Unit |
|---|---|---|
| Minimum gap (normal operation) | 8.5 | mm |
| Minimum gap (absolute operational limit) | 8.2 | mm |
| Gap taper (maximum) | 5.0 | mm |
| Maximum gap | 125 - 180 | mm |
| Gap resolution | 0.5 | µm |
| Gap repeatability (unidirectional) | <3 | µm |
| Gap stability | <5 | µm |
| Rate of gap change | 1 | mm/s |


APS revolver ID

# APS-U vs. APS ID requirements

| Parameter | APS-U Spec | APS Spec | Unit |
|---|---|---|---|
| Beam Energy | 6 | 7 | GeV |
| Min Gap | **8.2** | 11.5 | mm |
| RMS Ph Err | **3** | 8 | deg |
| X Trj | **1.25** | 2 | um |
| Y Trj | **0.4** | 2 | um |
| X ent/ext angle | **3.9** | 6 | urad |
| Y ent/ext angle | **1.25** | 3 | urad |
| J1x ups/dns | **25** | 50 | G-cm |
| J1y ups/dns | **78** | 100 | G-cm |
| J2x ups/dns | **5.25** | 100 | kG-$cm^2$ |
| J2y ups/dns | **16.38** | 100 | kG-$cm^2$ |
| Norm Quad | **50** | 50 | G |
| Skew Quad | **50** | 50 | G |
| Norm Sext | **1,100** | 200 | G/cm |
| Skew Sext | **560** | 100 | G/cm |
| Norm Oct | **1,700** | 300 | G/$cm^2$ |
| Skew Oct | **280** | 50 | G/$cm^2$ |
| Roll Off | **3** | 3 | $B/B_o$% @ X:±6mm |

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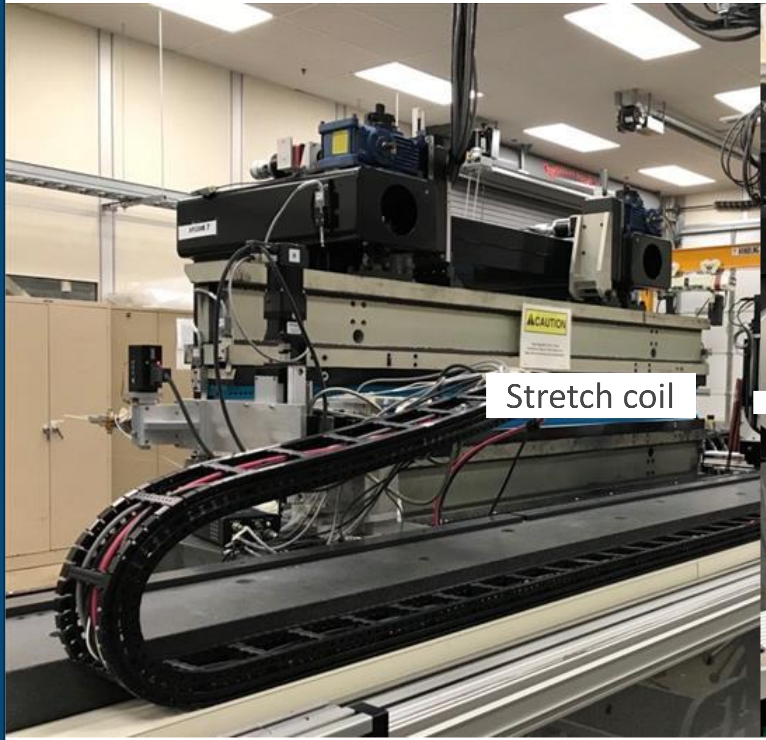
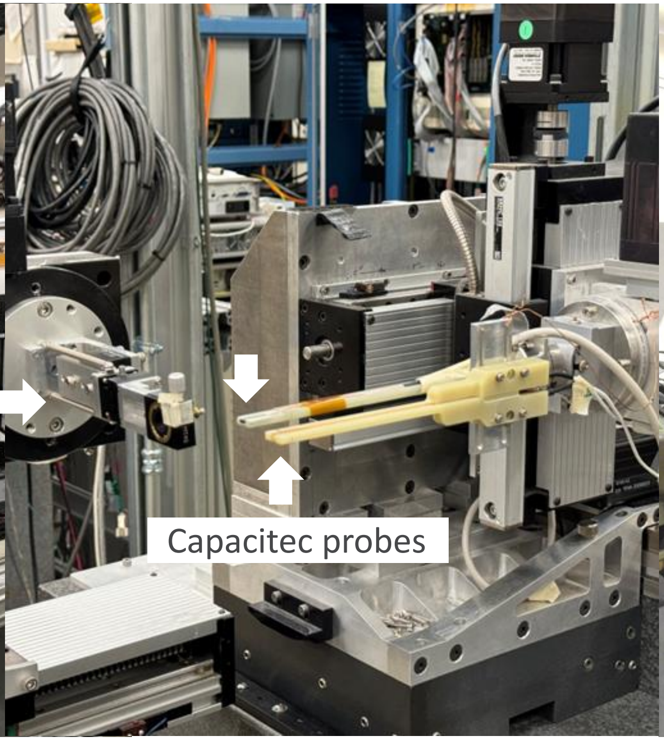
# ID magnet measurement lab

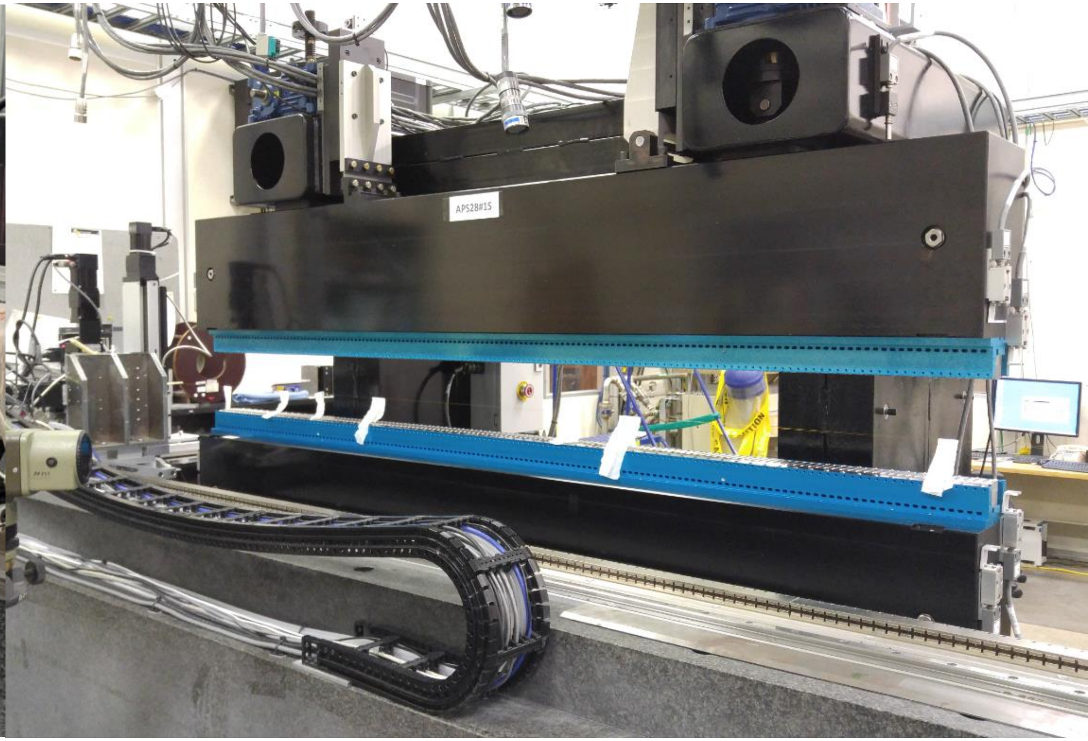
# ID magnet measurement lab




APS28#1S on 3-m bench



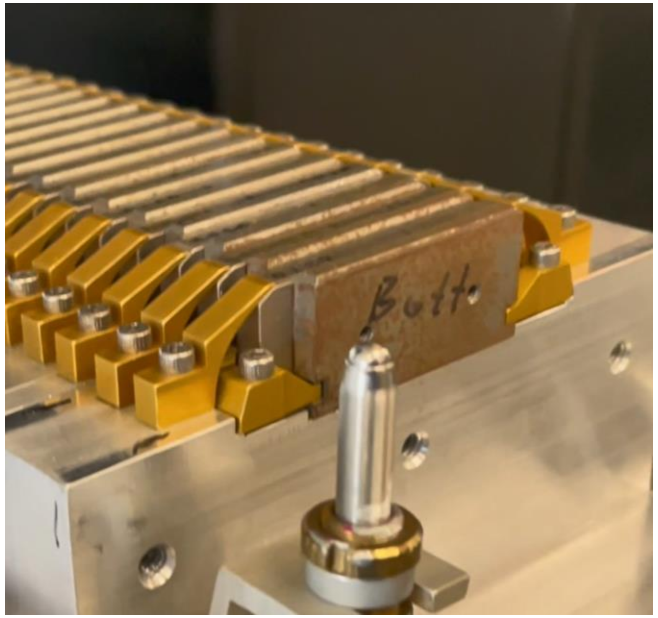

Hall probe and Capacitec probes



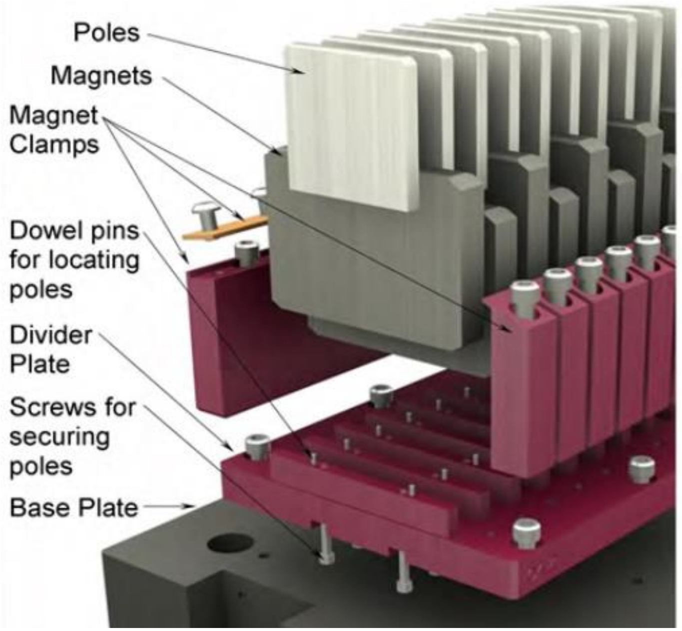
APS28#7 on 6-m bench

# APS planar permanent magnet undulator (PMU)

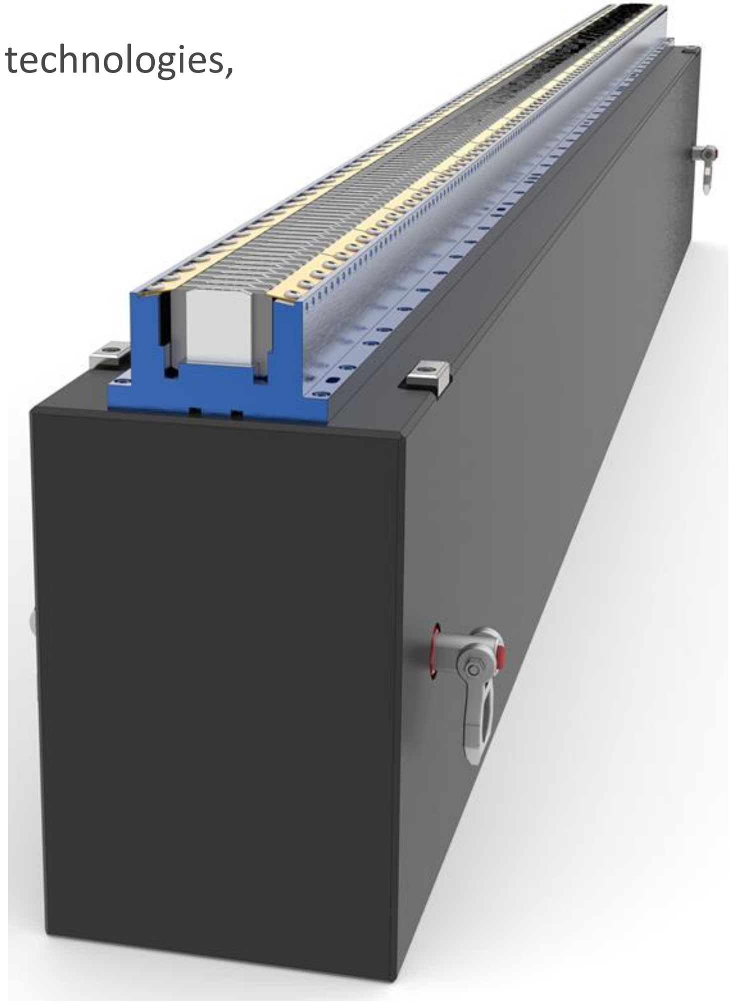
Machined to the specifications combined with the patented tuning technologies, we can cost effectively reach the state-of-the-art specifications.



Gen-1 APS undulators

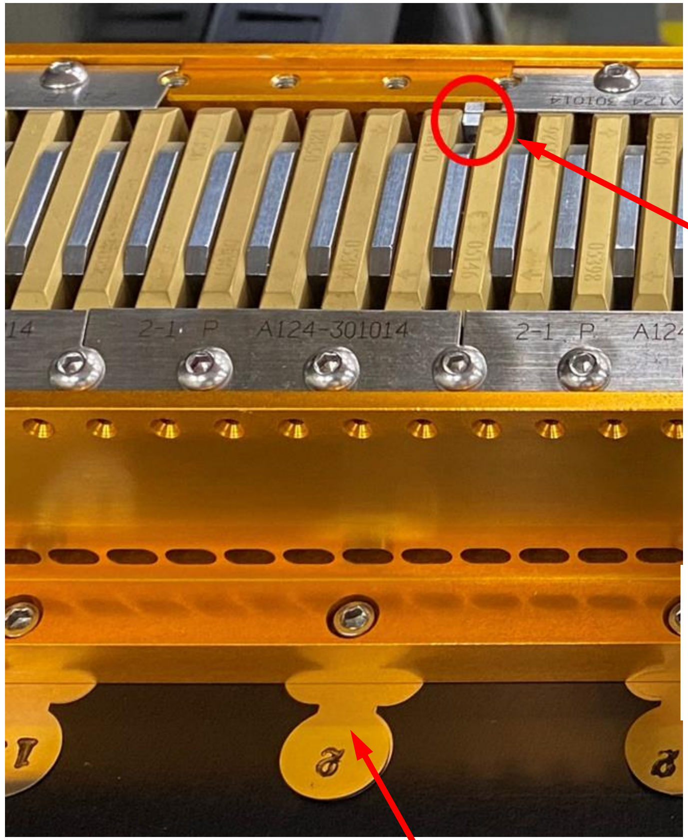


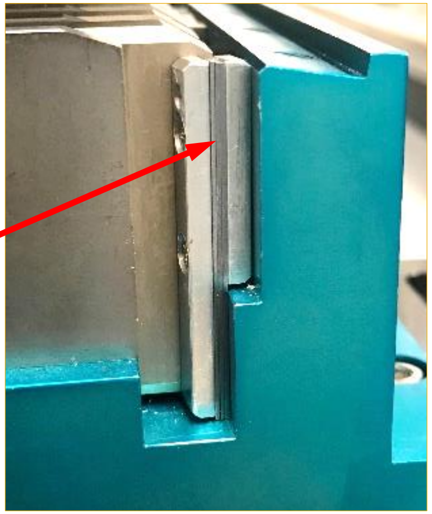

Gen-2 APS undulators



Gen-3 (new) APS undulators

# APS planar PMU tuning

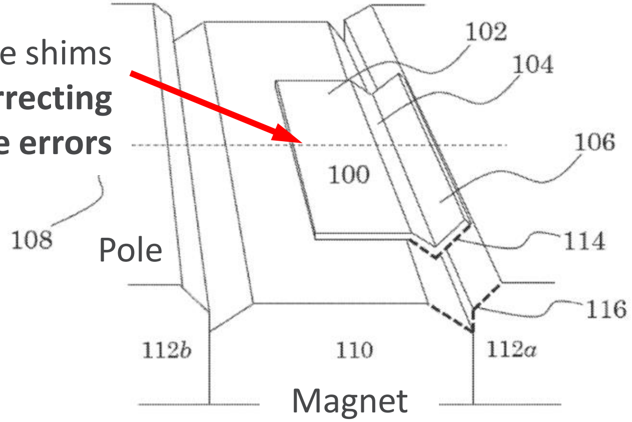


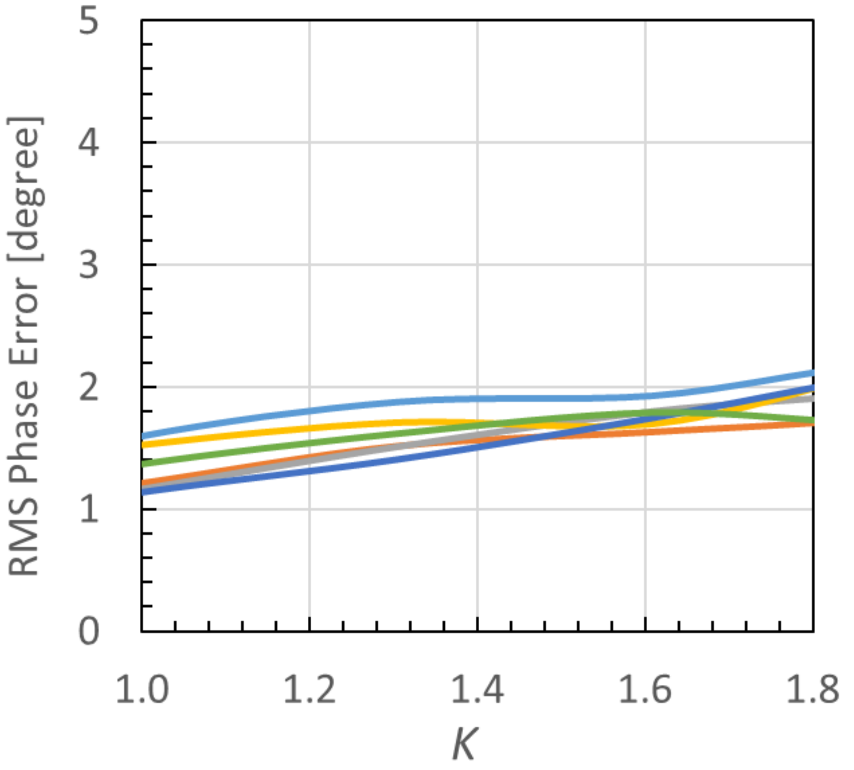



1. Magnetic side shims for **correcting trajectory errors**.

2. Mechanical shims for **correcting phase errors.**

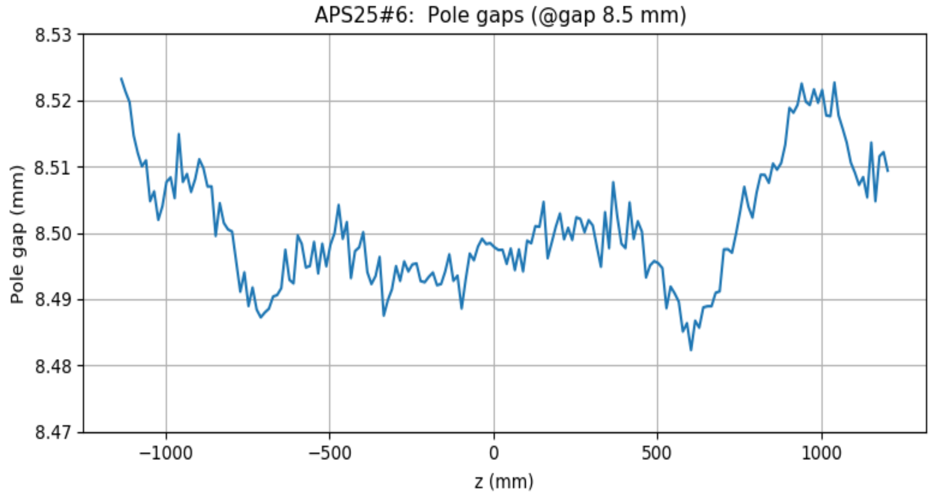
3. Surface shims for **correcting multipole errors**



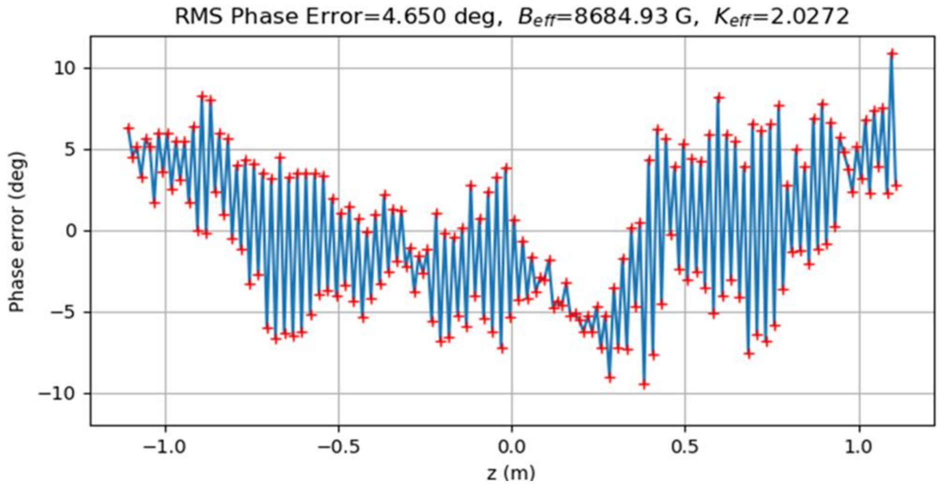




APS25 undulators RMS phase errors as a function of K, tuned to better than 2.2 degrees with the much simpler design.

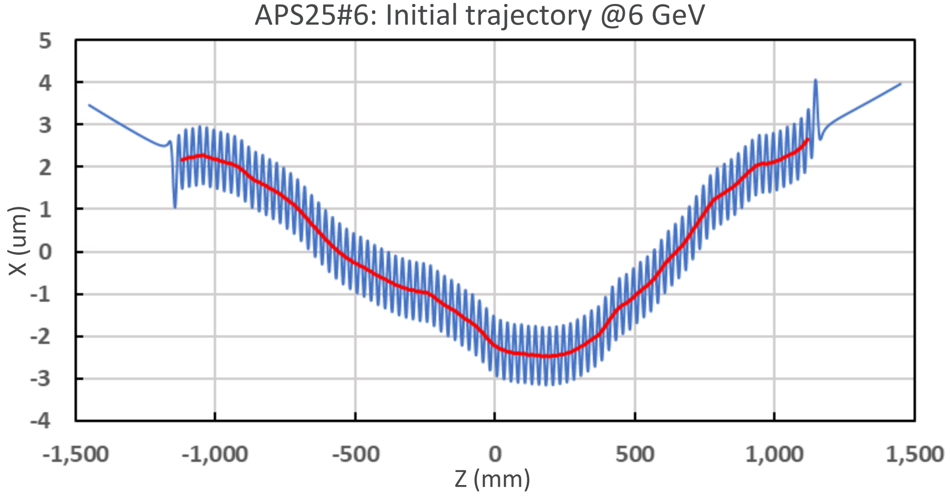
# ID tuning – example: APS25#6, initial mechanical shimming



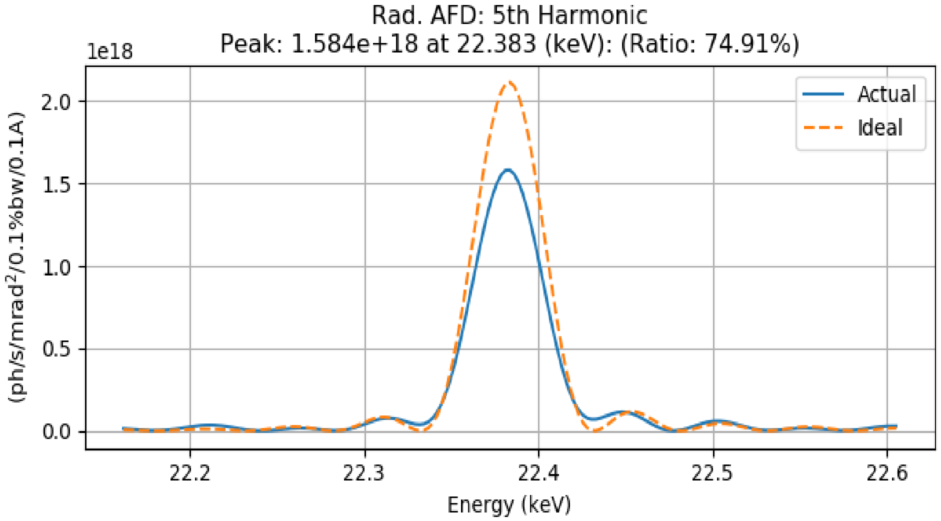

Capacitec measurement after initial gap mechanical shimming




Phase error at 8.5-mm gap setting

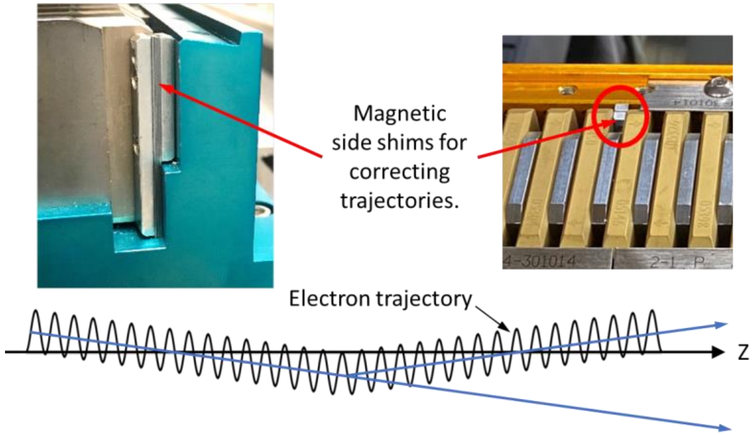



Initial trajectory at 8.5-mm gap

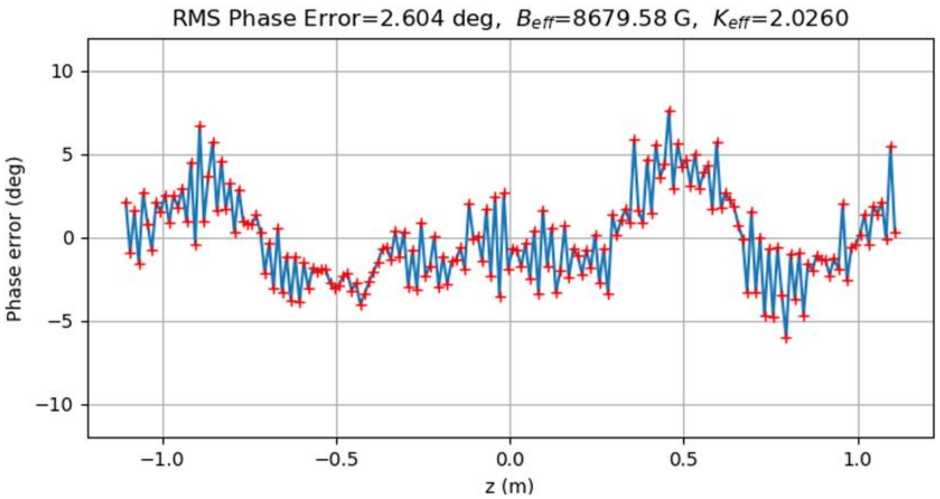



$5^{th}$ harmonic brightness

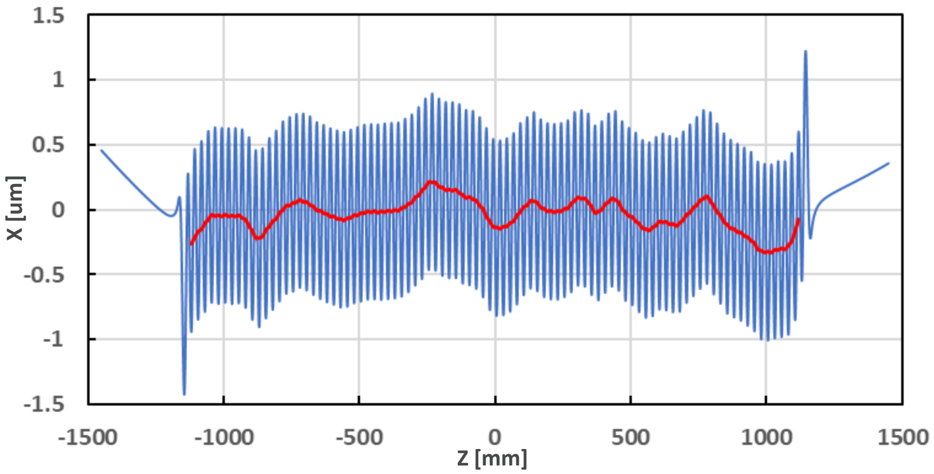
# ID tuning – example: APS25#6, trajectory tuning



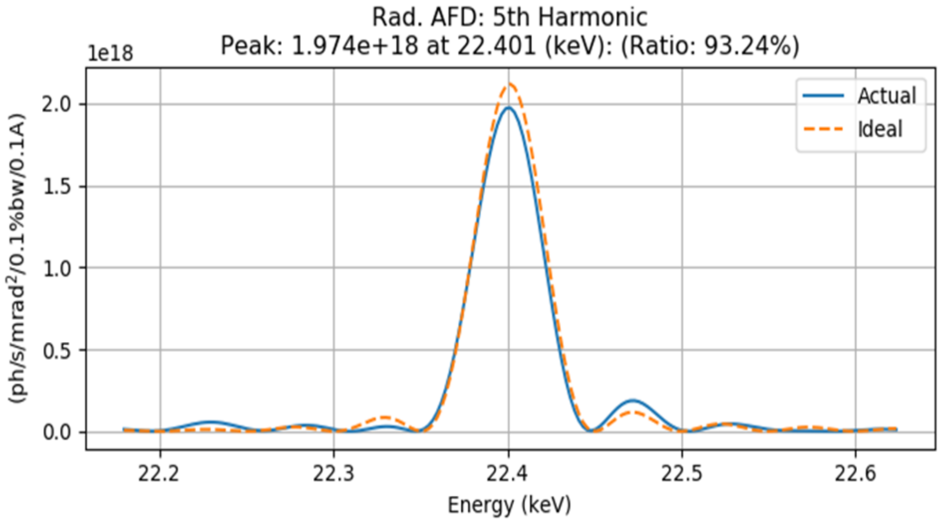

Evolutionary algorithm to optimize the trajectory tuning across all operational gap/current settings. The algorithm will predict how many places, where, what types, and how many shims to insert.




Phase error at 8.5-mm gap setting after trajectory tuning




Trajectories at 8.5-mm gap after trajectory tuning




5th harmonic brightness after trajectory tuning

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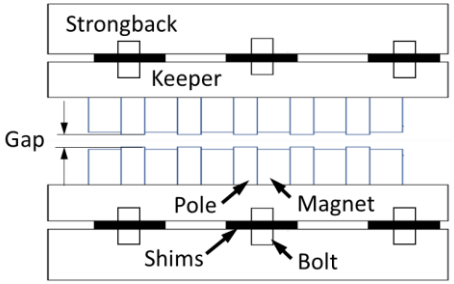
# ID tuning – example: APS25#6, phase tuning

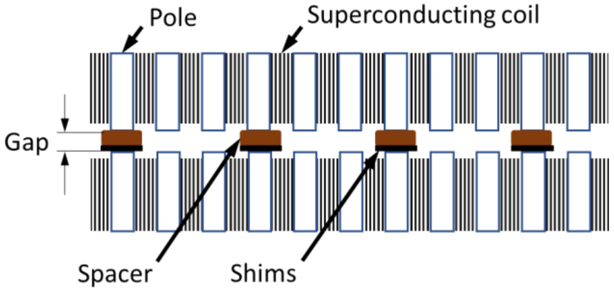
The gap profile error of an undulator is described by a slow-varying function $\delta g(i)$, then the phase error advance over one pole is determined by

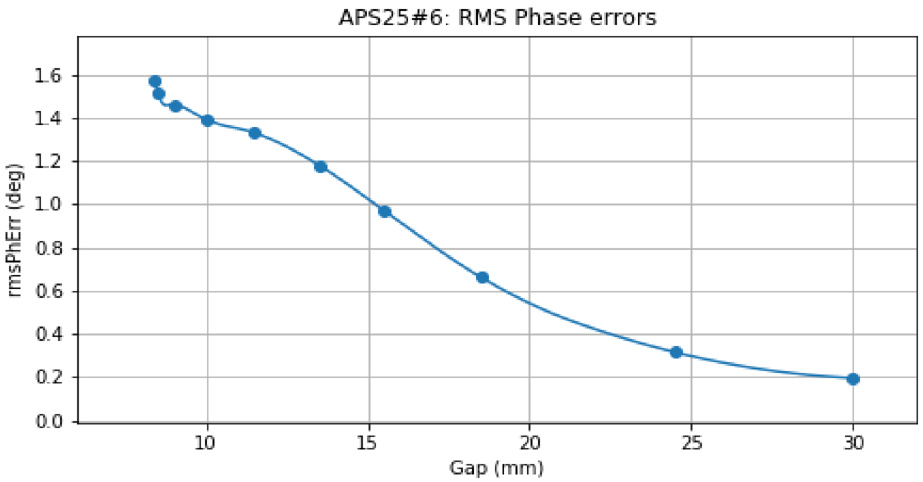
$$\delta\phi(i) = -\pi^2 \frac{2\overline{K}^2}{2+\overline{K}^2}\frac{\delta g(i)}{\lambda_u}$$

$\overline{K}$: the mean deflection parameter of the undulator

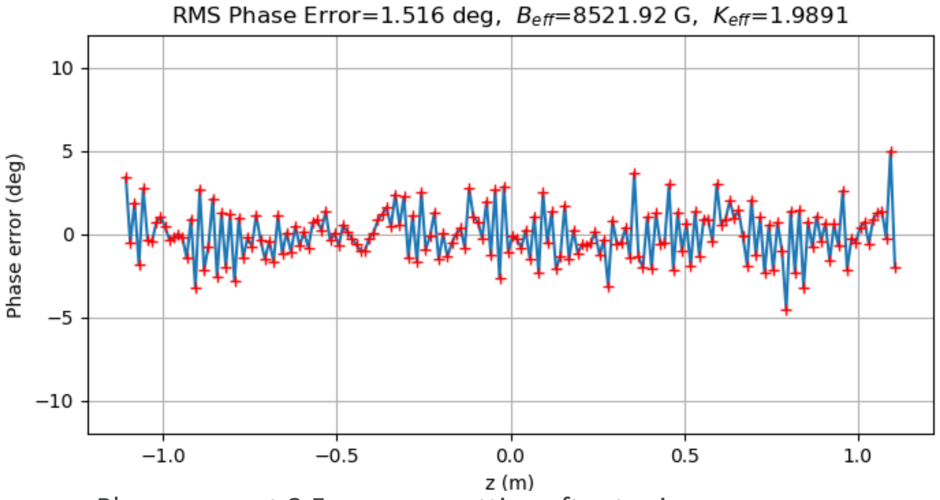
$\lambda_u$: undulator period length



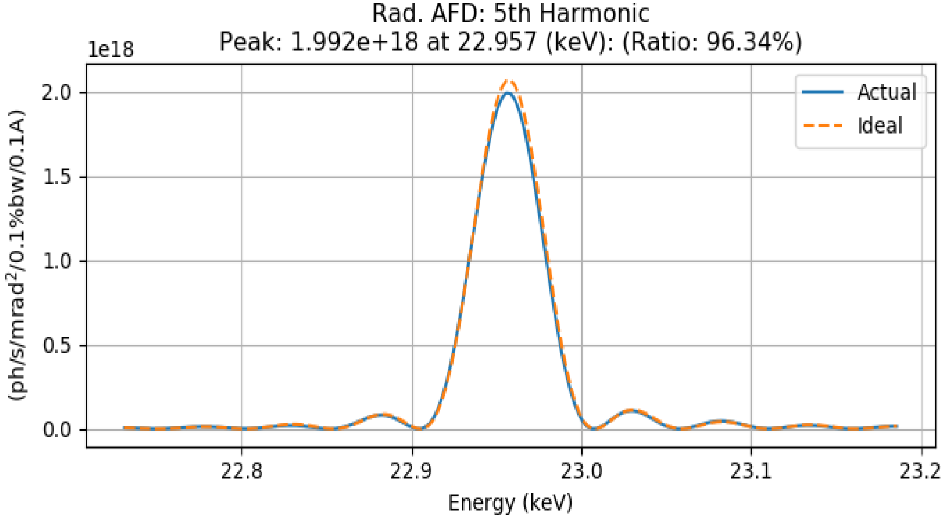




RMS phase errors after tuning

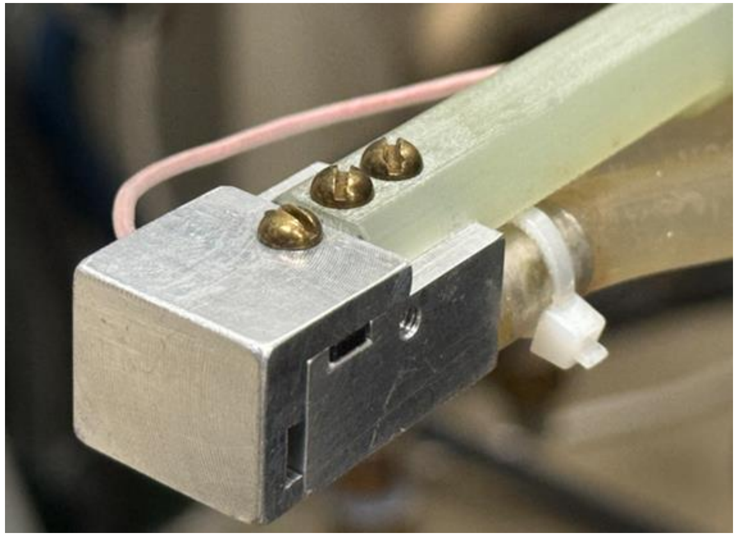


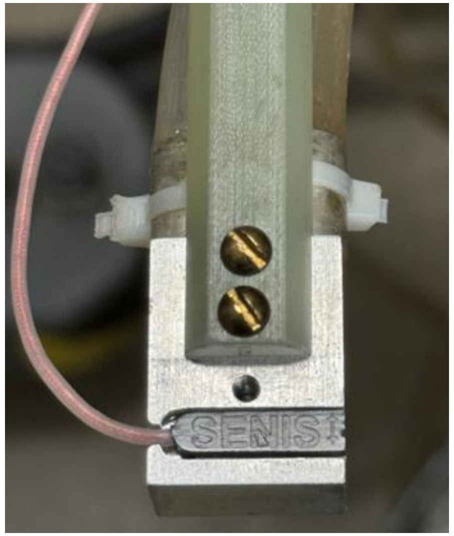

Phase error at 8.5-mm gap setting after tuning




5th harmonic brightness after tuning

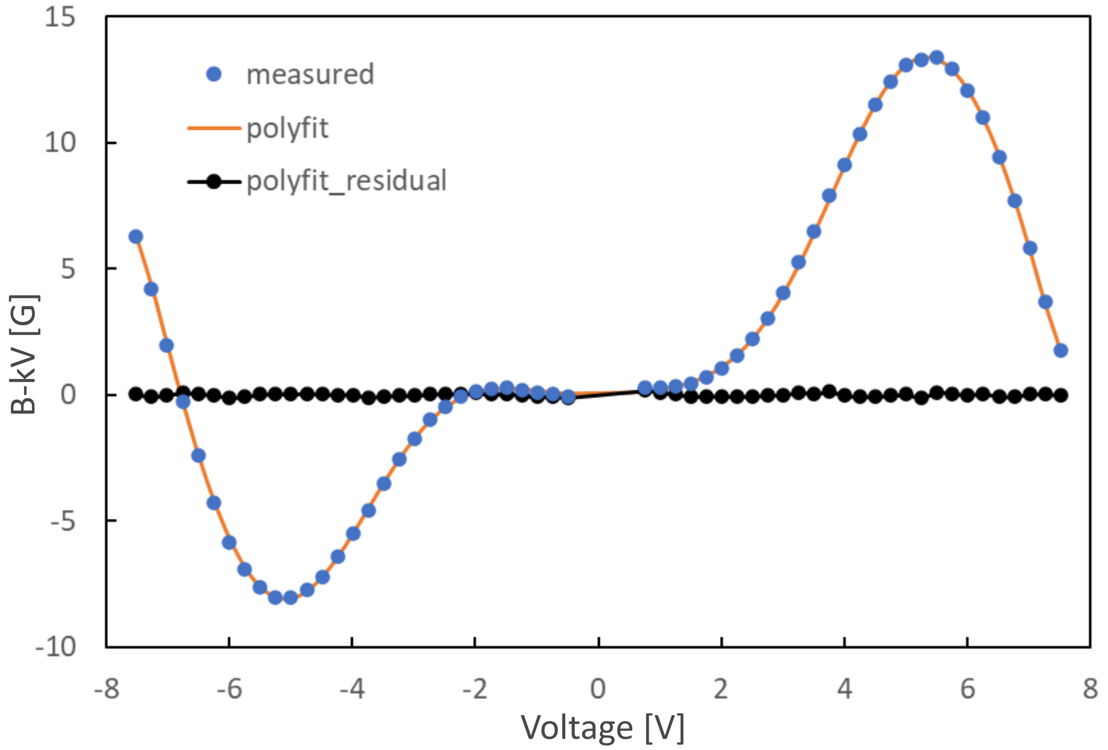
# Hall probe calibration system



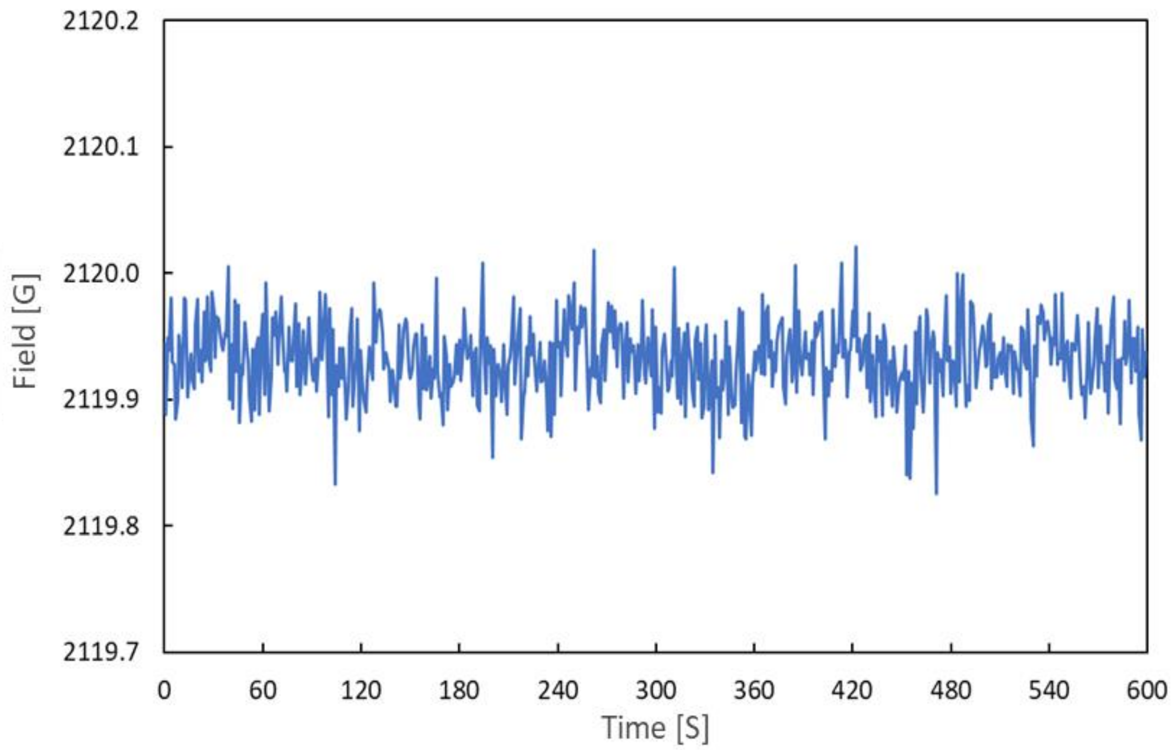



# Hall probe calibration

Hall sensor calibration accuracy: ~10 ppm

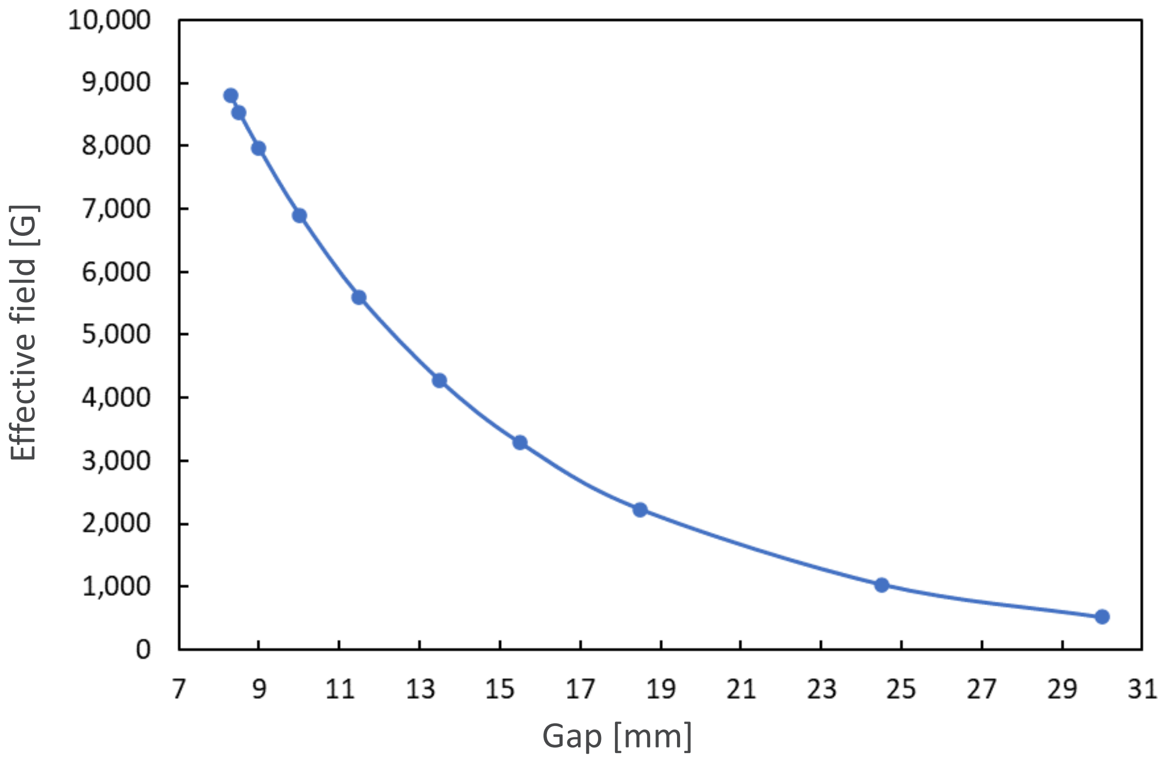



Senis TRHA-30009322 Hall sensor calibration curve

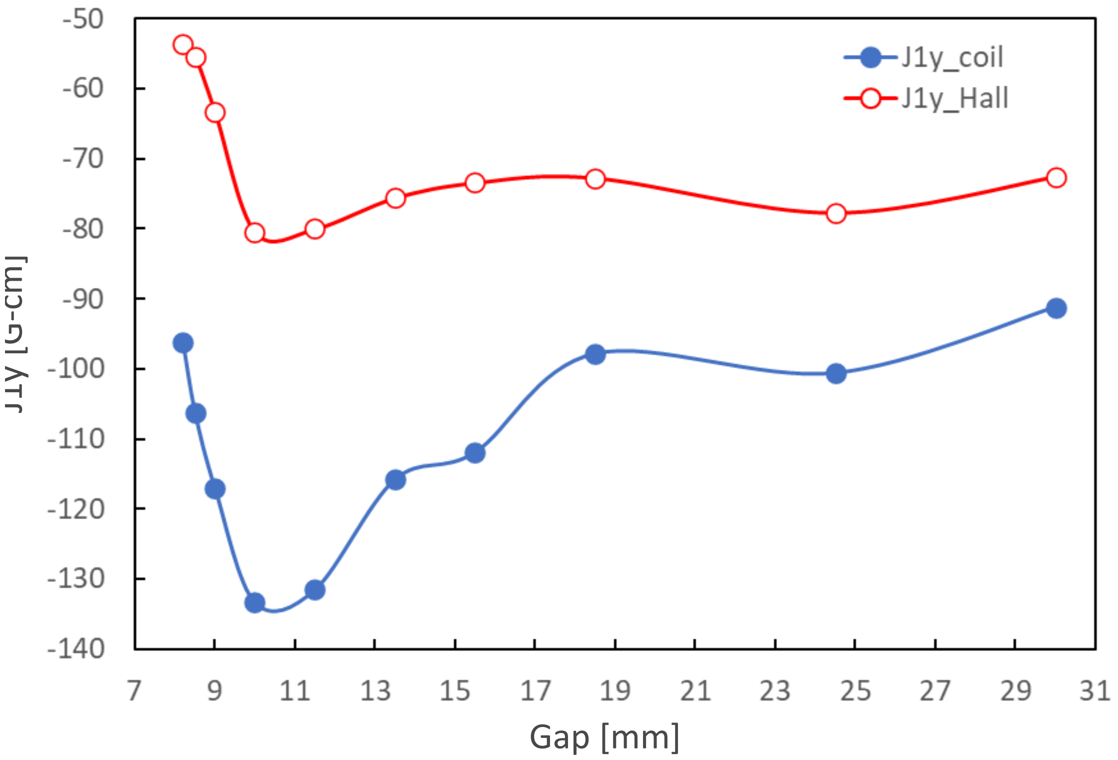



Hall sensor field time-dependent measurement

# Hall probe field integral measurement




APS25#4 measured effective field vs. gap




APS25#4 Hall probe and coil field integral measurements

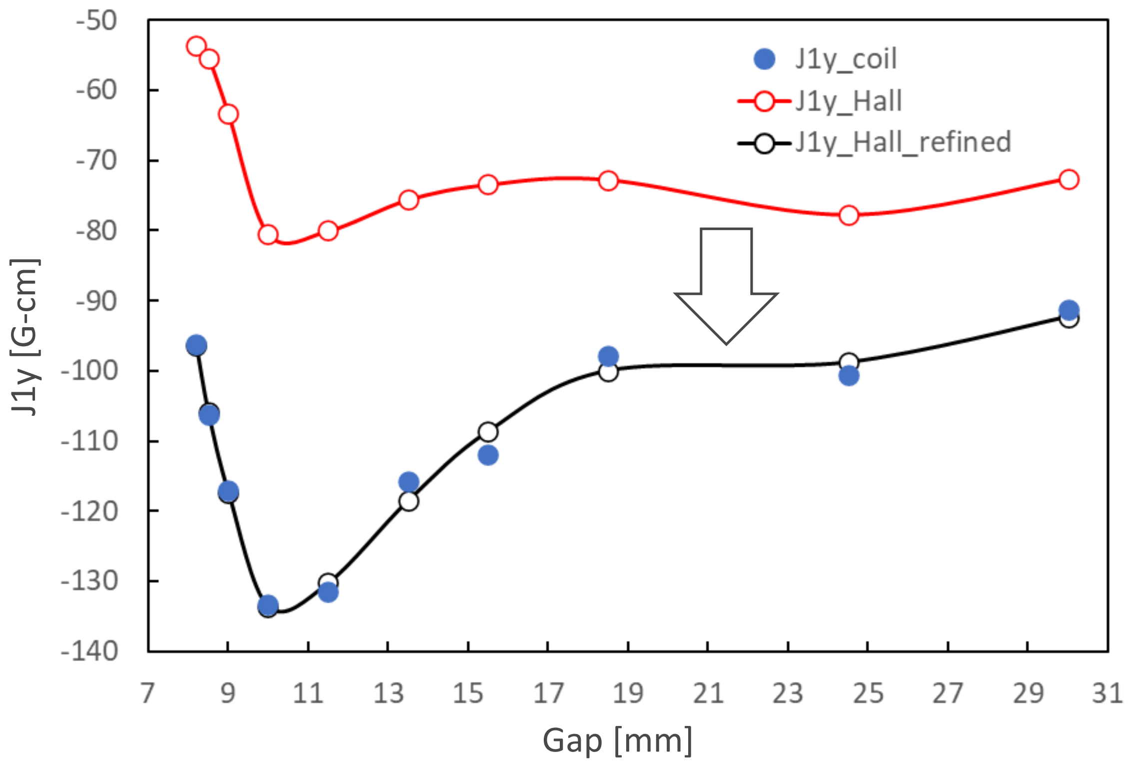
# Hall probe calibration refinement

The difference between the Hall sensor and the coil measurements can be written as:

$$\sum c'_{2n} * s_{2n} = J1y_{coil} - J1y_{hall}$$

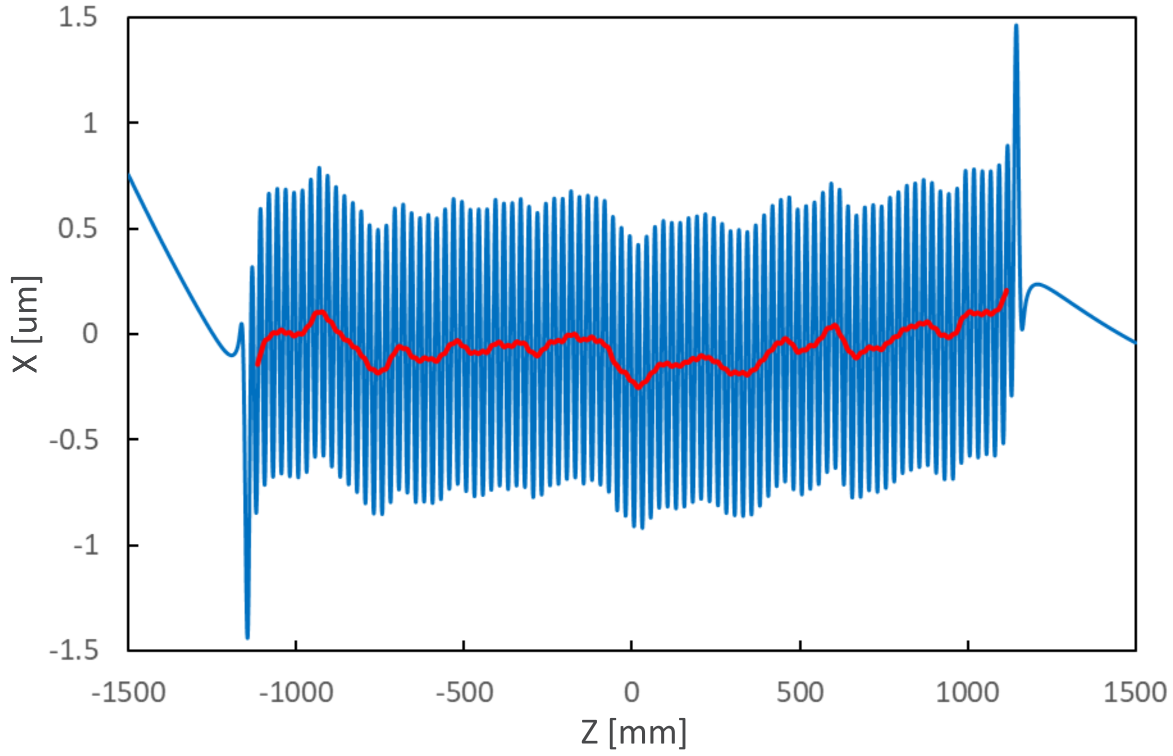
where $c'_{2n}$ is the refinement needed in the even order polynomial coefficients.

The above equation can be solved by the Least Squares Method, where the number of even terms being refined is smaller than the number of undulator measurements at different gaps.

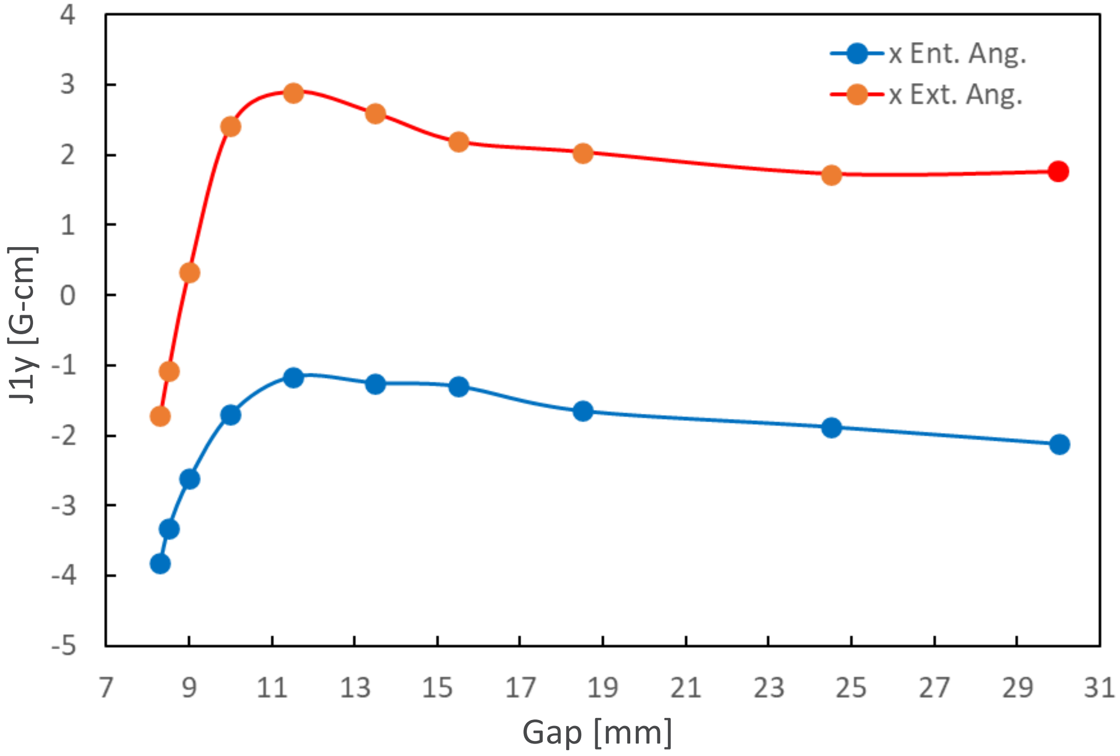



Hall probe and coil field integral measurements after refinement

# Hall probe beam entrance and exit angle measurement




APS25#4 X-trajectory at 8.5-mm gap and 6-GeV beam energy

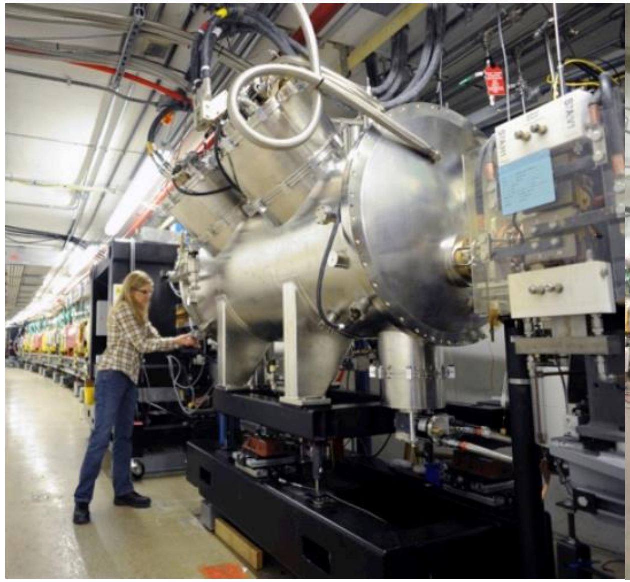



APS25#4 Hall probe entrance and exit angle vs gap

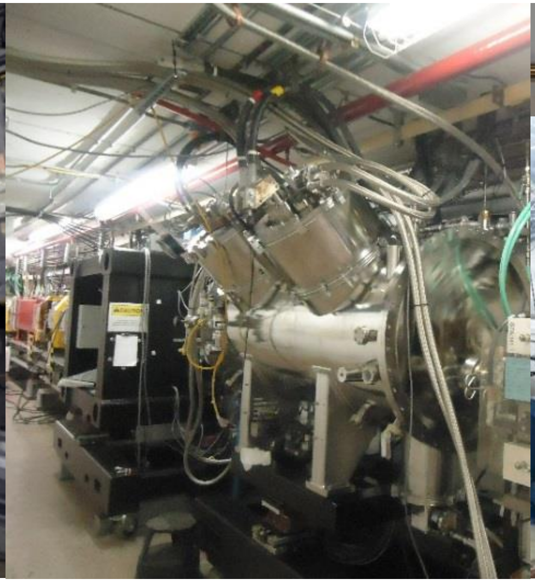
# APS superconducting undulators (SCUs)

- SCU0:
  - 16-mm period length
  - 0.33-m-long magnet
  - In operation: Jan2013-Sep2016
- SCU1(SCU18-1):
  - 18-mm period length
  - 1.1-m-long magnet
  - In operation: May2015-Apr2023
- SCU18-2:
  - 18-mm period length
  - 1.1-m-long magnet
  - In operation: Sep2016-Apr2023
- Helical SCU:
  - 31.5-mm period length
  - 1.2-m-long magnet
  - In operation: Jan2018-Apr2023
- $Nb_3Sn$ SCU:
  - 18-mm period length
  - 1.1-m-long magnet
  - In operation: Sep2016-May2023

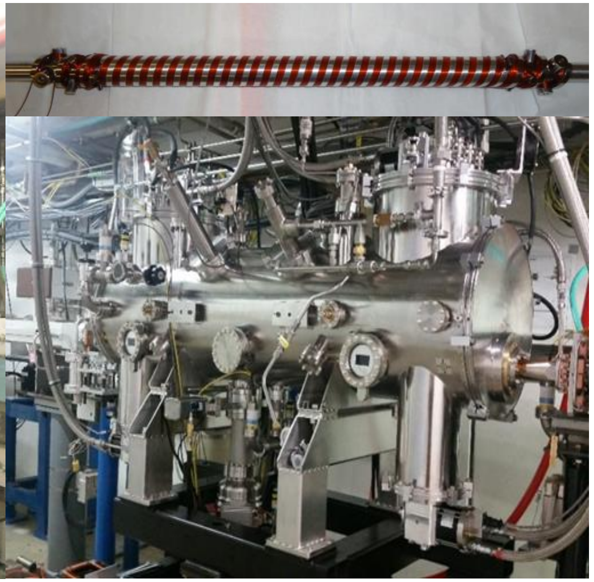
Completed and was in operation



Planar SCU18 in sector 1



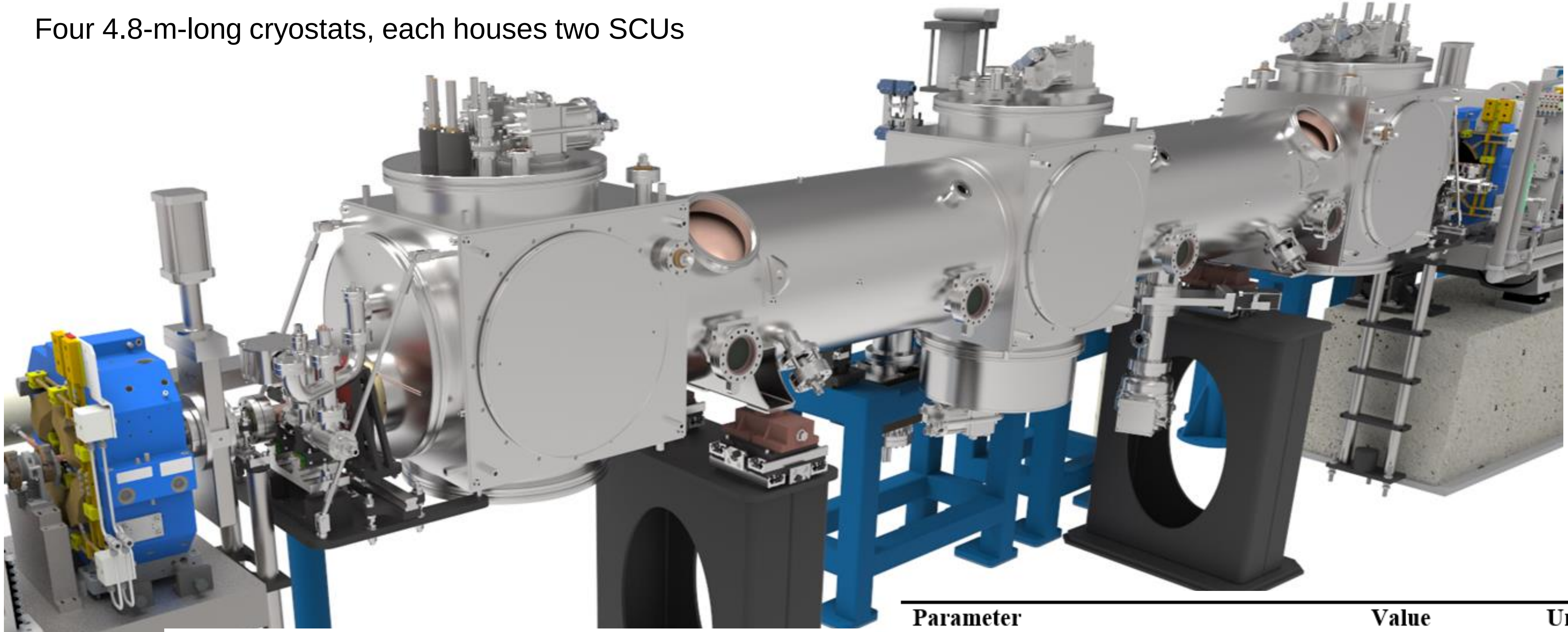
Planar SCU18 in sector 6



Helical SCU (HSCU) in sector 7

# APSU SCUs

Four 4.8-m-long cryostats, each houses two SCUs

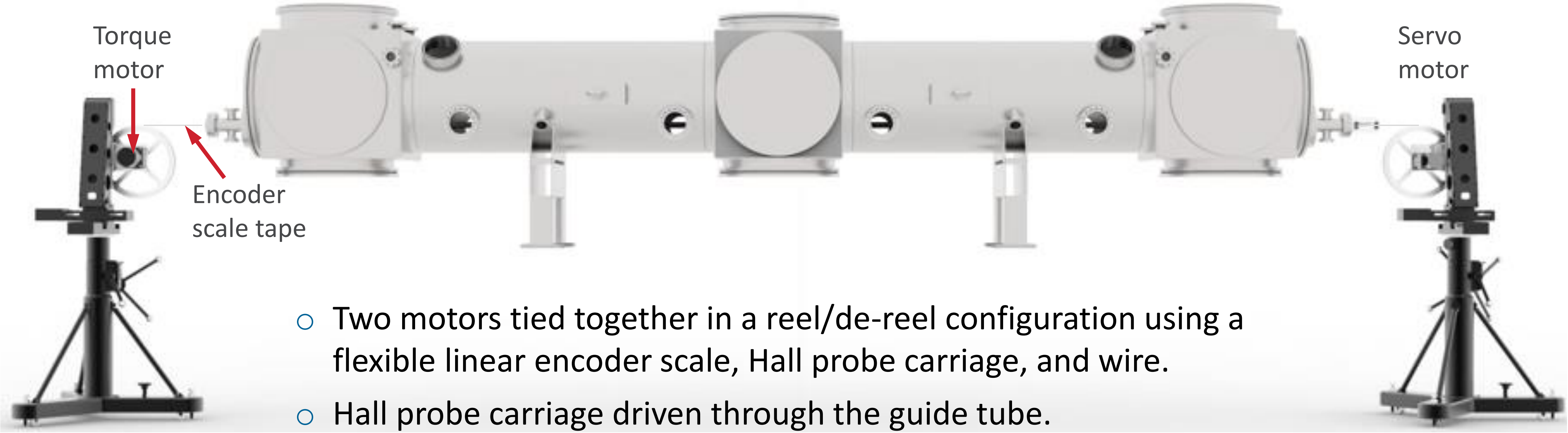


Four 4.8-m-long cryostats, each houses two SCUs

| Location | Configuration | Upstream | Downstream |
|---|---|---|---|
| Sector 1 | Inline | SCU16.5 | SCU16.5 |
| Sector 11 | Canted | SCU16.5 | SCU16.5 |
| Sector 20 | Inline | SCU16.5 | SCU16.5 |
| Sector 28 | Canted | SCU18.5 | SCU18.5 |

| Parameter | Value | Unit |
|---|---|---|
| Cryostat maximum length | 4.8 | m |
| Insertion device maximum length | 1.9 | m |
| Vertical magnetic gap | 8.0 | mm |
| ID chamber vertical aperture | 6.3 +0.1/-0.3 | mm |
| Vacuum chamber straightness in plane with small magnetic gap | +/- 50 | µm |
| ID rms phase error for any operational current | ~5 | degree |

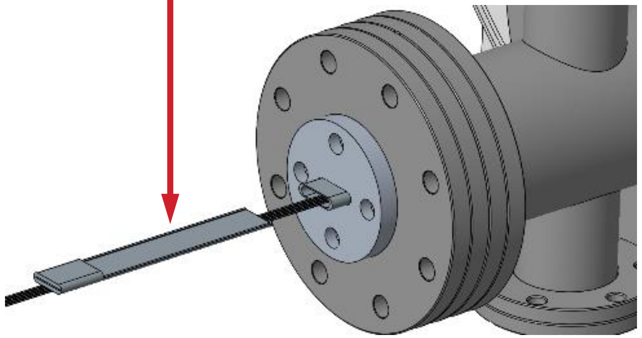
# APSU SCU portable measurement system

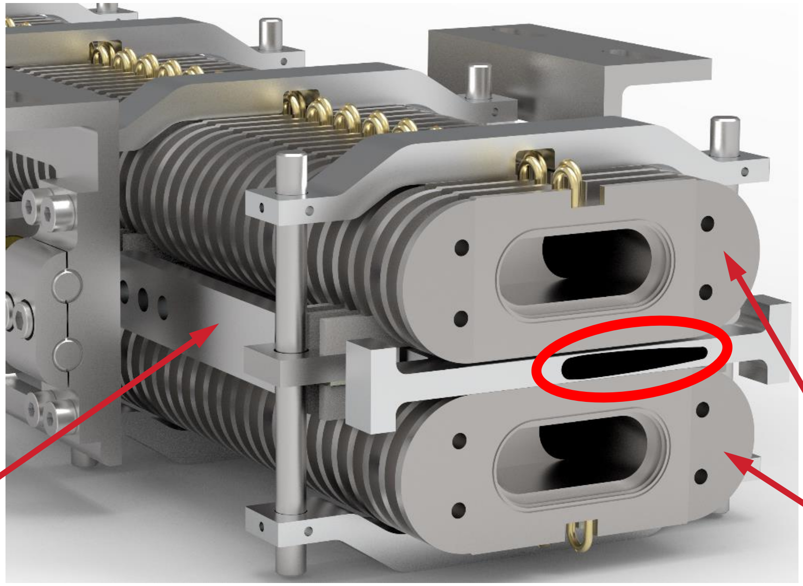



- Two motors tied together in a reel/de-reel configuration using a flexible linear encoder scale, Hall probe carriage, and wire.
- Hall probe carriage driven through the guide tube.
- Servo motor position control through feedback from linear encoder.
- Torque motor maintains tension.
- System eliminates the need for a long linear stage and is portable.

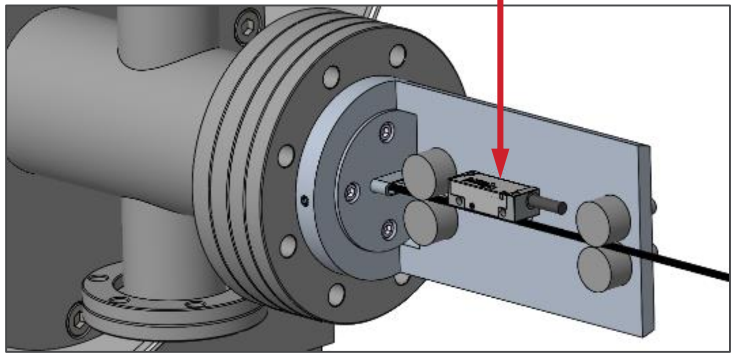
# Extruded and machined guiding tube

Hall probe carriage





Encoder read head and flexible linear scale

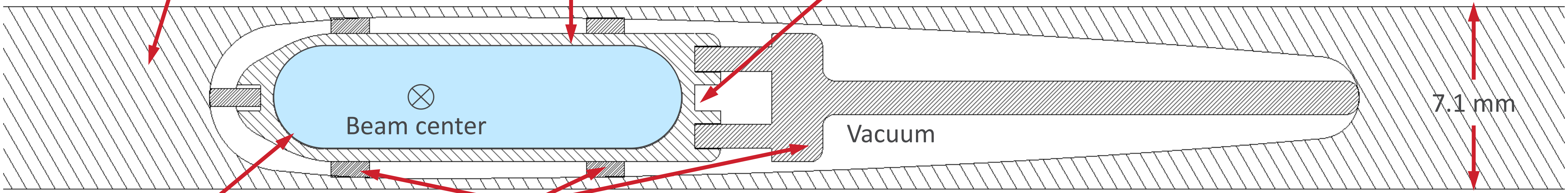


Aluminum beam chamber temp: ~20 K

Aluminum guiding tube temp: ~300 K, 1 atm

Channel for heater wires

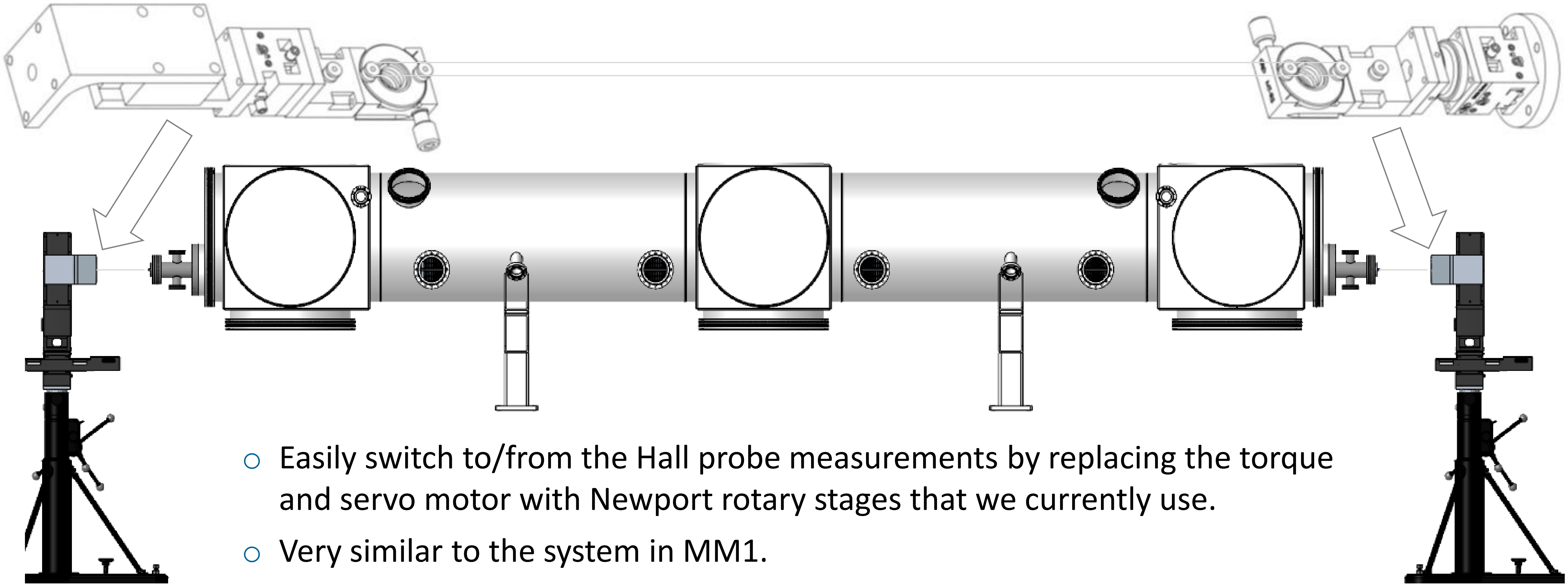
Magnets temp: 4.2 K, 8-m gap




16 mm x 4 mm measurement aperture

Torlon standoffs

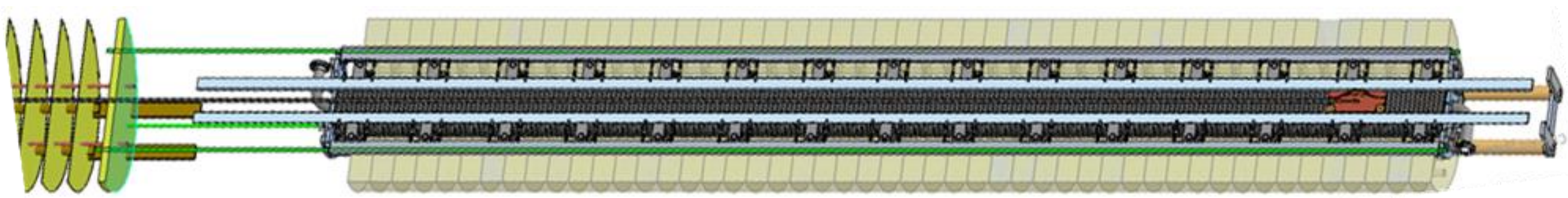
# APSU SCU stretched wire measurement system



- Easily switch to/from the Hall probe measurements by replacing the torque and servo motor with Newport rotary stages that we currently use.
- Very similar to the system in MM1.
- Can also be used for pulsed wire measurements by moving one stage assembly further from the cryostat.

# APS SCU vertical testing system

3D Hall sensor mounted on linear guiding rails to measure the field during and after SCU core quench training, for field verification and tuning.



Argonne NATIONAL LABORATORY



U.S. DEPARTMENT OF ENERGY

# Summary

- APS successfully completed its upgrade project.
- After the completion of the APSU project, the storage ring magnet measurement lab with 7 state-of-the-art measurement benches, will be relocated to the EAA, with 3 benches (one of each type).
- ID measurement lab is equipped with a 6-meter bench, a 3-meter bench and two stretch wire measurement systems.
- Superconducting undulator lab has a portable measurement system that is capable of measuring over 5 meters in length, and vertical measurement systems.

# Thank you!