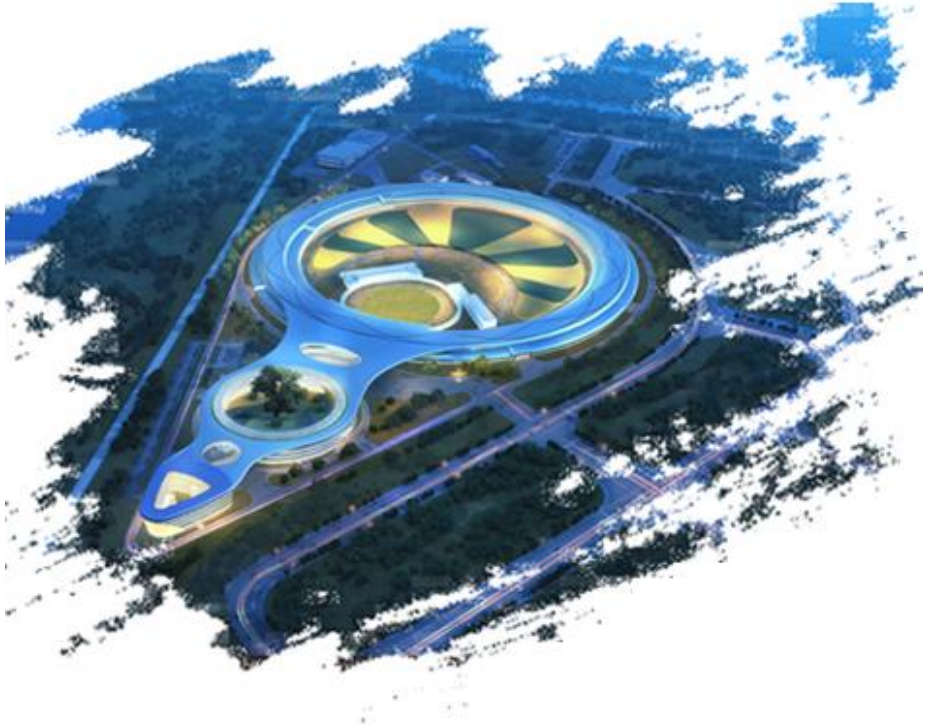
HEPS Insertion Device Development



Yuhui Li
Insertion Device
July 14 2026

CONTENT

1. ID development for HEPS
2. Domestic collaborative undulator development
3. Superconducting insertion devices
4. International cooperation
5. Summary

ID objectives for the 1st scenario

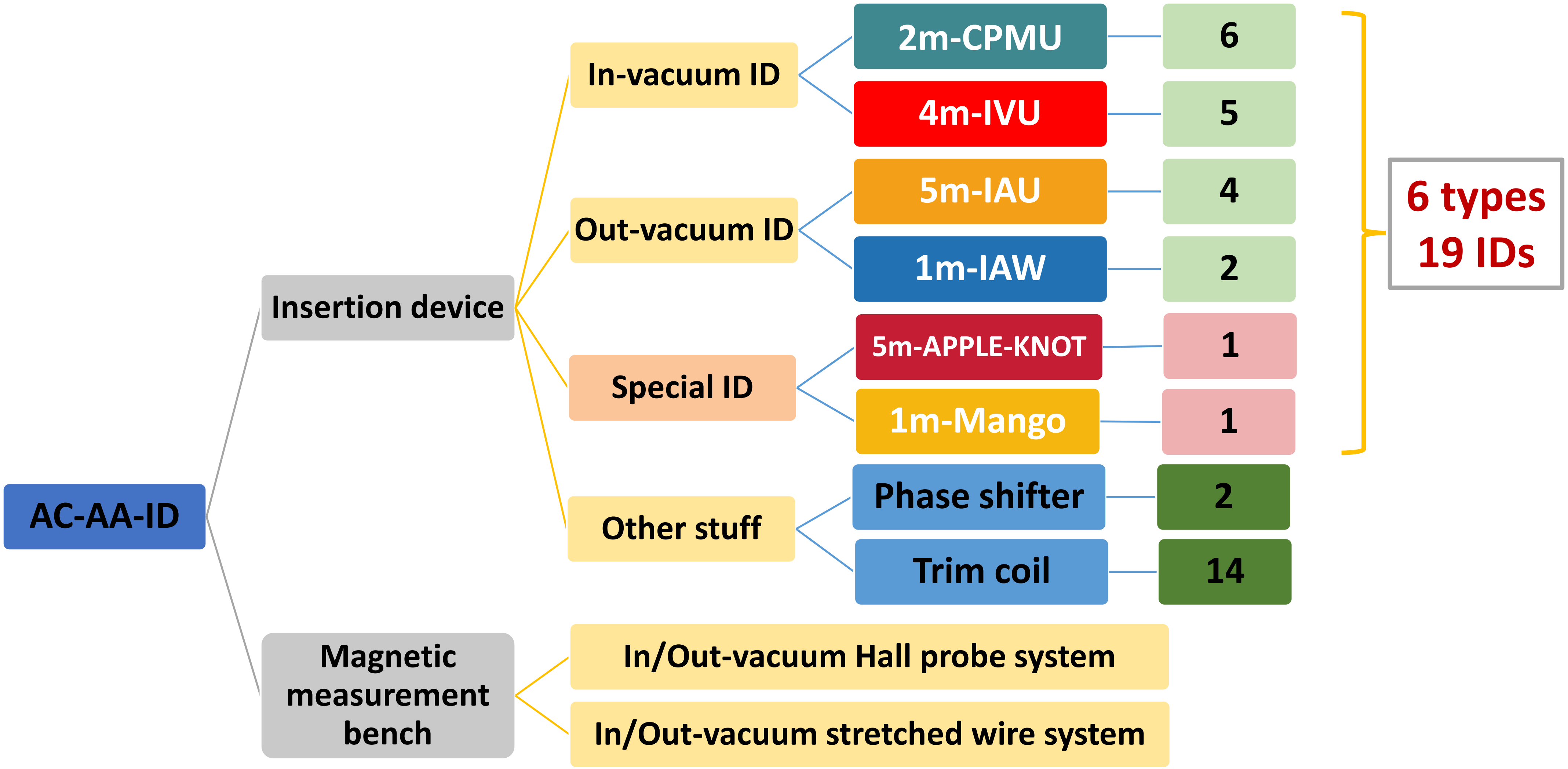
Our responsibility encompasses design, construction and commissioning of the insertion device system for beamlines

- 14 user beamlines
- 1 test beamline—for Optical components test
- Most beamlines harness insertion devices

	Light source	Number
User beamline	Bending magnet	1
User beamline	Insertion device	13
Test beamline	Insertion device	1

14 ID Beamline

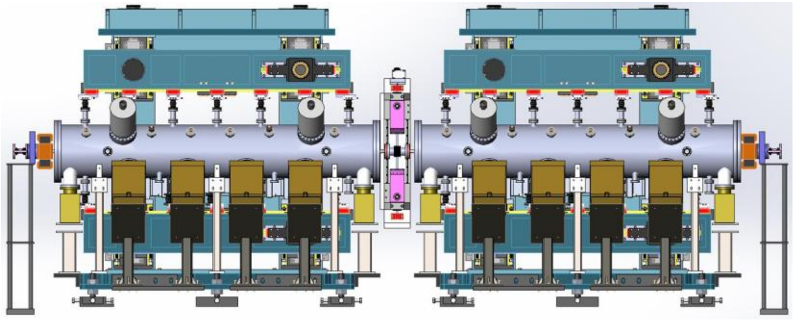
ID categories and quantities



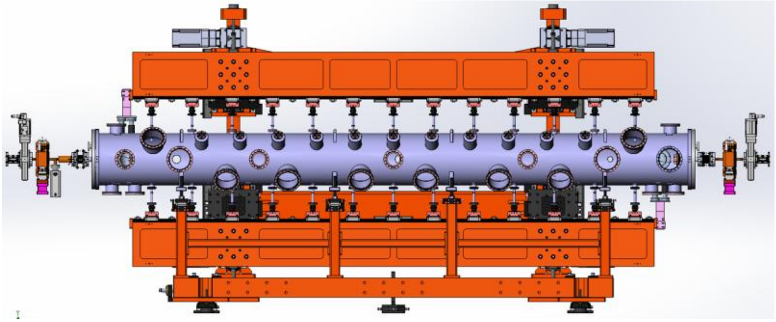
ID parameters overview

BL No.	Beamline	SS No.	ID Type	Length [m]	Period Length [mm]	B0[T]	Gap Range [mm]	Min. Phase Error RMS [Degree]	Photon Energy [keV]	β
B1(A)	Engineering Materials Beamline	ID07	CPMU	2	16.7	1.19	5.2-10	3	50-170	Low
B1(B)			CPMU	2	16.7	1.19	5.2-10	3		
B2	Hard X-ray Nanoprobe Multimodal Imaging Beamline	ID19	IVU(SmCo)	4	22.6	1.1	5.2-15.2	3	4.8-40	Low
B3(A)	Structural Dynamics Beamline	ID23	CPMU	2	12	0.81	5.2-7.0	4	20.9-24, 62.7-72	Low
B3(B)			CPMU	2	14.2	1.00	5.2-9.9	4	14.4-20.9, 43-62.7	
B4	Hard X-ray Coherent Scattering Beamline	ID09	IVU(SmCo)	4	19.9	0.97	5.2-14.0	3	7.33-13.34, 22-40	Low
B5	Hard X-Ray High Energy Resolution Spectroscopy Beamline	ID33	IVU(NdFeB)	4	18.6	1.04	5.2-13.0	4	7.1-16.88, 21.3-25	Low
B6	High Pressure Beamline	ID31	IVU(SmCo)	4	19.9	0.97	5.2-8.0	3	20-50	Low
B7(A)	Hard X-Ray Imaging Beamline	ID21	CPMU	2	18.8	1.35	5.2-13.1	3	10-90	Low
B7(B)			Wiggler	1	73	1.64	11	--	40-300	
B7-C			Mango Wiggler	1	50.7/50	1	12.4-34	--		
B8	X-ray Absorption Spectroscopy Beamline	ID46	IAU	5	35	0.88	11-24.5	4	4.8-45	High
B9	Low-Dimension Structure Probe Beamline	ID05	IVU(SmCo)	4	22.6	1.1	5.2-15.2	3	4.8-40	Low
BA	Microfocussing X-Ray Protein Crystallography Beamline	ID02	IAU	5	32.7	0.8	11-22.8	4	5-18	High
BB	Pink Beam SAXS Beamline	ID08	IAU	5	25	0.54	11.2-17.5	6	8-12, 24-33	High
BC	High Resolution Nanoscale Electronic Structure Spectroscopy Beamline	ID41	APPLE-KNOT	5	256.8	0.87/1.07	14.7-67.4	--	0.1-2	Low
BE	Transmission X-Ray Microscopy Beamline	ID30	IAU	5	32.7	0.8	11-21.2	4	5-15	High
BF(A)	Test Beamline	ID42	CPMU	2	22.8	1.18	7.2-16.0	3	10-90	High
BF(B)			Wiggler	1	73	1.64	11	--	40-300	

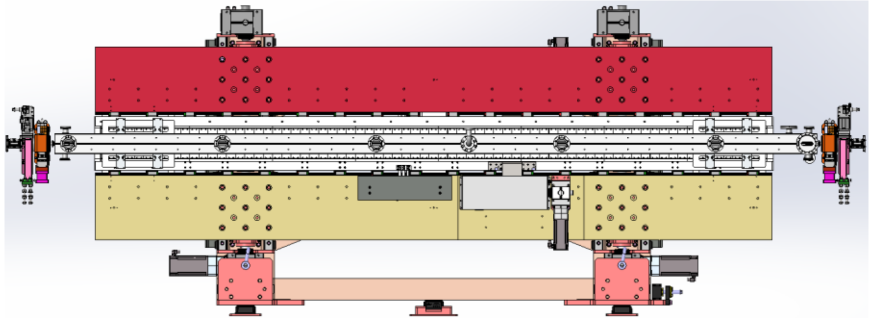
Online installation combination



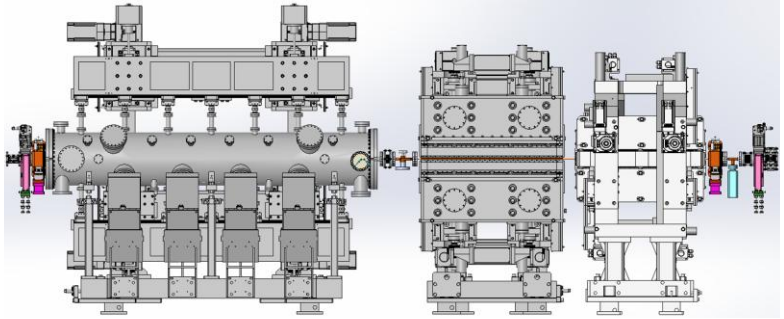
2m-CPMU + PS + 2m-CPMU



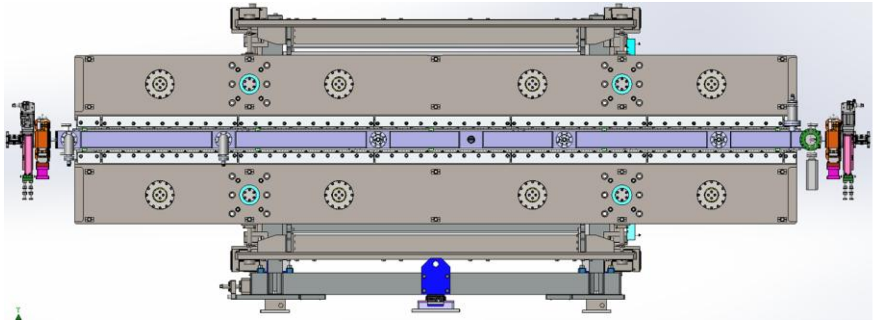
4m-IVU



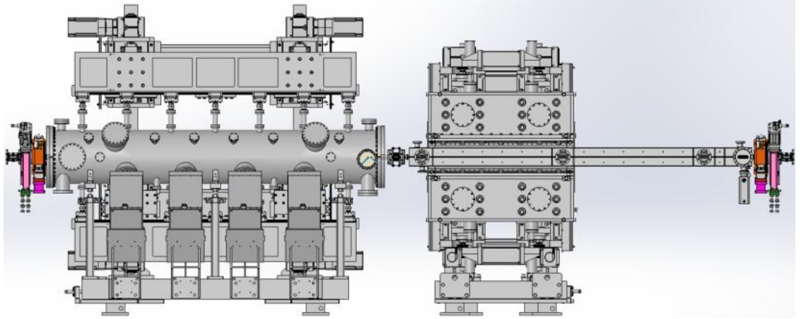
5m-AK



CPMU + IAW + Mango



5m-IAU

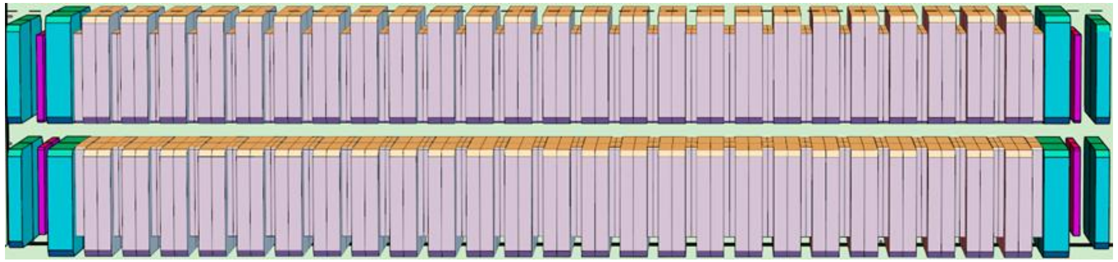


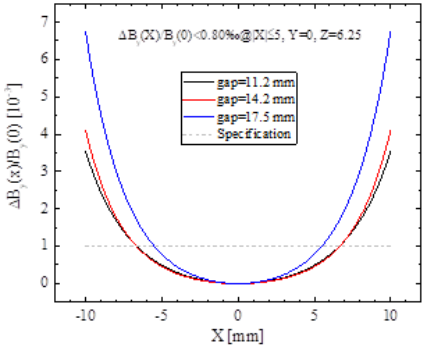
CPMU+IAW

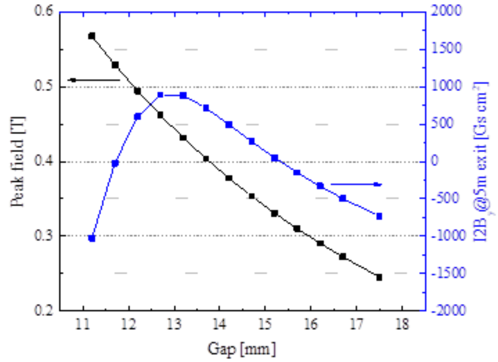
Development of In Air planar devices

Hybrid structure with ~1m modules

- Design concerns: peak field, B0 roll-off, size of magnet & pole, end design, variation of attraction force, layout
- Mechanical stability, deformation due to force load at various gap
- Control system with high resolution

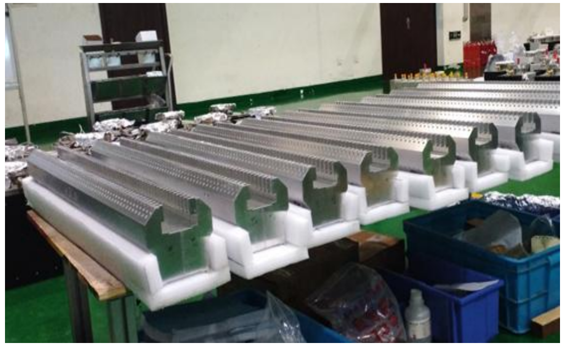




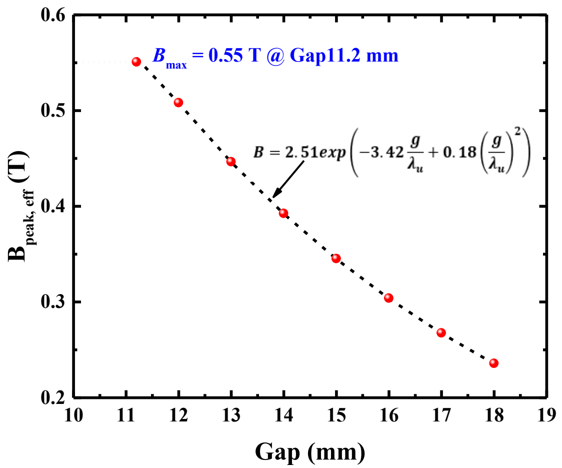


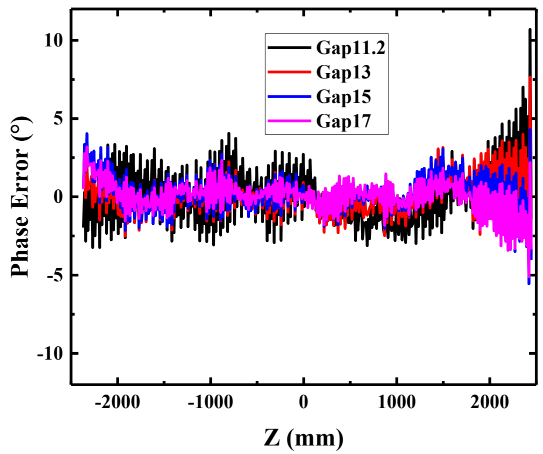
No.	Beamline	ID No.	Length [m]	Period Length [mm]	Working Gap [mm]	Peak Field [T]
R02IAU	BA	IAU32.7-1	5	32.7	11 - 22.8	0.80
R08IAU	BB	IAU25	5	25	11.2 - 17.5	0.54
R30IAU	BE	IAU32.7-2	5	32.7	11 - 21.2	0.80
R46IAU	B8	IAU35	5	35	11 - 24.5	0.88

No.	Beamline	ID No.	Length [m]	Period Length [mm]	Working Gap [mm]	Peak Field [T]
R21IAW	B7(B)	IAW73-1	1	73	11 - 52	1.64
R42IAW	BF(B)	IAW73-2	1	73	11 - 52	1.64



IAU quality for installation





ID No.	IAU35	IAU32.7-1	IAU25	IAU32.7-2
Working Gap (mm)	[11,16]	[11,13]	[11.2,15.2]	[11,17]
Specification (RMS phase error)	4.0	4.0	6.0	4.0
Test results	3.3	2.3	2.0	3.3
Working Gap (mm)	[16,35]	[13,22.8	[15.2,17.5	[11.7,21.2
Specification (RMS phase error)	6.0	6.0	10.0	6.0
Test results	3.9	3.8	1.2	4.6

IAU Phase error

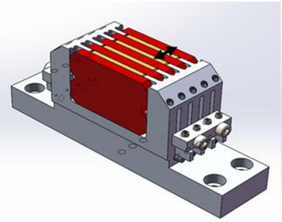
Integral and multipole fields summary

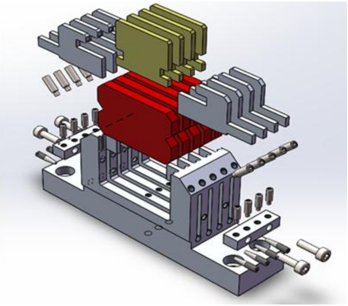
Item	Specification	IAU35		IAU32.7-1		IAU25		IAU32.7-2		Unit
		Test results		Test results		Test results		Test results		
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	
First integral of the magnetic field (x, y) @ working gap	100	36	91	11	60	15	35	15	56	Gs·cm
Second integral of the magnetic field (x, y) @ working gap	20000	11914	15690	6634	18786	10749	8569	1663	10506	Gs·cm^2
Quadrupole component	300	85	51	50	63	9	39	44	55	Gs
Hexapole component	400	150	286	89	260	150	89	89	87	Gs/cm
Octupole component	800	191	255	162	131	36	152	234	120	Gs/cm^2
Variation of the first integral @ X = [-3, +3] mm	100	51	48	36	35	15	16	23	30	Gs·cm

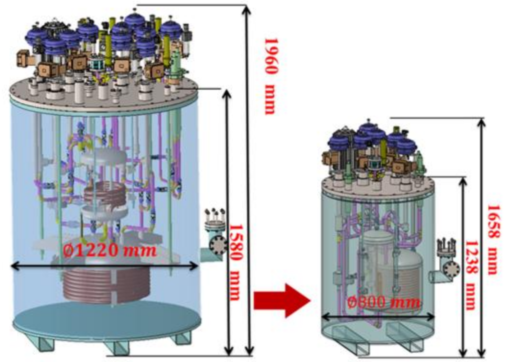
CPMU development

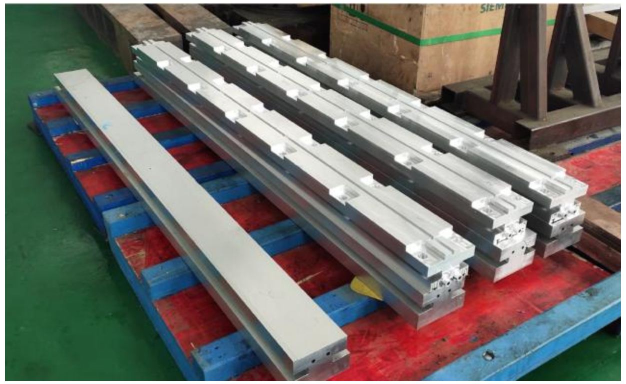
- Development initiated in the phase of TF, 2 rounds optimization for mechanical details
- The material of PrFeB was tested in a comprehensive way, remanence with respect of temperature, demagnetization behavior. i.e. were measured
- Two cold boxes were developed with optimization for a more compact design with full function
- Measurement in a cryogenic condition, control system calibration adapting low temperature condition

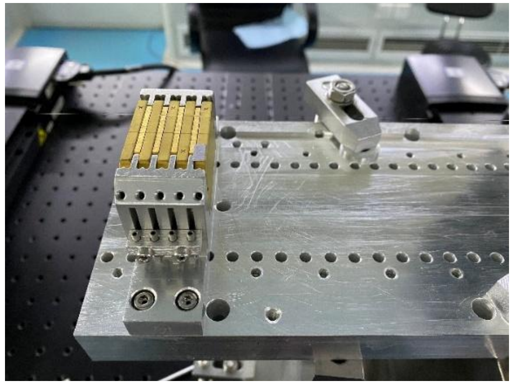
No.	Beamline	ID No.	Length [m]	Period Length [mm]	Working Gap [mm]	Peak Field [T]
R07CPMU1	B1(A)	CPMU16.7-1	2	16.7	5.2 - 10	1.19
R07CPMU2	B1(B)	CPMU16.7-2	2	16.7	5.2 - 10	1.19
R21CPMU	B7(A)	CPMU18.8	2	18.8	5.2 - 13.1	1.35
R23CPMU1	B3(A)	CPMU12	2	12	5.2 - 7	0.81
R23CPMU2	B3(B)	CPMU14.2	2	14.2	5.2 - 9.9	1.00
R42CPMU	BF(A)	CPMU22.8	2	22.8	7.2 - 16	1.18











Final status measurement of CPMU

period(mm)	Length(m)	Gap(mm)	Beamline	Min. Phase Error RMS(°)	Measured Max phase error(°)
12	2	5.2-7	Structural Dynamics Beamline	4	3.19
14.2	2	5.2-9.9	Structural Dynamics Beamline	4	2.71
16.7-1	2	5.2-10	Engineering Materials Beamline	3	2.7
16.7-2	2	5.2-10	Engineering Materials Beamline	3	2.9
18.8	2	5.2-13.1	Hard X-Ray Imaging Beamline	3 (gap5.2mm-7.6mm) 6 (gap>7.6mm)	3 3.3
22.8	2	7.2-16	Test Beamline	3 (gap5.2mm-12.3mm) 6 (gap>12.3mm)	2.8

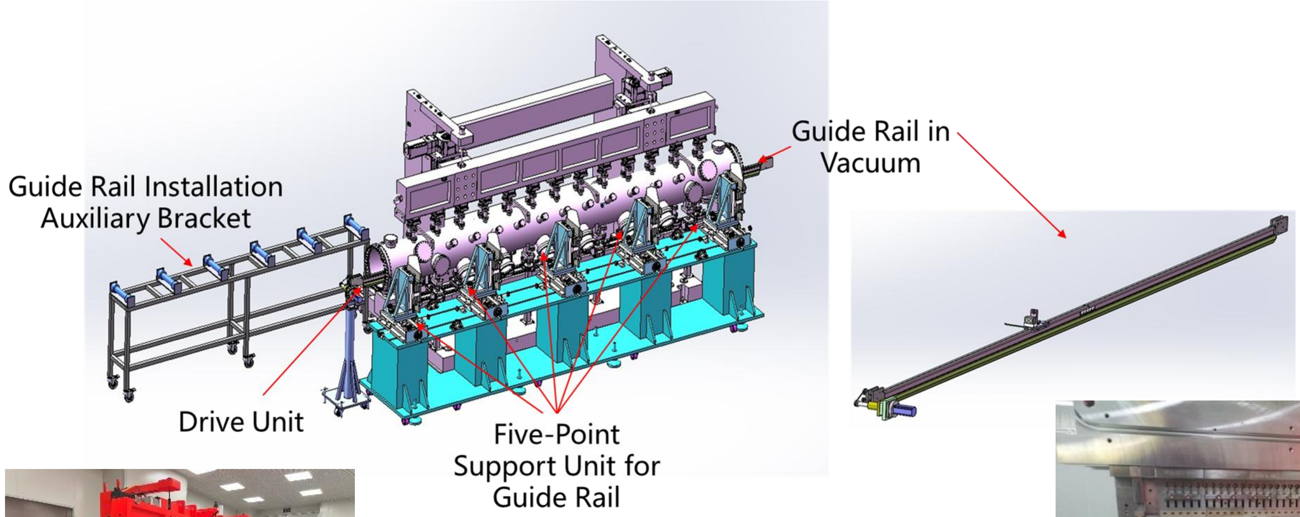
Item	Specification	CPMU12		CPMU14.2		CPMU16.7-1		CPMU16.7-2		CPMU18.8		CPMU22.8		Unit
		Test results		Test results		Test results		Test results		Test results		Test results		
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	
First integral of the magnetic field (x, y) @ working gap	100	39	37	91	24	43	51	90	77	54	96	35	68	Gs·cm
Second integral of the magnetic field (x, y) @ working gap	20000	10290	10554	13247	5603	7682	17340	10381	11966	5568	11912	8490	19875	Gs·cm^2
Quadrupole component	300	43	48	95.2	141.6	59	53	155	68	111	128	84	229	Gs
Hexapole component	400	76	313	170.8	267.3	203	162	143	69	184	110	262	119	Gs/cm
Octupole component	800	411	226	602.55	493.85	605	335	785	225	597	361	393	452	Gs/cm^2
Variation of the first integral @ X = [-3, +3] mm	100	36	43	87.2	34.2	66	25	98	31	73	88	65	97	Gs·cm

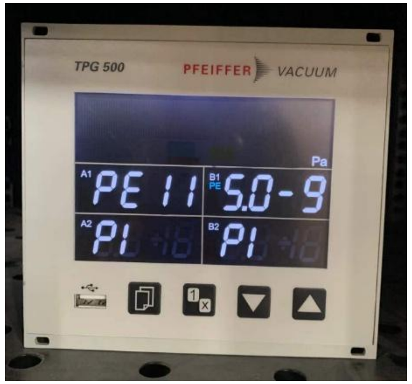
ID parameters overview

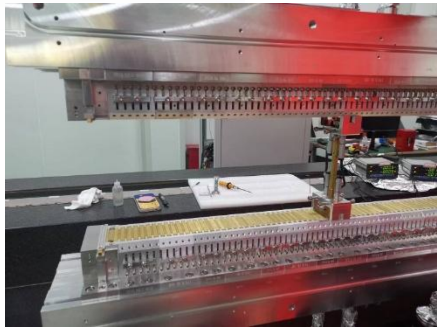
- In-vacuum device, 4-meter-long,
- Engineering concerns: structure stability + ultra-high vacuum
- 4-m long in vacuum measurement system with high precision
- Field quality resisting the vacuum backout: performance test

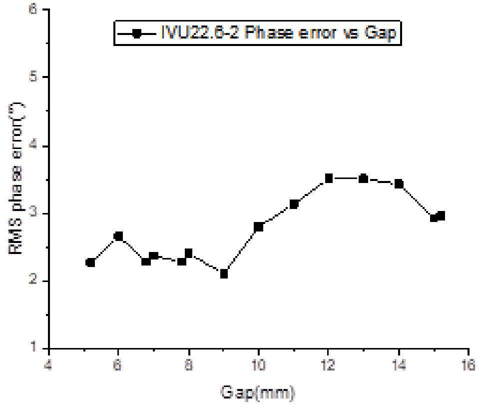
before and after vacuum bakeout, quality maintained

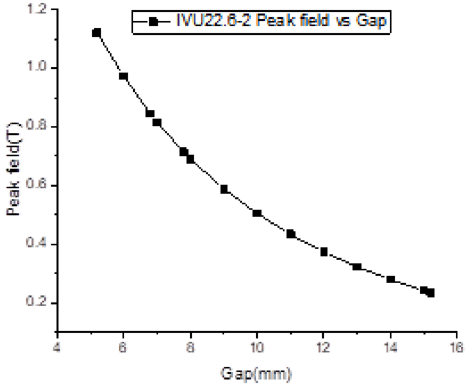
No.	Beamline	ID No.	Length [m]	Period Length [mm]	Working Gap [mm]	Peak Field [T]
R05IVU	IVU22.6-1	B9	4	22.6	5.2 - 15.2	1.10
R09IVU	IVU19.9-1	B4	4	19.9	5.2 - 14	0.97
R19IVU	IVU22.6-2	B2	4	22.6	5.2 - 15.2	1.10
R31IVU	IVU19.9-2	B6	4	19.9	5.2 - 8	0.97
R33IVU	IVU18.6	B5	4	18.6	5.2 - 13	1.04











IVU final status measurement

period(mm)	Length (m)	Gap(mm)	Beamline	Min. Phase Error RMS(°)	Measured Max phase error(°)
18.6	4	5.2-13	Hard X-Ray High Energy Resolution Spectroscopy	4（gap<5.9mm） 6（gap>5.9mm）	3.8 5
19.9	4	5.2-8	High Pressure	3（gap<6.8mm） 4（gap>6.8mm）	2.5 3.7
19.9	4	5.2-14	Hard X-ray Coherent Scattering	3（gap<6.1mm） 4（6.1mm<gap<8mm） 6（gap>8mm）	2.7 2.5 3
22.6	4	5.2-15.2	Hard X-ray Nanoprobe Multimodal Imaging	3（gap<6.8mm） 4（6.8mm<gap<7.8mm） 6（gap>7.8mm）	2.9 3.7 4.2
22.6	4	5.2-15.2	Low-Dimension Structure Probe	3（gap<6.8mm） 4（6.8mm<gap<7.8mm） 6（gap>7.8mm）	2.4 2.7 4.4

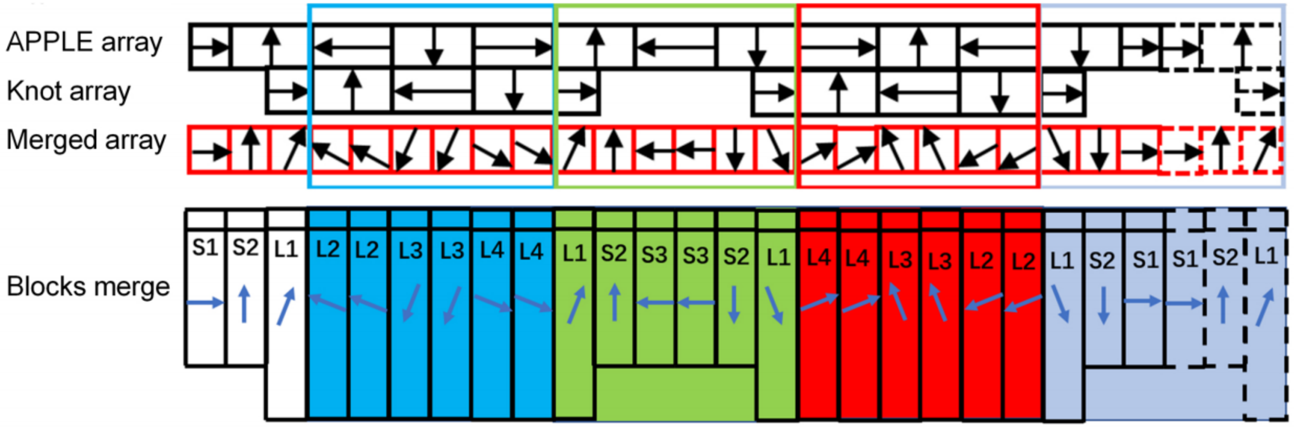
Item	Specification	IVU18.6		IVU19.9-1		IVU19.9-2		IVU22.6-1		IVU22.6-2		Unit
		Test results		Test results		Test results		Test results		Test results		
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	
First integral of the magnetic field (x, y) @ working gap	100	97	95	60	91	88	82	85	56	48	41	Gs·cm
Second integral of the magnetic field (x, y) @ working gap	20000	6029	18384	12946	10766	18806	17674	10448	11847	14138	7809	$Gs\cdot cm^2$
Quadrupole component	300	128	77	149	118	122	158	133	119	141	32	Gs
Hexapole component	400	43	361	258	94	47	326	322	351	152	208	Gs/cm
Octupole component	800	315	490	168	521	566	691	303	124	631	444	Gs/cm^2
Variation of the first integral @ X = [-3, +3] mm	100	62	47	80	84	94	34	88	62	93	18	Gs·cm

4-array APPLE knot undulator

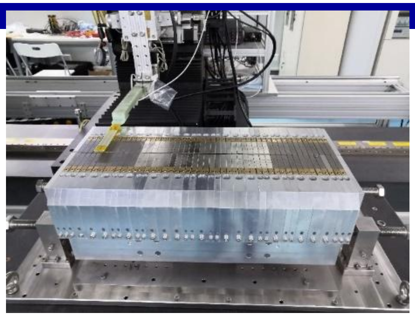
- Challenge: high energy machine yields overwhelming on-axis heat load in EUV zone.
- Solution: APPLE-Knot undulator innovates the design by implementing an additional magnet array along the traditional APPLE-II undulator
- Our contribution: merging the two arrays by using tilted magnetization blocks, improving the field strength and further optimizing the performances at all gaps
- Many engineering challenges

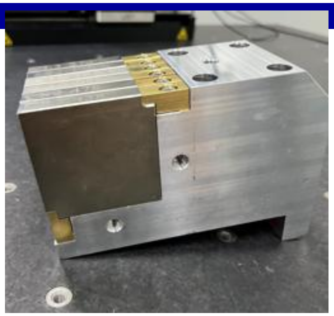
Design parameters of the merged APPLE–Knot undulator.

Period length $3\lambda_u$ (mm)	256.8
Corresponding APPLE magnets period length λ_u (mm)	85.6
Corresponding Knot magnets period length 1.5 λ_u (mm)	128.4
Number of periods	18
Dimension of blocks merged by APPLE and Knot magnets (mm)	55 × 55 × 10.7
Dimension of blocks corresponding to blank segments (mm)	55 × 40 × 10.7
The ratio of the magnitudes of magnetization between the APPLE and Knot components	5:2
Clearance between arrays (mm)	1
Gap in horizontal mode @100–2000 eV (mm)	17.30-67.40
Array 1/3 shift in horizontal mode @100 eV (mm)	0/0
Gap in vertical mode @100–2000 eV (mm)	15.00-60.90
Array 1/3 shift in vertical mode @ 100 eV (mm)	42.8 (λ_u/2) / −42.8 (-λ_u/2)
Gap in circular mode @ 100–2000 eV (mm)	14.70-58.00
Array 1/3 shift in circular mode @ 100 eV (mm)	64.2 (3 λ_u/4) / −21.4 (- λ_u/4)



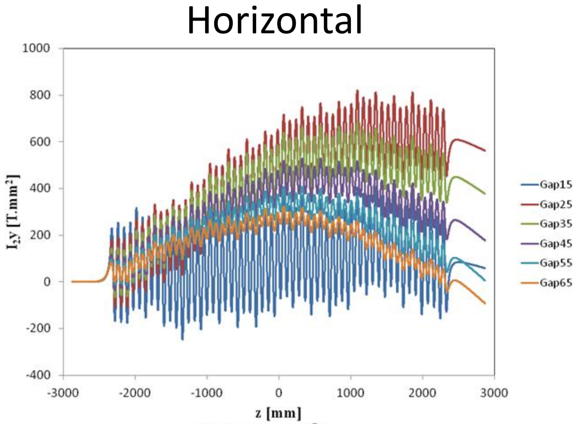
AK undulator tuning and performance

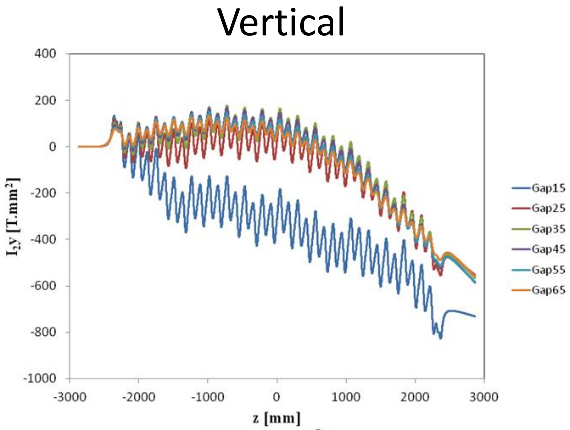


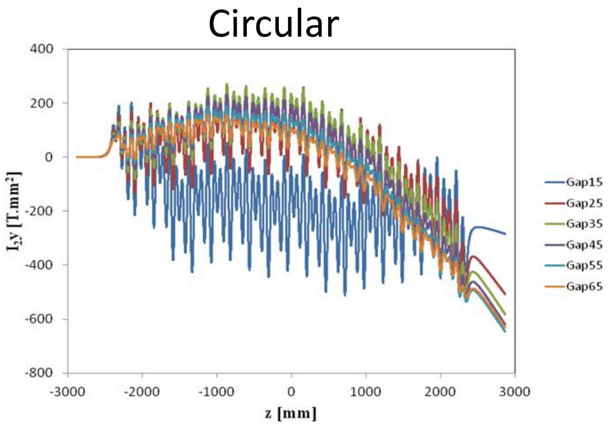


- Special module design and current strips for field correction
- Small field integral and satisfied polarization achieved

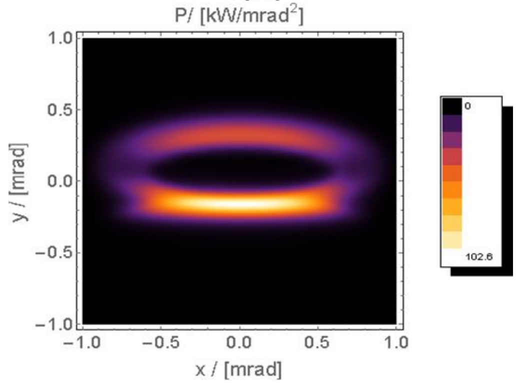
Magnetic field performance, Vertical second field integral

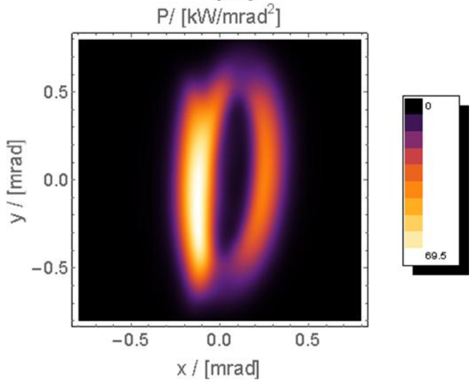


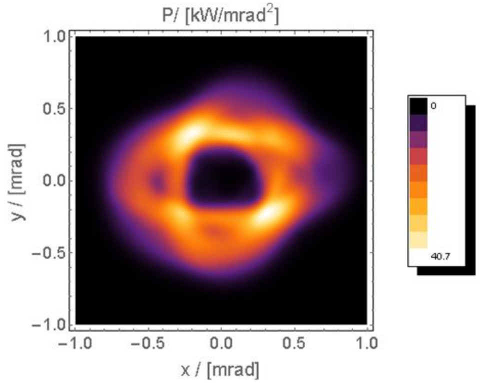




Optical performance, Power spatial distribution @Gap=15mm

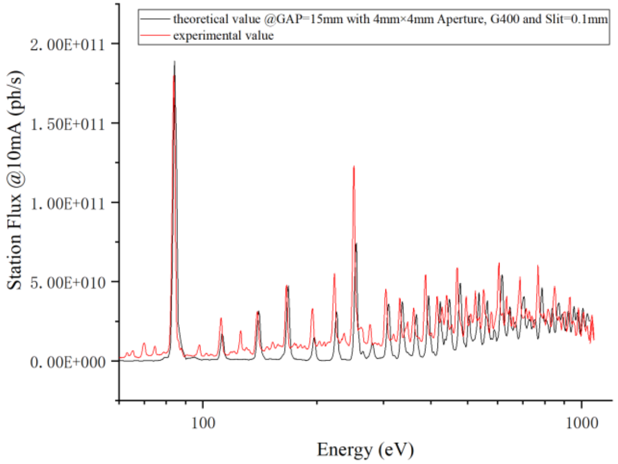


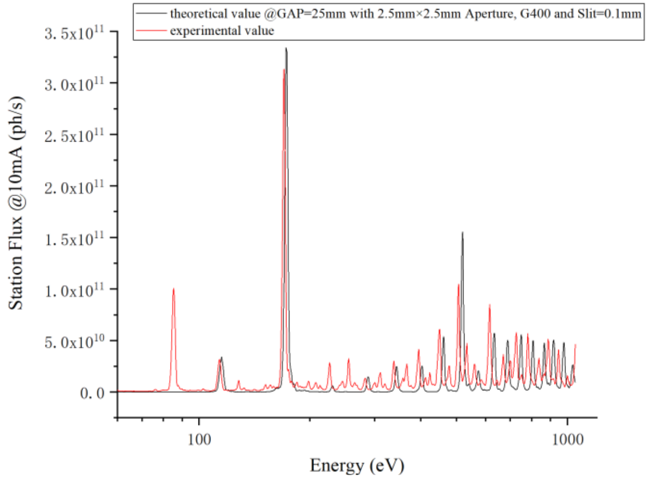


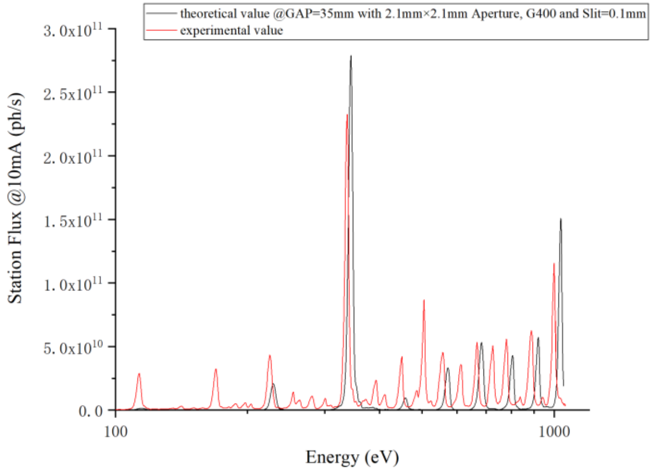


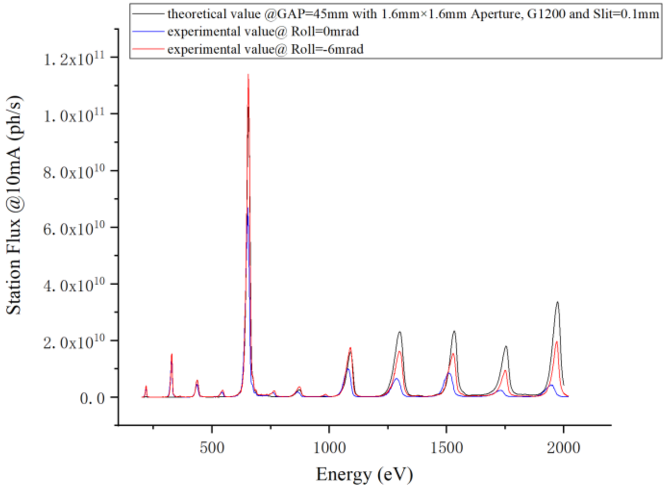
On-line performance

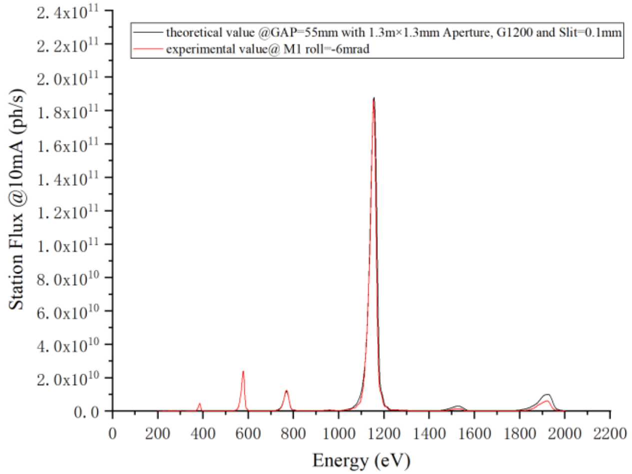
- The flux spectrum were measured at various gaps: 15, 25, 35, 45, 55, 65 mm
- The measurement agrees with the theoretical expectation well

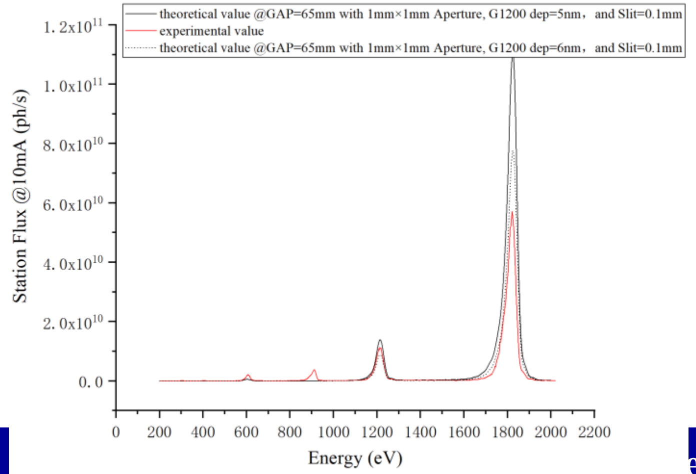








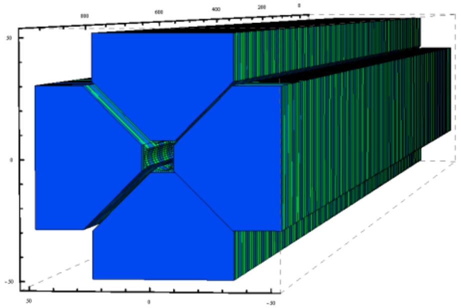


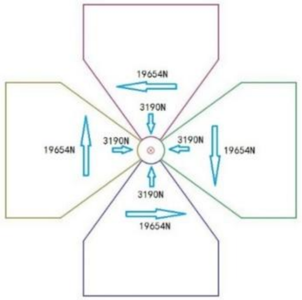


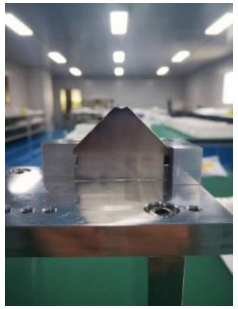
“MANGO” Wiggler

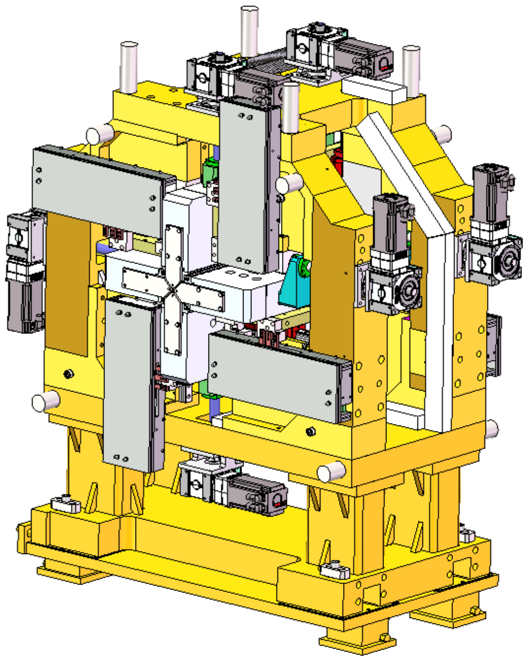
- The appellation ‘Mango wiggler’ derives from the distinctive mango-shaped contour of its radiation field.
- Delta-type ID, with slight difference in λu between the vertical/horizontal field
- The large angular divergence of radiation especially in vertical direction has special advantages for Large - field X-ray phase contrast imaging (XPCI).

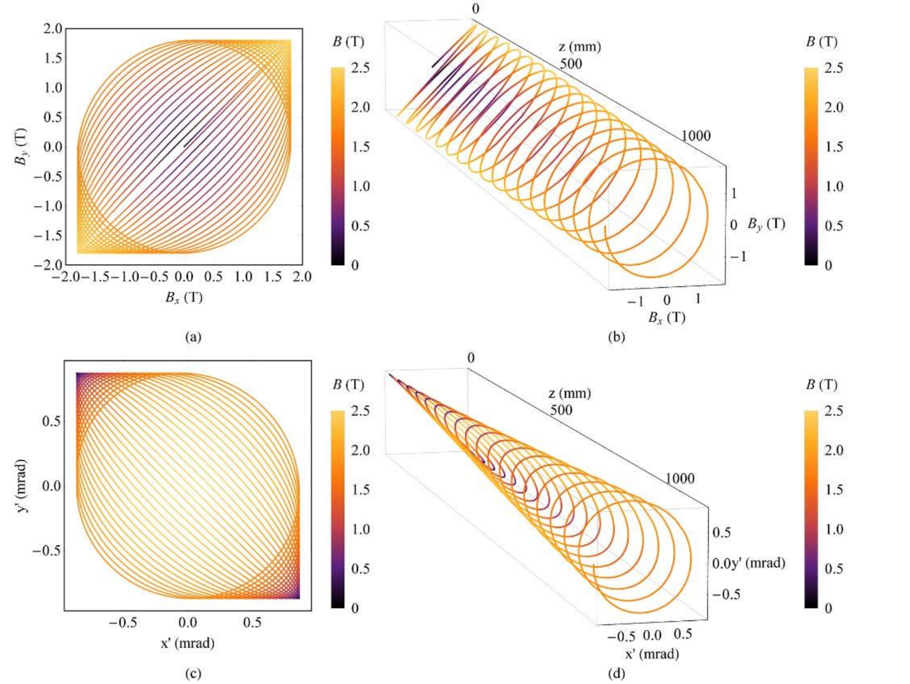
Design Parameters of Mango Wiggler	
Period Length $\lambda x/\lambda y$ [mm]	50.70/50.00
No. of Periods Nx/Ny	17.75/18
Peak Field B_{0x}/B_{0y} [T]	0.2-1.0







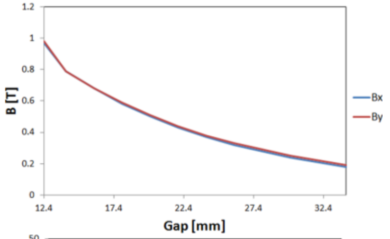


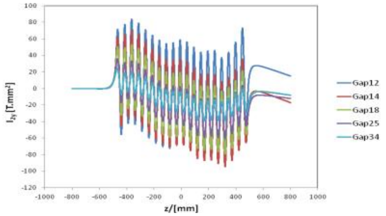


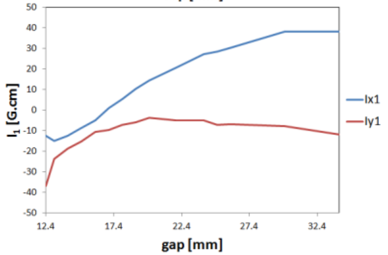
Magnetic field and angular trajectory of electrons in the Mango wiggler

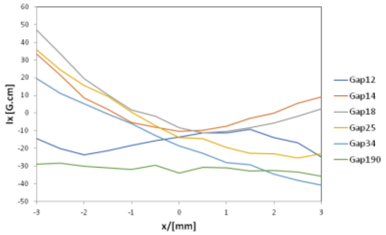
Wiggler tuning and expected performance

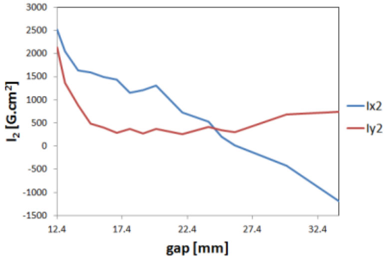
- Magnetic performance tuning is through magnet height adjustment, shimming and magic finger

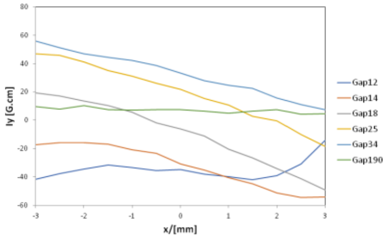


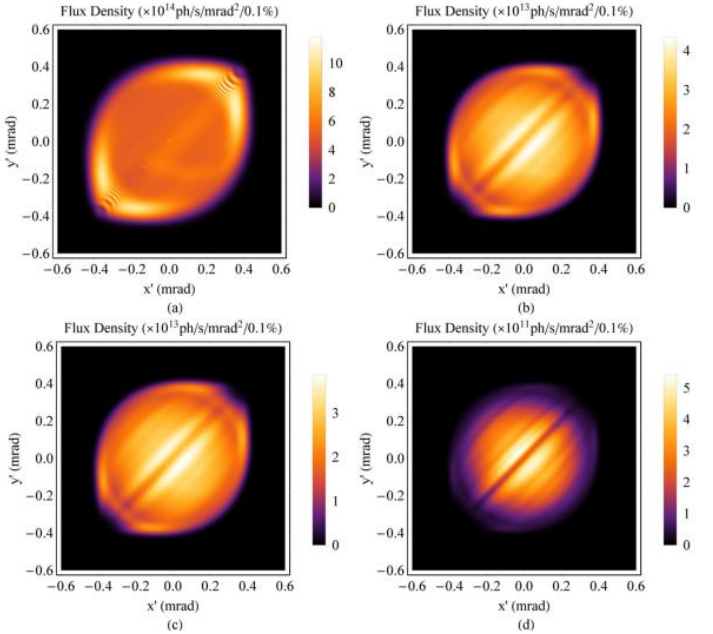




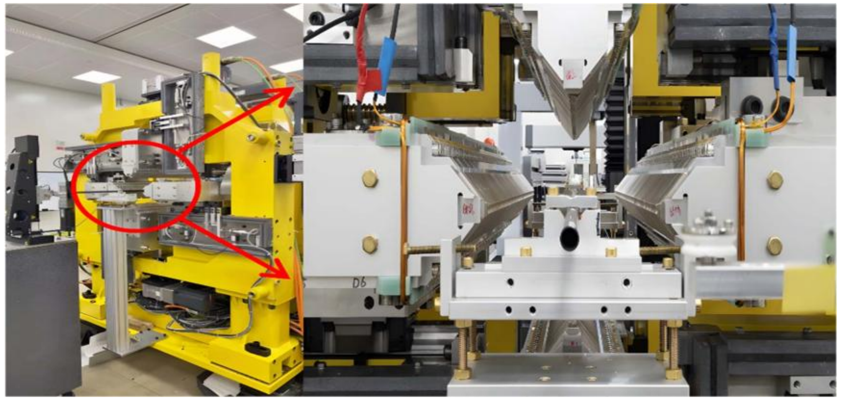






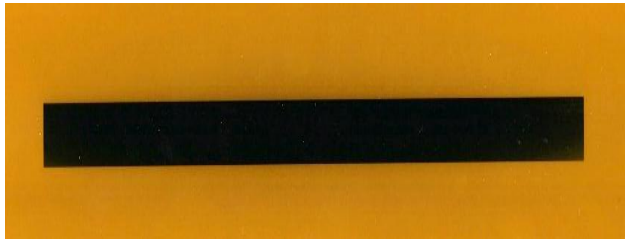


Angular distribution of the flux density for the HEPS Mango wiggler, simulated based on data measured at the smallest gap (12.1 mm). (*a*) SR energy at 48.8 keV. (*b*) SR energy at 147 keV. (*c*) SR energy at 151 keV. (*d*) SR energy at 300 keV.

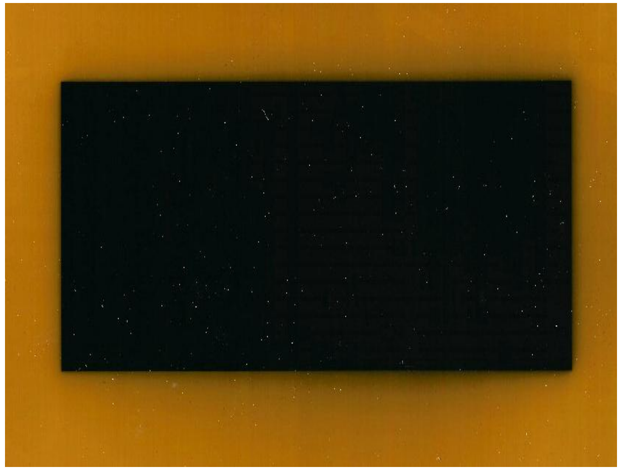


On line performance

- The mango wiggler successfully works at HEPS, providing the largest SR image in the world



Traditional IAW @ HEPS, the radiation beam size： 189mmx13mm



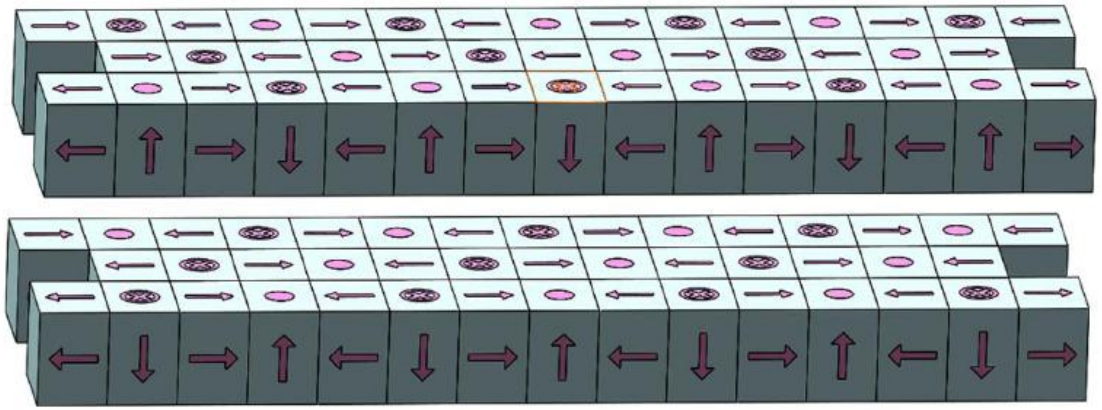
Mango wiggler @ HEPS, the radiation beam size：
189mmx73mm (full size > 270x270mm)

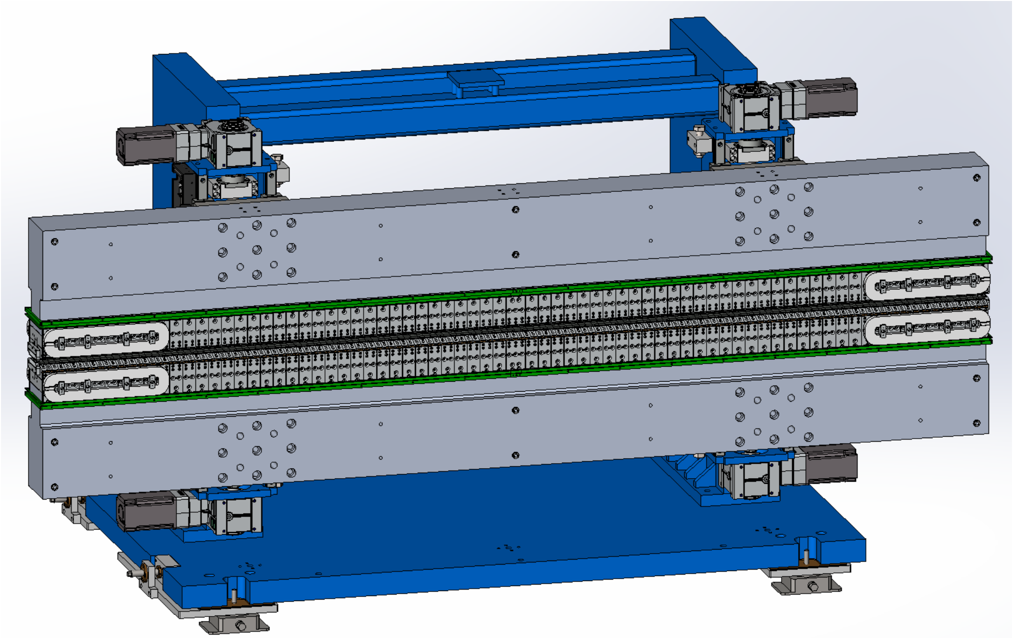
CONTENT

1. ID development for HEPS
2. Domestic collaborative undulator development
3. Superconducting insertion devices
4. International cooperation
5. Summary

Circular undulator for HALF

- The helical undulator has been developed for the Hefei Advanced Light Facility (HALF), covering the photon energy range of 5–20 eV.
- Allows fast scanning over a large photon energy range with sustained high circular polarization.

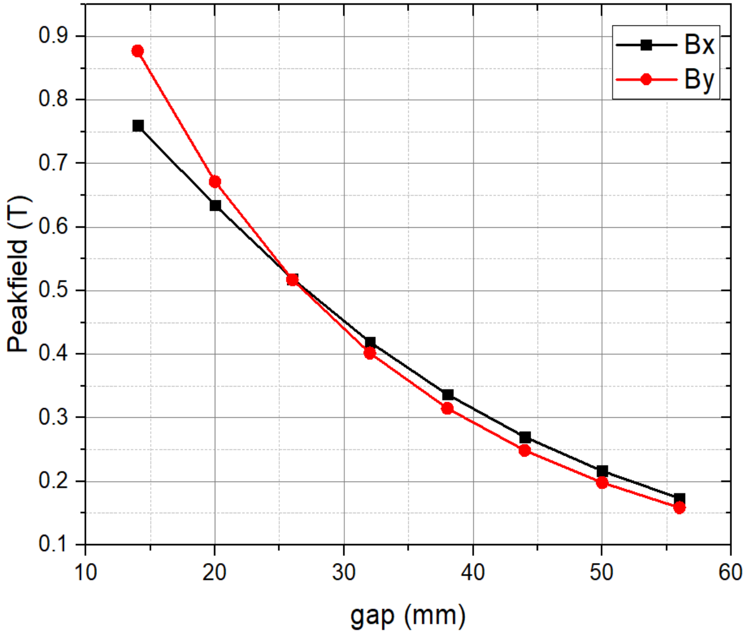


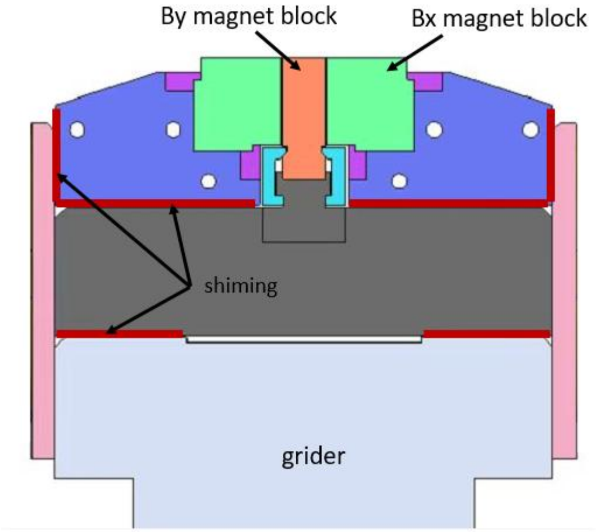


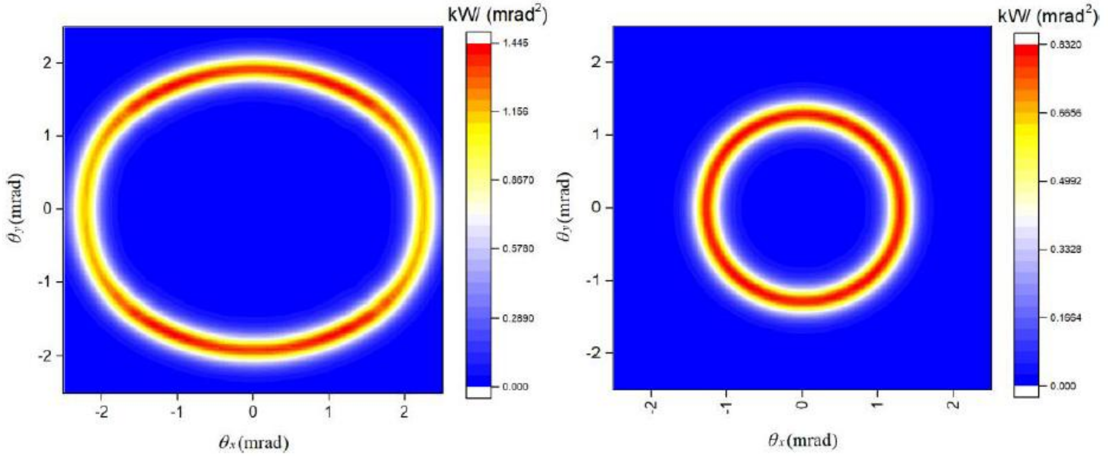
- ✓ **Central magnet array generates By**
- ✓ **Side magnet arrays generate Bx**

Design challenges

- The design optimizes the balance between the horizontal and vertical fields across the entire operating gap range, ensuring high circular polarization
- The central magnet blocks are slender and require complex clamping structure.







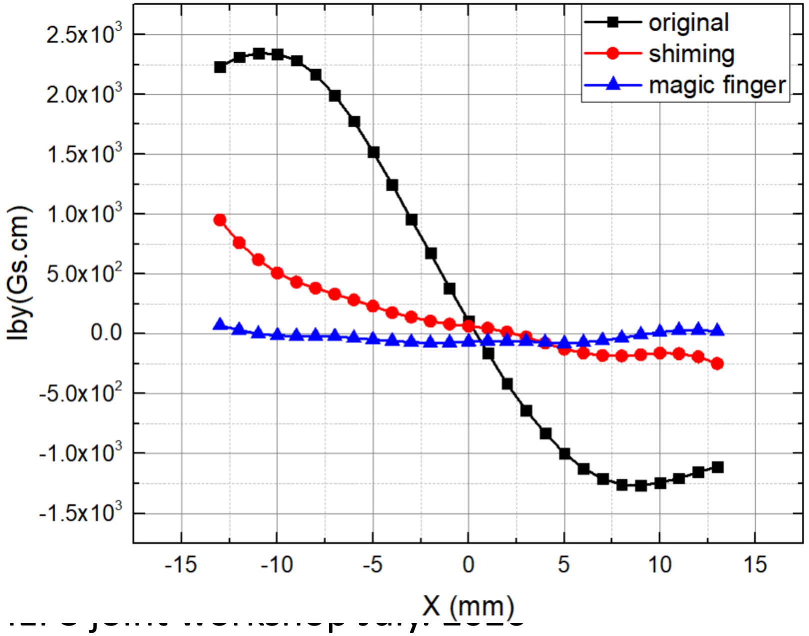
Angular distribution of power density

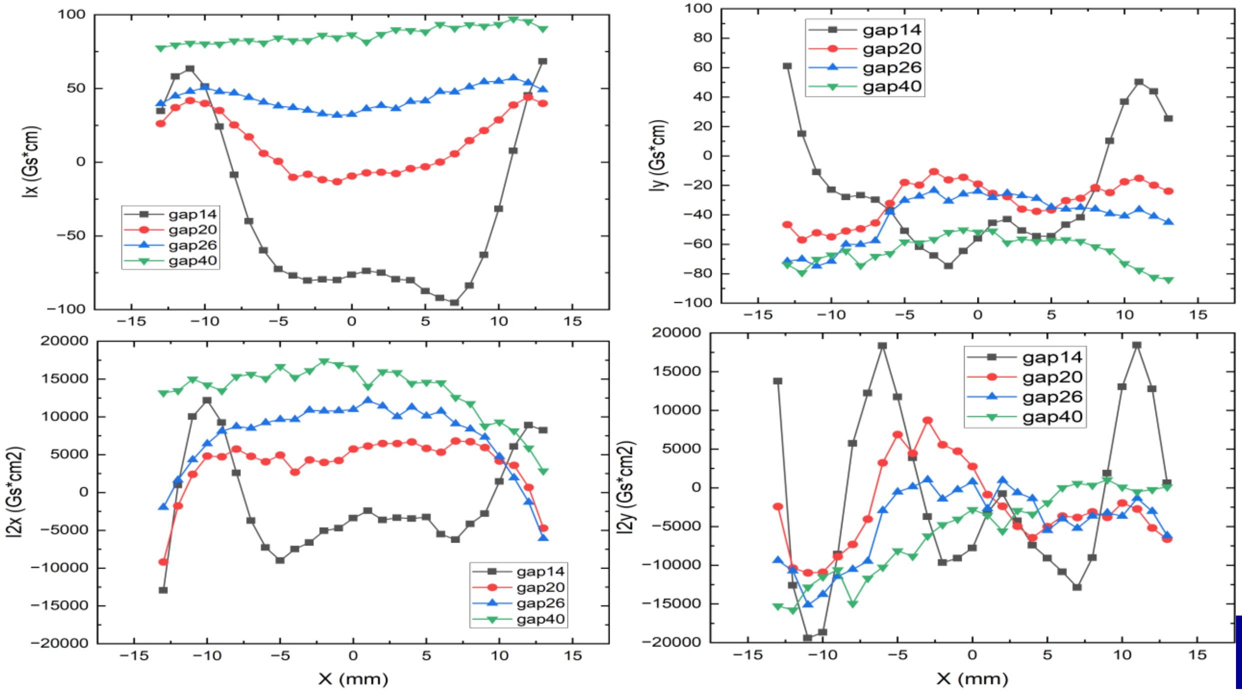
@gap=14mm,gap=20mm

Tuning and final status measurement

- Multipole field tuning: combined shims + end coils + magnet block height.
- Great endeavors paid for the field roll-off, due to the small magnet wideness of 18.6 mm and stringent requirement to the 1st & 2nd field integral across a wide transverse range of ±13 mm.

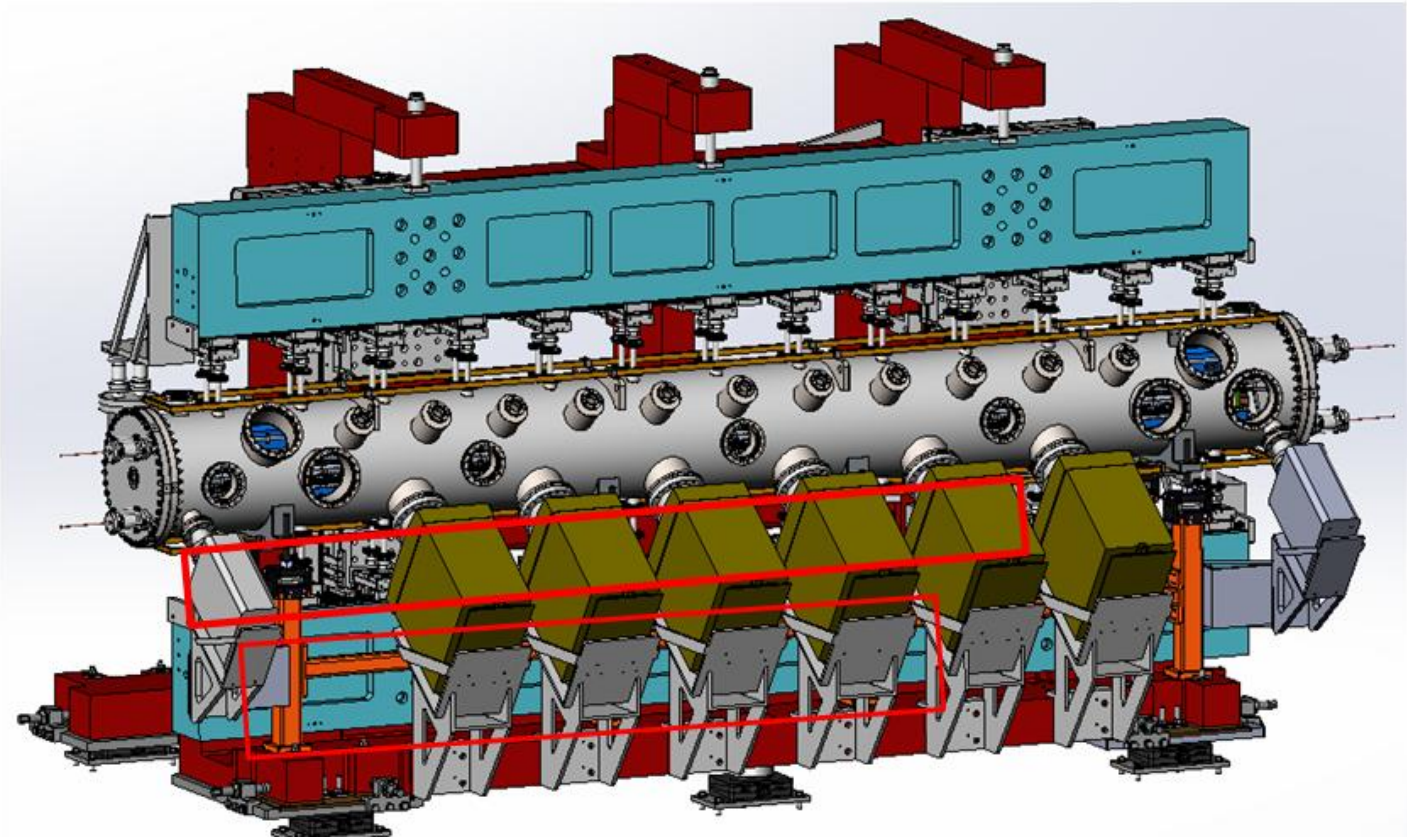
period(mm)	Length(m)	Gap(mm)	Min. Phase Error RMS(°)	Variation of the first /second integral(x, y) @ X = [-13, +13] mm
115	4.2	14-40	10°	±100Gs.cm/±20000Gs.cm2

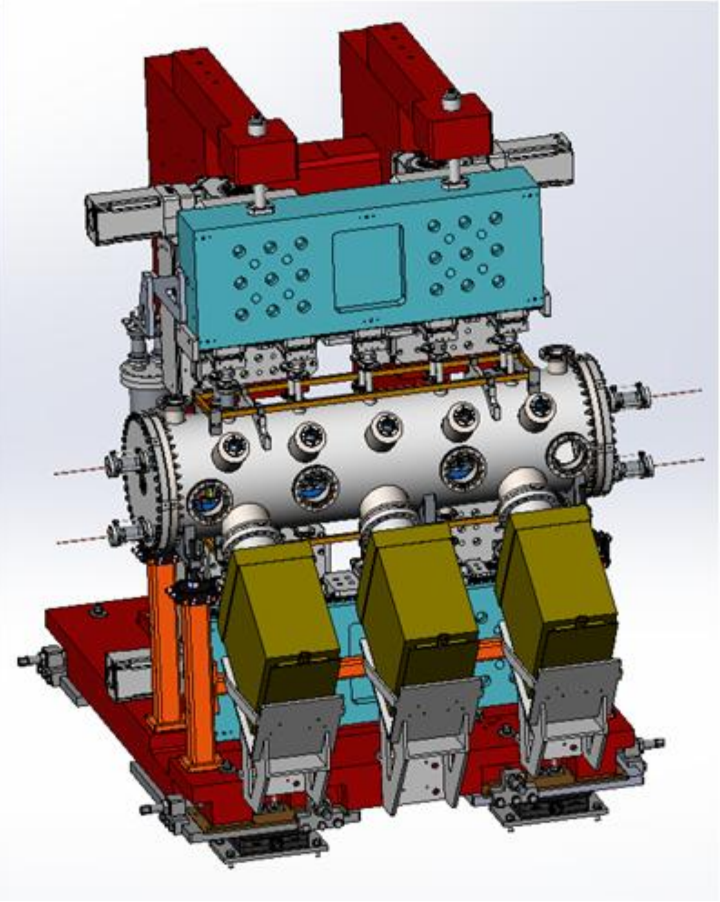




In-vacuum undulators

- IVU21a 4.2m, IVU21b 1.5m



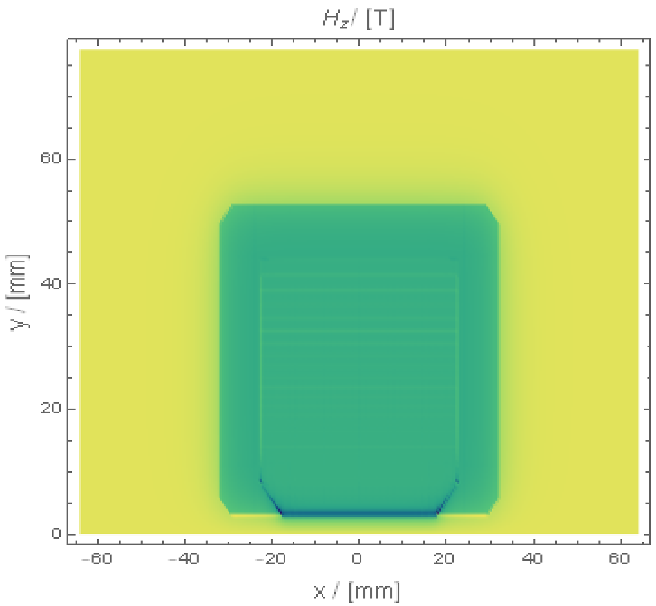


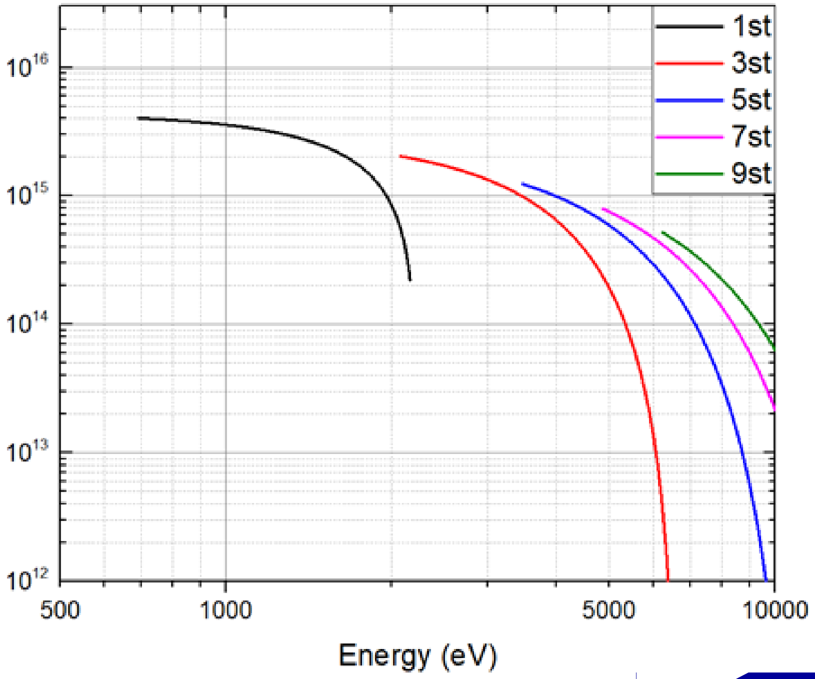
Specification and challenges

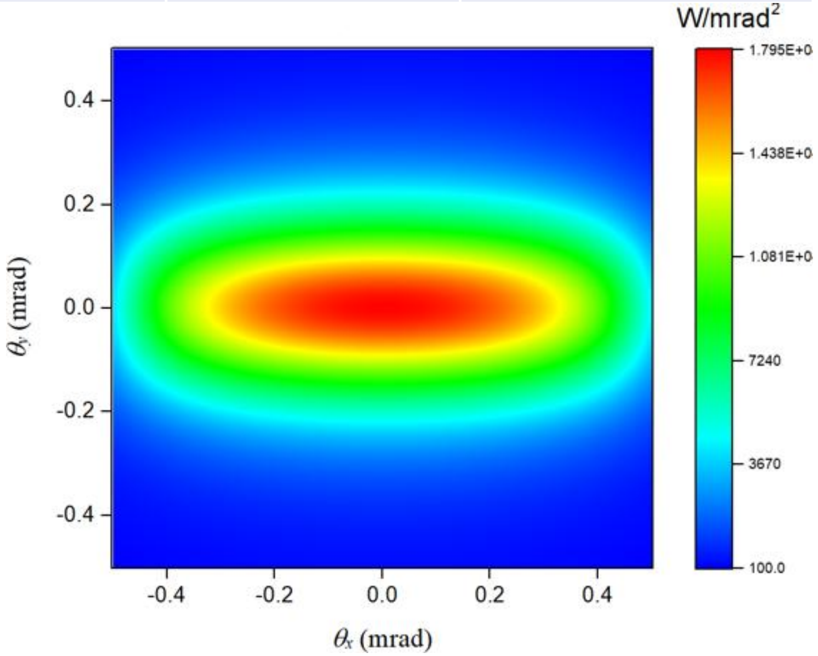
- Design challenges: requirement for strong field and wide good field range
- Wide magnet blocks with small thickness introduce strong demagnetization risk.

Pole： 51*41*3.35mm   magnet block： 64*50*7mm

	IVU21a	IVU21b
period（mm）	20.7	20.7
Gap（mm）	6~20	6~20
Keff	2.08	2.08
Number of periods	**182**	**52**
Total length（m）	**4.2**	**1.5**
photon energy range(ev)	**2100~9000**	**700~10000**





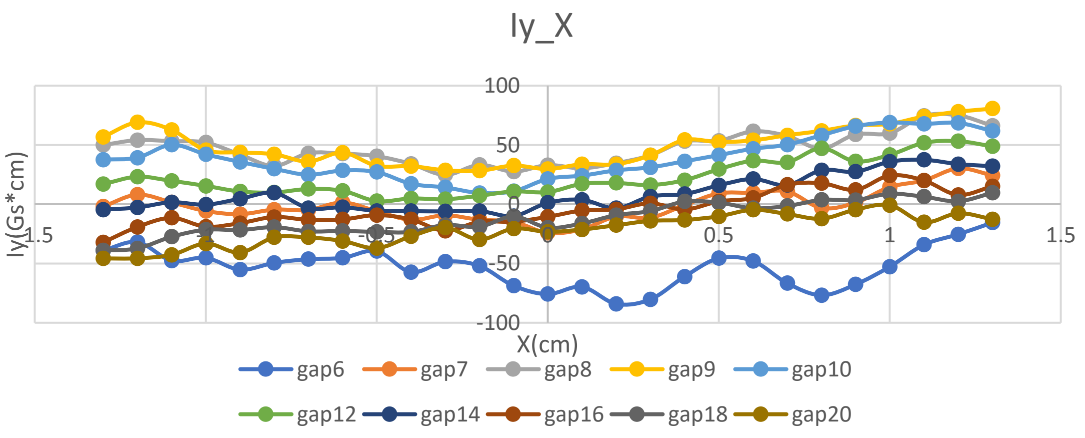


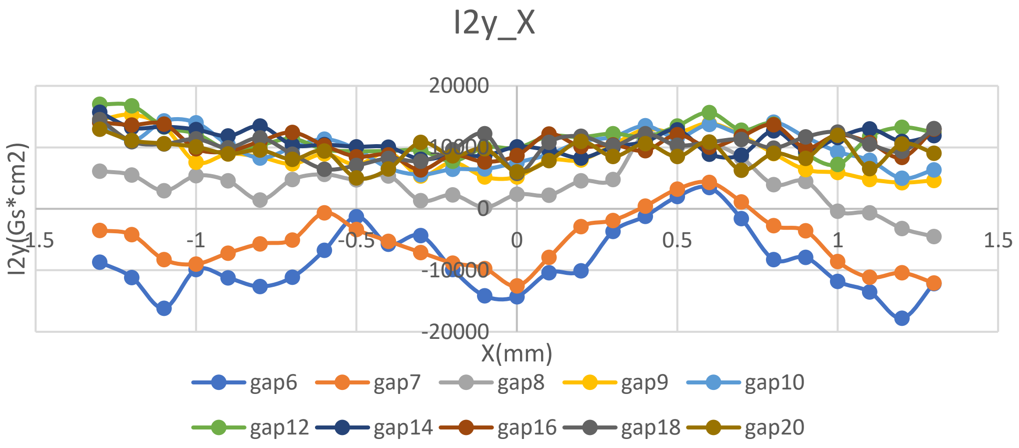
Angular distribution of power density(IVU21a)

Tuning and final status measurement

- First & second field integrals span ±13 mm along X direction.
- Both undulators have finished out-vacuum and in-vacuum magnetic field measurement, with vacuum baking in progress.

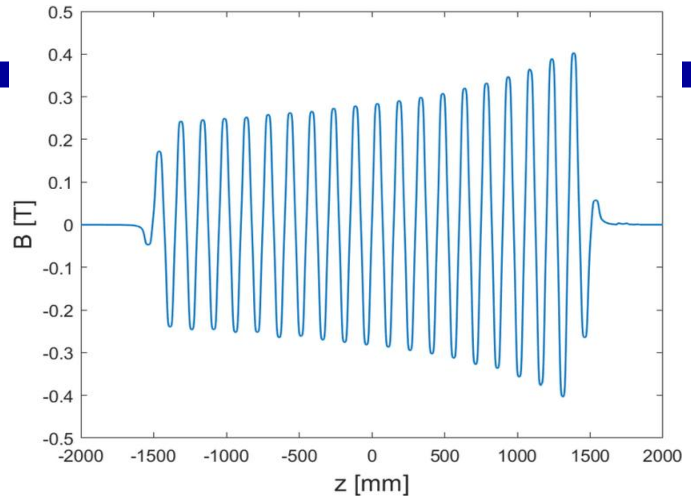
period(mm)	Min. Phase Error RMS(°)	Variation of the first /second integral(y) @ X = [-13, +13] mm
IVU21a	≤3.5° (gap: 6~9mm) ; ≤5° (gap: 9~20mm)	±100Gs.cm/±20000Gs.cm2
IVU21b	≤3° (gap: 6~9mm) ; ≤4° (gap: 9~20mm)	



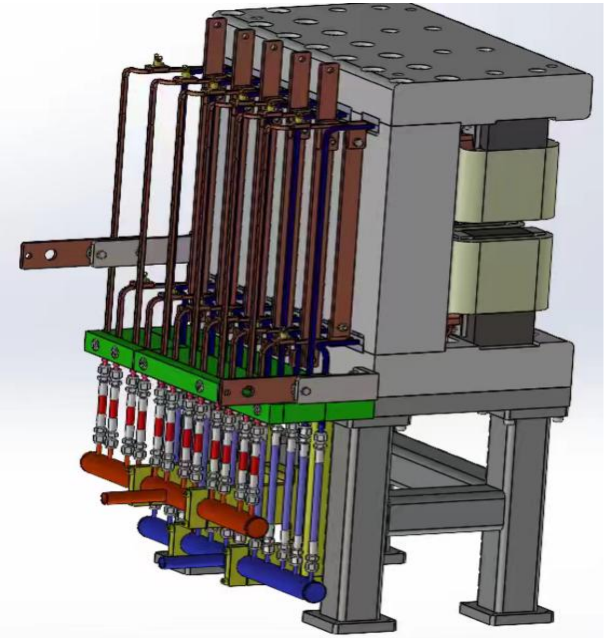


EM taper undulator

- Electromagnetic taper undulator, no previous experience anywhere.
- Two operation modes: uniform field mode & taper mode.
- Control complexity: current & magnetic field calibration, standardized cycle process; nearly 50 power supply units
- 3-period prototype development underway



Period	150±0.04mm
Gap	⩾20mm
Number of periods	19
Keff	3~6.3
First integral of the magnetic field @ working gap （with corrector coils）	-100~100Gs.cm
2nd integral @ working gap （with corrector coils）	-2000~2000Gs.cm2
Electron beam trajectory straightness	＜50μm@60Mev
Mode 1: Uniform field mode	Uniform K value for every period
Mode 2: Taper field mode	3.6154、3.7111、3.7111、…、5.3706、5.6256、6.0749

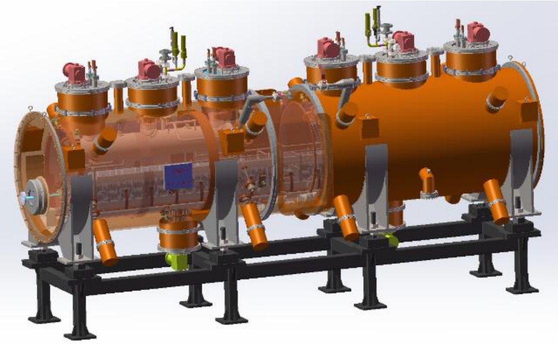


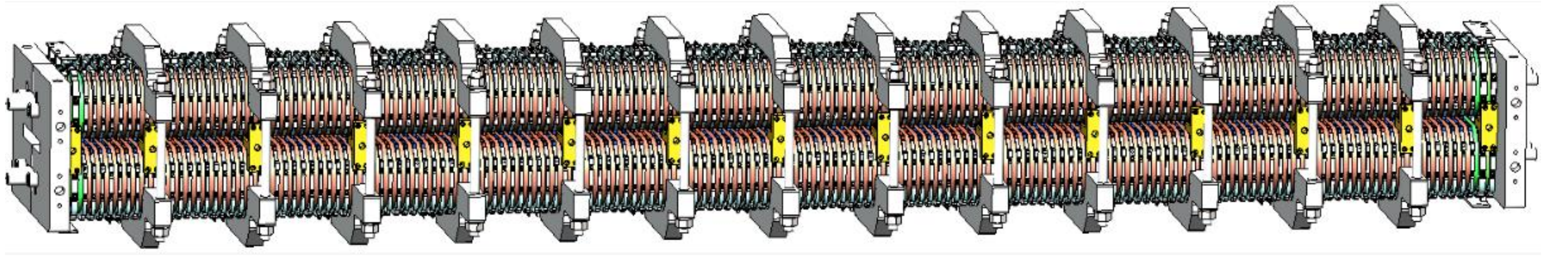
CONTENT

Motivation and Specifications

- Different scaling law to the permanent devices, allowing stronger field especially to a long period device.
- SCU19 : 1.5 m+1.5m total length for FEL prototype.
- Comprehensive tuning measures: positioning blocks, end correction coils, gap control, local field tuning
- Target: Phase error ≤ 5° @ 1.07 T Capable of online operation.

	Specification
Period(mm)	19
gap	≥8.3mm
Peak field	1.07T





The on-axis field:

B_0 $n \to 1$

Electric UND:

$$B_y = \sum_{n=1,3,5,..} \frac{2\mu_0}{n^2\pi^2} j\lambda_u \sin\left(\frac{nk_u a}{2}\right) e^{-\frac{nk_u g}{2}} \left(1-e^{-nk_u b}\right) \sin(nk_u z)$$

Permanent UND:

$$B_y = \sum_{n=1,3,5,..} -\frac{8M\mu_0}{n\pi} \sin\left(\frac{nk_u a}{2}\right) e^{-\frac{nk_u g}{2}} \left(1-e^{-nk_u b}\right) \sin(nk_u z)$$

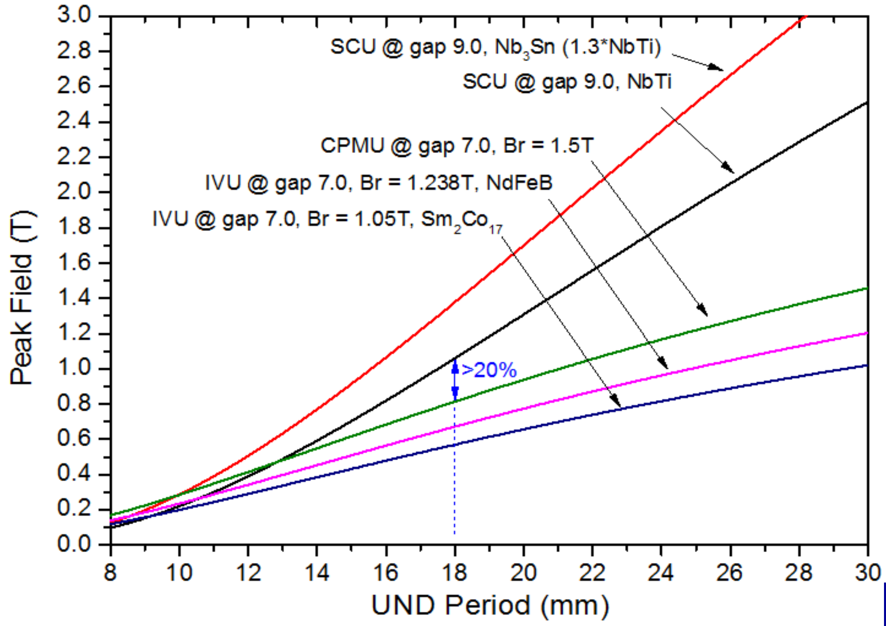
Scaling law:

- Electric UND: The field is propotional to the product of $j\lambda_u$

  ⇨ Voilation of the geometry scaling law, difficult for small size magnet

- PPM UND: The field is propotional to the magnetization M

  ⇨ Fullfil the geometry scaling law, good for small size magnet



Key technology R&D

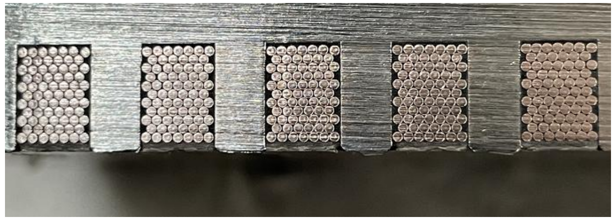
- Goal： develop a SCU with merit of practical utility (low phase /field integral error, sufficient length, …,)
  - ➢ unlike PPMU, it is difficult to SCU to correct field error after fabrication
- Measures： small modules and try errors for fast technology iteration

Research for an appropriate coil frame
Insulation, coil reversing, pole fixing, surface polishing, …

Develop helium free cryo-plateform

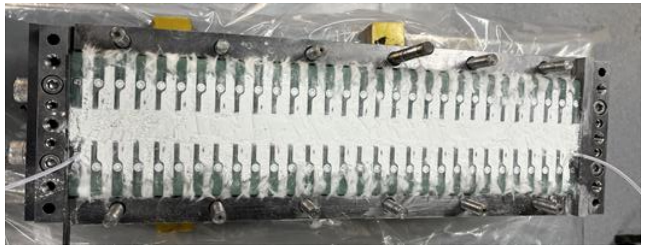
Module test with low cost； …

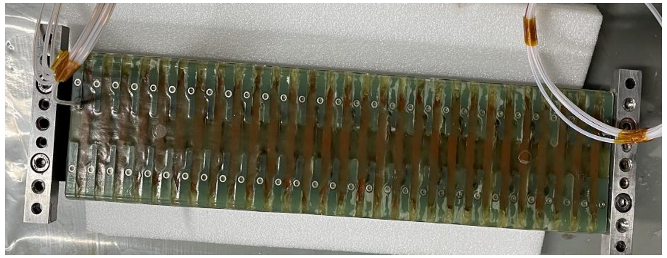
Winding machine, for key parameters
Proper tension, position control； …



Epoxy impregnation, glass fiber filling

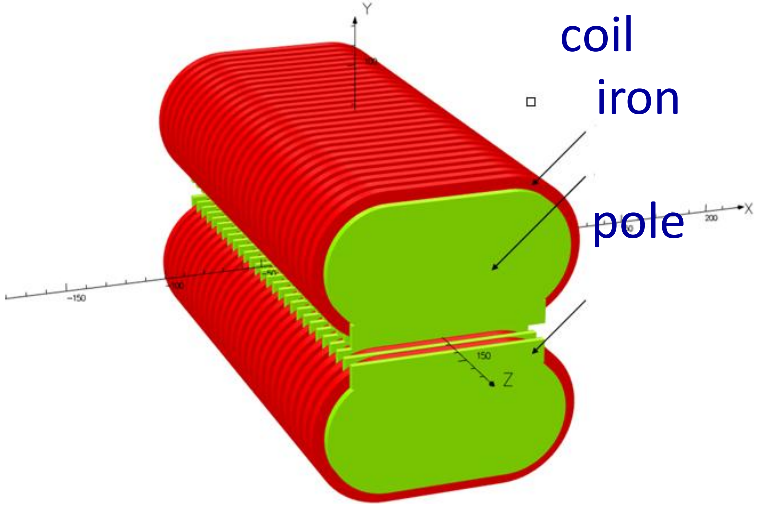
reduce the epoxy cracks…

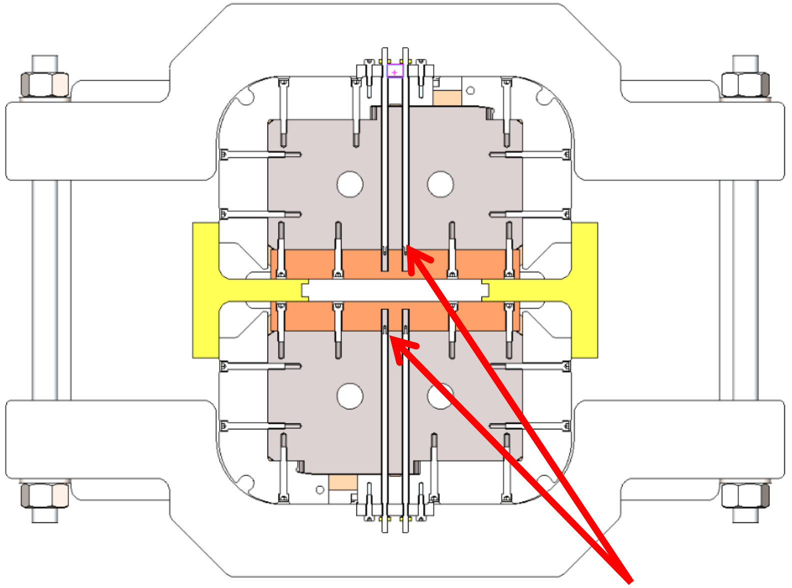


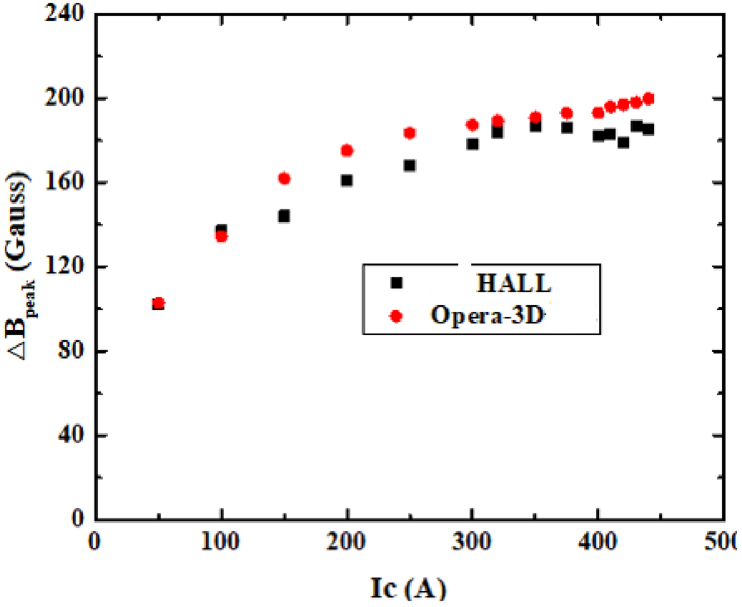


Tuning and measurement

- Peak field reaches 1.26 T @ 400A with 81% load line
- Magnetized columns installed between adjacent poles for localized field error correction
- Results: Correction posts deliver the same effect as 0.1 mm pole tuning on conventional undulators.
- Outlook: Initial results indicate that the phase error is expected smaller than 5 degrees





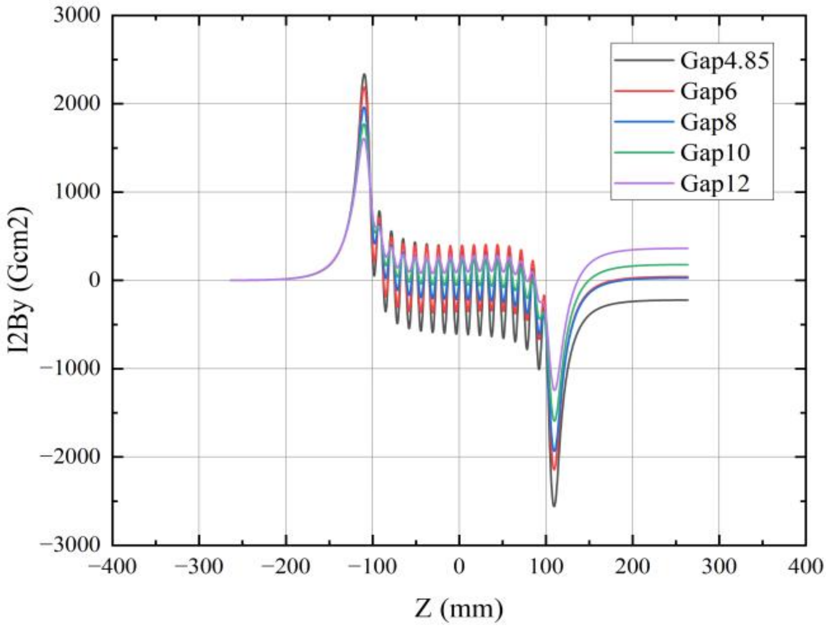


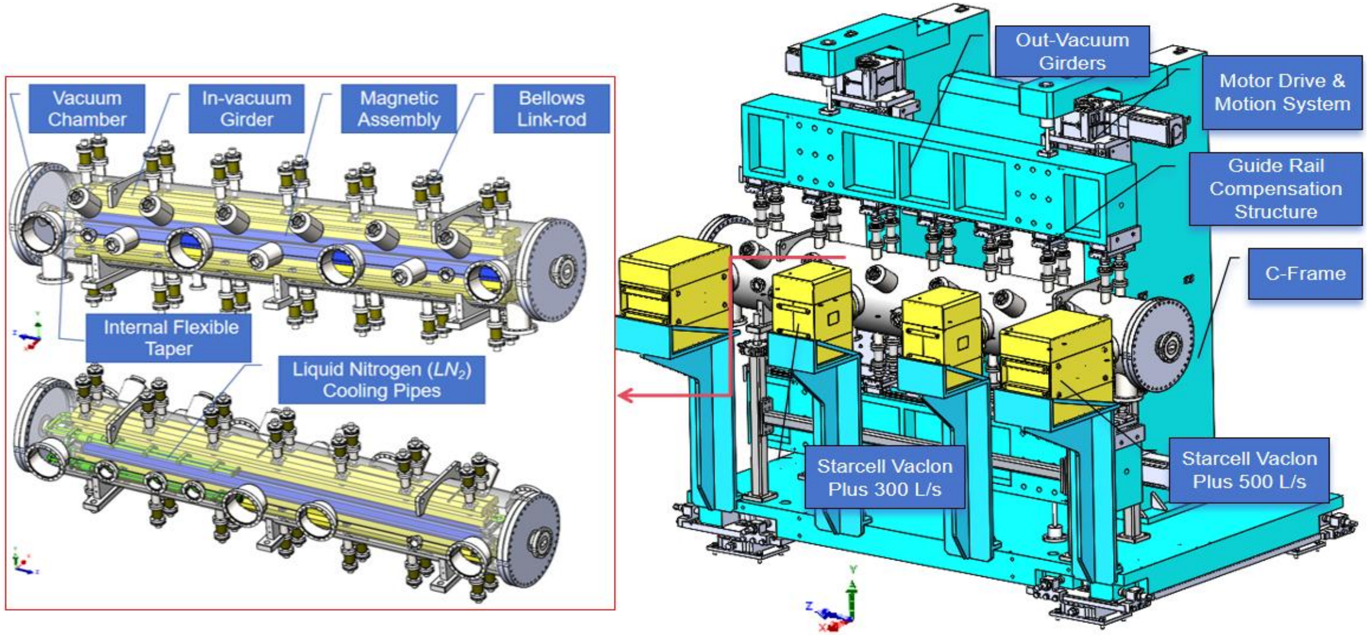
CONTENT

CPMU for SIRIUS

- 4 CPMUs developed for SIRIUS
- Short period, high K value
- Small-gap magnetic measurement (minimum magnetic gap:3.8/4.85mm)

	CPMU13.6	CPMU14.2	CPMU15.3	CPMU15.8
Period	13.6	14.2	15.3	15.8
Number of full periods	147	141	131	127
Br	≥1.68T（70K）			
nominal VCA	4.65	3.6	3.6	3.6
Keff@nominal VCA (acceptance value)	1.28@4.65/4.45	1.80@3.6/3.4	2.04@3.6/3.4	2.18@3.6/3.4





Summary

- The ID team has developed a broad range of advanced insertion devices, successfully addressing numerous technical challenges along the way.
- Comprehensive expertise: theory, simulation, engineering, controls, vacuum technology, cryogenics, and precision metrology.
- Strong industry partnerships: close collaboration with suppliers of magnets, poles, control components, and mechanical fabrication workshops.
- Advanced platforms: temperature-stable laboratories with ample floor space, alongside multiple measurement benches capable of characterizing both superconducting and permanent-magnet devices (in both air and vacuum environments).

Thank you for your attention