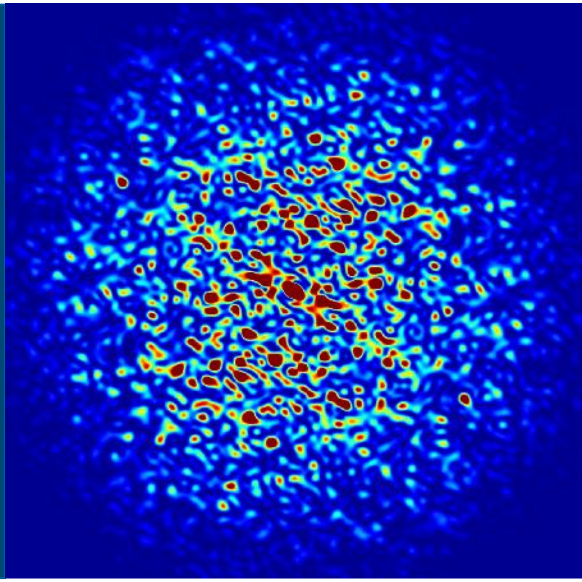
MAGNETIC MEASUREMENTS AT THE ADVANCED PHOTON SOURCE*



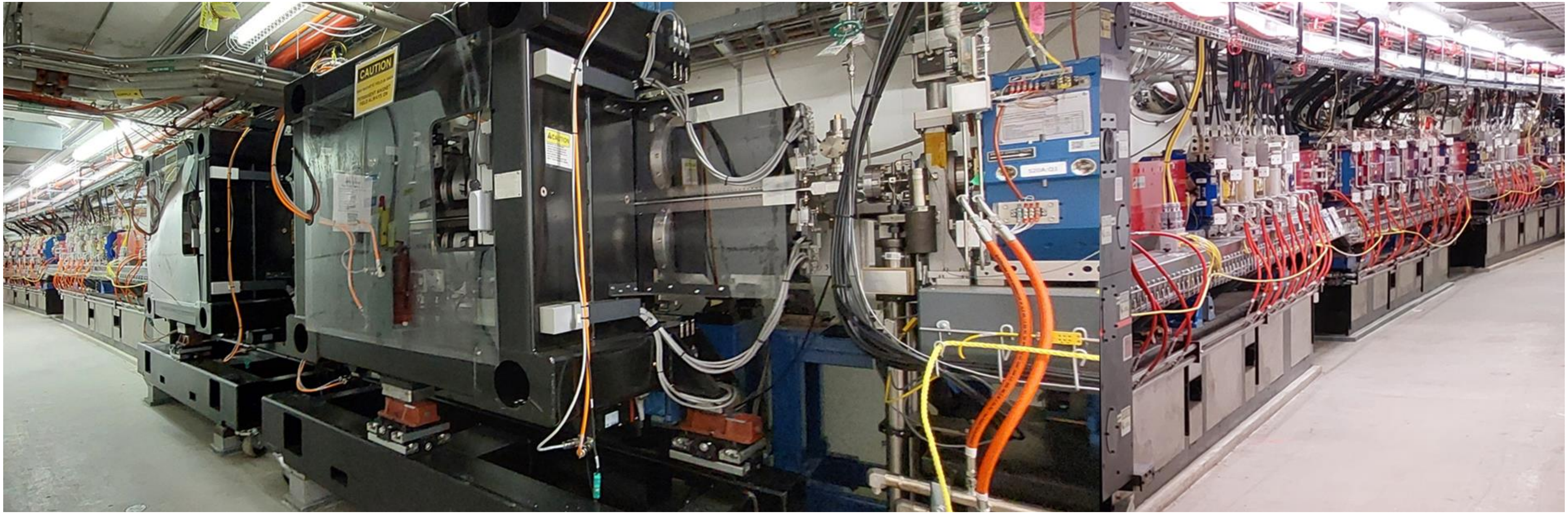
Joseph Z. Xu
On behalf of the APS magnetic measurement team
Argonne National Laboratory

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



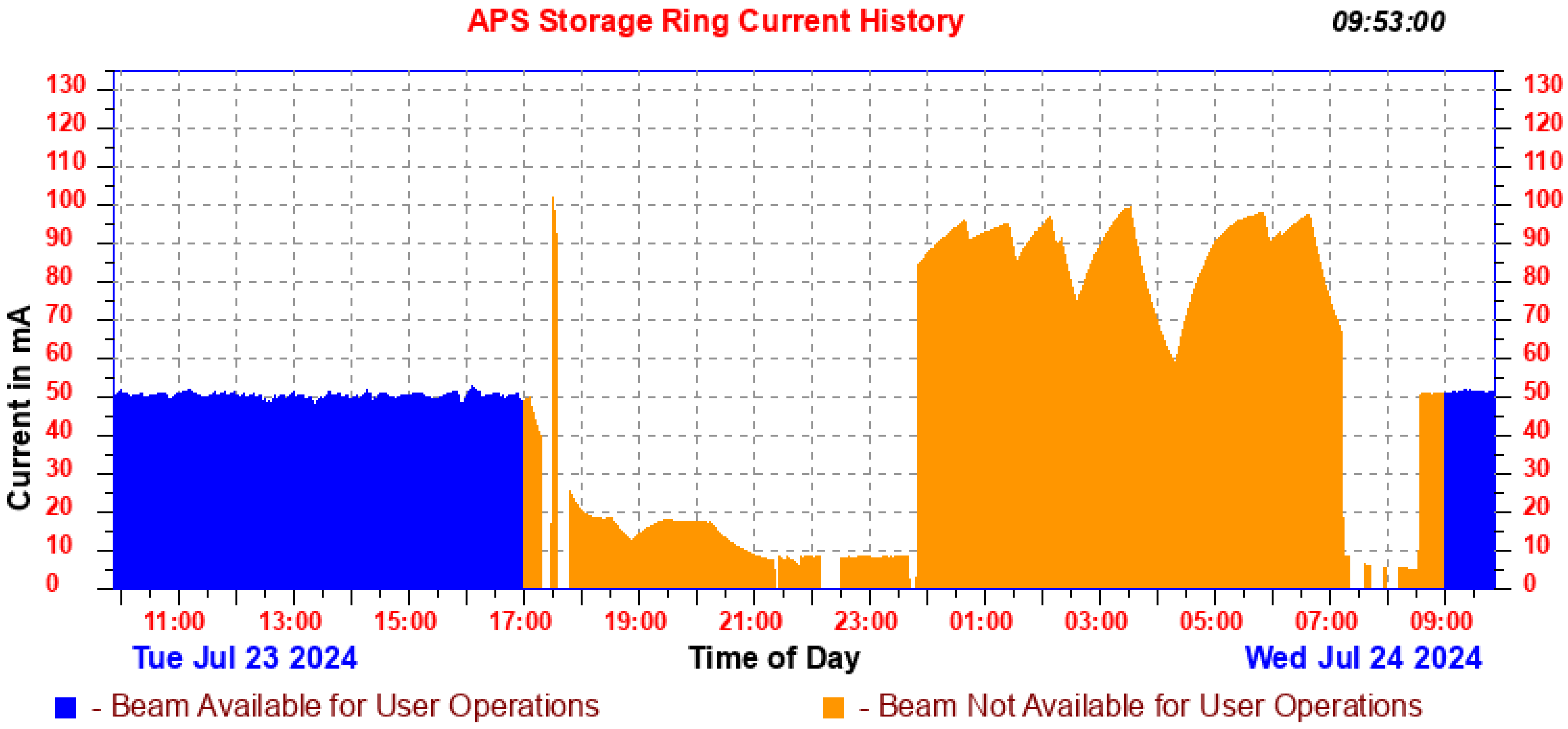
Section of the APS-U storage ring

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.)

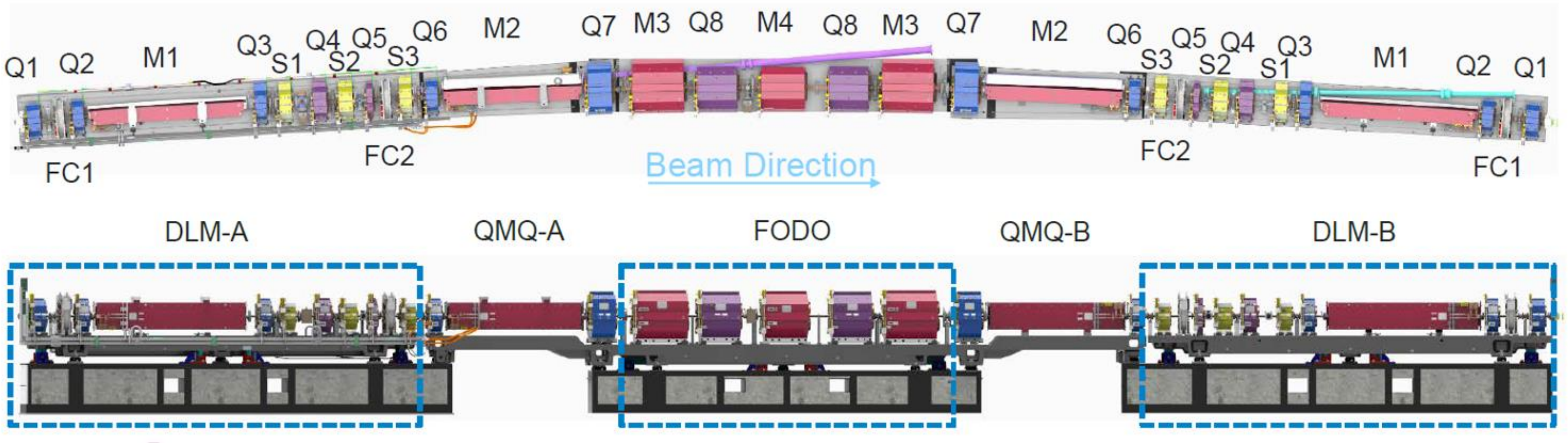
Maofei Qian (Physicist, upgraded the systems and the procedures.)

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

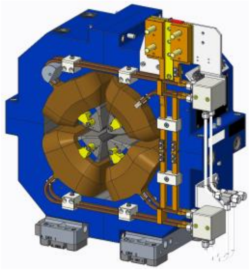
SCU measurement:

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

APS-U storage ring magnets



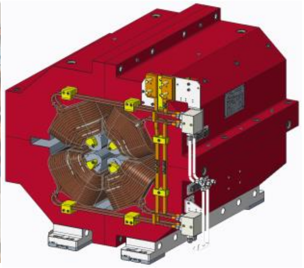
APSU SR Mag	Types	Pole material	Qty req	Qty order
M1	Longitudinal gradient dipole	steel	80	82
M2	Longitudinal gradient dipole	steel	80	82
M3	Transverse gradient dipole	VP	80	82
M4	Transverse gradient dipole	VP	40	42
Q1	Quadrupole	VP	80	82
Q2	Quadrupole	steel	79	81
Q3	Quadrupole	steel	81	83
Q4	Reverse 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

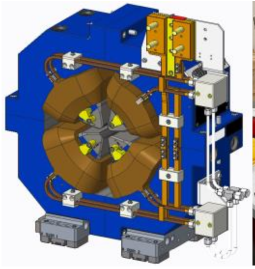

Q3

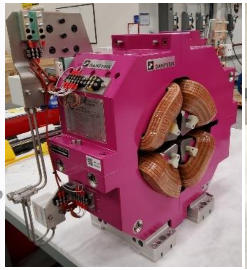

Q5

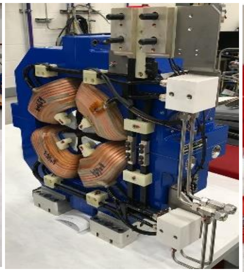

Q7

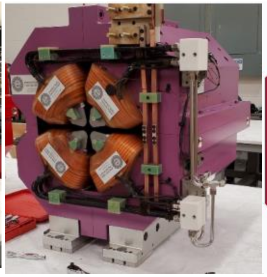

M3

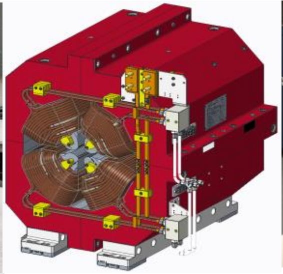

M1


Q2


Q4

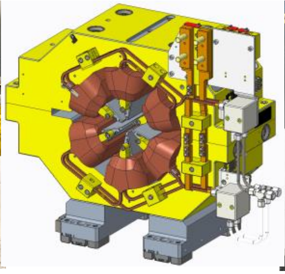

Q6


Q8


M4


M2


S1/S3


S2


FC

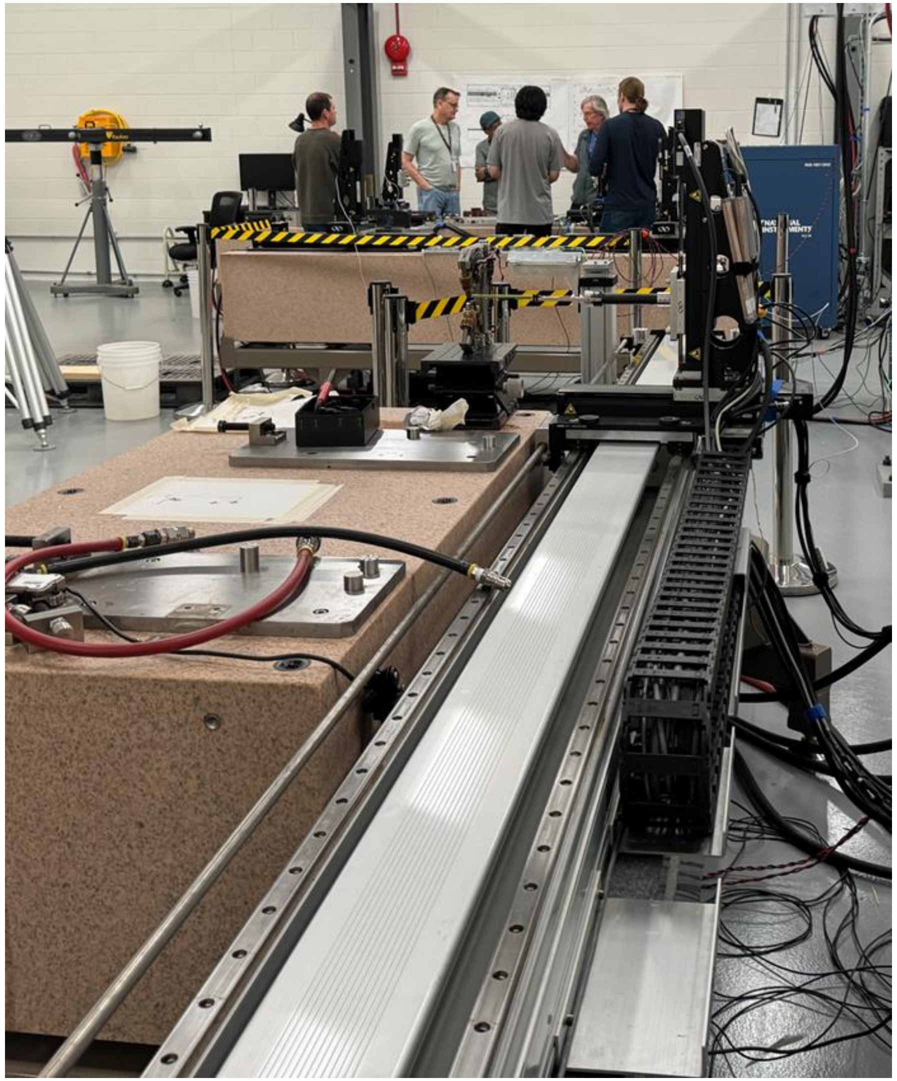
Field quality and alignment requirements

- Maximum field deviation in terms of integrated field harmonics is ±10×10^{-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 1×10^{-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).

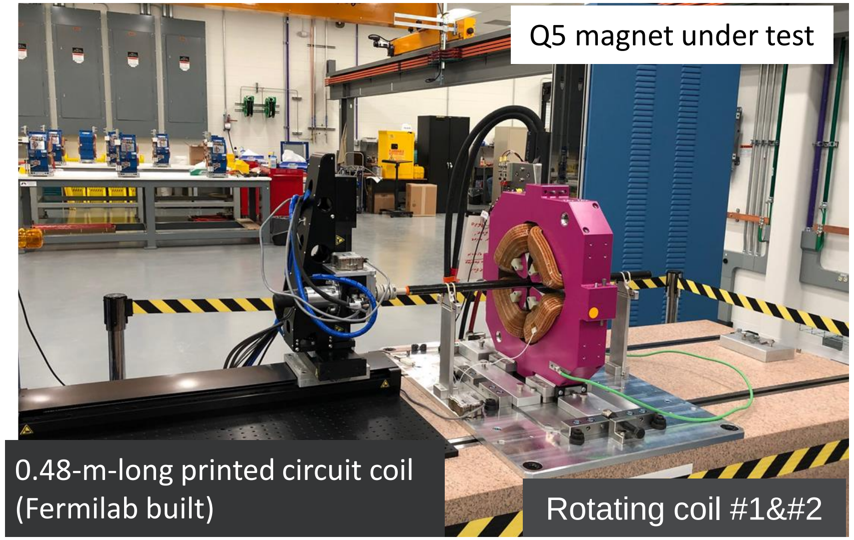
- Alignment requirements (*APS-U Accelerator Functional Requirements Document*):

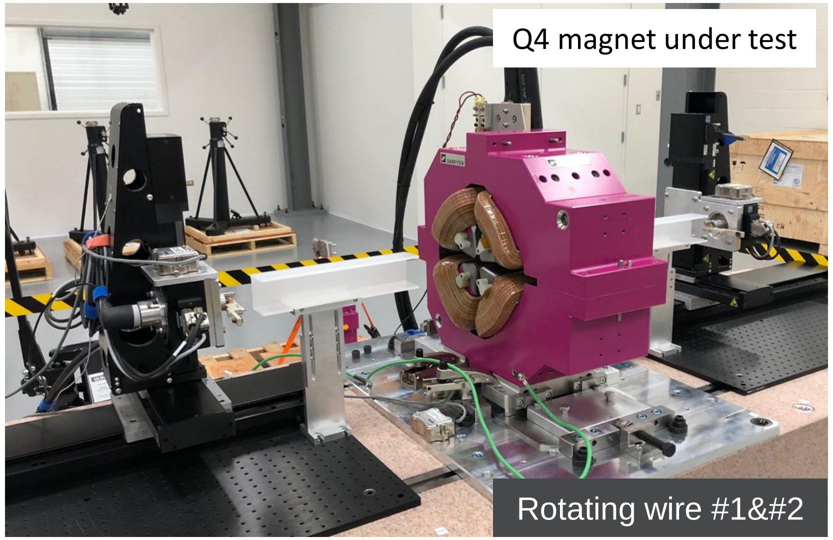
Girder to girder alignment			
DLM to FODO; 1 sigma cutoff	μm rms	100	(by survey)
QMQ to DLM or FODO; 1.5 sigma cutoff	μm rms	50	(by survey)
Elements within a girder			
Magnet to magnet (2 sigma cutoff)	μm rms	30	(magnetic + survey)
Dipole roll	mrad	0.4	(survey of poles + mechanical)
Quadrupole roll	mrad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

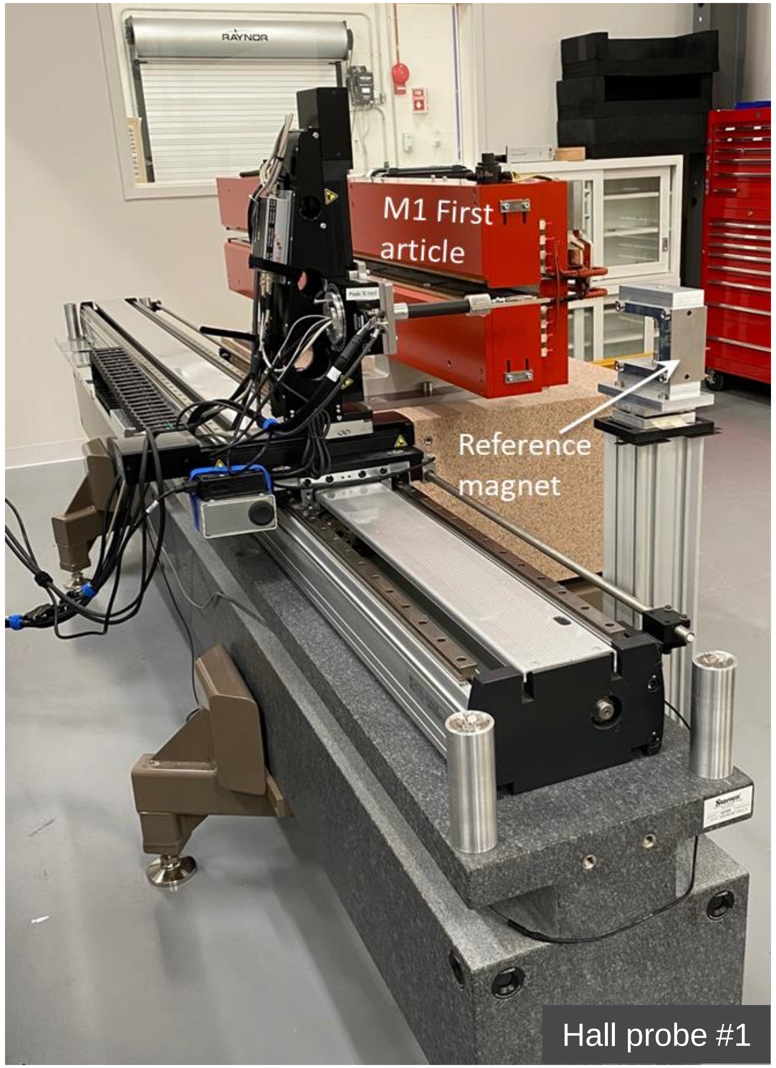
Storage ring magnet measurement lab

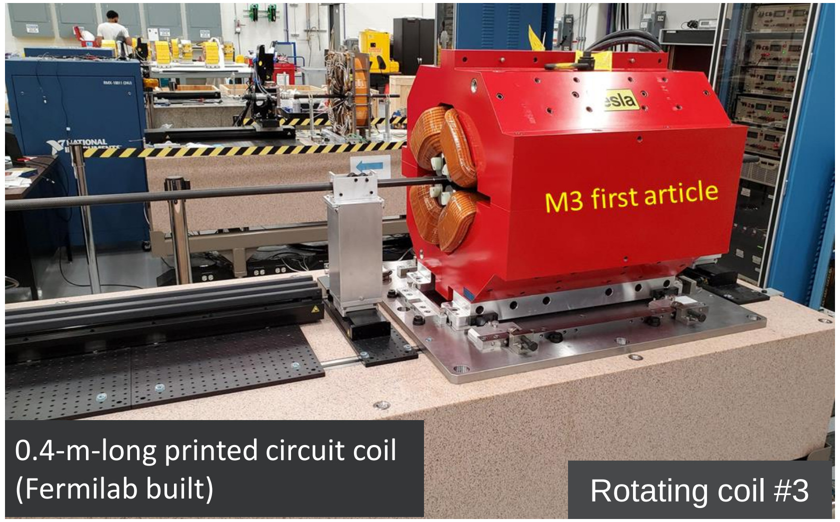


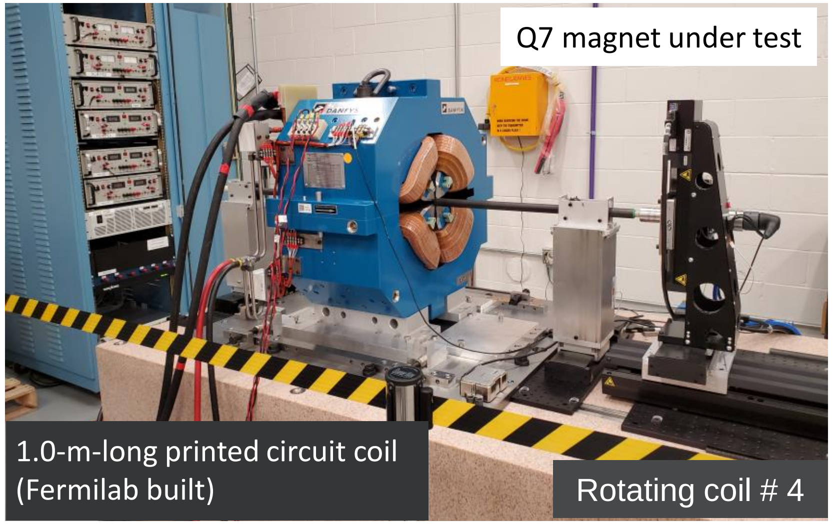
Storage ring magnet measurement benches











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
CAUTION
SHELTER
USE ONLY
NON-RESIDENTIAL
NON-STRUCT

APS-U ID specifications

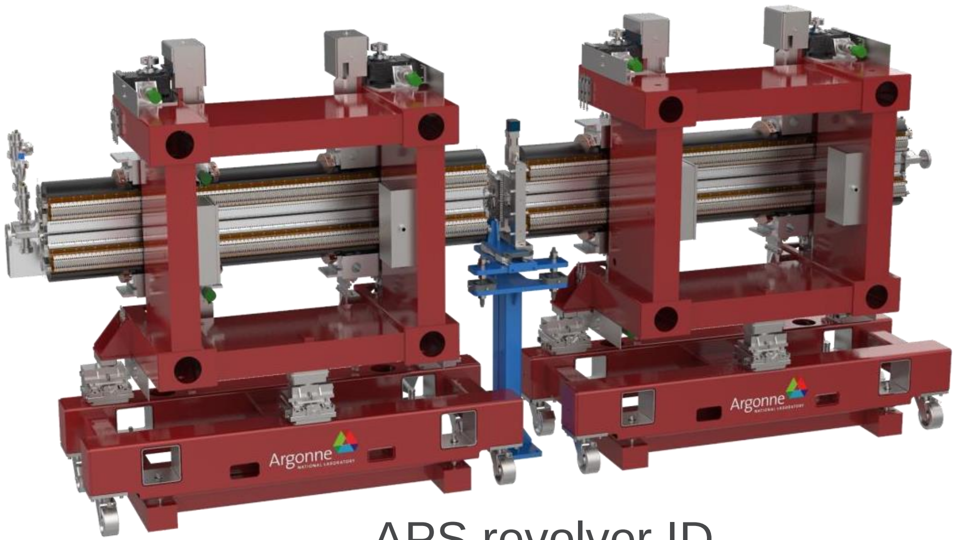
APS planar ID

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



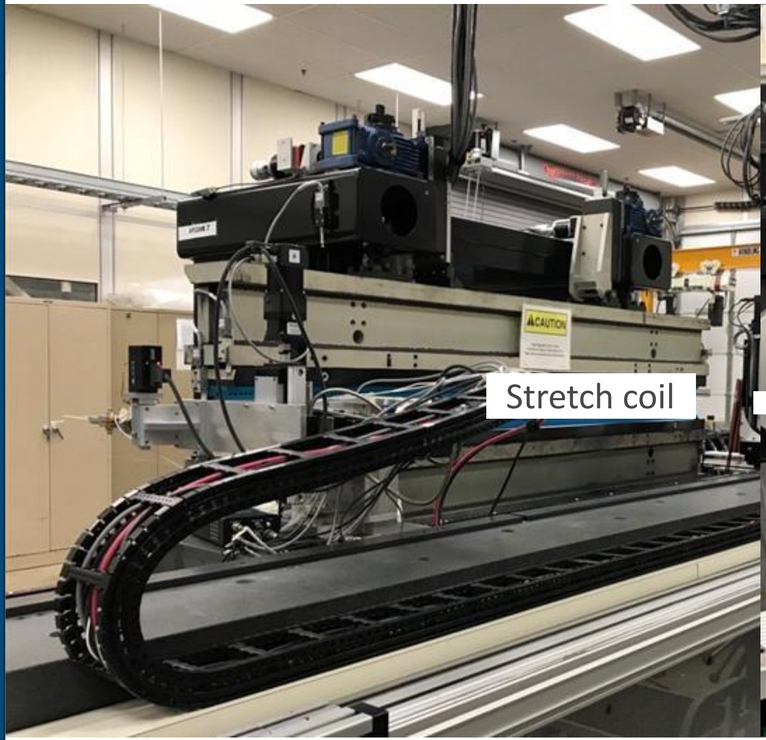
APS revolver ID

APS-U vs. APS ID requirements

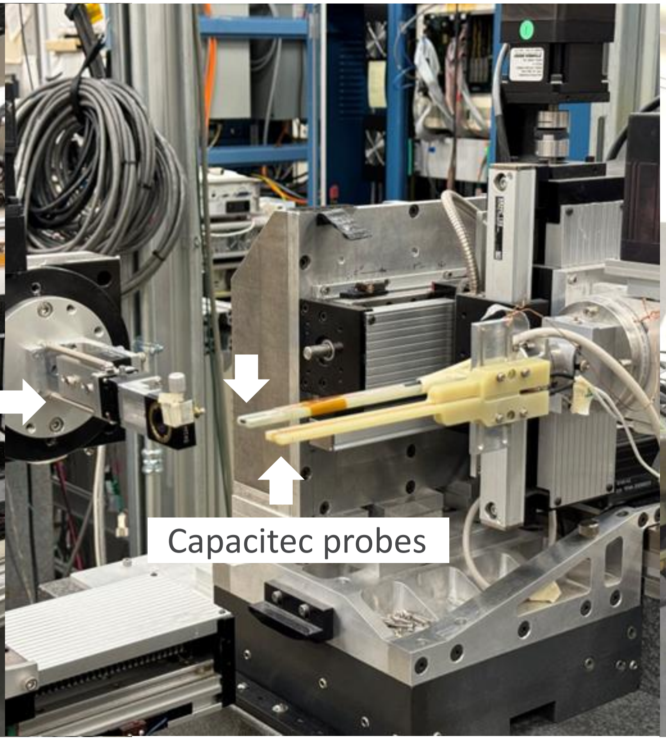
Parameter	APS-U Spec	APS Spec	Unit
Beam Energy	6	7	GeV
Min Gap	**8.2**	11.5	mm
RMS Ph Err	**3**	8	deg
X Trj	**1.25**	2	um
Y Trj	**0.4**	2	um
X ent/ext angle	**3.9**	6	urad
Y ent/ext angle	**1.25**	3	urad
J1x ups/dns	**25**	50	G-cm
J1y ups/dns	**78**	100	G-cm
J2x ups/dns	**5.25**	100	kG-cm^2
J2y ups/dns	**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

ID magnet measurement lab

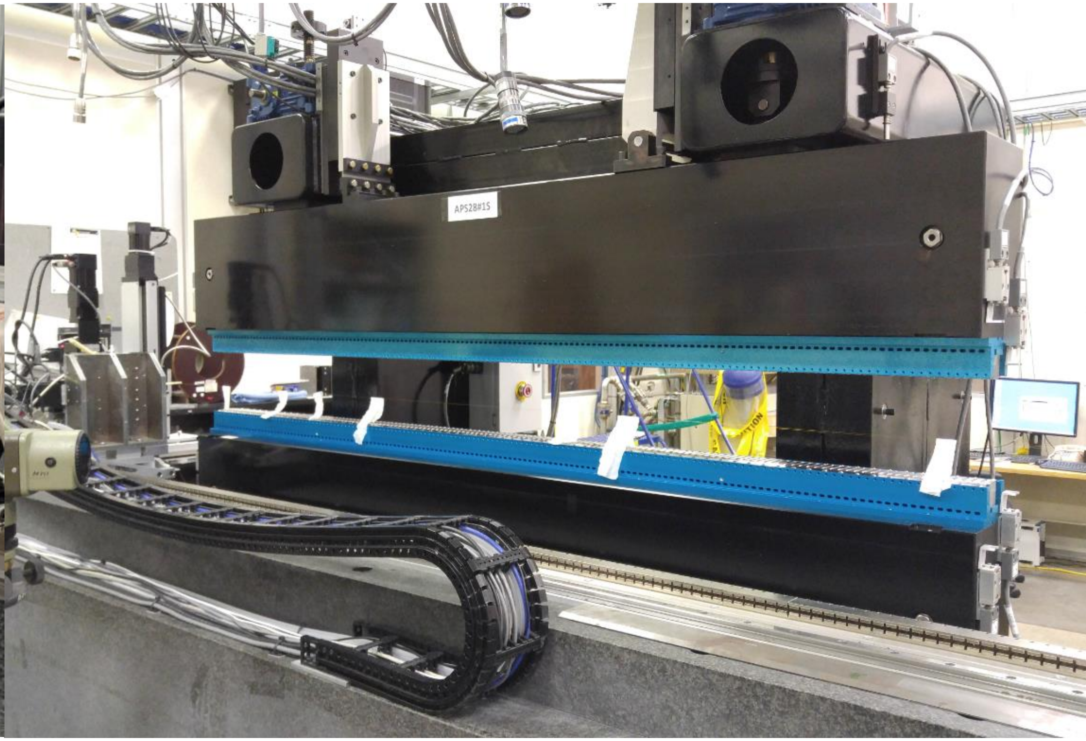
ID magnet measurement lab



APS28#1S on 3-m bench



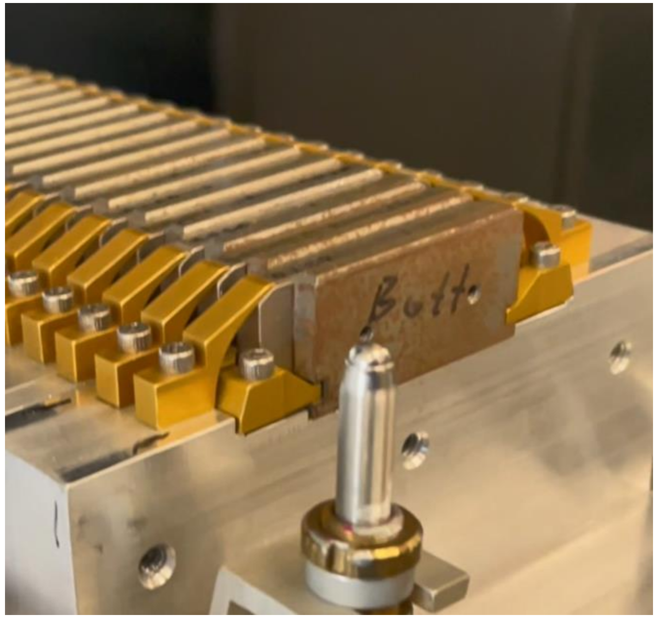
Hall probe and Capacitec probes



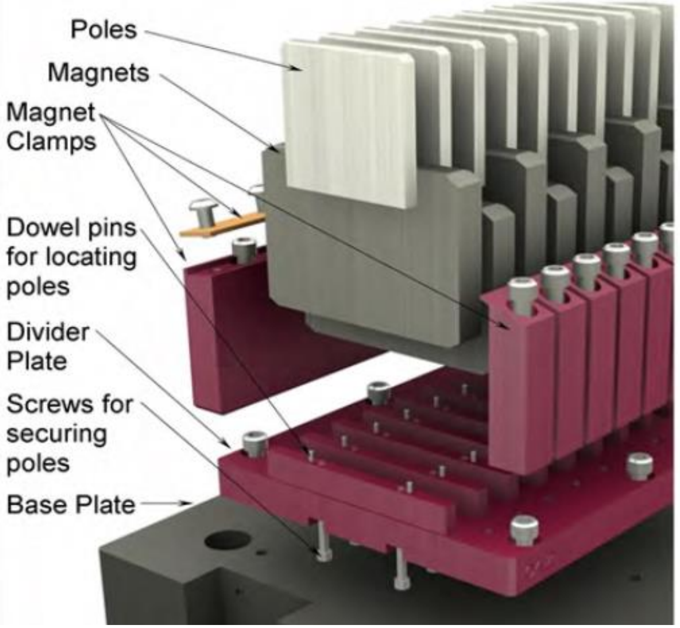
APS28#7 on 6-m bench

APS planar permanent magnet undulator (PMU)

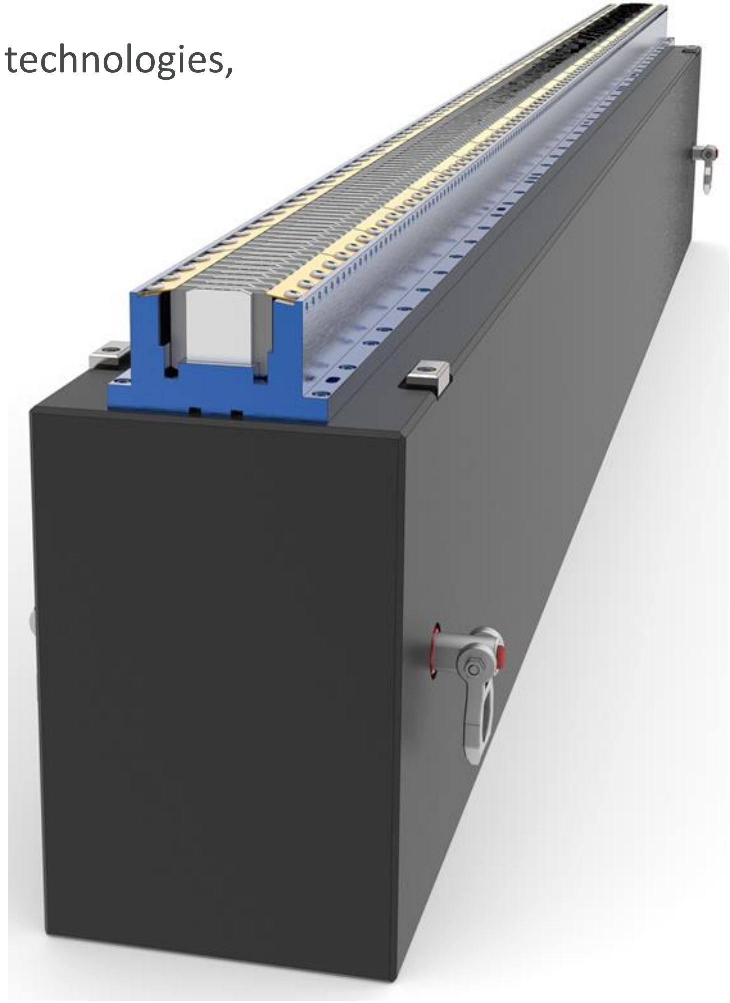
Machined to the specifications combined with the patented tuning technologies, we can cost effectively reach the state-of-the-art specifications.



Gen-1 APS undulators

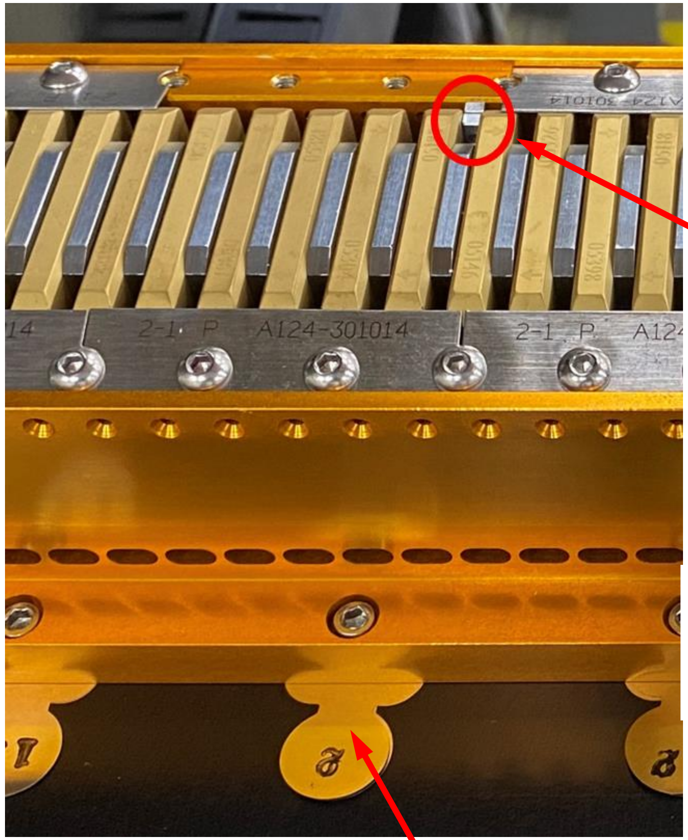


Gen-2 APS undulators

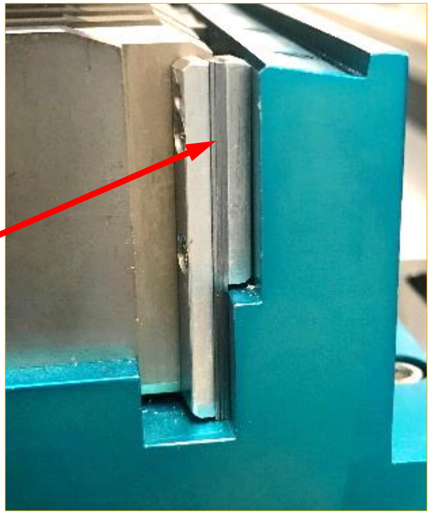


Gen-3 (new) APS undulators

APS planar PMU tuning

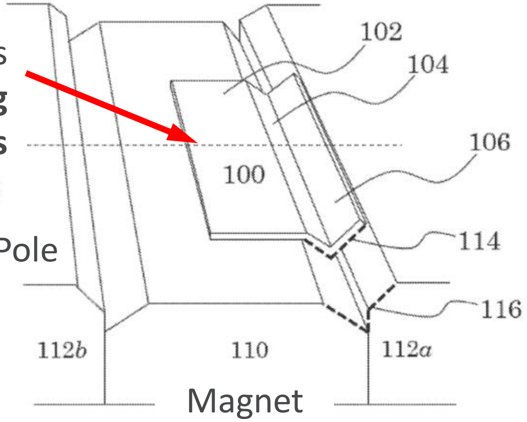


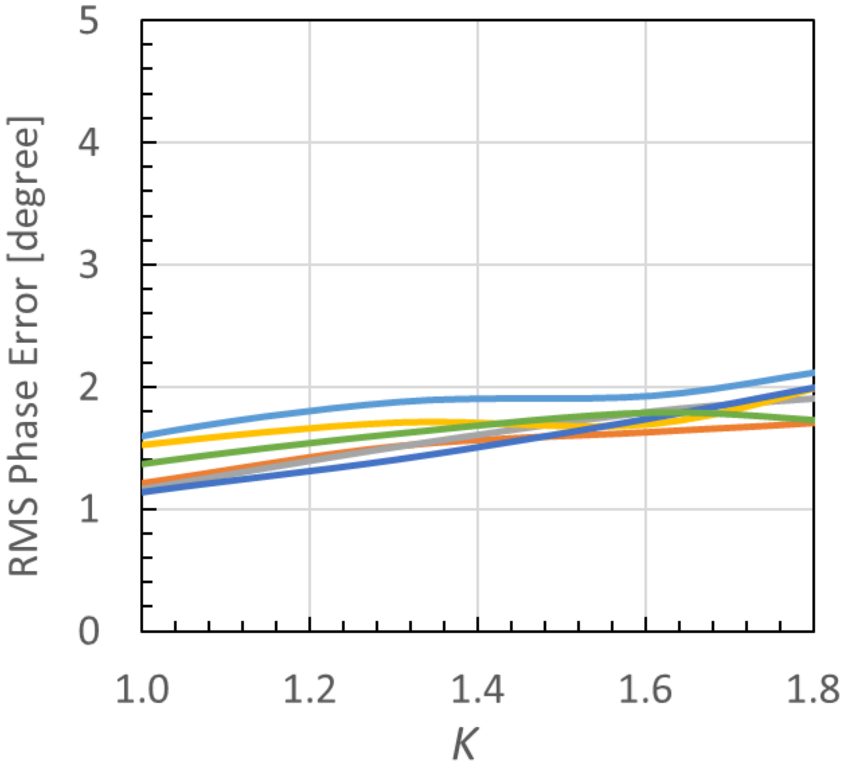
1. Magnetic side shims for **correcting trajectory errors**.



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

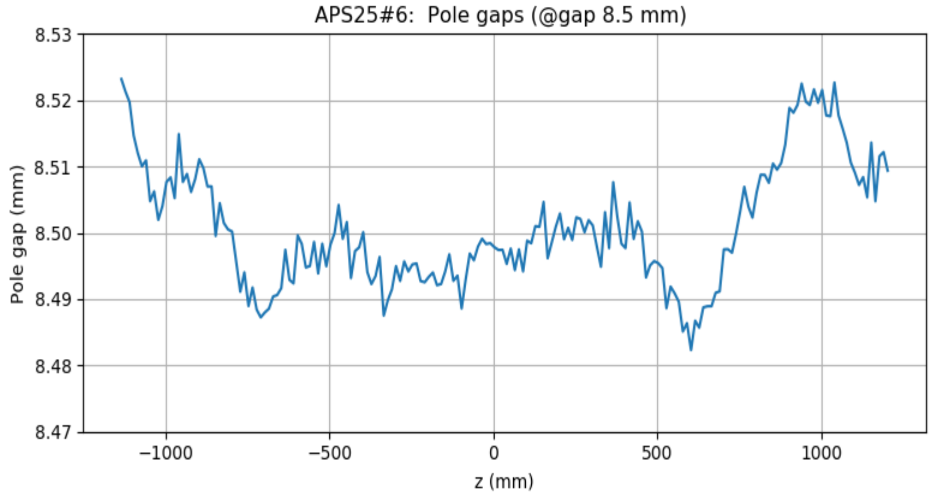
3. Surface shims for **correcting multipole errors**



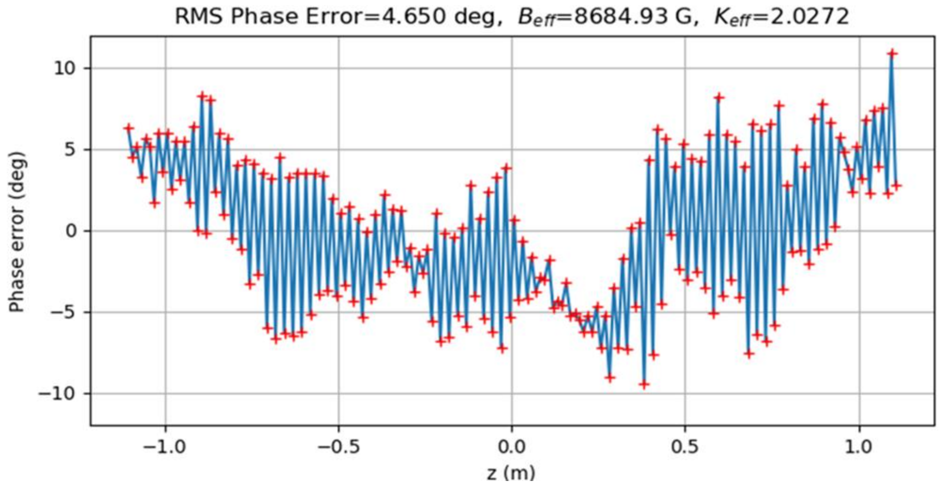


APS25 undulators RMS phase errors as a function of K, tuned to better than 2.2 degrees with the much simpler design.

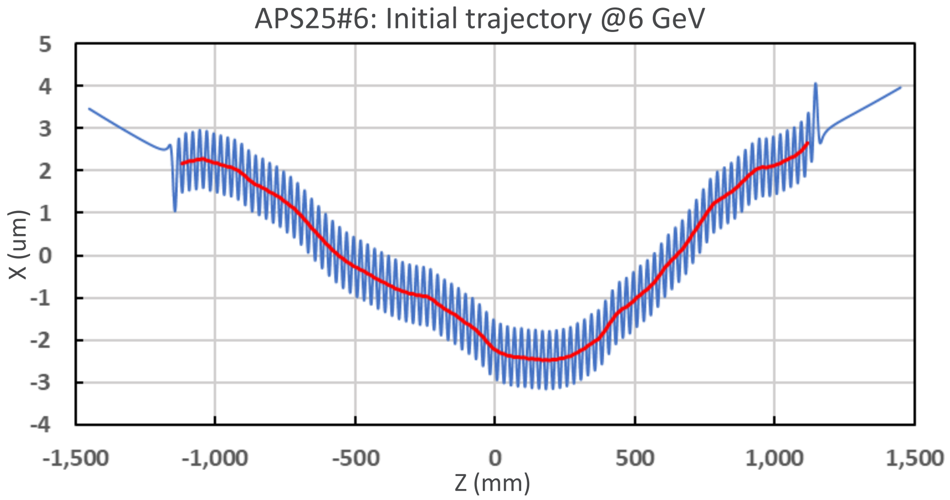
ID tuning – example: APS25#6, initial mechanical shimming



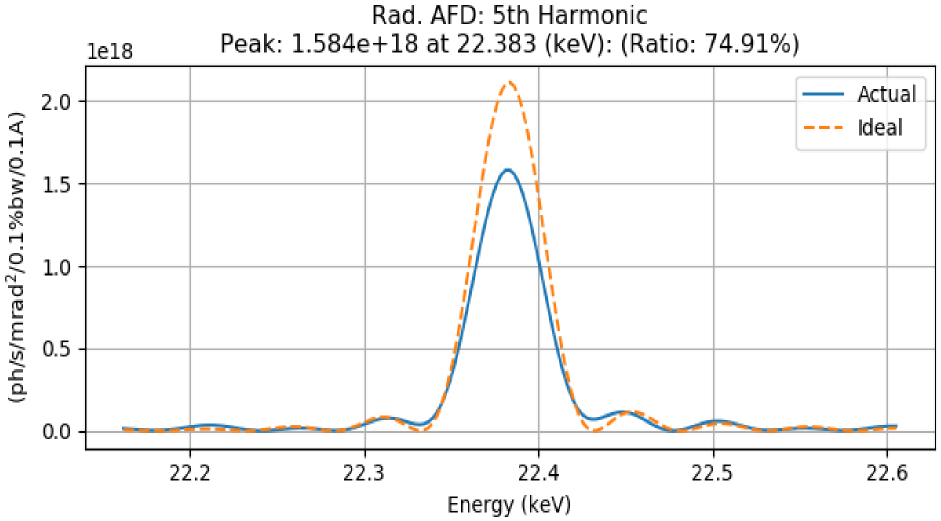
Capacitec measurement after initial gap mechanical shimming



Phase error at 8.5-mm gap setting



Initial trajectory at 8.5-mm gap



5[th] harmonic brightness

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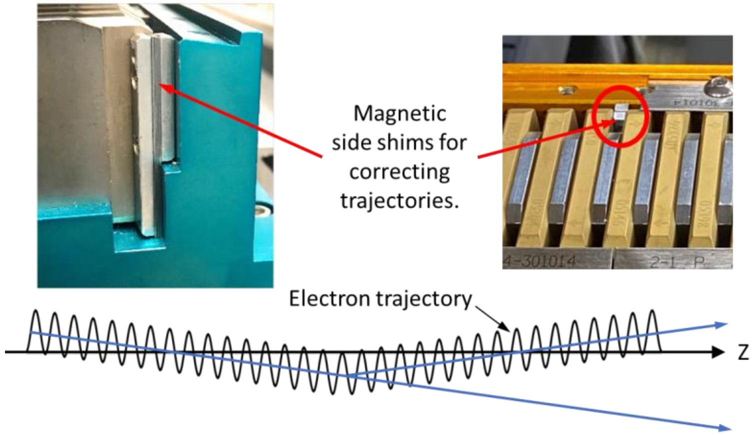
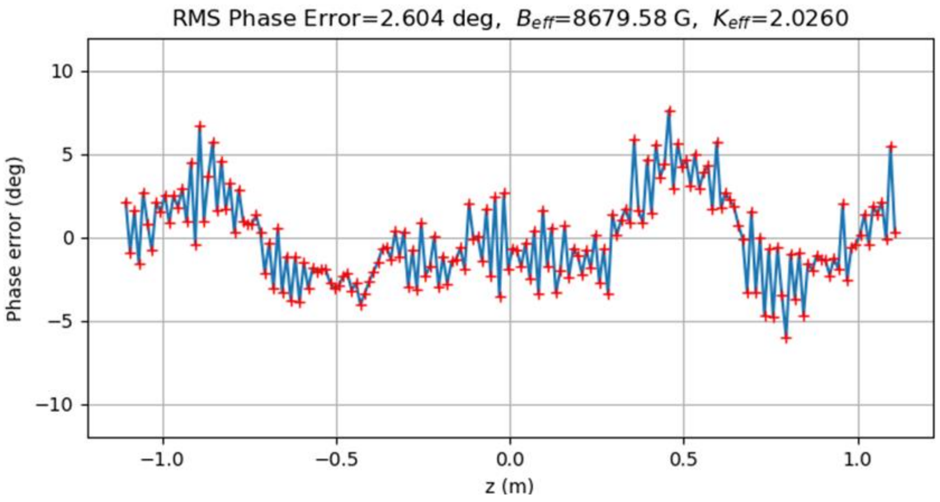
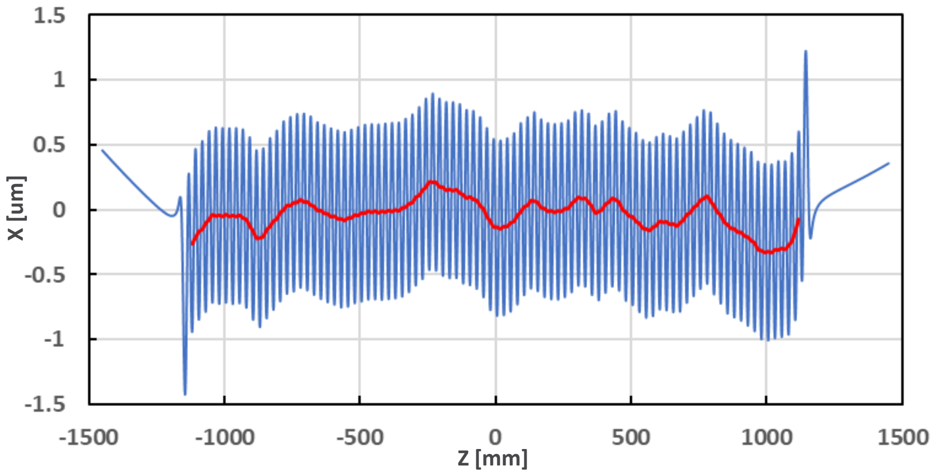
ID tuning – example: APS25#6, trajectory tuning



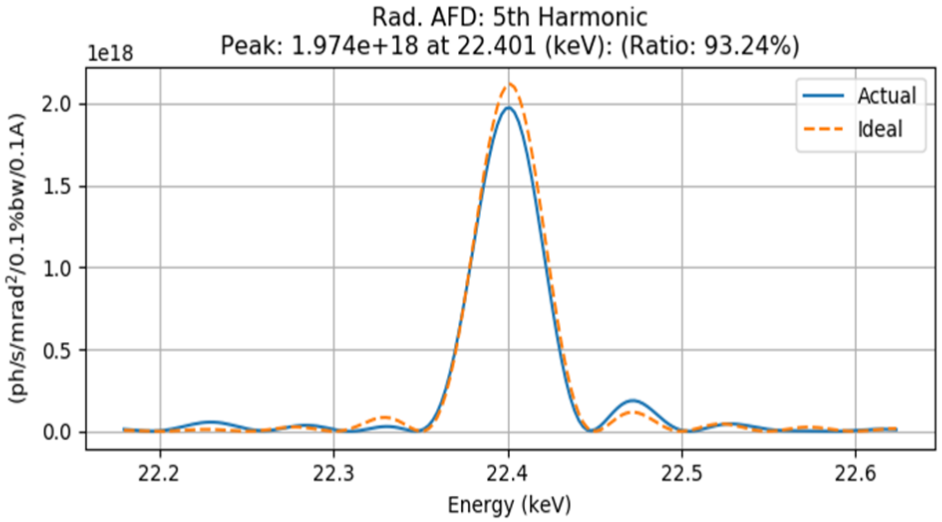
Evolutionary algorithm to optimize the trajectory tuning across all operational gap/current settings. The algorithm will predict how many places, where, what types, and how many shims to insert.



Phase error at 8.5-mm gap setting after trajectory tuning



Trajectories at 8.5-mm gap after trajectory tuning



5^{th} harmonic brightness after trajectory tuning

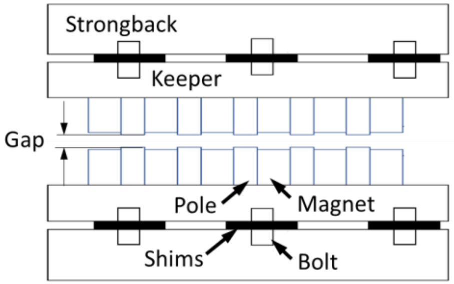
ID tuning – example: APS25#6, phase tuning

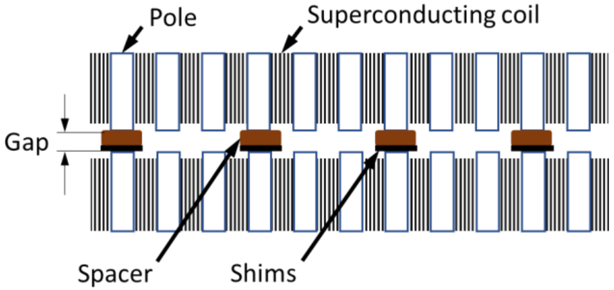
The gap profile error of an undulator is described by a slow-varying function $\delta g(i)$, then the phase error advance over one pole is determined by

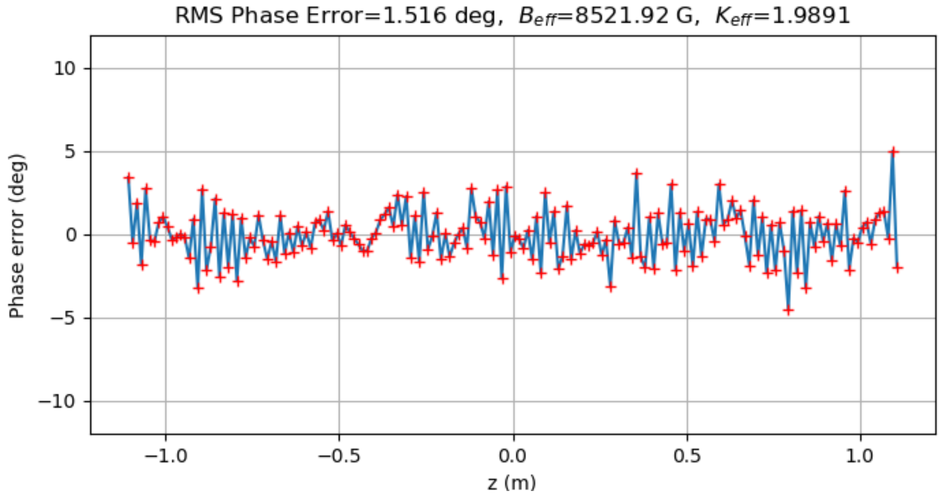
$$\delta\phi(i) = -\pi^2 \frac{2\bar{K}^2}{2+\bar{K}^2}\frac{\delta g(i)}{\lambda_u}$$

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

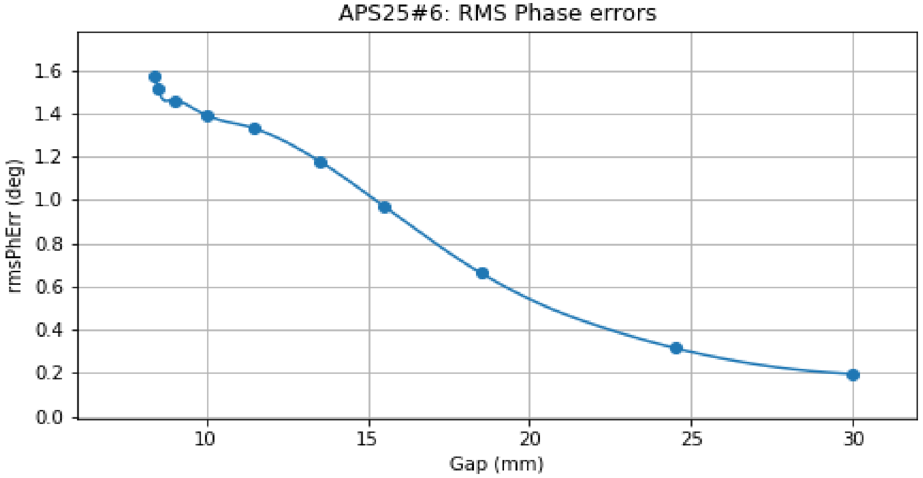
λ_u: undulator period length



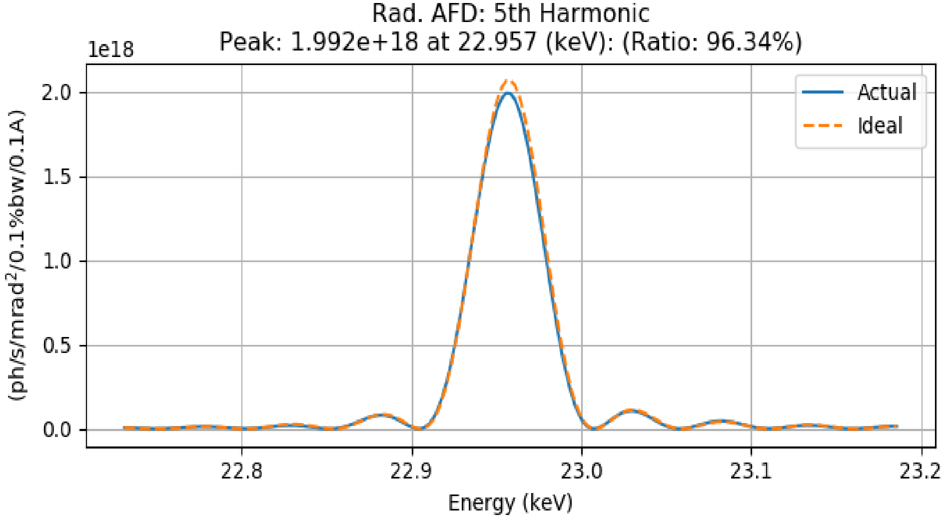




Phase error at 8.5-mm gap setting after tuning

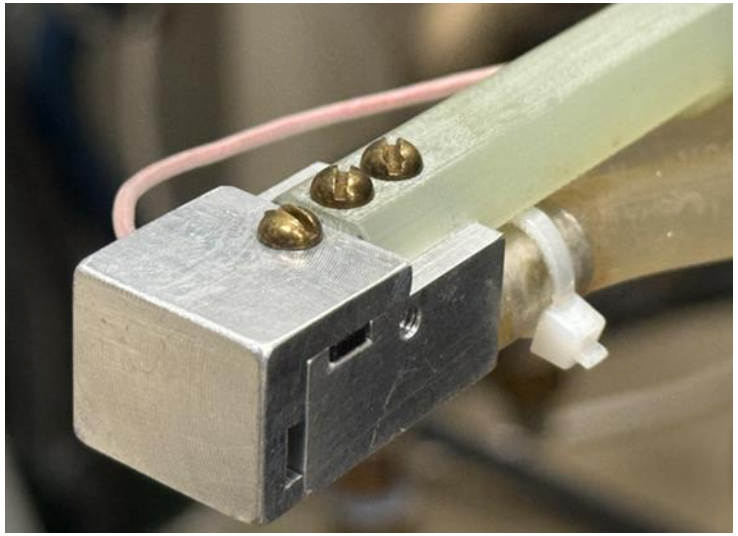


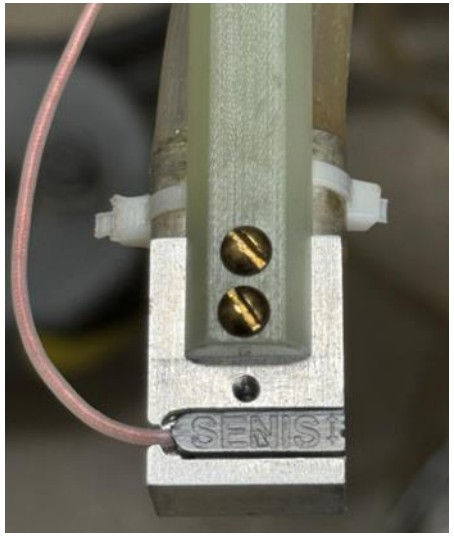
RMS phase errors after tuning



5th harmonic brightness after tuning

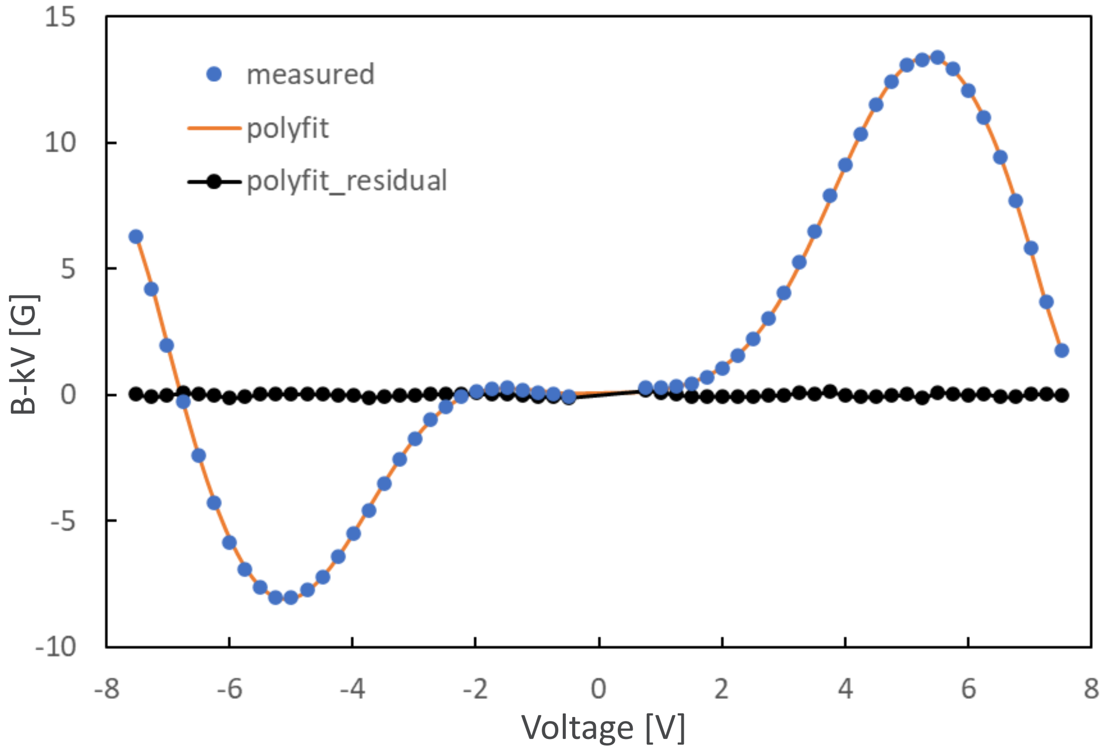
Hall probe calibration system



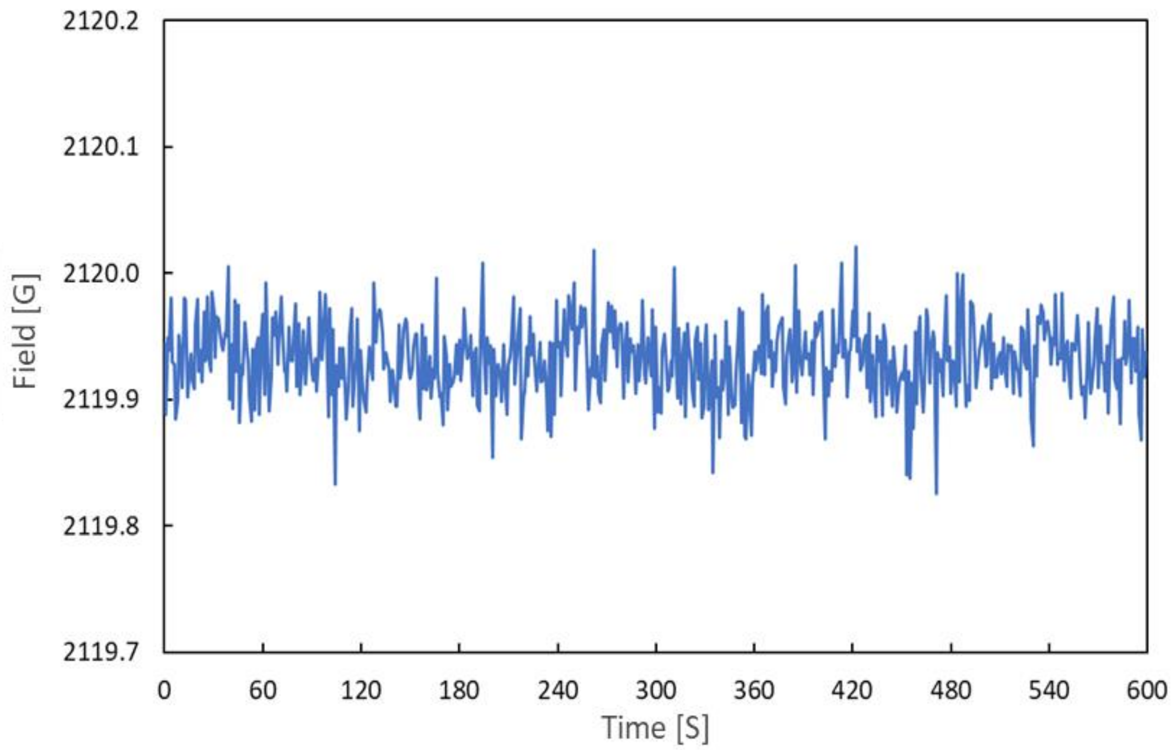


Hall probe calibration

Hall sensor calibration accuracy: ~10 ppm

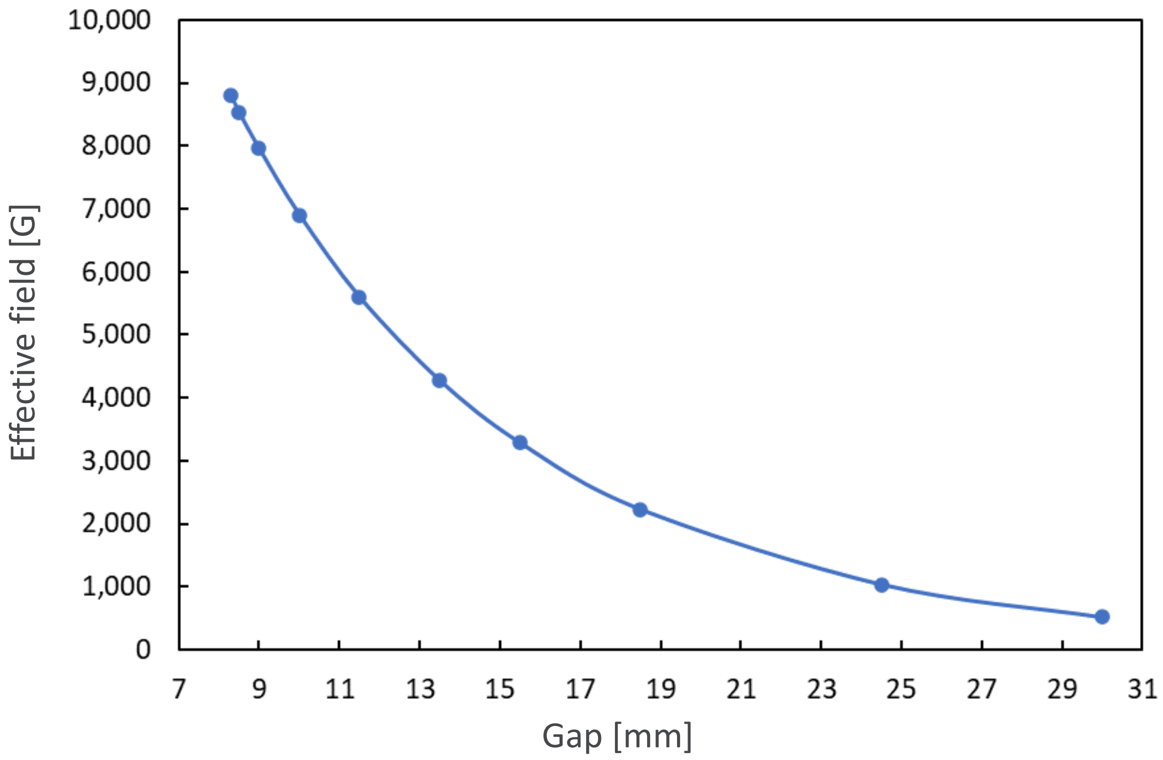


Senis TRHA-30009322 Hall sensor calibration curve

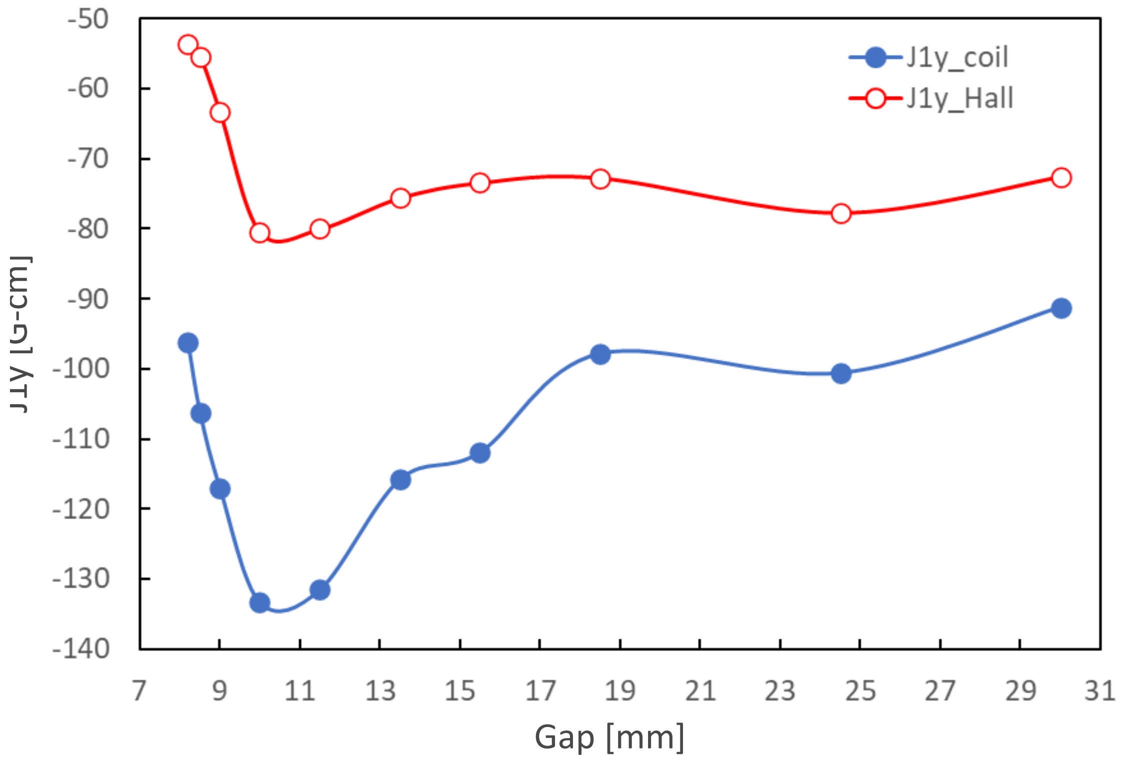


Hall sensor field time-dependent measurement

Hall probe field integral measurement



APS25#4 measured effective field vs. gap



APS25#4 Hall probe and coil field integral measurements

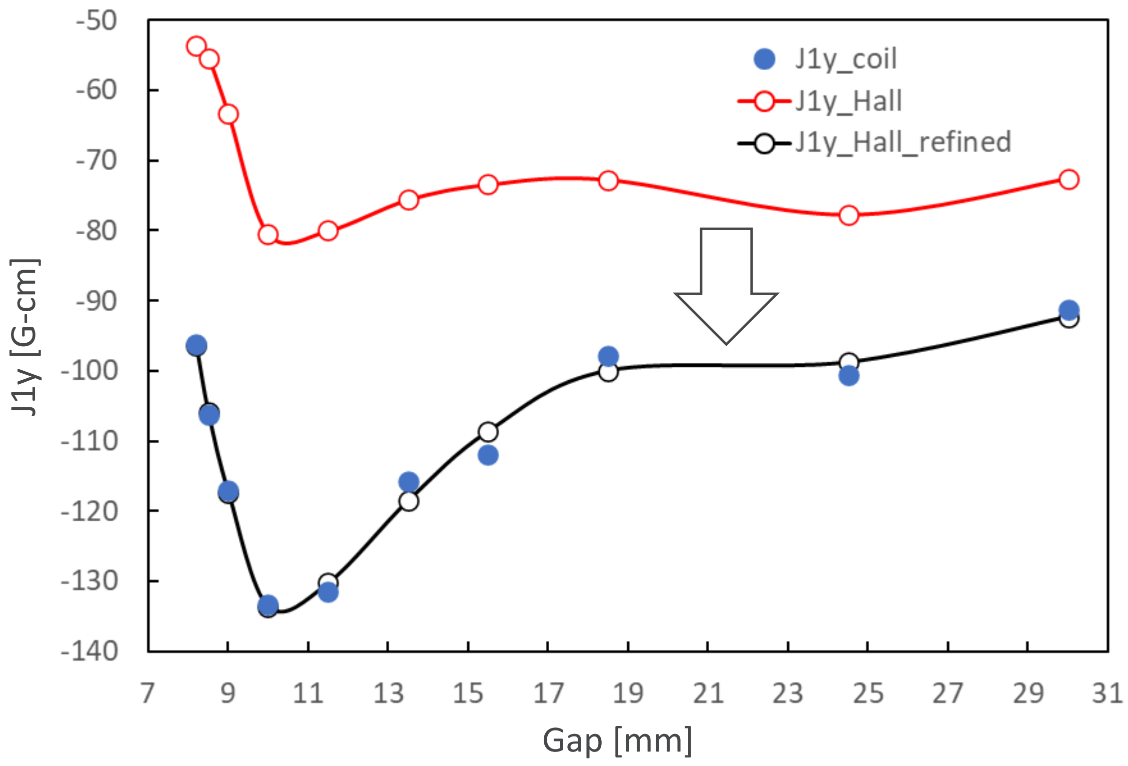
Hall probe calibration refinement

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

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

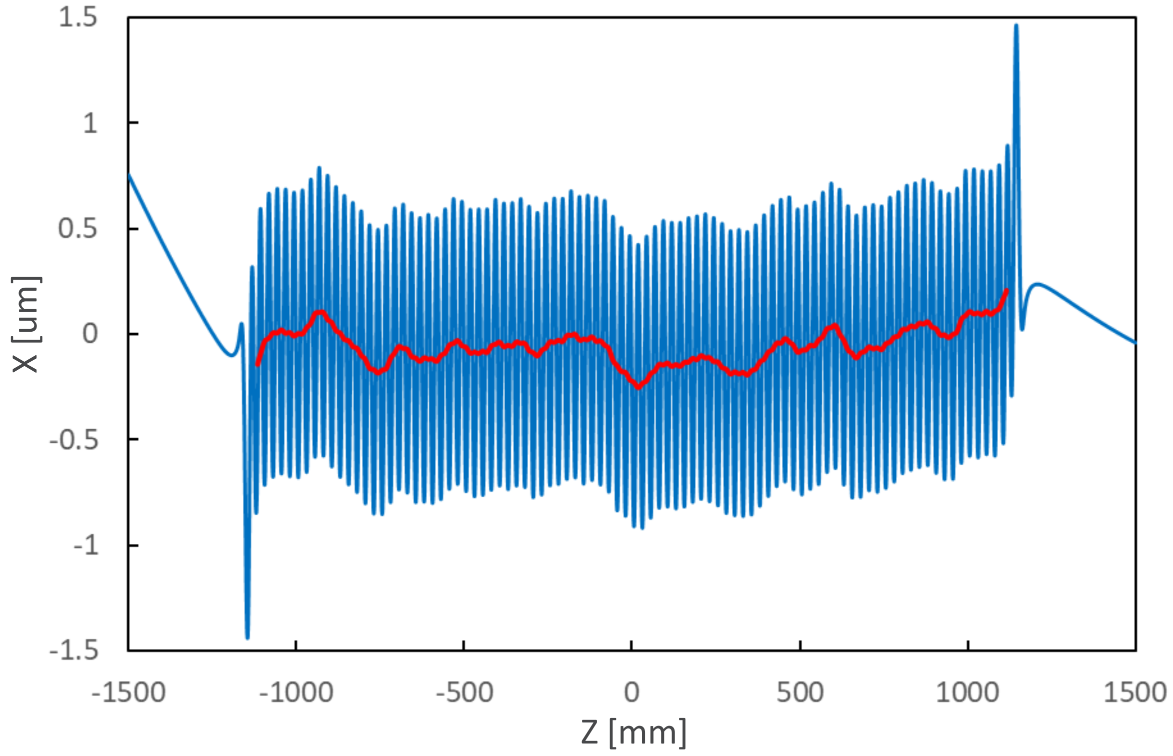
where c'_{2n} is the refinement needed in the even order polynomial coefficients.

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.

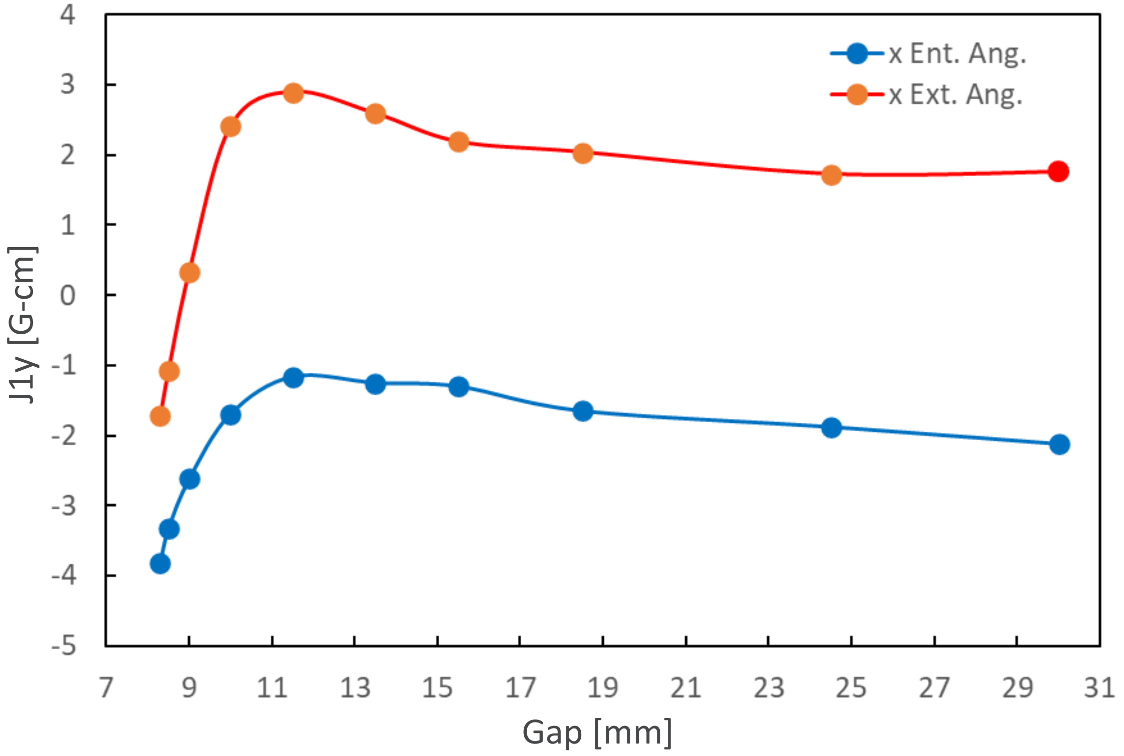


Hall probe and coil field integral measurements after refinement

Hall probe beam entrance and exit angle measurement



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

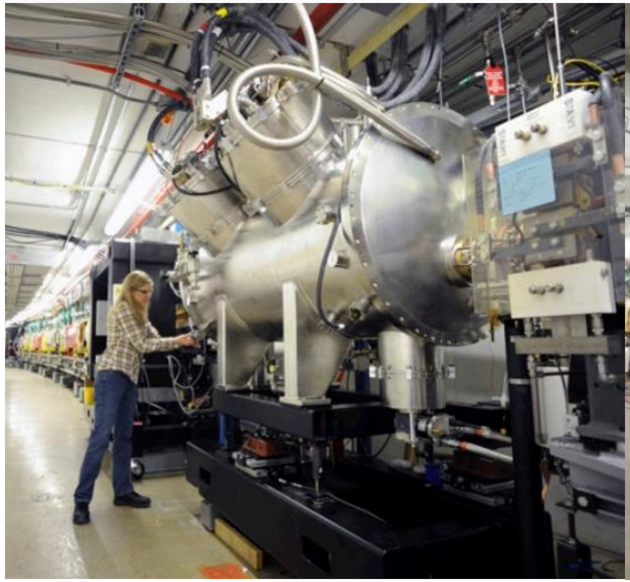


APS25#4 Hall probe entrance and exit angle vs gap

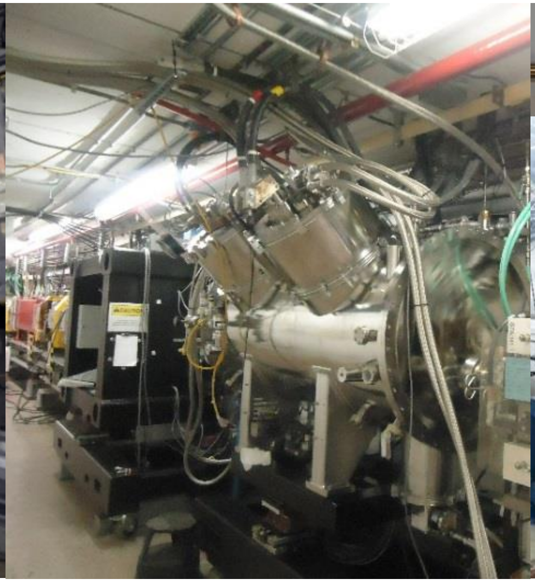
APS superconducting undulators (SCUs)

- 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

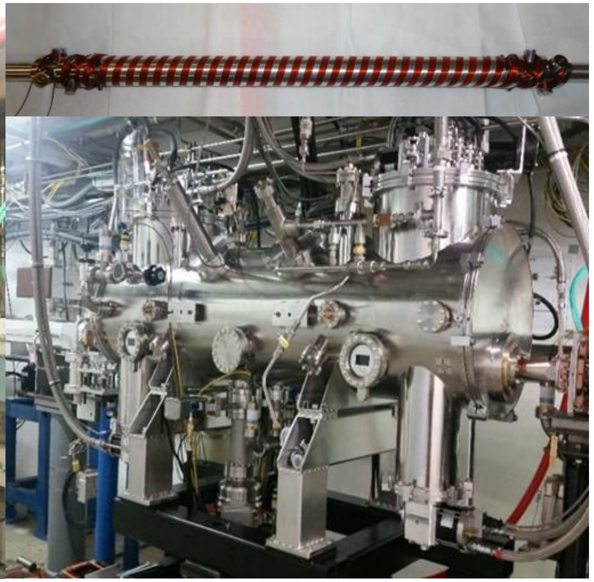
Completed and was in operation



Planar SCU18 in sector 1



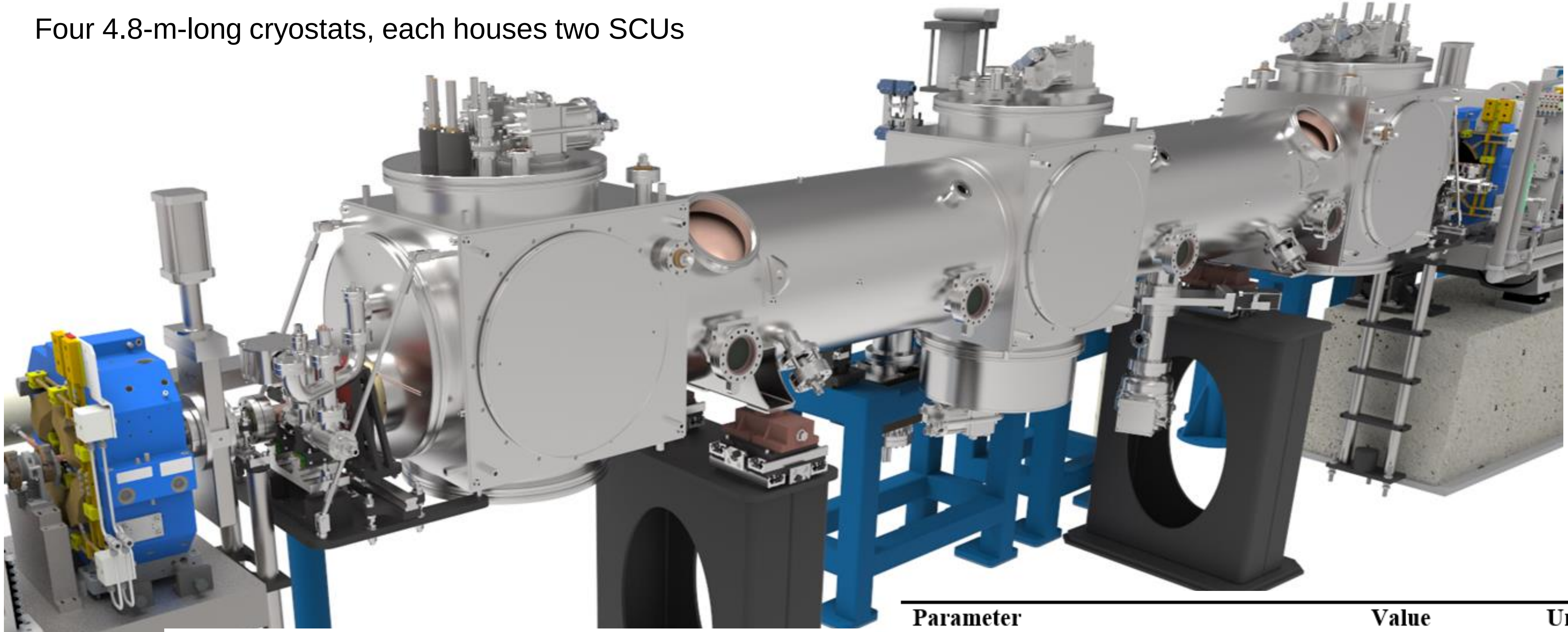
Planar SCU18 in sector 6



Helical SCU (HSCU) in sector 7

APSU SCUs

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

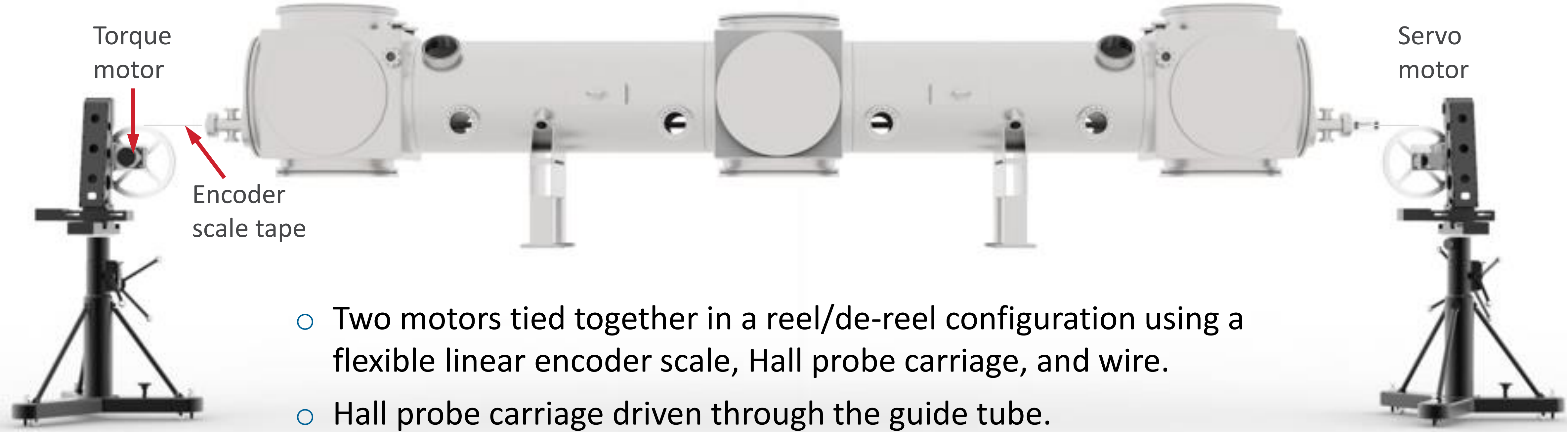


Four 4.8-m-long cryostats, each houses two SCUs

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

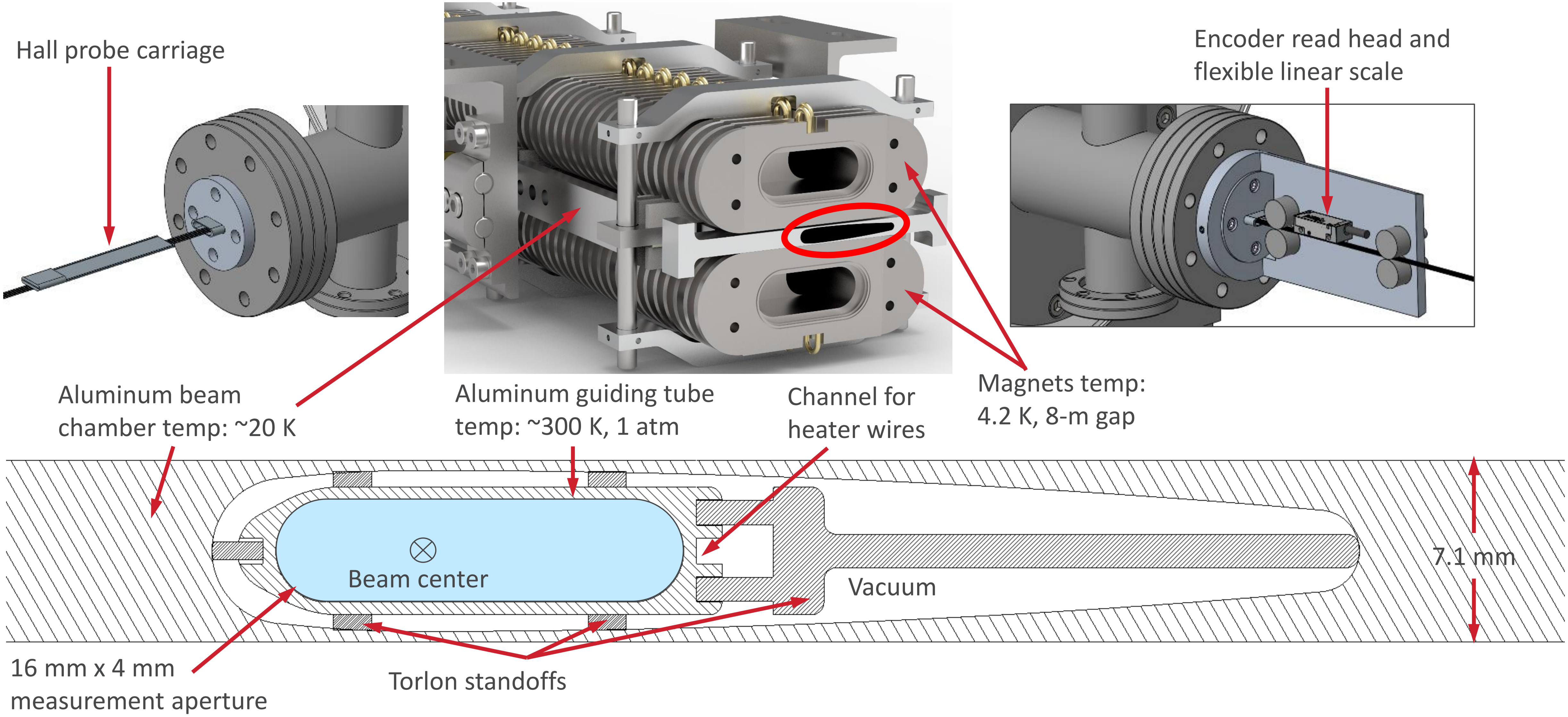
Parameter	Value	Unit
Cryostat maximum length	4.8	m
Insertion device maximum length	1.9	m
Vertical magnetic gap	8.0	mm
ID chamber vertical aperture	6.3 +0.1/-0.3	mm
Vacuum chamber straightness in plane with small magnetic gap	+/- 50	µm
ID rms phase error for any operational current	~5	degree

APSU SCU portable measurement system

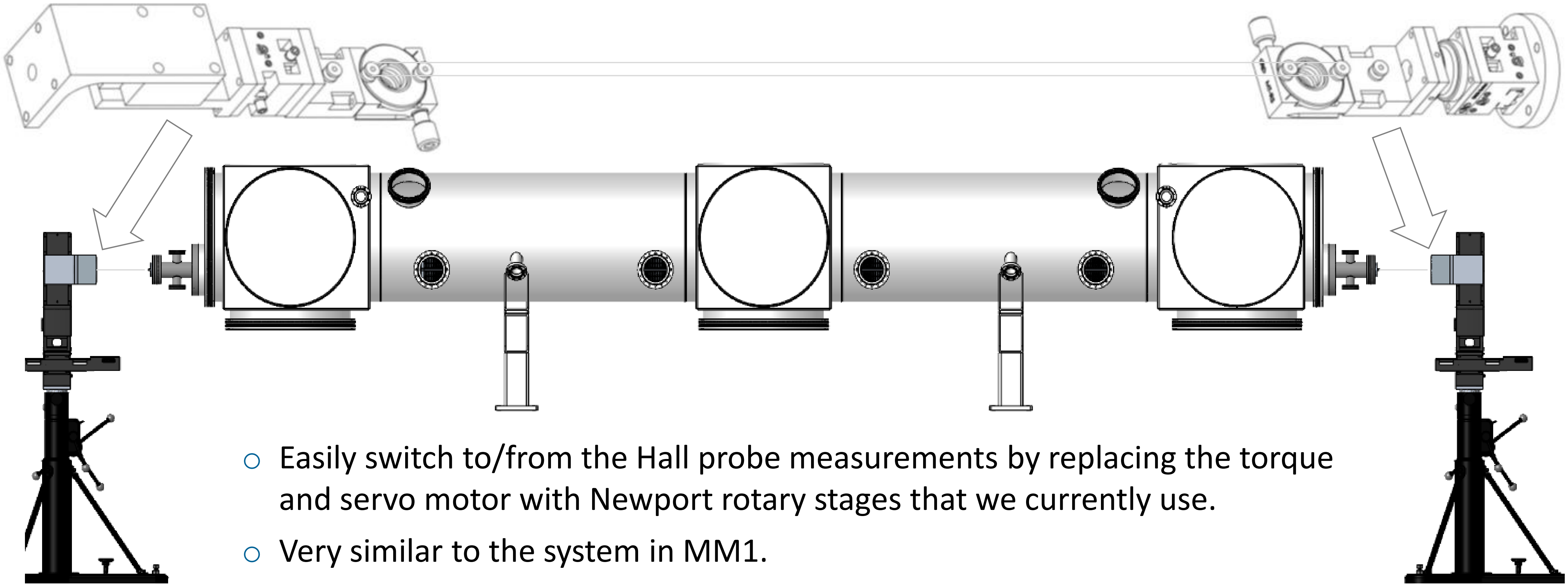


- Two motors tied together in a reel/de-reel configuration using a flexible linear encoder scale, Hall probe carriage, and wire.
- Hall probe carriage driven through the guide tube.
- Servo motor position control through feedback from linear encoder.
- Torque motor maintains tension.
- System eliminates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

Extruded and machined guiding tube



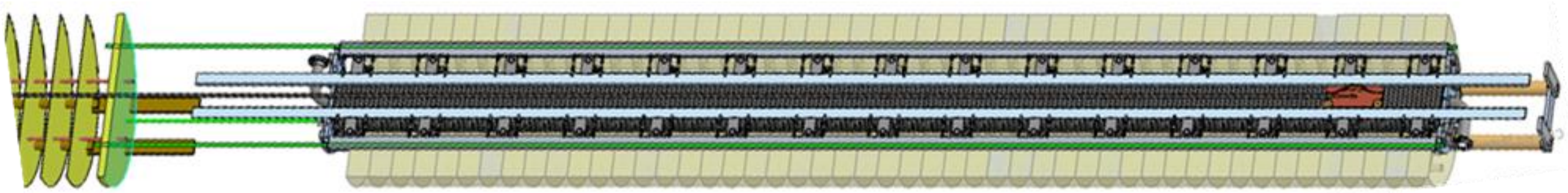
APSU SCU stretched wire measurement system



- 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.



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!