Recent R&D Progresses of High-Temperature Superconducting Undulators at Zhangjiang Laboratory

Kai Zhang, on behalf of the HTSU program

Zhangjiang Laboratory, Shanghai

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Acknowledgment

ZJLAB： W. Li

SINAP, CAS ： D. Wei，Z. Chen，Y. Tong

SARI, CAS ： C. Liu，B. Liu，H. Deng，Z. Zhao

Shanghai Uni.： D. Zhou，C. Cai

Xi’an Juneng： C. Li，W. Zhang，H. Zhang

PSI ： M. Calvi，A. Arsenault

Uni. Cambridge： A. Dennis，J. Durrell

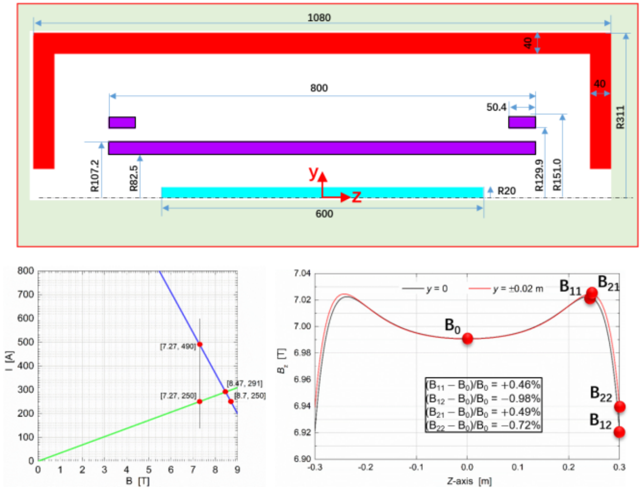
King’s College London： M. Ainslie

CRISMAT： J. Noudem, Y. Xing, P. Bernstein

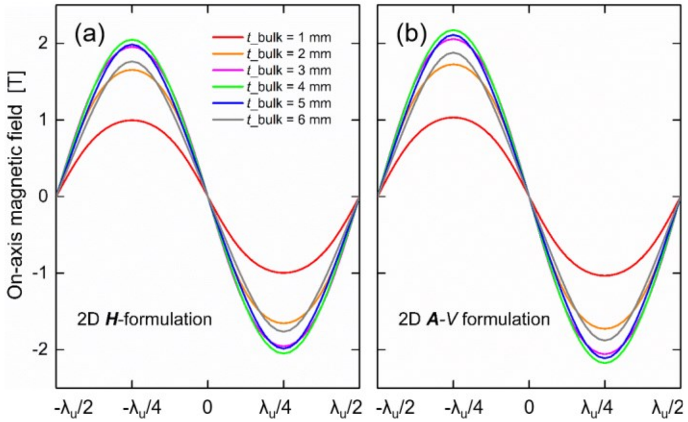
Outline

- **HTSU12: a 50-period Bulk High-Tc Superconducting Undulator**
  - Magnetic and Mechanical Design Considerations
  - Fabrication and Characterization of REBCO Bulk Units
  - Undulator Assembly and System Integration
  - Magnetic Field Measurement Methodology
  - Cryogenic Cooling and Temperature Regulation
  - Magnetic Field Characterization and Performance Optimization
- **Short-Sample Demonstration Program**
  - MgB_2 Bulk Planar Configuration
  - REBCO Tape-stack and REBCO Coil-based Helical Configuration
  - New Geometry REBCO Bulk Planar Configuration
- **Conclusion**

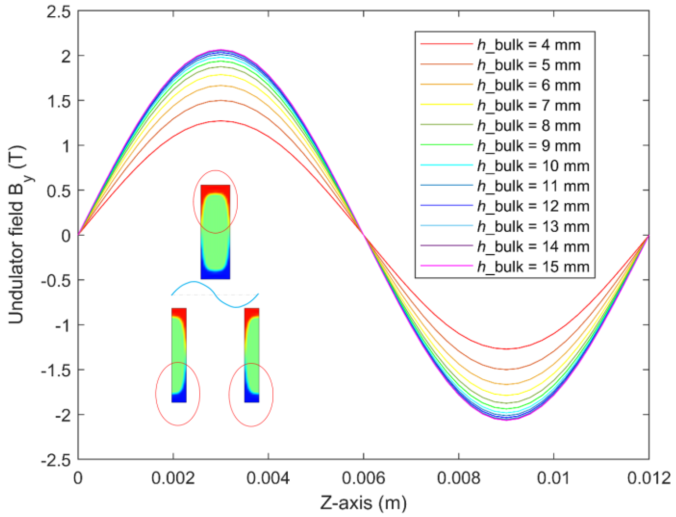
Magnetic Design Considerations of HTSU12



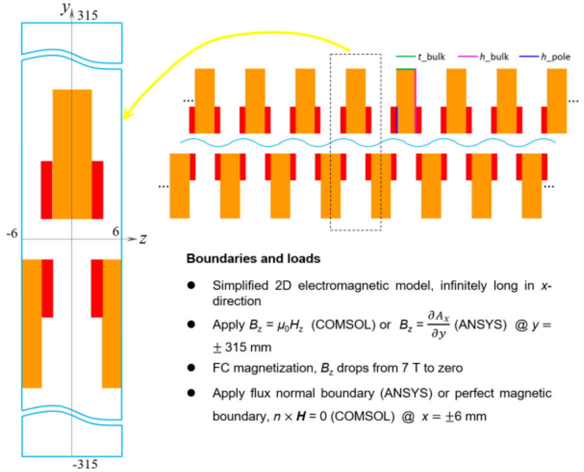
Optimal design of a 7 T solenoid magnet



Comparison of the undulator field for BHTSU with various bulk thickness

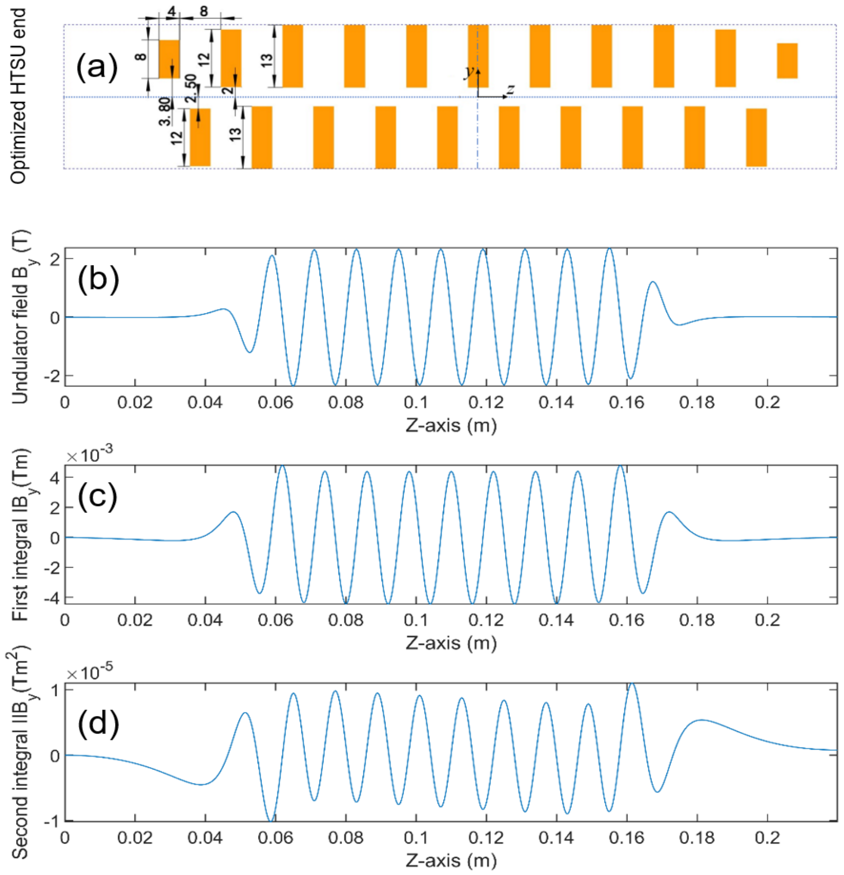


Influence of the height of the ReBCO bulk on the on-axis magnetic field By



2D periodical FEA model of the bulk HTS undulator

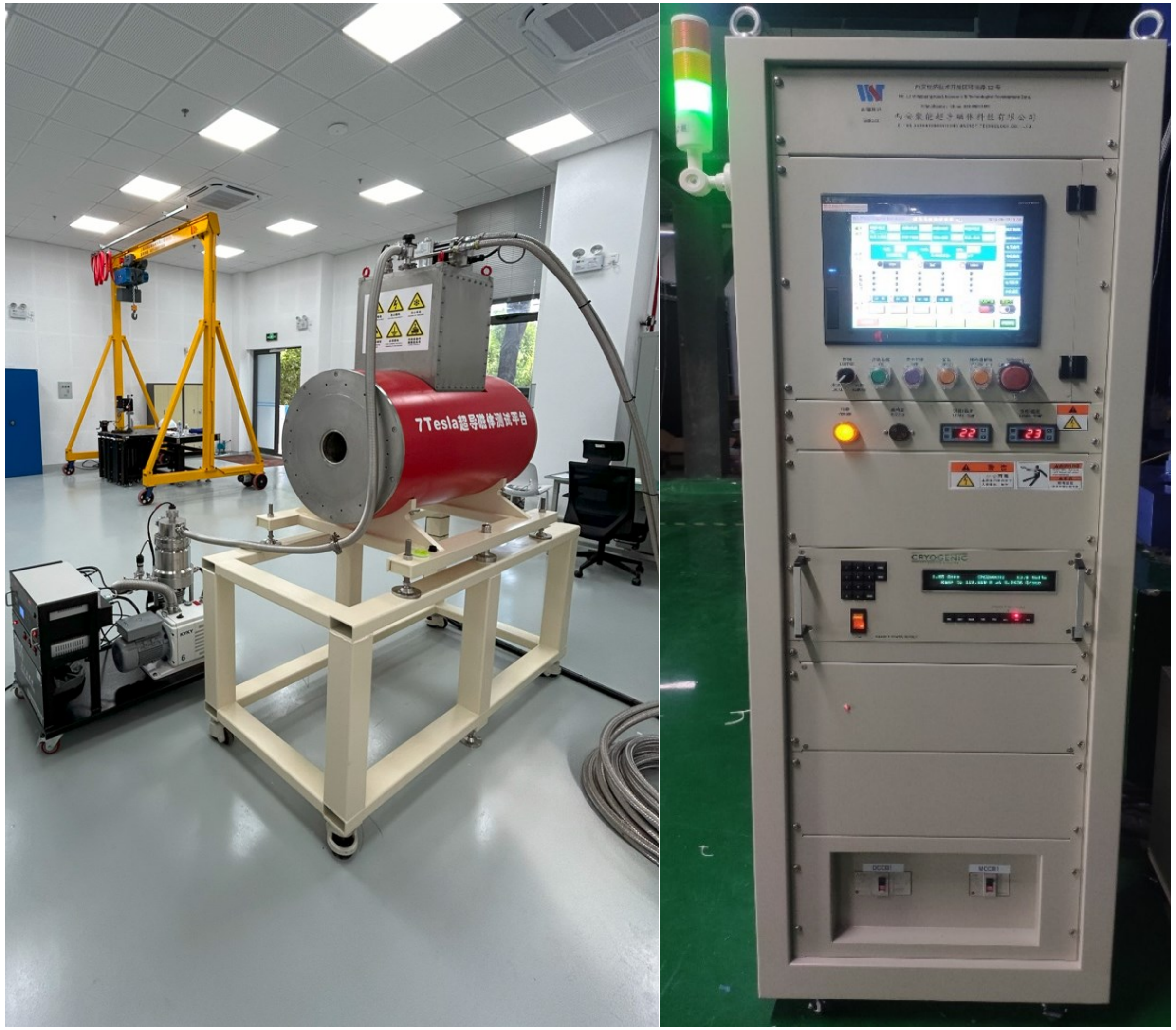
λu = 12 mm, g = 4.5 mm, B_0 > 1.8T



(a) Optimal design of the end of the bulk HTSU; (b) On-axis magnetic field By(z), (c) first field integral IBy(z) and (d) second field integral IIBy(z).

D. B. Wei et al,IEEE Trans. Appl. Supercond., vol. 34, no. 5, pp. 4100705, 2024

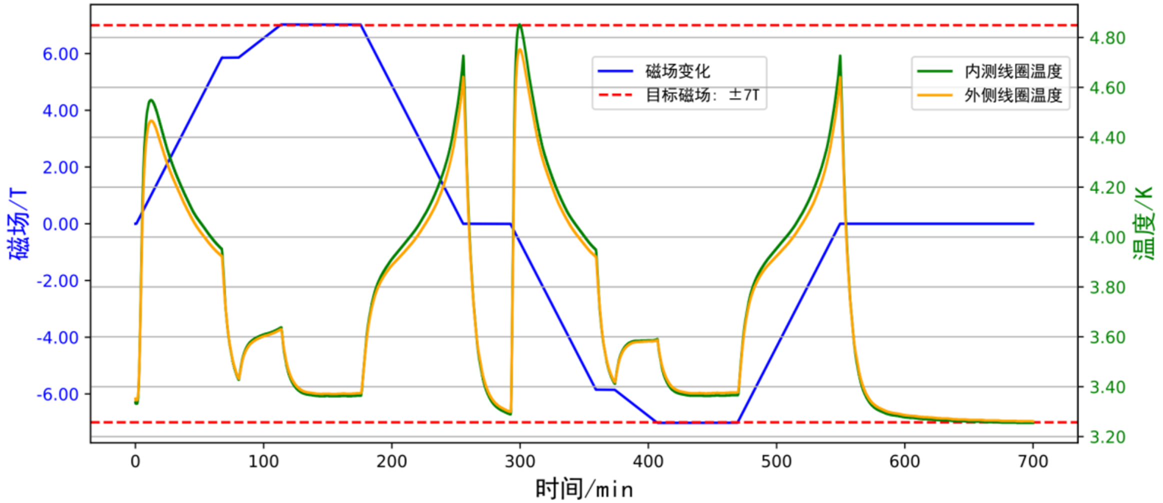
Development of a 7 T Superconducting Solenoid



On-site test of the 7 T solenoid

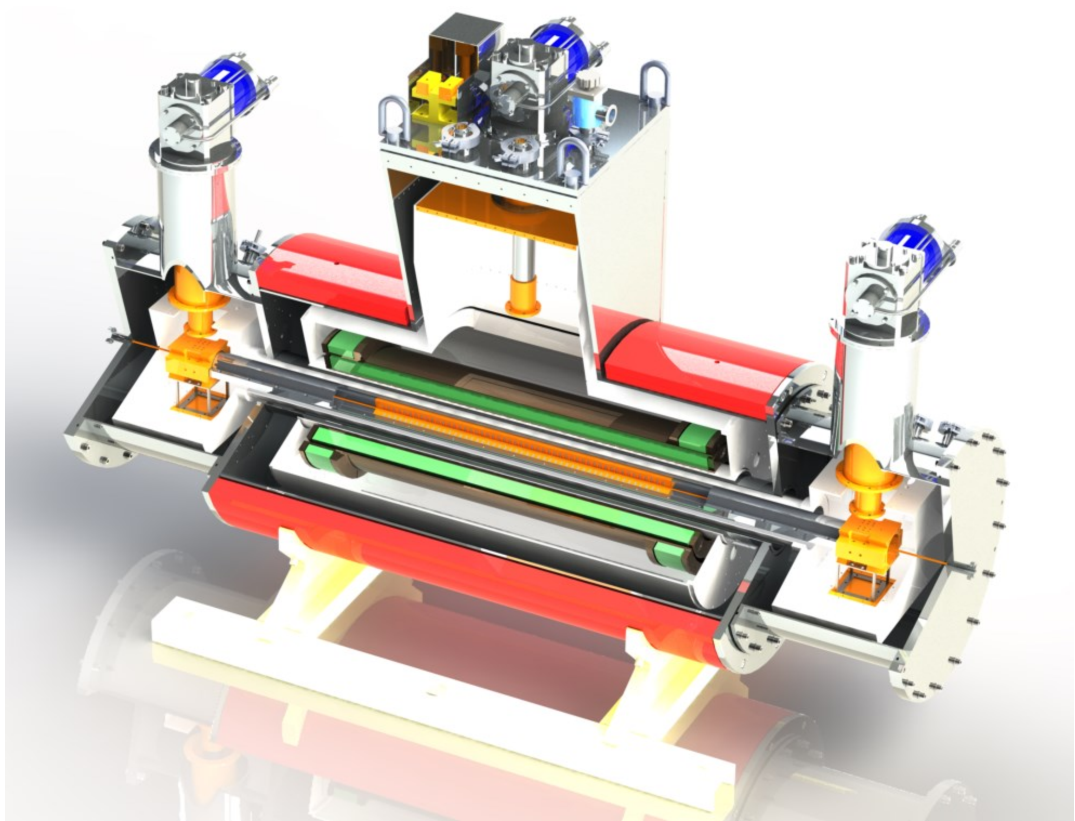
Testing of the 7 T Superconducting Solenoid Magnet

No.	Main Parameter	Required	Achieved	Acceptance
1	Central field	7T	7T	合格
2	Cooling Method	Conduction cooled	Conduction cooled	合格
3	Yoke Thickness	≤40mm	40mm	合格
4	Uniform region	Φ40*600mm	Φ40*600mm	合格
5	Field inhomogeneity	< 1%	1.38%	确认接受
6	Warm bore	> 116mm	120mm	合格
7	Power supply	Bipolar	Bipolar	合格

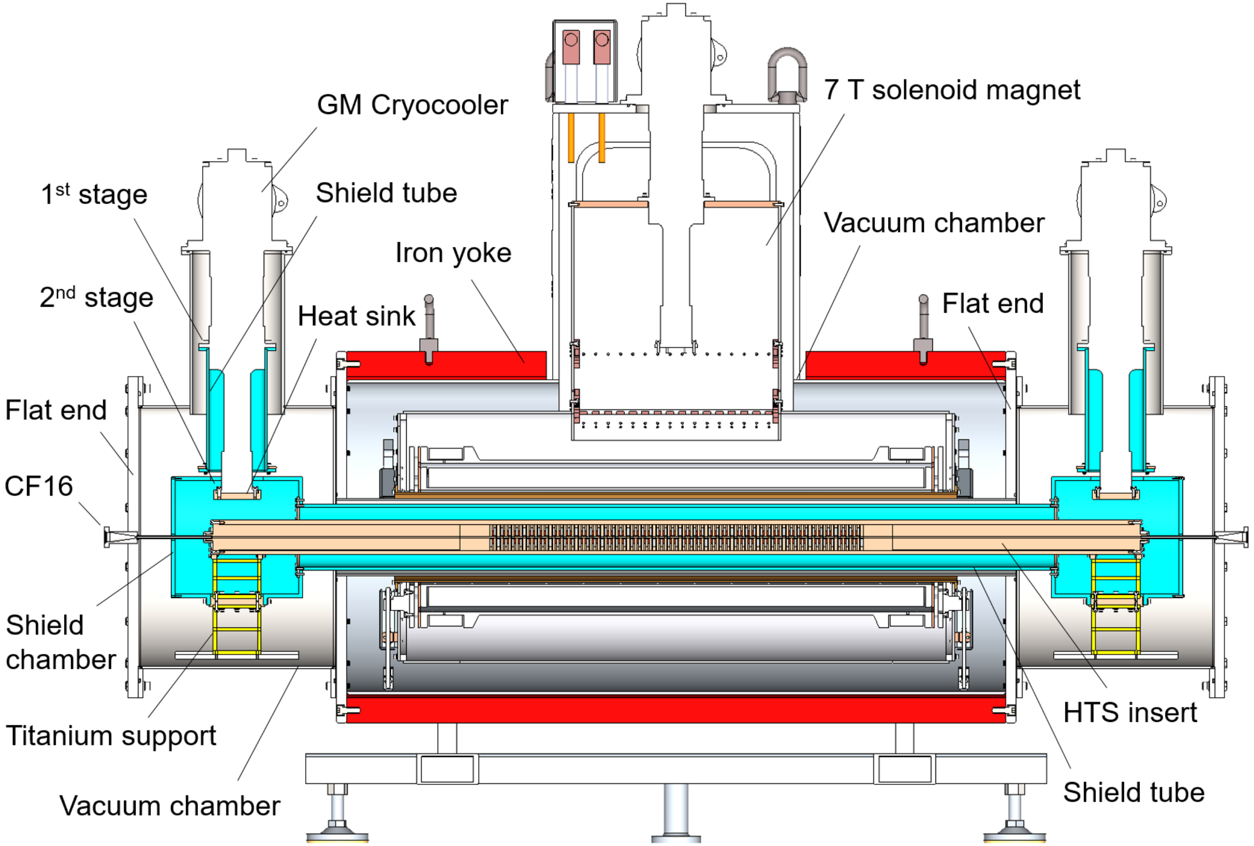


Current ramp, stability retention, and bipolarity verification

Mechanical Design Considerations of HTSU12



Cut-view of HTSU12



Mid-section view of HTSU12

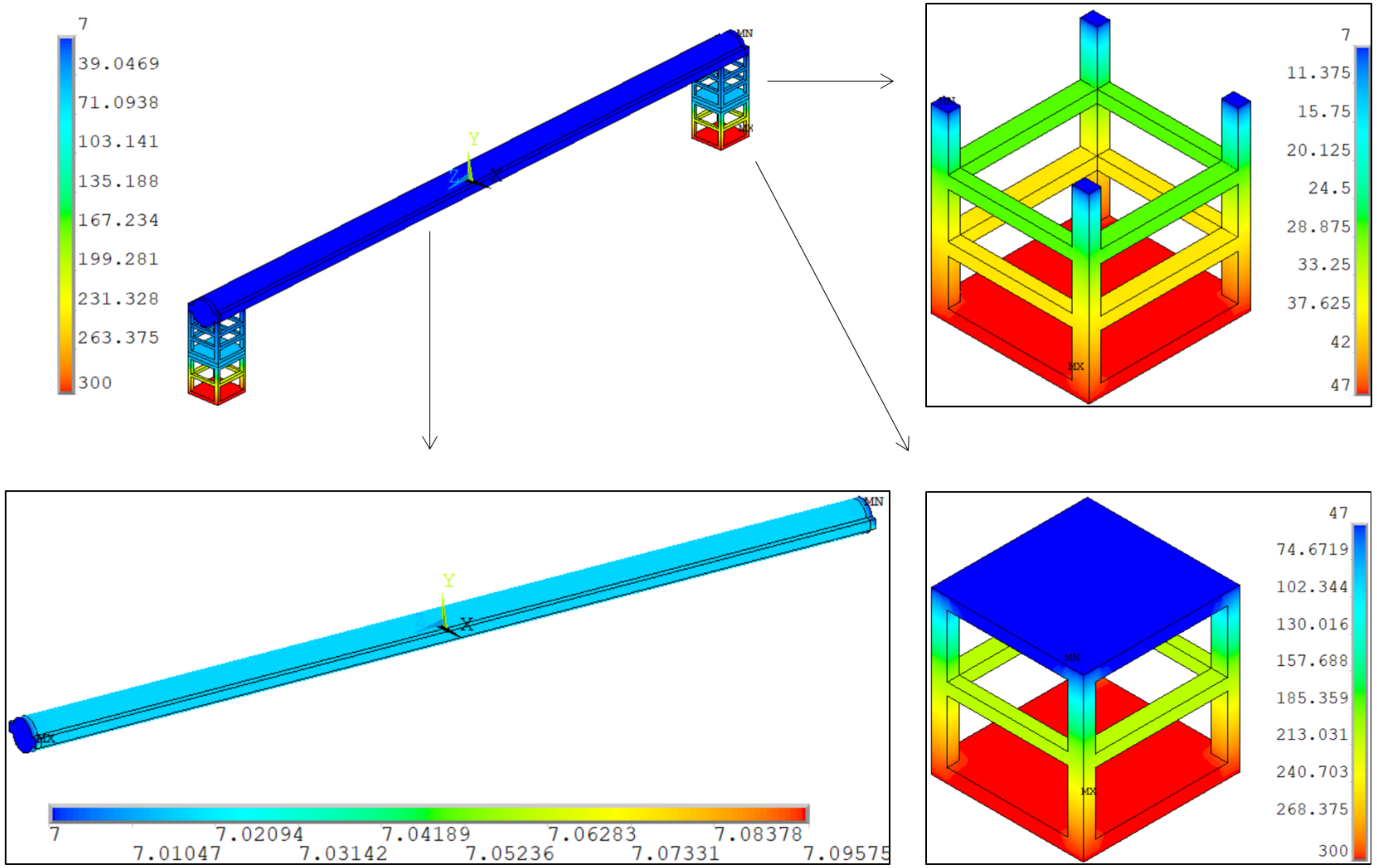
K. Zhang et al., IEEE Trans. Appl. Supercond., vol. 35, no. 5, pp. 4100205, 2025
Z. W. Chen et al., Superconductivity, vol. 12, pp. 100134, 2024

Mechanical Design Considerations of HTSU12

6-Degree-of-Freedom Platform

A dedicated 6-degree-of-freedom positioning platform was developed for HTSU12 to enable precise alignment and fine adjustment along the x, y, and z axes, as well as their corresponding rotational degrees of freedom, during beam-test installation at Shanghai Soft X-ray Free-Electron Laser Facility.

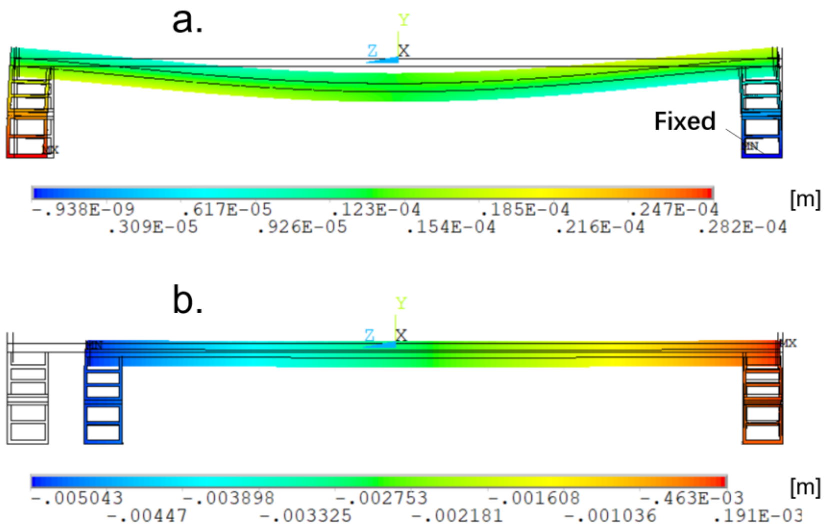
Temperature Across the HTSI and Its Mechanical Support



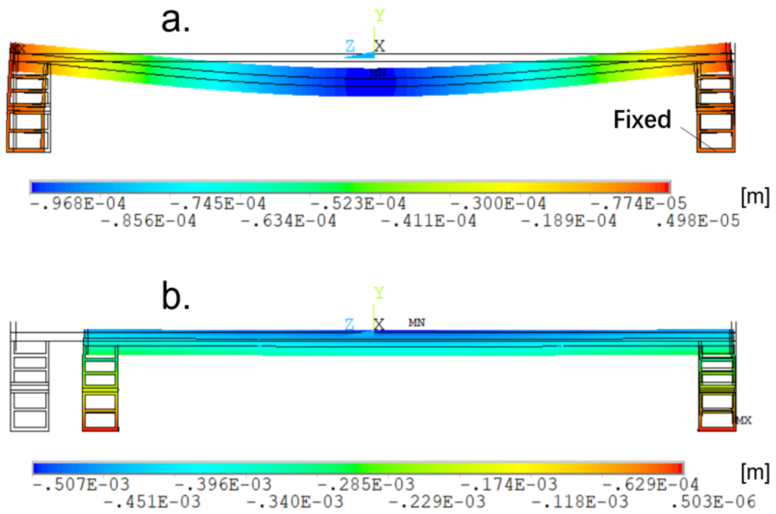
Temperature profile under operational conditions for the cold mass and its support structure, including the 1.5 m-long HTS-VTI, the top-half of TiAl6V4 support framework, and the bottom-half of TiAl6V4 support framework.

K. Zhang et al., IEEE Trans. Appl. Supercond., vol. 35, no. 5, pp. 4100205, 2025

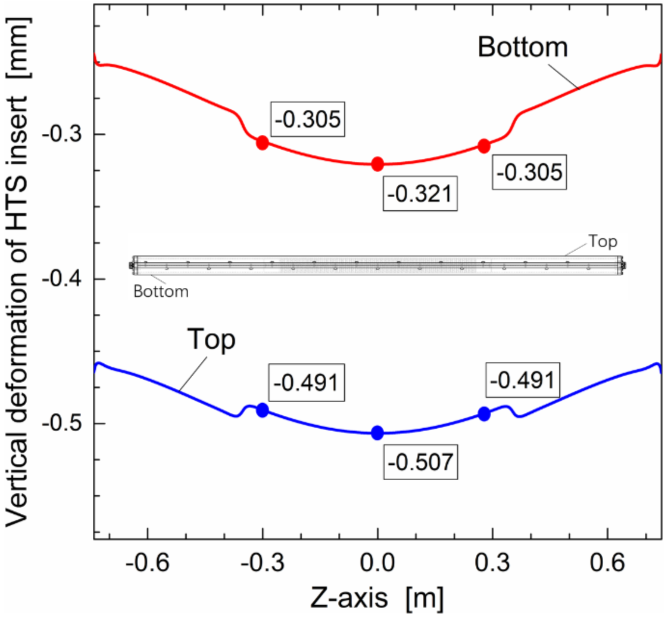
Mechanical Deformation Simulation



Longitudinal displacement, UZ of the 1.5 m-long HTS-VTI and the TiAl6V4 support frameworks (a) under gravity and (b) after further cooling to operational conditions, not to scale.



Vertical displacement, UY of the 1.5 m-long HTS-VTI insert and the TiAl6V4 support frameworks (a) under gravity and (b) after further cooling to operational conditions, not to scale.



Vertical displacement, UY of the top and bottom lines of the HTS-VTI under operational conditions. The difference between UY at the center and UY at the ends is ~16 μm within the effective undulator length of 0.6 meter.

K. Zhang et al., IEEE Trans. Appl. Supercond., vol. 35, no. 5, pp. 4100205, 2025

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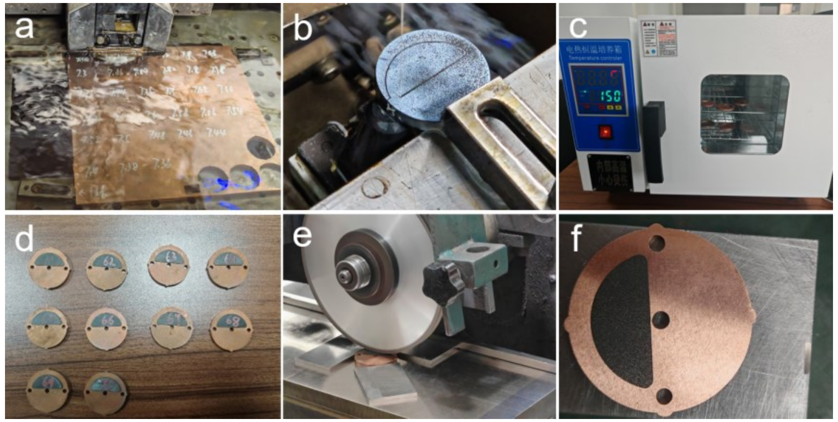
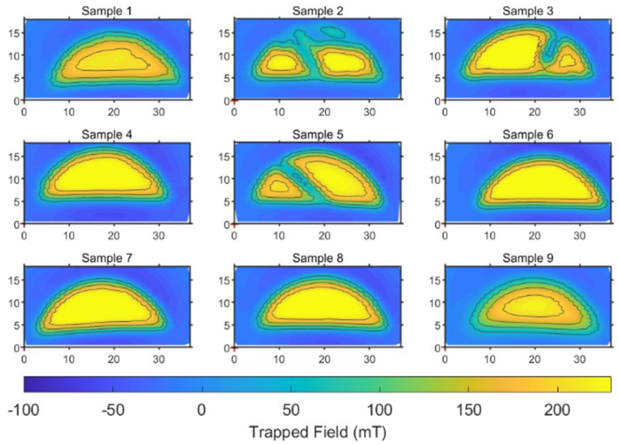
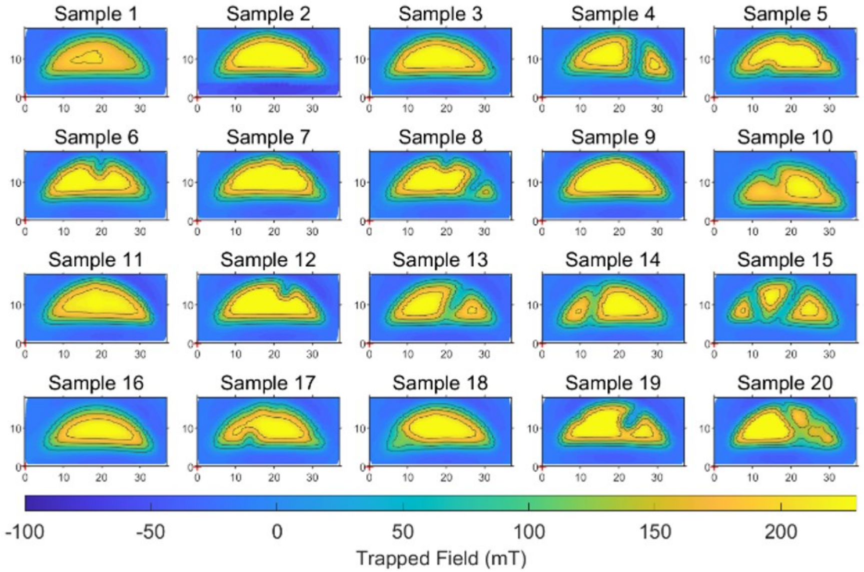
Fabrication and Characterization of REBCO Bulk Pieces



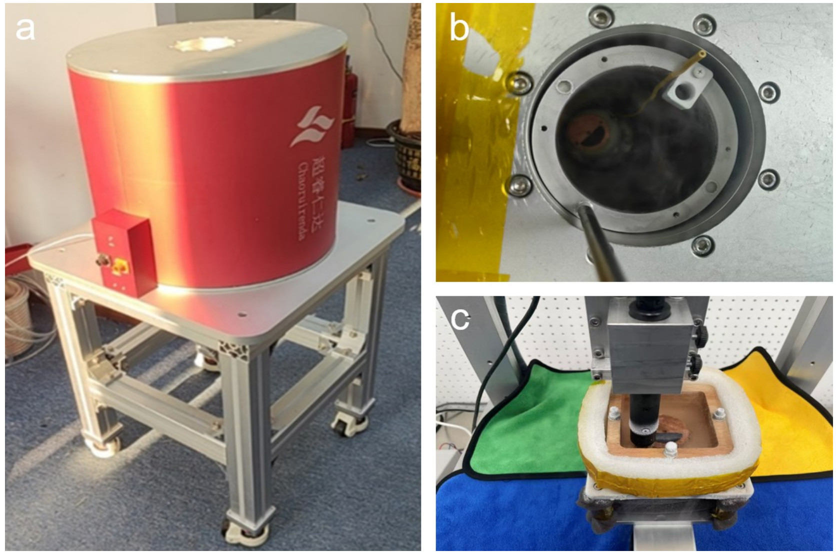
Fabrication and assembly of REBCO bulk units



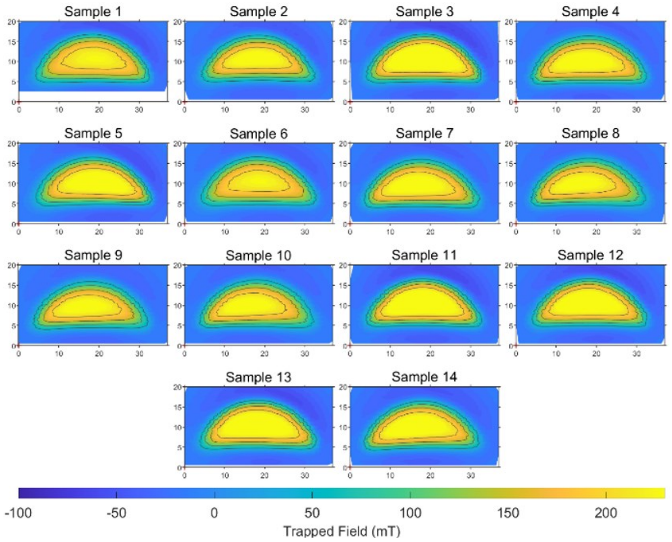
1st batch， 2D field mapping



2nd batch， 2D field mapping



77 K magnetic field mapping



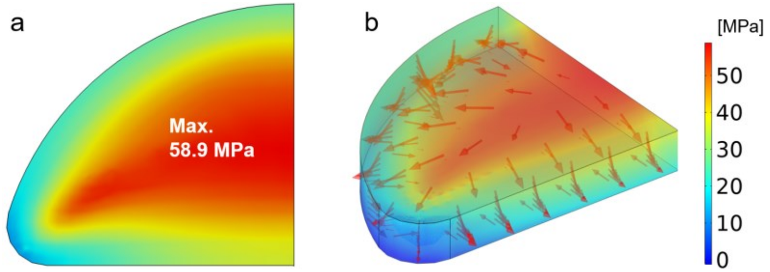
3rd batch， 2D field mapping

Improve EDM cutting technique

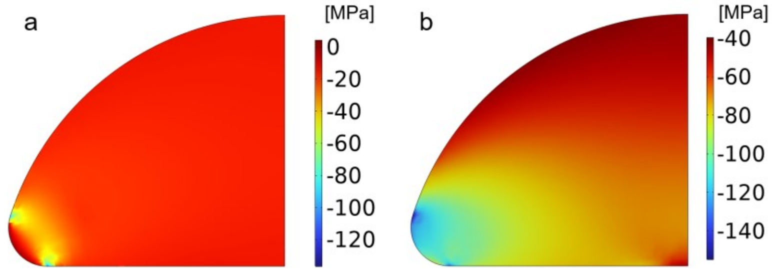
Avoid damage during shrink-fit assembly

REBCO units， >90% acceptance rate

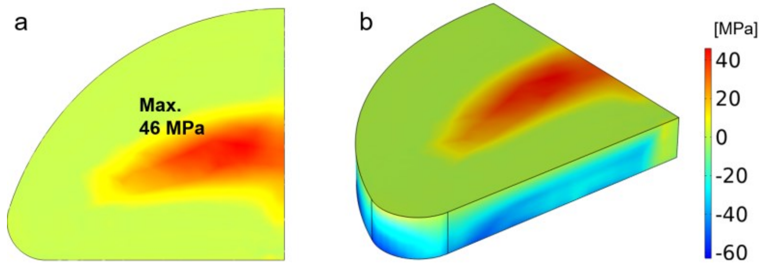
Mechanical Strain Measurement



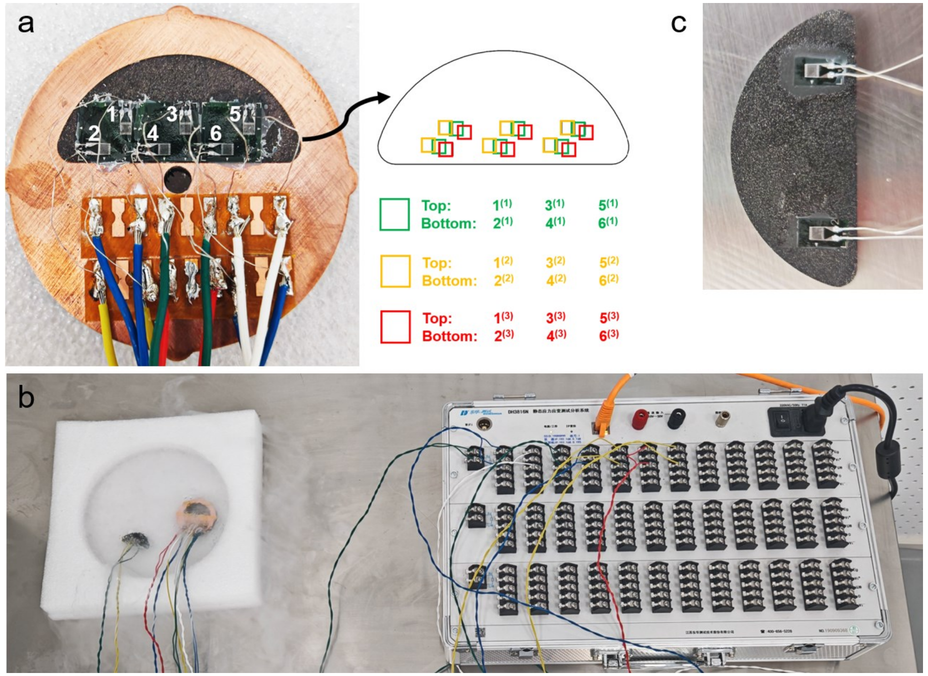
Tensile stress after magnetization



Shrink-force induced compressive stresses



Peak tensile stress reduced due to applied pre-stress



Mechanical strain measurement system

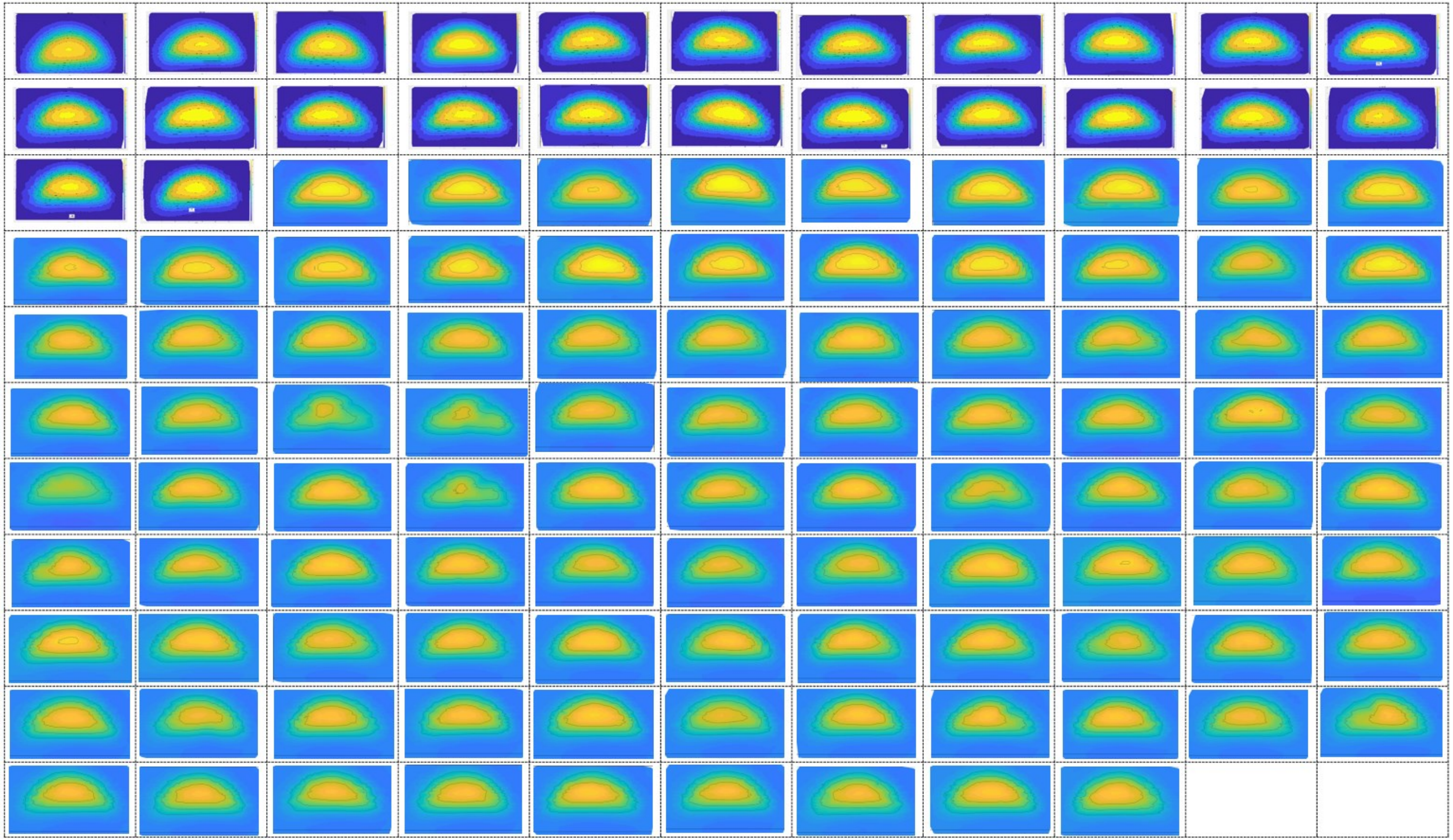
D. B. Wei et al., IEEE Trans. Appl. Supercond., vol. 35, no. 5, pp. 8400205, 2025

Measured vs. simulated

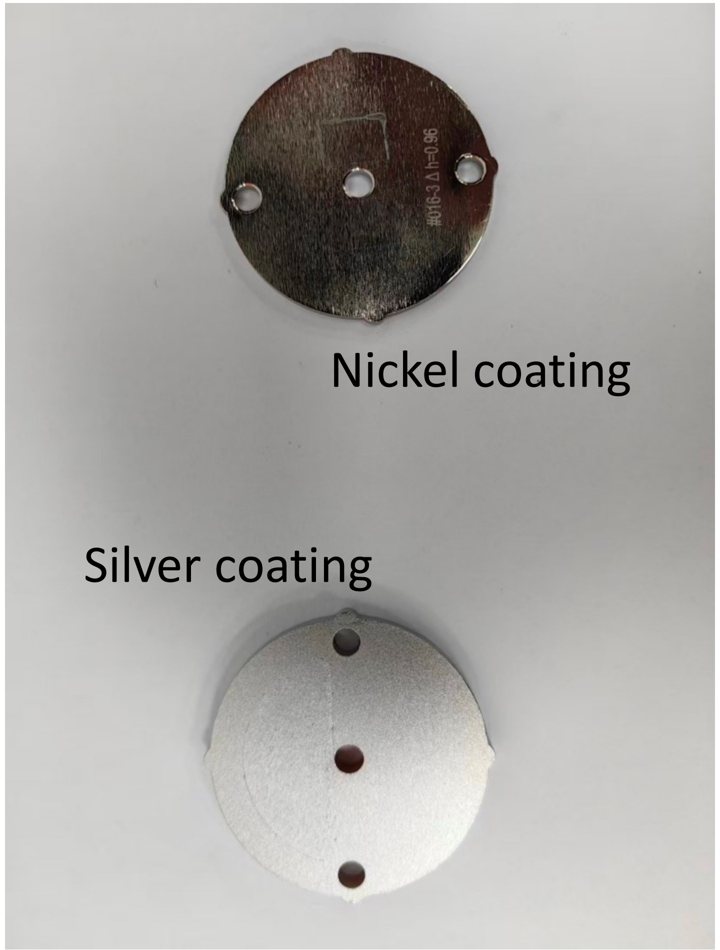
Gauge	Measured [$\times 10^{-6}$]	simulated [$\times 10^{-6}$]
$1^{(1)}$	-35.9	-37.6
$3^{(2)}$	4.8	45.7
$5^{(1)}$	-135.9	-147.3
$2^{(1)}$	-633.6	-616.1
$4^{(1)}$	-528.7	-508.8
$6^{(3)}$	-561.7	-586.3

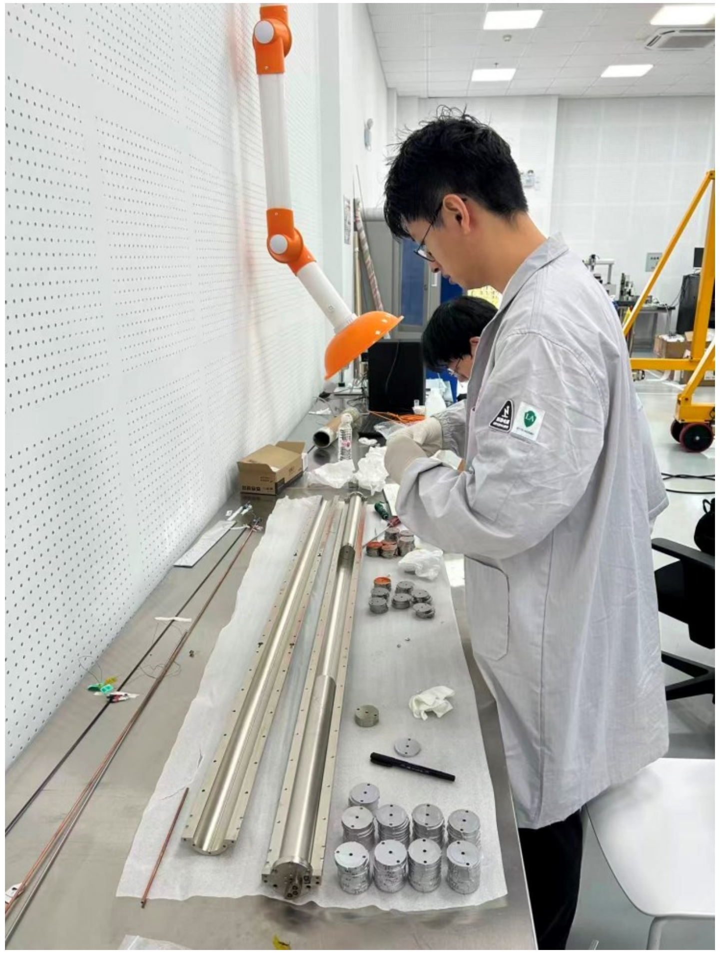
~120 Qualified REBCO Bulk Pieces

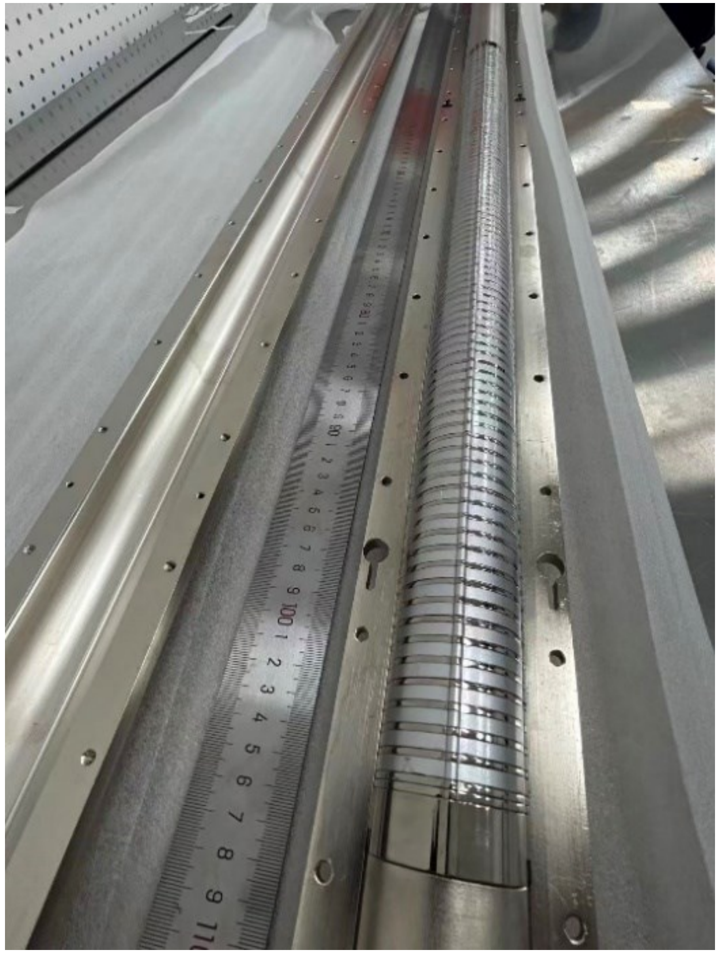
77 K Field Mapping



Surface Coating and Assembly of HTSI







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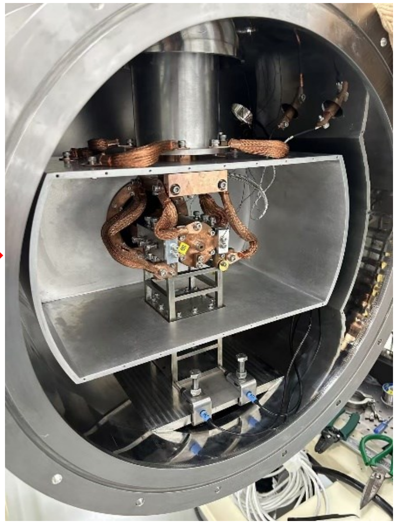
Undulator Assembly and System Integration

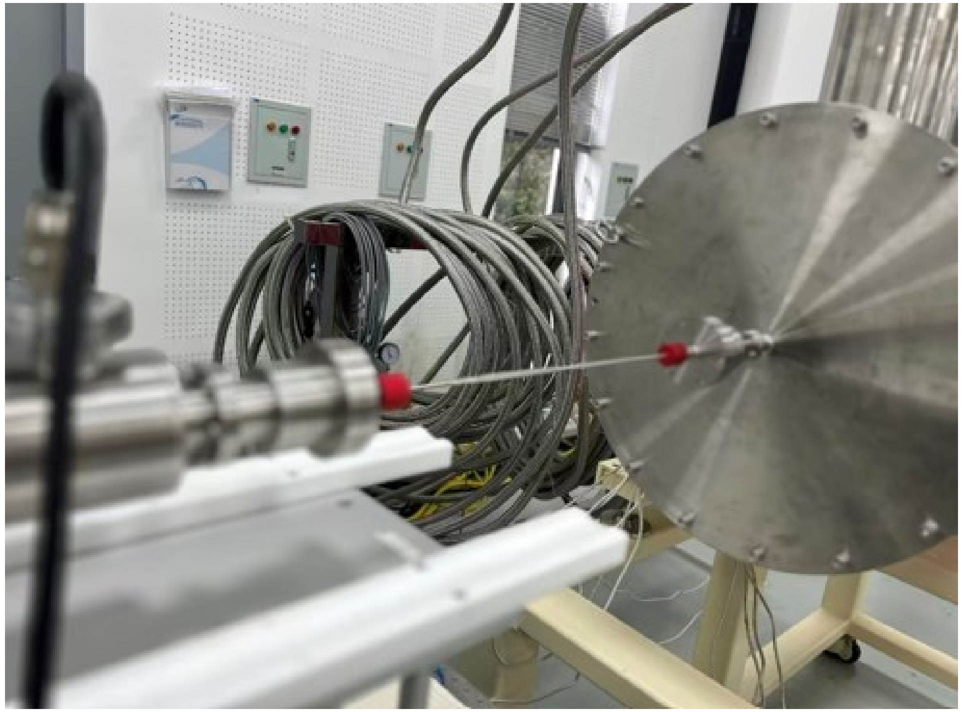






Undulator Assembly and System Integration



Integration of the long Hall probe into the cryostat

Full assembly of HTSU12 and the associated magnetic field measurement system

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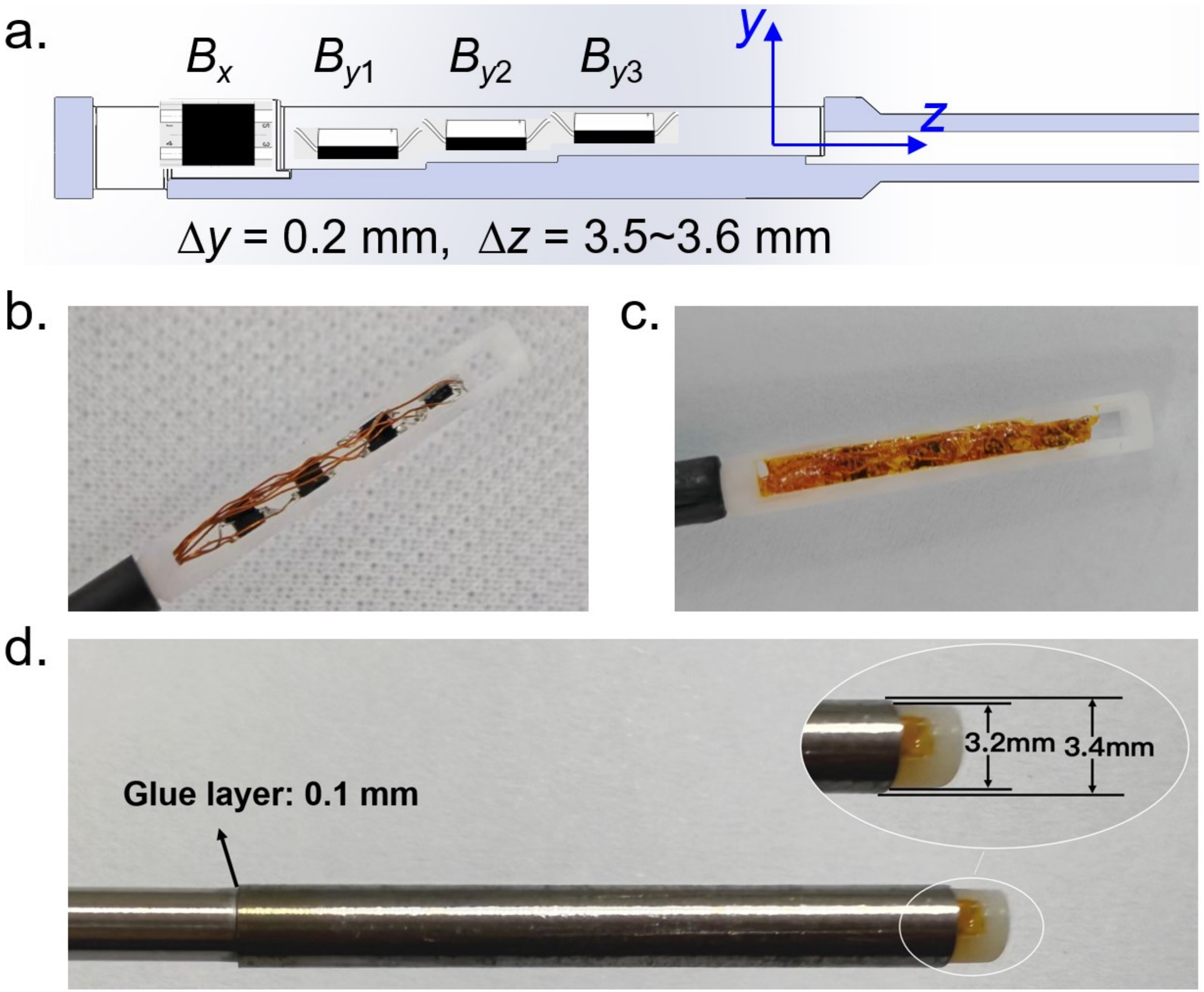
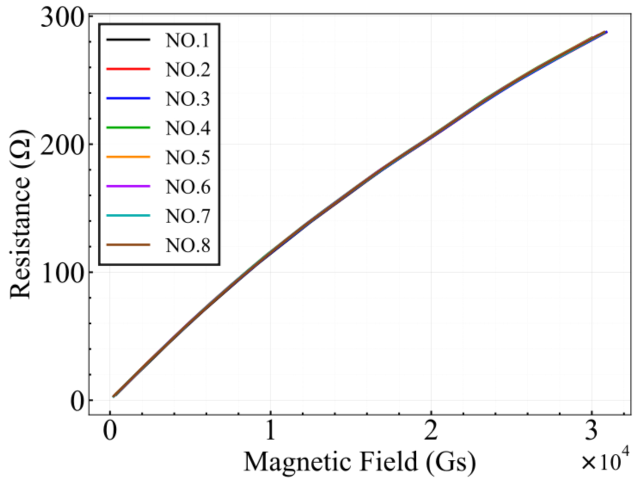
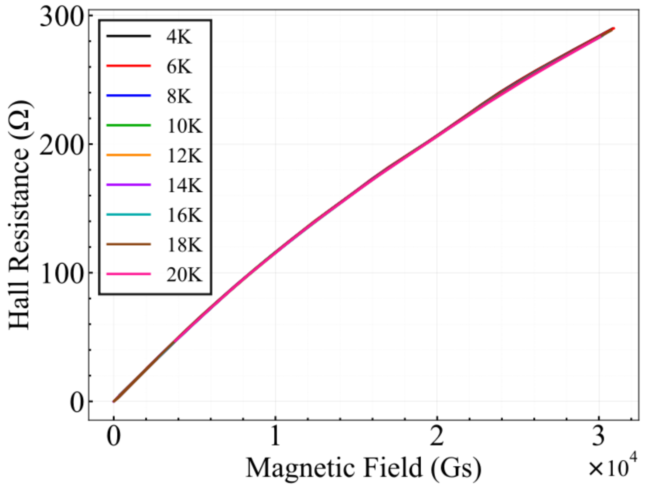
Hall Probe and Sensor Calibration





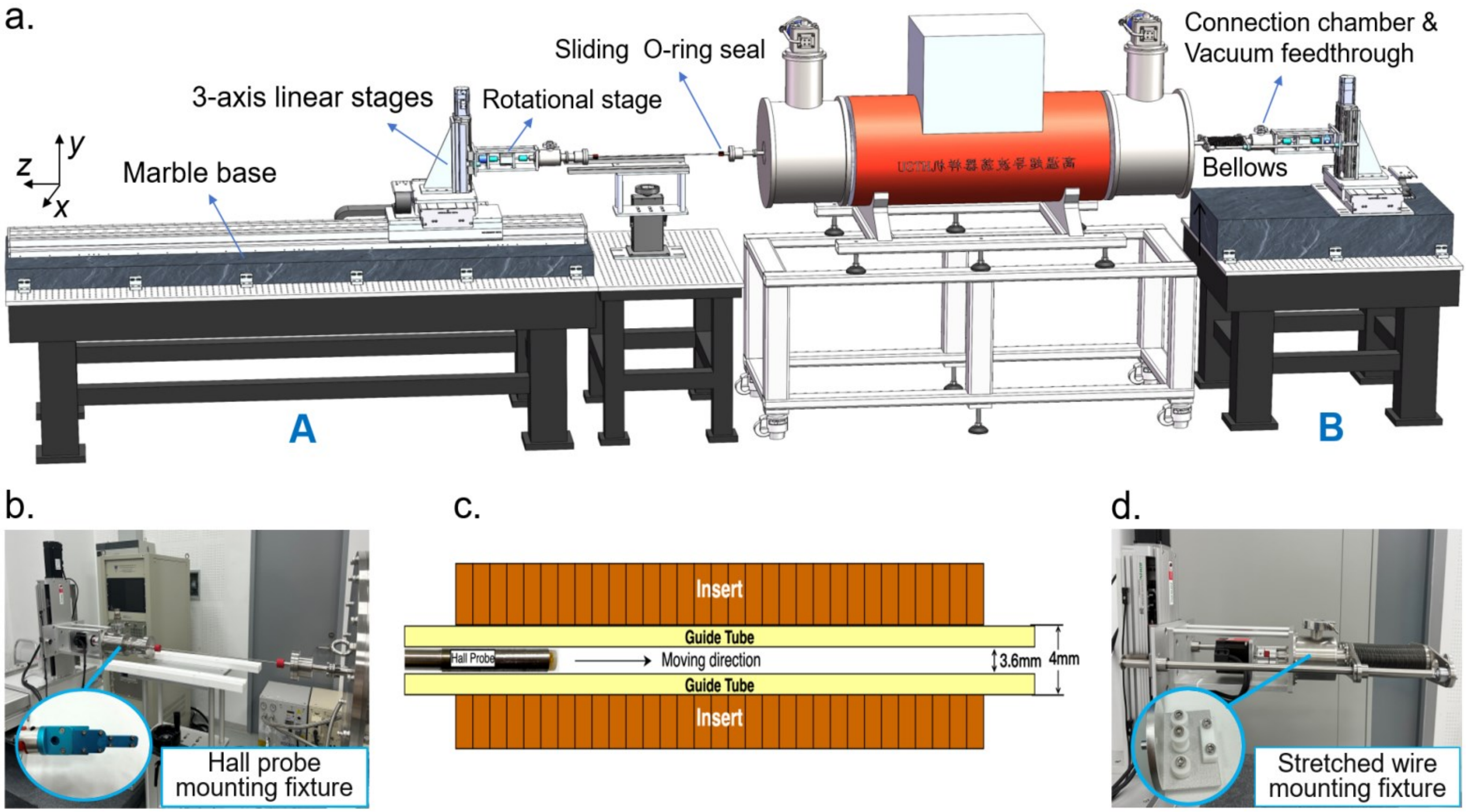
Calibration curves of eight InAs Hall sensors measured at 10 K, showing the dependence of Hall resistance (Hall voltage divided by excitation current) on magnetic field strength.



Calibration curves of an InAs Hall sensor measured over magnetic fields from 0 to 3 T and temperatures from 4 to 20 K.

C. Liu et al., IEEE Trans. Appl. Supercond., vol. 36, no. 5, pp. , 9001805, 2026

Magnetic Field Measurement System



(a) Schematic of the multifunctional magnetic field measurement system developed for the 50-period bulk HTS undulator at SXFEL.

(b) Schematic of measurement bench A equipped with a 2-m-long Hall probe tube; the associated Hall probe mounting fixture is enlarged for clarity.

(c) Schematic showing the 3.4-mm-diameter Hall probe moving along a copper guide tube temporarily mounted to ensure smooth translation of the 2-m-long Hall probe tube, not to scale.

(d) Schematic of measurement bench B equipped with metal bellows; the associated stretched-wire mounting fixture is enlarged for clarity.

C. Liu et al., IEEE Trans. Appl. Supercond., vol. 36, no. 5, pp. , 9001805, 2026

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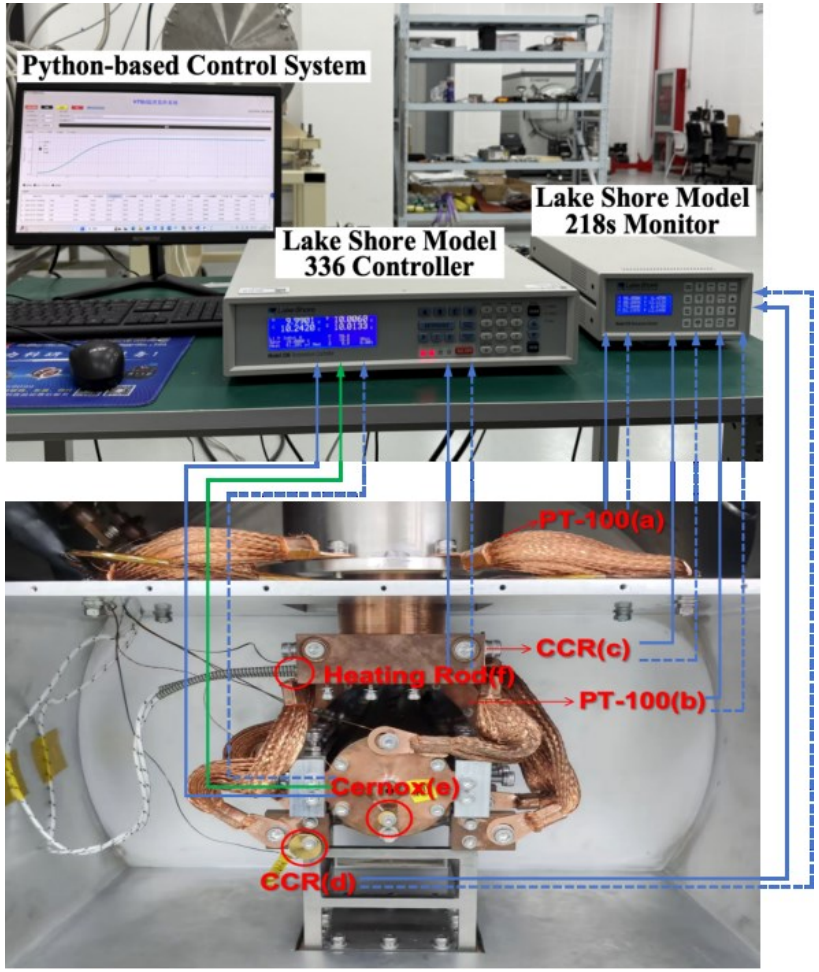
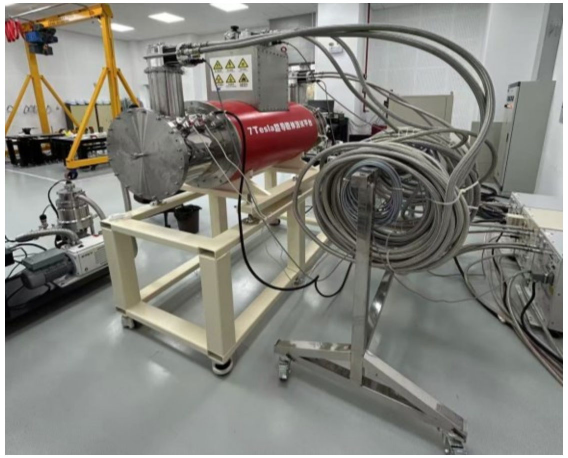
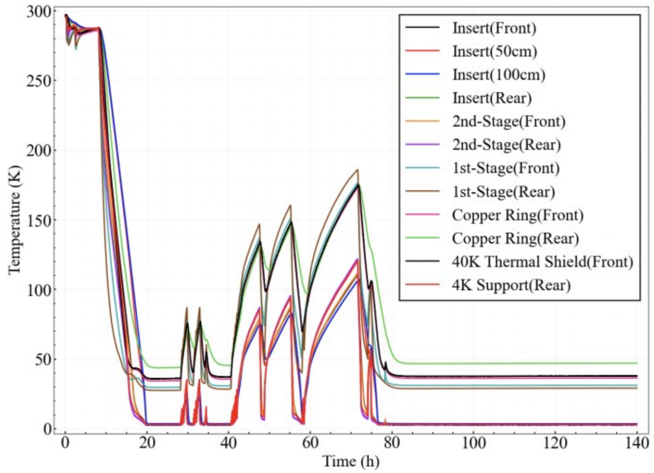
Conduction Cooling and Optimization

- **6 rounds of system optimization and cooling experiments have been completed**
  HTS insert finally cooled to reached 2.75K (front), 3.46K (50cm), 3.58K (100cm), and 2.77K (rear)





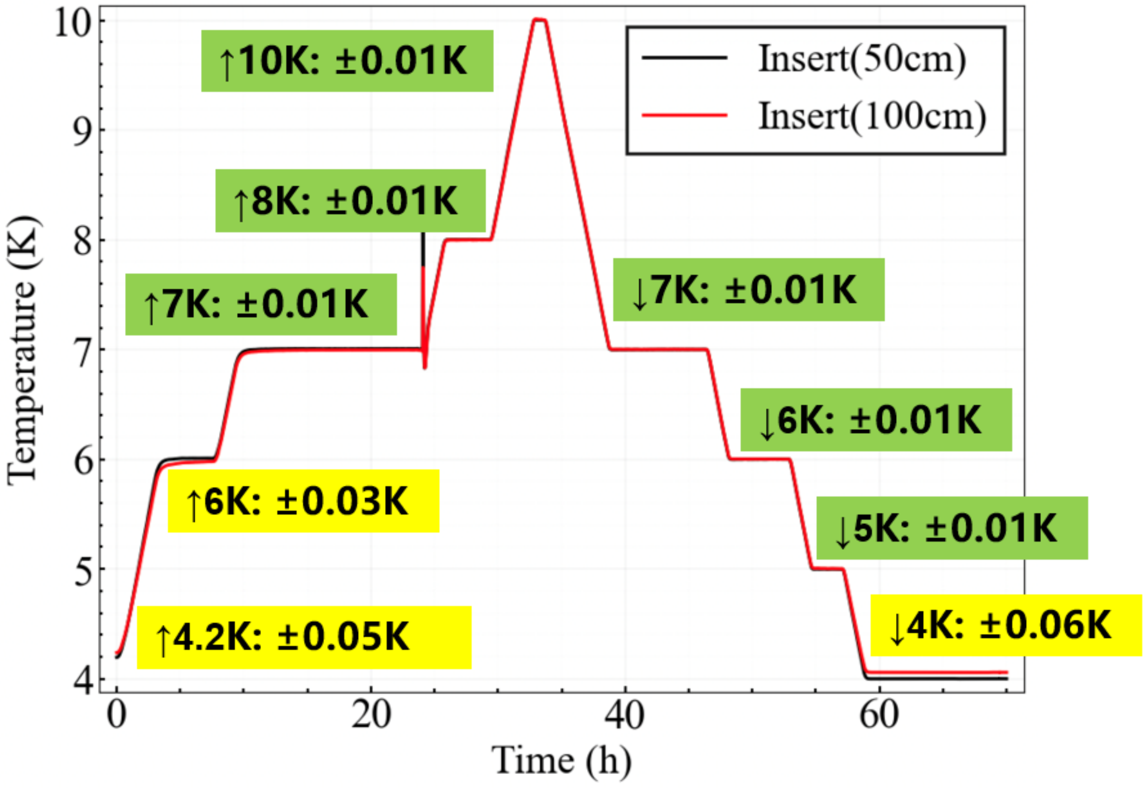


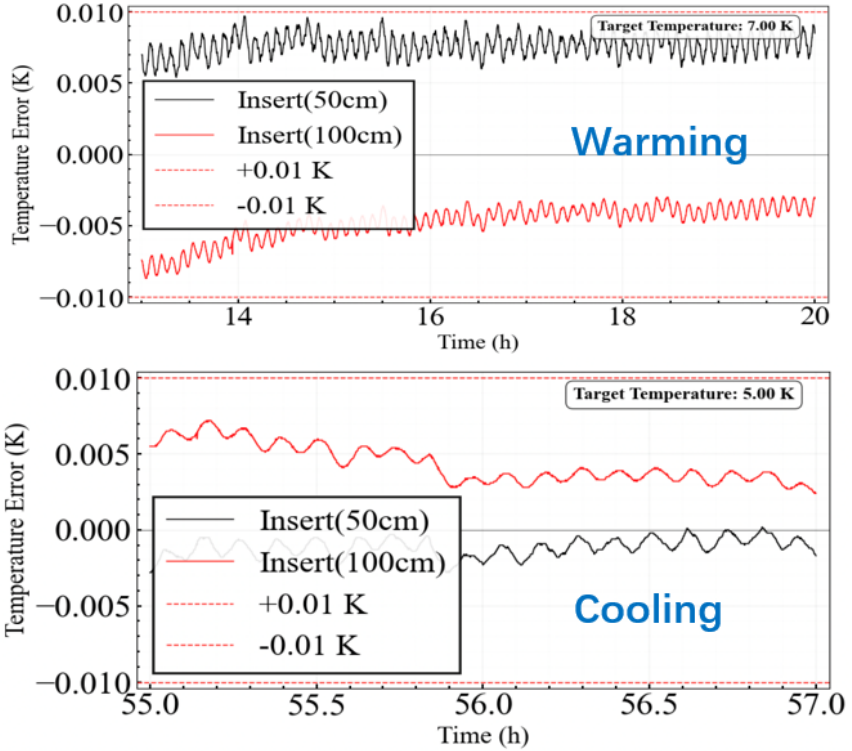
NO.	Cooling Results / K												Key Improvements
	Insert				2nd–Stage		1st–Stage		4K Thermal Anchor		Copper Ring		
	Front	50cm	100cm	Rear	Front	Rear	Front	Rear	Front	Rear	Front	Rear	
1	Sensors Not Inst				36.24	11.71	*	165.67	36.21	*	165.18	181.59	–
2	*	11.34	13.88	11.55	5.55	4.50	115.51	55.58	*	18.63	130.01	118.06	Added MLI to radiation shields
3	8.56	8.58	9.20	8.58	4.28	4.32	90.60	50.74	11.75	12.66	97.89	79.54	1. +10 MLI layers; 2. More copper braids
4	8.01	7.99	8.80	7.94	7.24	3.54	49.95	56.63	40K Anch.: 74.88	40K Anch.: 74.68	71.69	72.75	1. Indium sheets at interfaces; 2. Direct thermal link from cold head to insert
5	7.47	7.41	8.45	7.31	6.91	3.43	50.37	56.92	40K Anch.: 75.78	40K Anch.: 77.78	72.57	73.63	Stainless–steel screws → PTFE isolation sleeves
6	**2.75**	**3.46**	**3.58**	**2.77**	**3.02**	**2.79**	**31.21**	**29.16**	**40K Thermal shield: 37.81**	**4K Support: 2.98**	**36.39**	**47.10**	**Structural upgrades**

C. Liu et al., IEEE Trans. Appl. Supercond., vol. 36, no. 3, pp. , 9000105, 2026

Accurate Temperature Control

- Completed three rounds PID control, including heated from 4.2K to 10K and cooled from 10K back to 4K.
- Experimental results demonstrate:
  - During heating, temperature stability was better than ±0.01K at 7K, 8K, and 10K; better than ±0.03K at 6K; and better than ±0.03K at 4.2K;
  - During cooling, stability was better than ±0.01K at 5K, 6K, 7K, and better than ±0.06K at 4K.





C. Liu et al., IEEE Trans. Appl. Supercond., vol. 36, no. 3, pp. , 9000105, 2026

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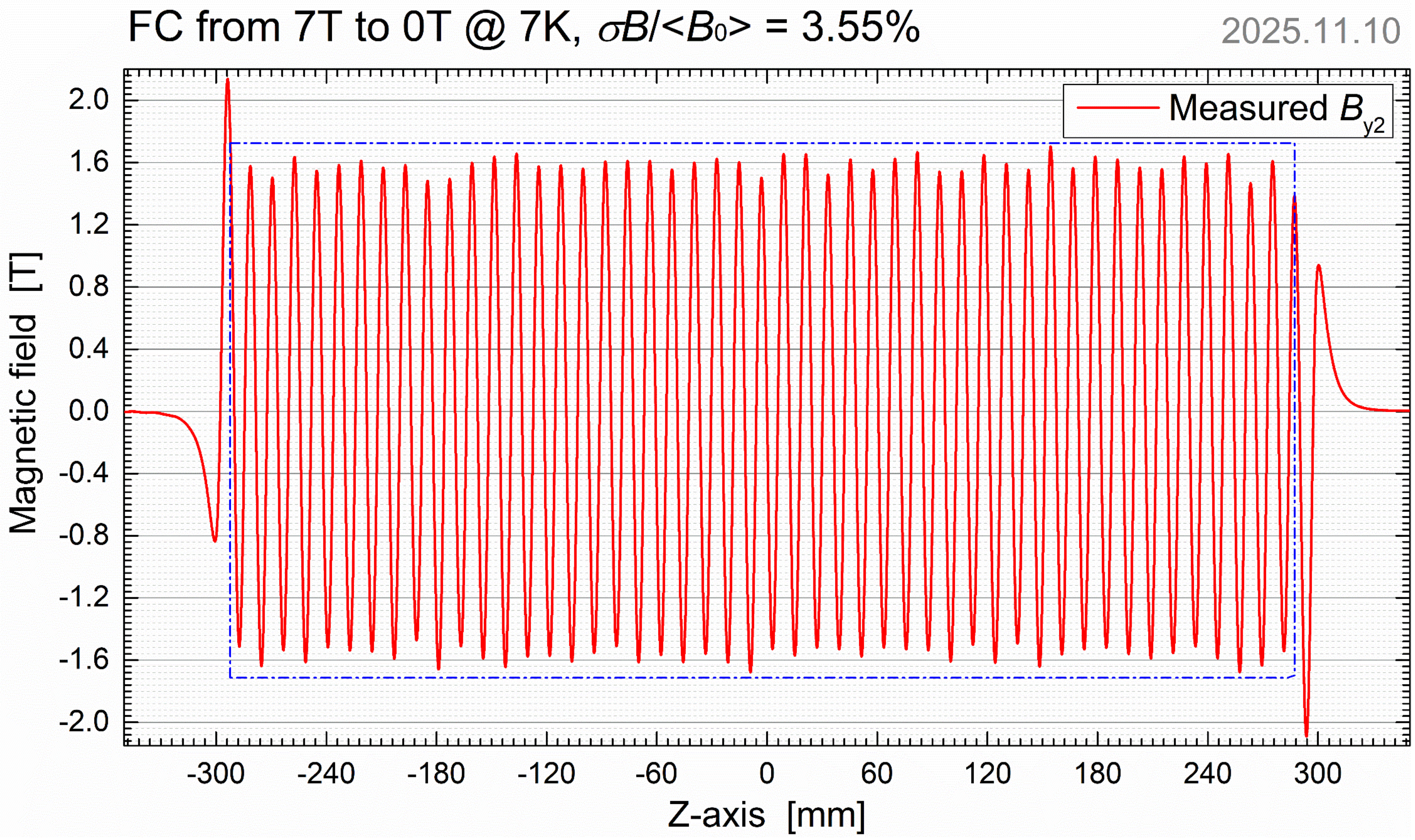
Magnetization Test Trials

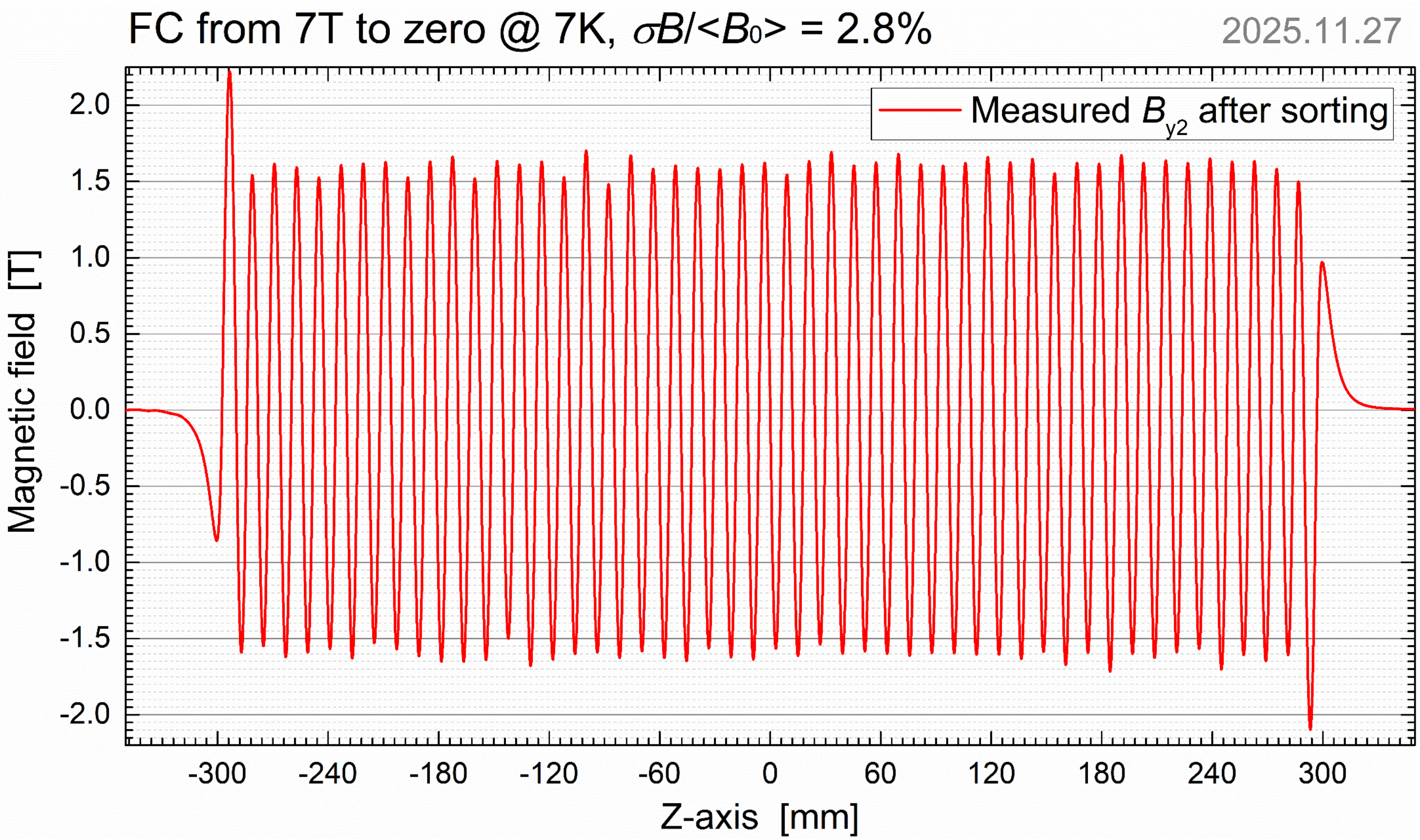
轮次	编号	磁测时间	参数			探头调中	备注
1	1.1	2025.11.01	FC, 10K磁化, 未冻结	7T->6T, ΔB=1T, 0.01A/s	V=1mm/s, Δz=0.1mm	×	所有电压表均连接至By0 (此轮测试结束后已更正)
	1.2			6T->5T, ΔB=2T, 0.02A/s			
	1.3			5T->3.32T, ΔB=3.36T, 0.02A /s			
	1.4	2025.11.07	FC, 9K磁化, 7K冻结	7T->0T, ΔB=7T, 0.003A/s	V=0.5mm/s, Δz=0.05mm	FC, ΔB=1T, 10K磁化, 未冻结	/
	1.5	2025.11.10	FC, 7K磁化, 6K冻结	7T->0T, ΔB=7T, 0.002A/s			
2:停电重启	2.1	2025.11.27	FC, 7K磁化, 6K冻结	7T->0T, ΔB=7T, 0.002A/s	V=0.5mm/s, Δz=0.05mm	ZFC, ΔB=1T, 7K磁化, 未冻结	旋转过程中联轴器脱落，探头未完全调中
	2.2	2025.12.03		7T->0T, ΔB=7T, 0.003A/s			
	2.3	2025.12.05			V=0.1mm/s, Δz=0.01mm		
	2.4	2025.12.10		7T->-1.5T, ΔB=8.5T, 0.002A/s	V=0.2mm/s, Δz=0.02mm		
	2.5	2025.12.17	FC, 10K磁化, 8K冻结	7T->-3T, ΔB=10T, 0.002A/s			
3:第1次垫补	3.1	2026.01.05	FC, 7K磁化, 6K冻结	7T->0T, ΔB=7T, 0.003A/s	V=0.2mm/s, Δz=0.02mm	×	联轴器脱落
	3.2	2026.01.09					
4:更换刚性联轴器	4.1	2026.01.16	FC, 7K磁化, 6K冻结	7T->0T, ΔB=7T, 0.004A/s	V=0.2mm/s, Δz=0.02mm	FC, ΔB=1T, 10K磁化, 9K冻结	/
5: 发现霍尔片间存在夹角后复测	5.1	2026.01.22	FC, 7K磁化, 6K冻结	7T->0T, ΔB=7T, 0.004A/s	V=0.2mm/s, Δz=0.02mm	×	探头旋转90度，目的为确定霍尔片x-y夹角
	5.2	2026.01.26		7T->0T, ΔB=7T, 0.002A/s		FC, ΔB=1T, 7K磁化, 6K冻结 (测试过程中冻结)	通过By霍尔片找中轴，随后旋转90度
6: 改装螺旋结构	6.1	2026.02.04	FC, 9K磁化, 8K冻结	6T->0T, ΔB=6T, 0.003A/s	V=0.2mm/s, Δz=0.02mm	×	/
	6.2	2026.02.05		6T->0T, ΔB=6T, 0.004A/s			

注：1、电压—霍尔片位置对应关系：电压1-Bx/电压2-B+-/电压3-By0/电压4-By+；2、破真空后重新降温即视为新一轮

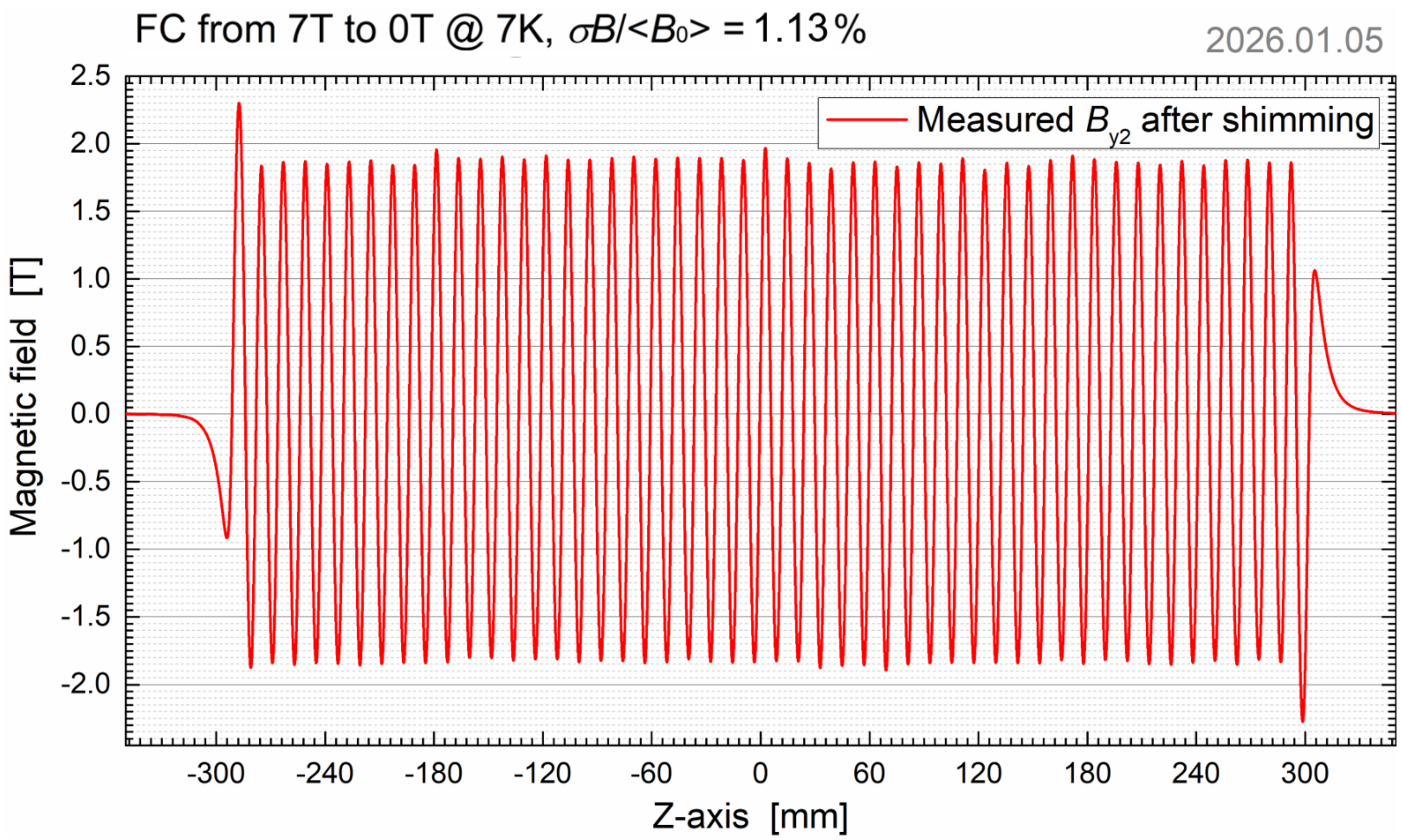
Initially Measured By(z)



Measured By(z) After Sorting



Measured By(z) After Initial Shimming



Ongoing efforts, e.g. inverse analysis, levitation force evaluation of each REBCO bulk, 77 K field mapping, are made to further improve the field uniformity.

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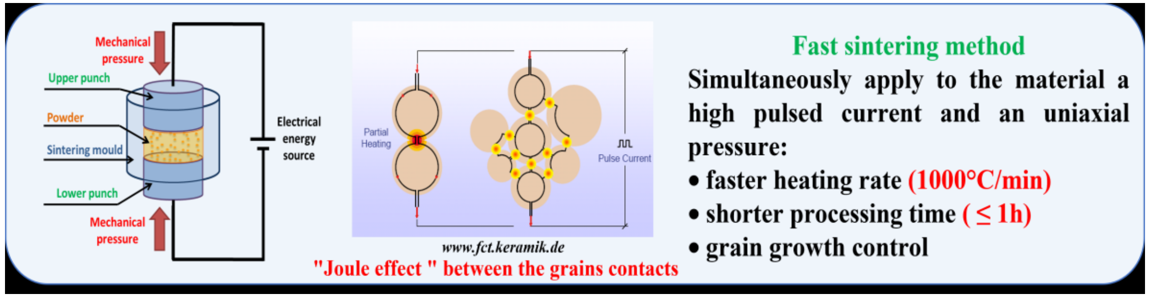
Highly-dense MgB_2 Bulks from CRISMAT

Courtesy of Prof. J. Noudem

In-situ Mg+2B
(density: 94%)
WC mold
Sintering conditions:
i) compaction: 500°C
+ 260 MPa / 15 min
ii) synthesis: 650 °C
+ 280 MPa / 20 min
iii) sintering: 750°C
+ 300 MPa / 30 min



Spark Plasma sintering (SPS)

20 MgB_2 bulks received from CRISMAT

Noudem JG, Xing Y, Bernstein P, et al.. J Am Ceram Soc. 2020; 103: 6169–6175.
Xing Y, Bernstein P, Miryala M, Noudem JG.. Nanomaterials. 2022; 12(15):2583.

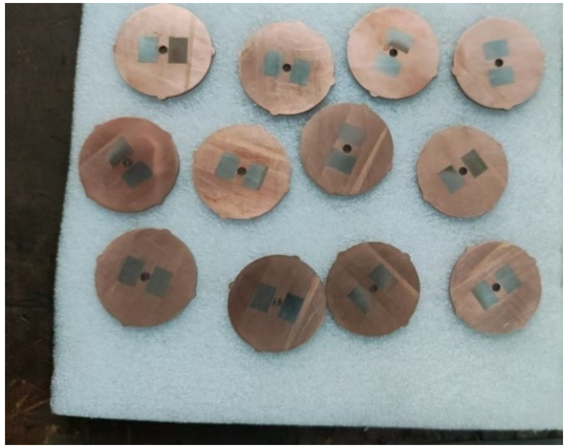
Machining and Short Sample Fabrication

EDM to cut the bulk

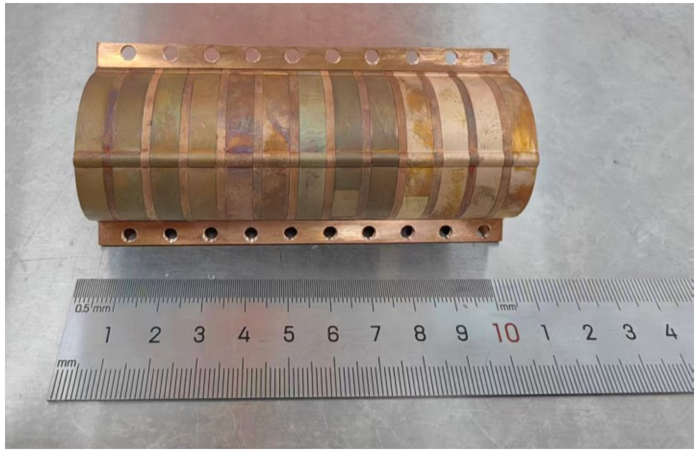
After EDM

Heat the copper disk

After assembly

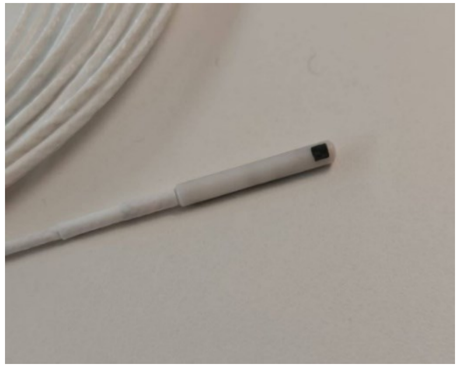
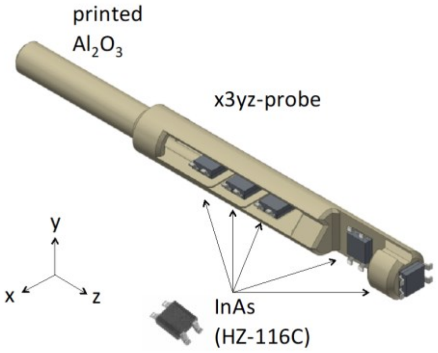


CoFe pole



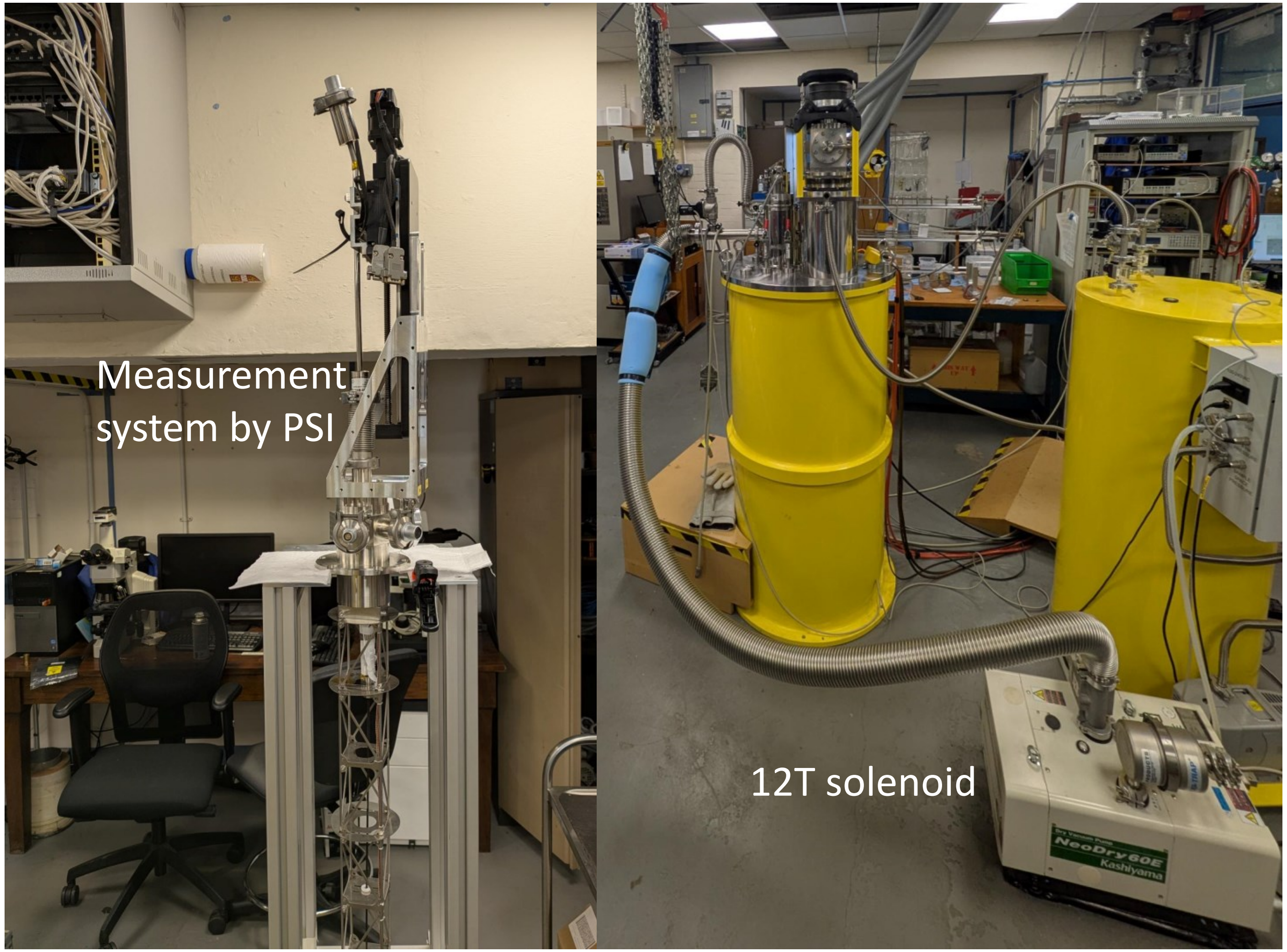
Short model

Experimental Setup

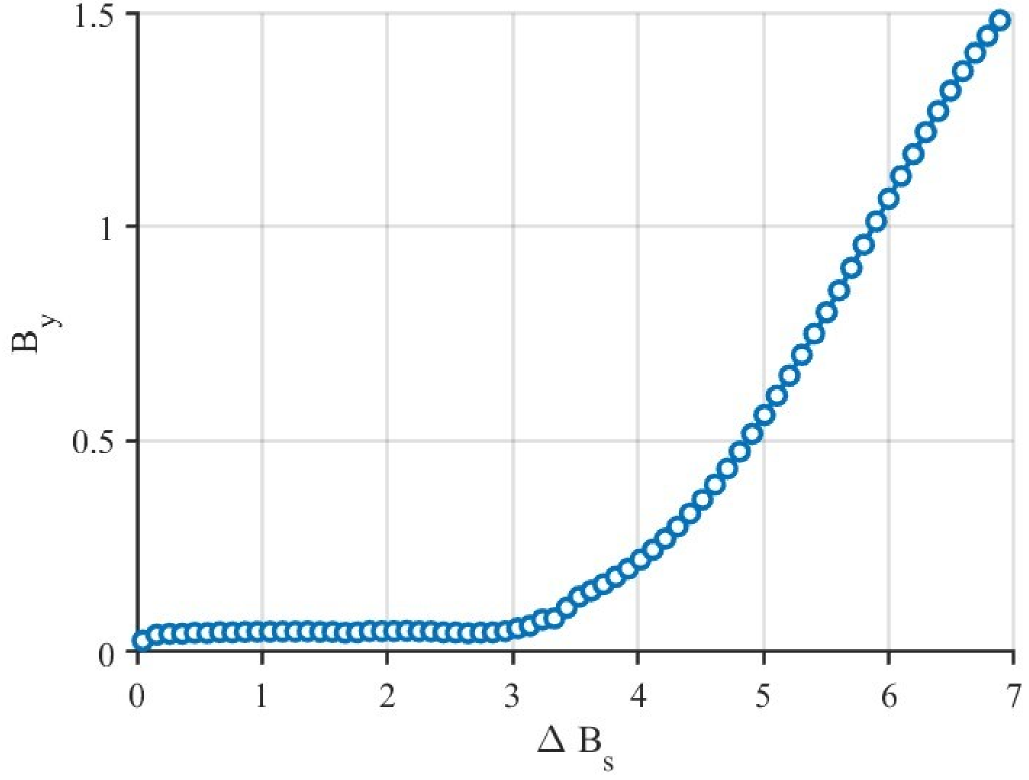



Hall probe by PSI

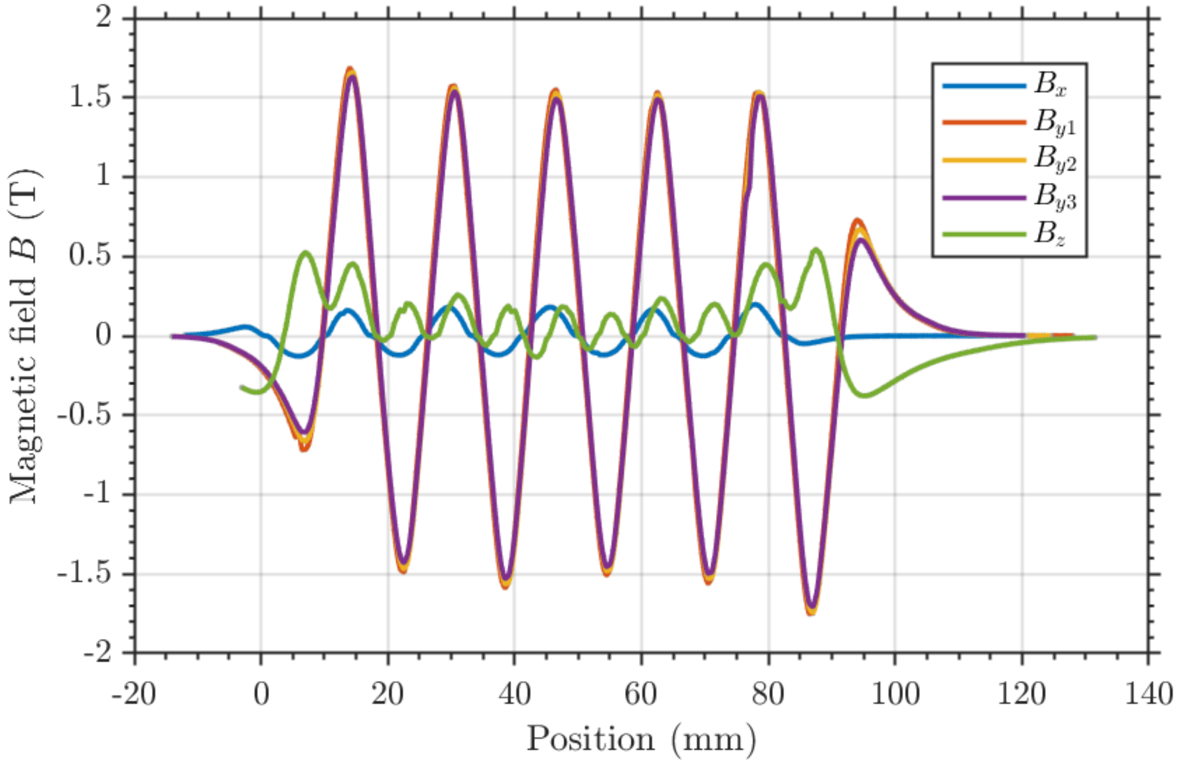
MgB_2 short model: λ_u = 16 mm, g = 4 mm



Round 1: FC From 7 T to Zero @ 20 K

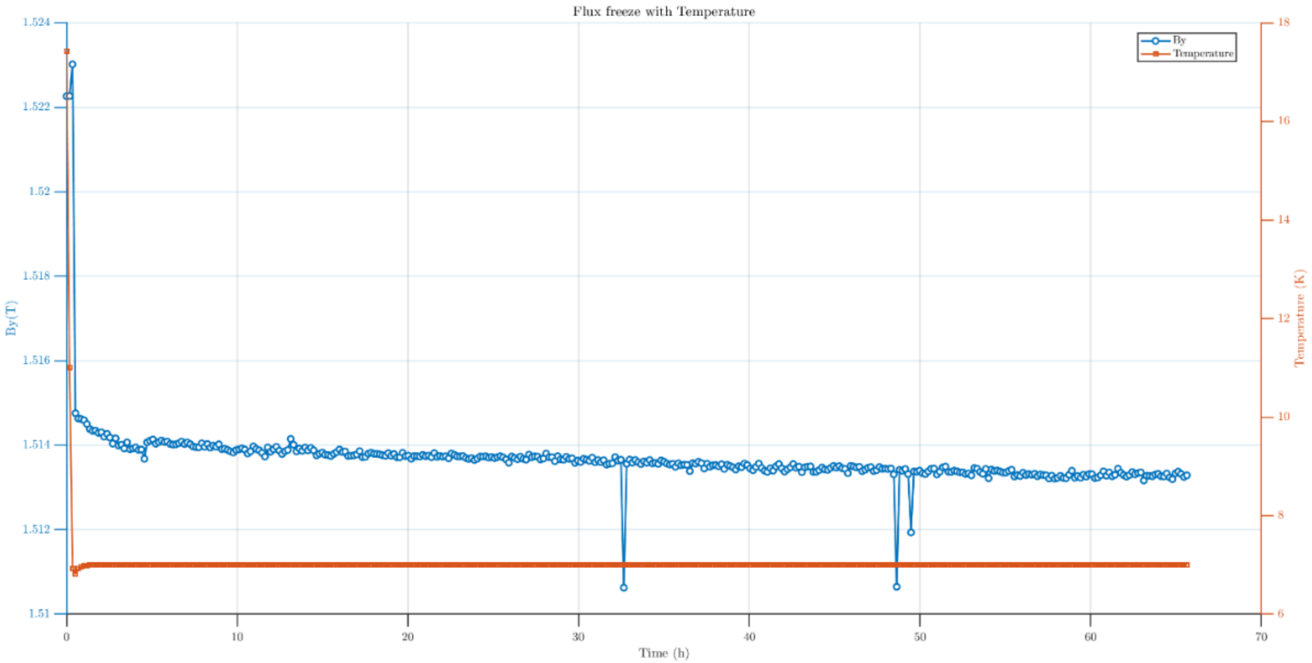


Relation between the mean undulator field B_y and ΔB_s

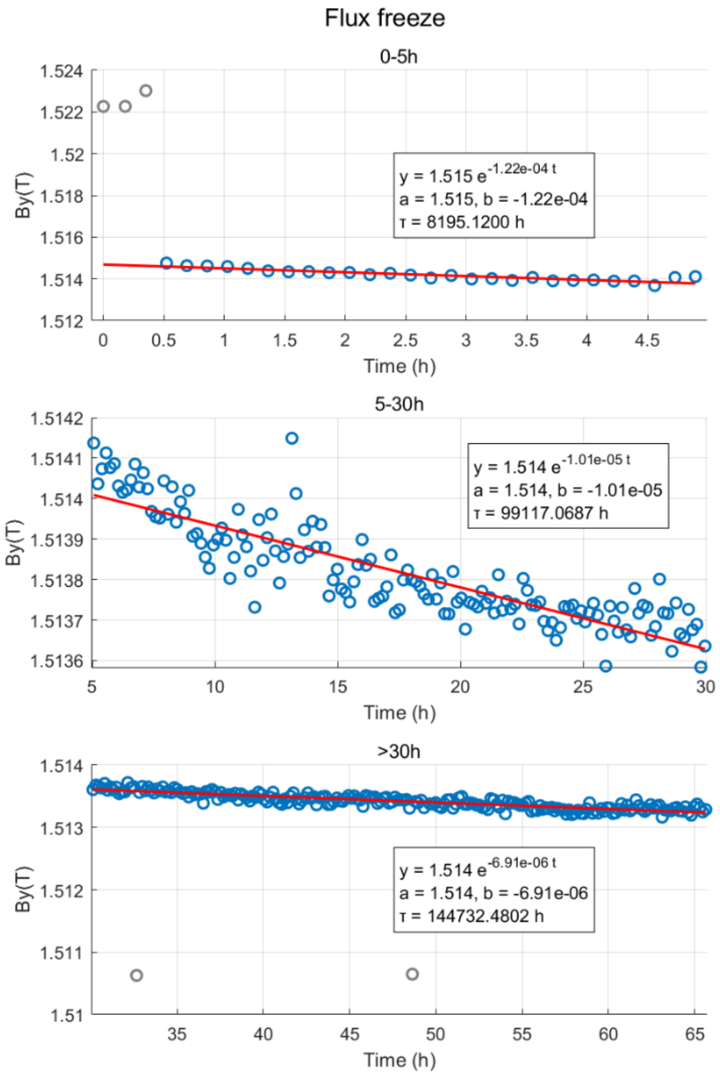


Measured magnetic field profiles at ΔB_s = 7 T

Flux Freezing at 7 K, Mean Undulator Field's Decay



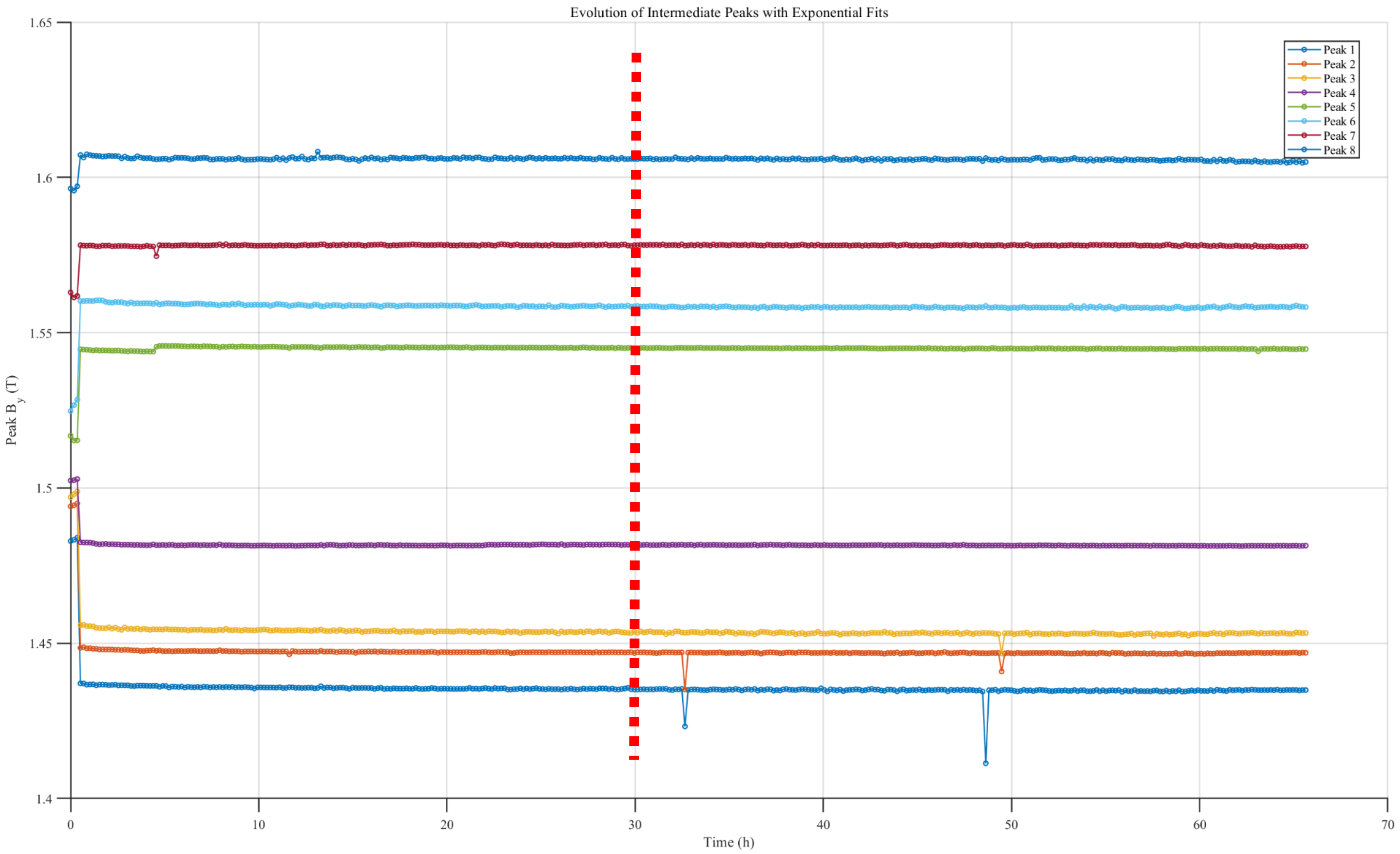
Measured mean undulator field after flux freezing at 7 K



$$B_y = B_0 e^{-\frac{t}{\tau}}$$

τ_3 = 144732 h = 16.5 yrs

Flux Freezing at 7 K, Each Peak Field's Decay



After flux freezing for 30 hrs

τ_1 = 88703 hrs = 10.1 yrs

τ_2 = 422752 hrs = 52.0 yrs

τ_3 = 86786 hrs = 9.9 yrs

τ_4 = 133631 hrs = 15.2 yrs

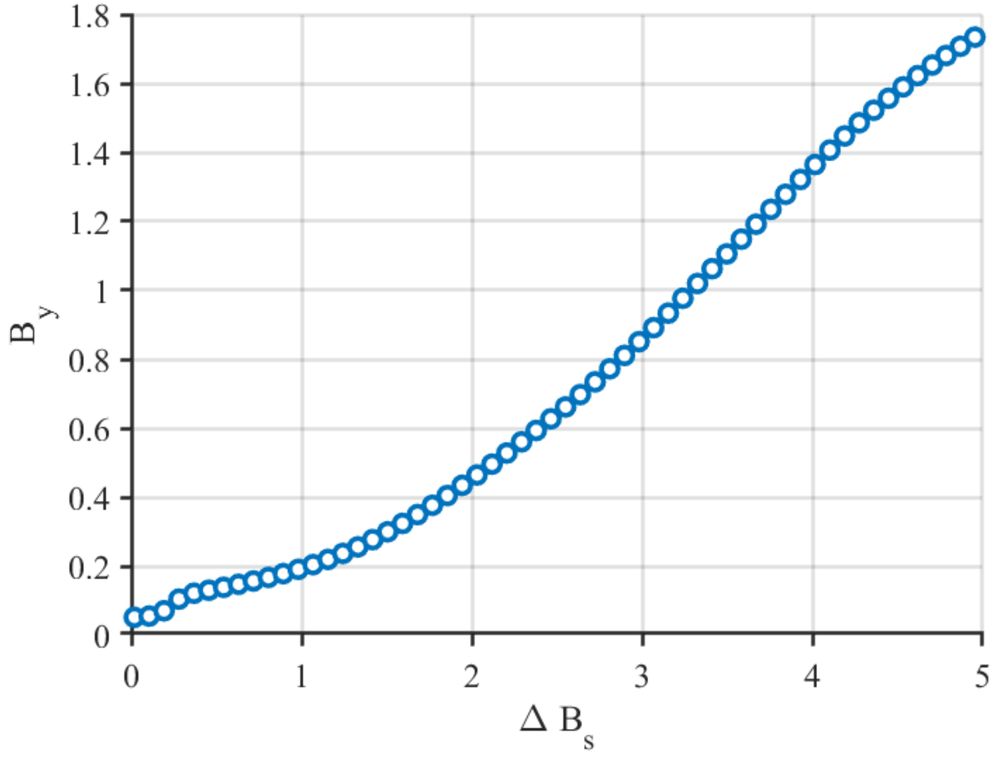
τ_5 = 125248 hrs = 14.3 yrs

τ_6 = 263505 hrs = 30.1 yrs

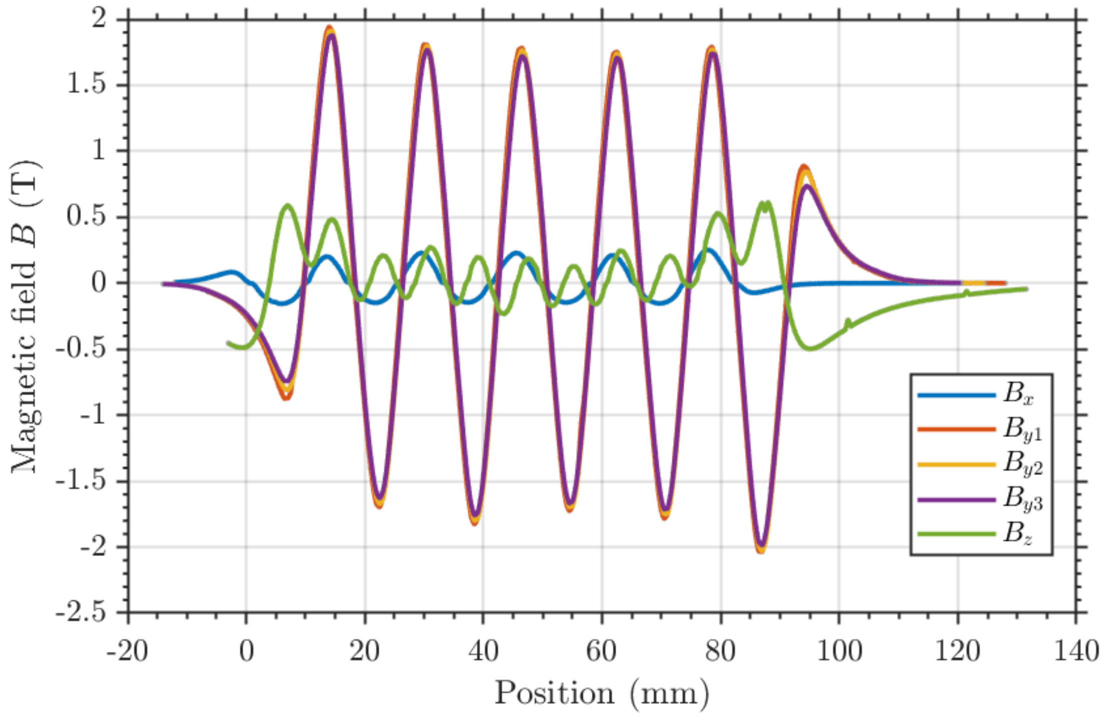
τ_7 = 106634 hrs = 12.1 yrs

τ_8 = 57665 hrs = 6.6 yrs

Round 2: FC From 5 T to Zero @ 15 K

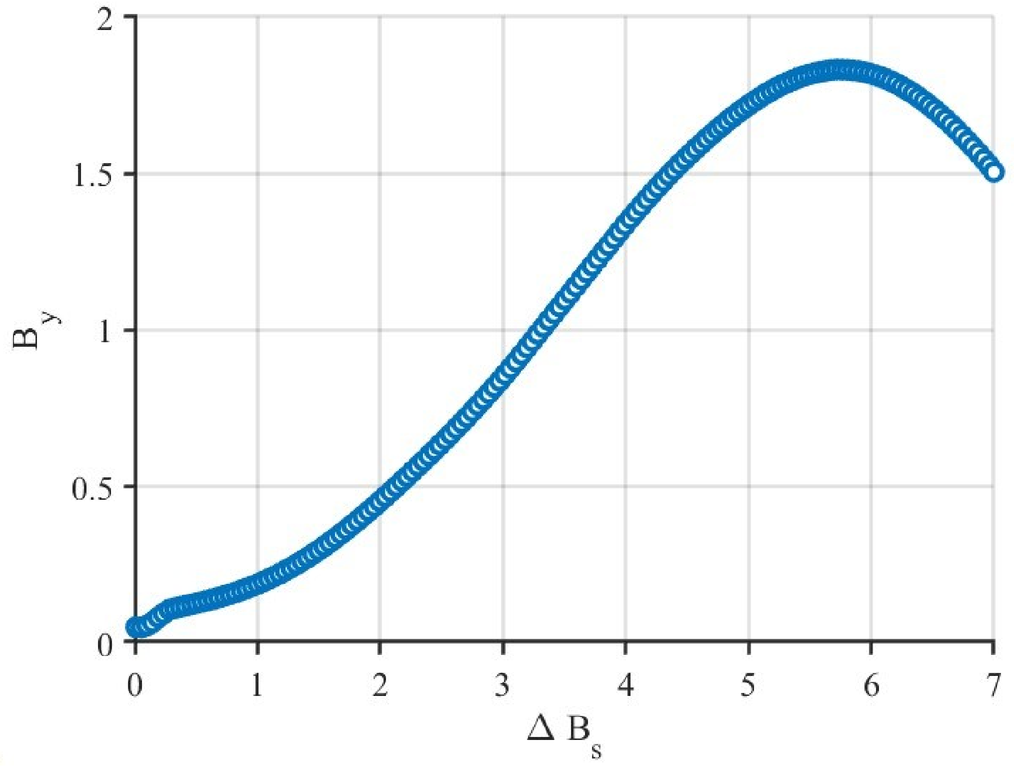


Relation between the mean undulator field B_y and ΔB_s

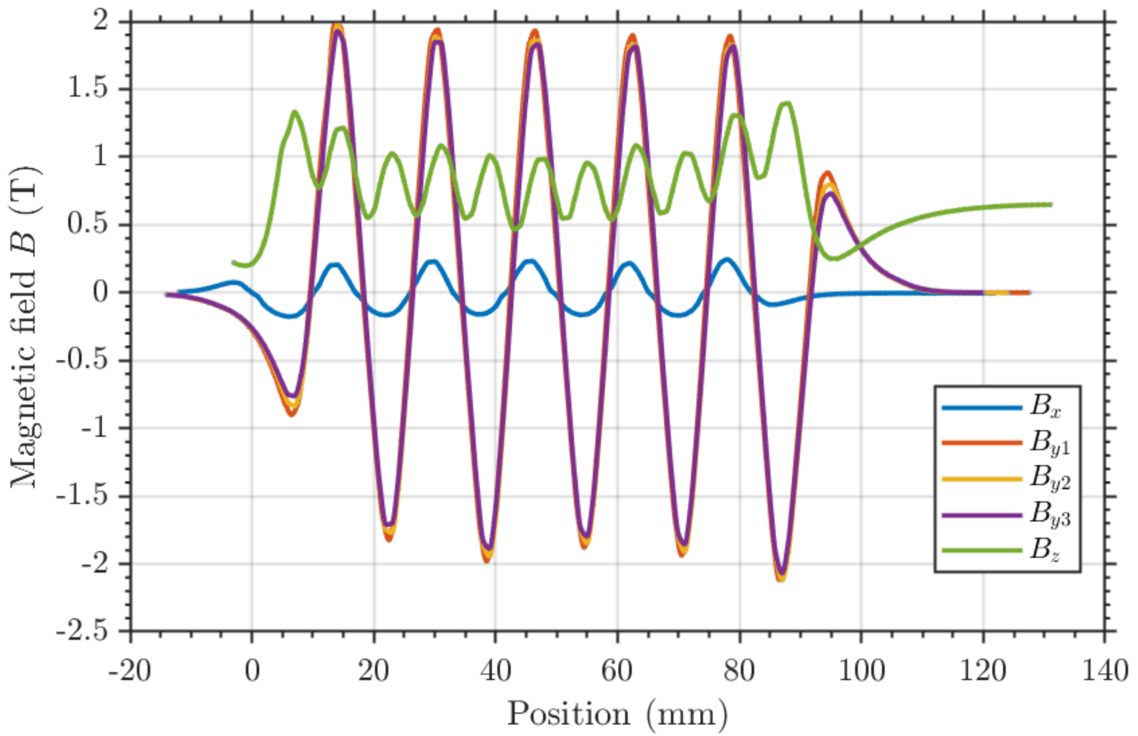


Measured magnetic field profiles at ΔB_s = 5 T

Round 3: FC From 5 T to -2 T @ 15 K

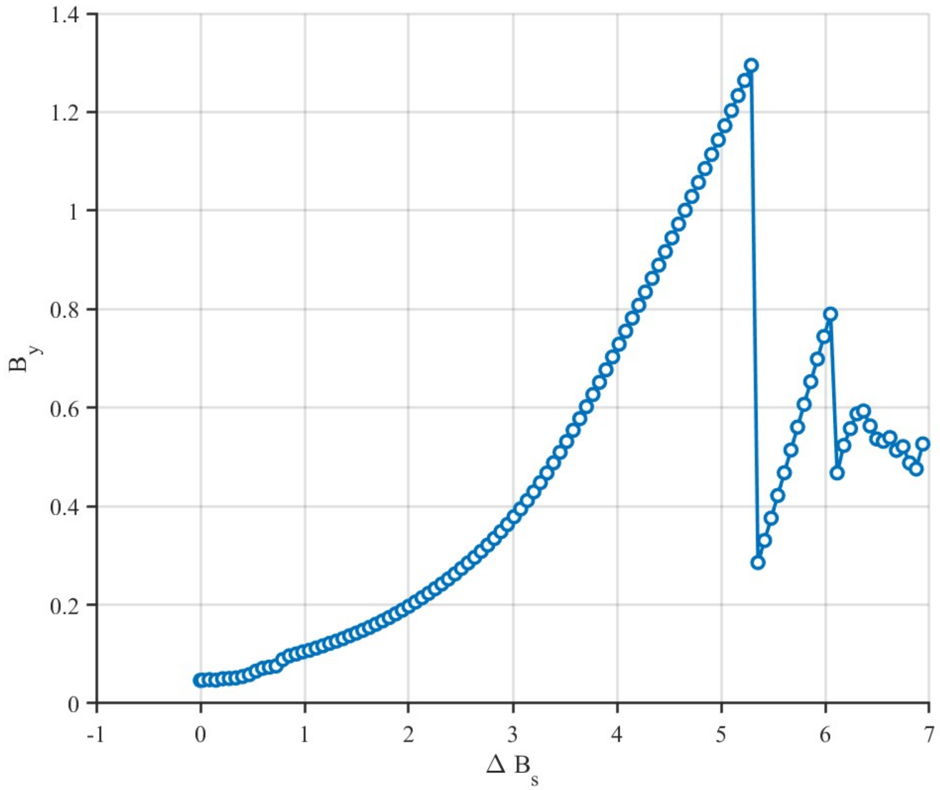


Relation between the mean undulator field B_y and ΔB_s

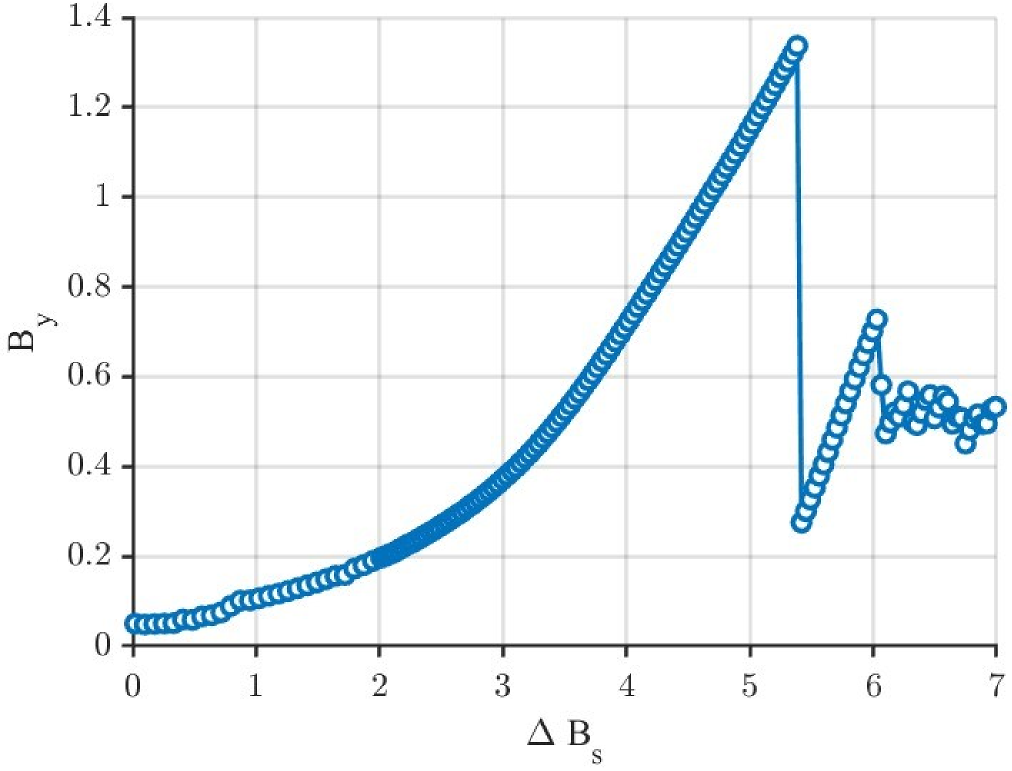


Measured magnetic field profiles at $\Delta B_s = 5.72$ T

Round 4: FC From 7 T to zero @ 10 K



Relation between the mean undulator field B_y and ΔB_s: ramp rate 1 T/h



Relation between the mean undulator field B_y and ΔB_s: ramp rate 0.5 T/h

Flux jumps occurred at 10 K, the next test will try to start magnetization from 5T.

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REBCO Tape-stack Helical Model

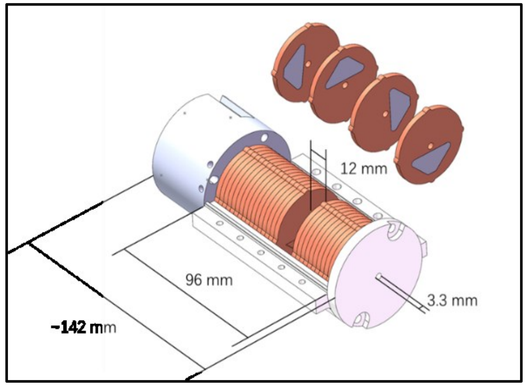
- A 6-periods helical SCU12 prototype based on stacked REBCO tapes was fabricated and tested.

  λ_u=12 mm

  g = 6 mm

  B_{sim} = ~ 48 mT

  B_0 = ~ 33 mT (FC from 0.3 T to 0 at 77 K)

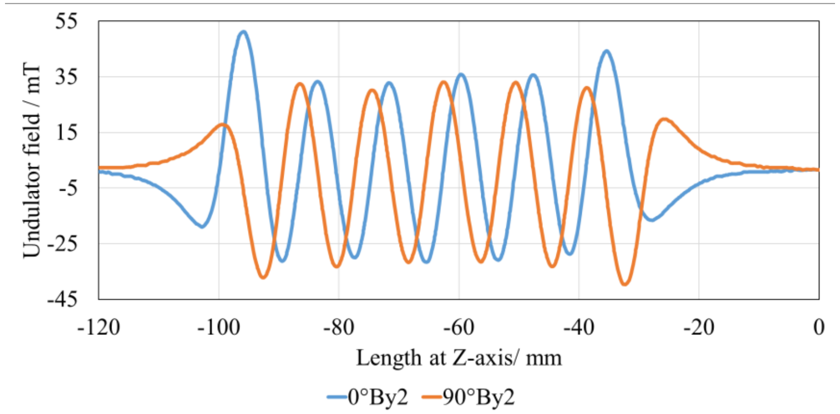


8-periods prototype design

Welding sample

6-periods prototype

Vertical field measurement system equipped with 0.3 T solenoid and 77 K



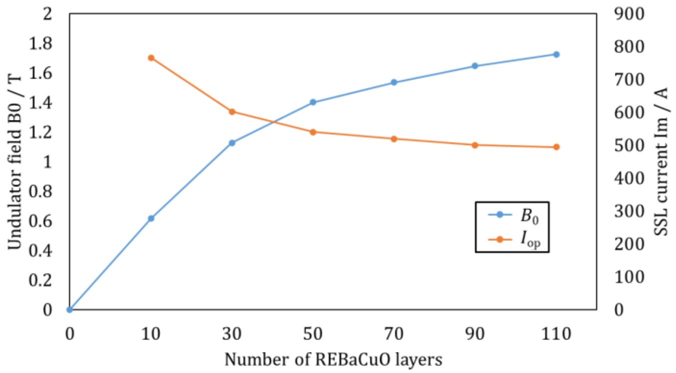
Helical field along the Z-axis after FC from 0.3 T to 0 at 77 K

Z. W. Chen et al., IEEE Trans. Appl. Supercond., vol. 36, no. 3, pp. , 4100205, 2026

This short model is now in Cambridge, soon to be tested.

REBCO Coil-based Helical Model

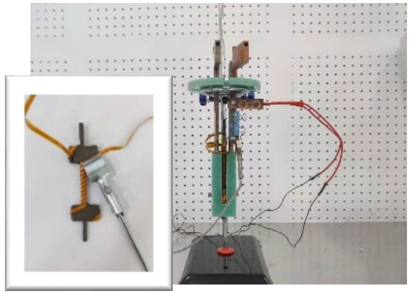
- Optimization results a field of 1.64 T can be obtained with 90 tapes and 500 A.

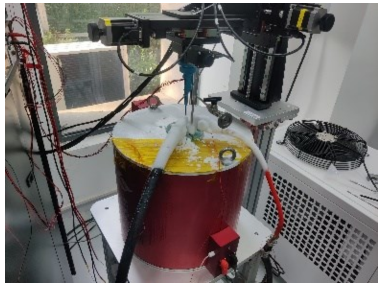


λ_u=12 mm
g = 6 mm

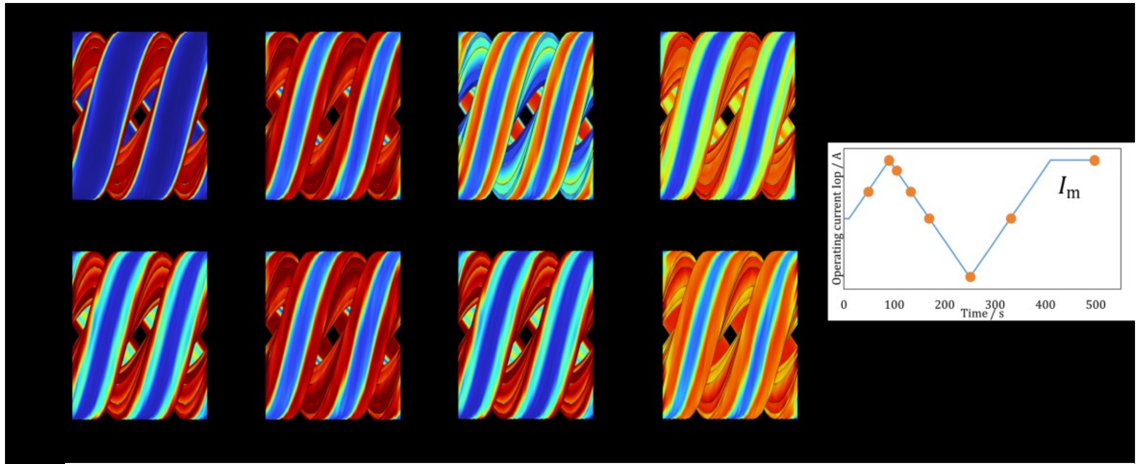
The relationship between I_{op}, B_0 and the number of HTS layers for HTSHSCU model.

- Two layer prototype fabrication and measurement charged with 40 A at 77 K, quenched > 90 A

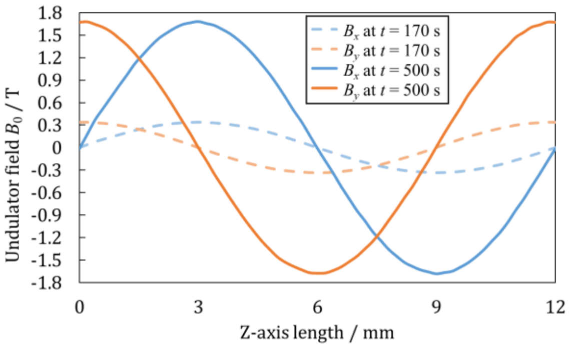




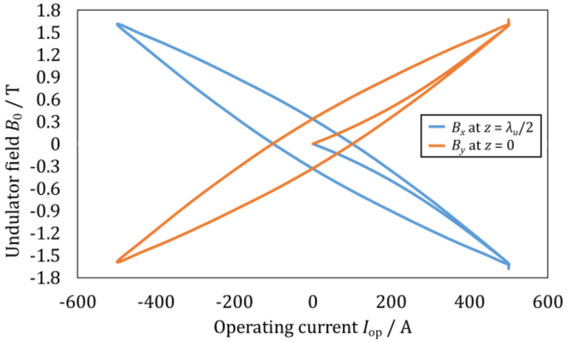
- Screening current induced field effect, remanent field and hysteresis behavior between B_0 and I_{op}



The temporal behavior of current density distribution and current operation strategy



B_0 and remanent field distributions (at the zero-net-current operating point, t=170s and 330s)



The hysteresis behavior between B_0 and I_{op}

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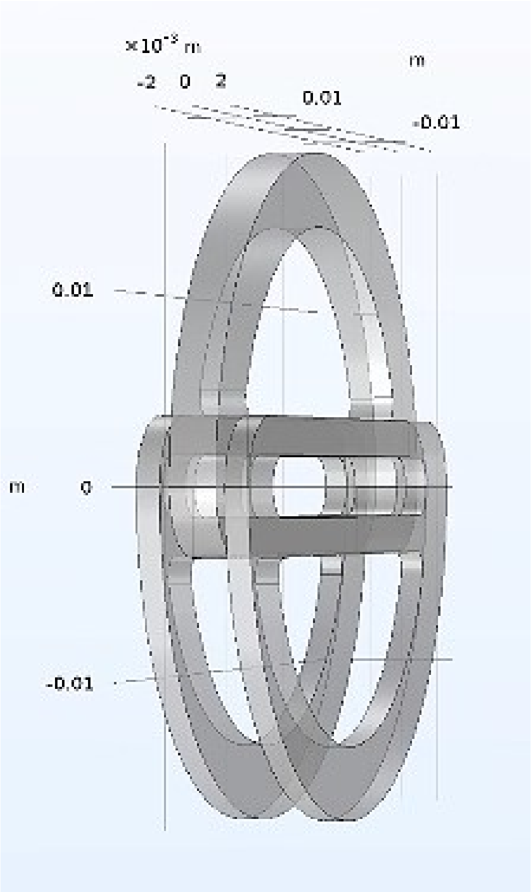
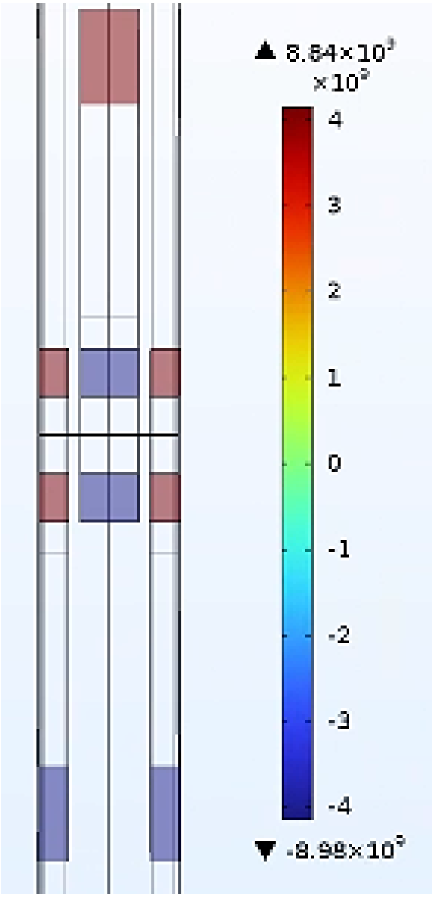
New Bulk Geometry for HTSU of 8 mm Period

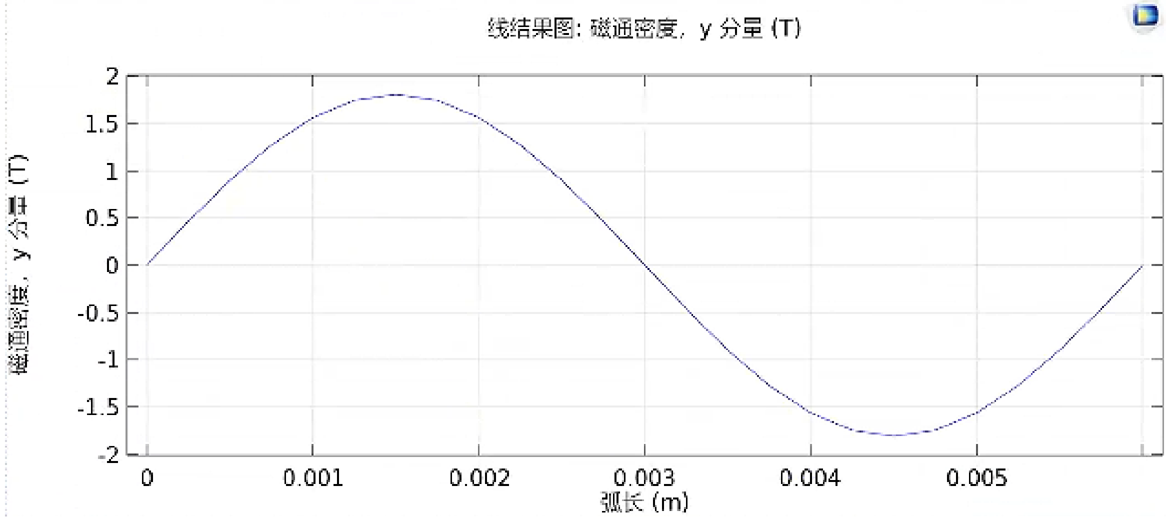
- 2 mm thick bulks
- 3.3 mm magnetic gap
- 17 mm radius
- 8 mm period length



Periodical model



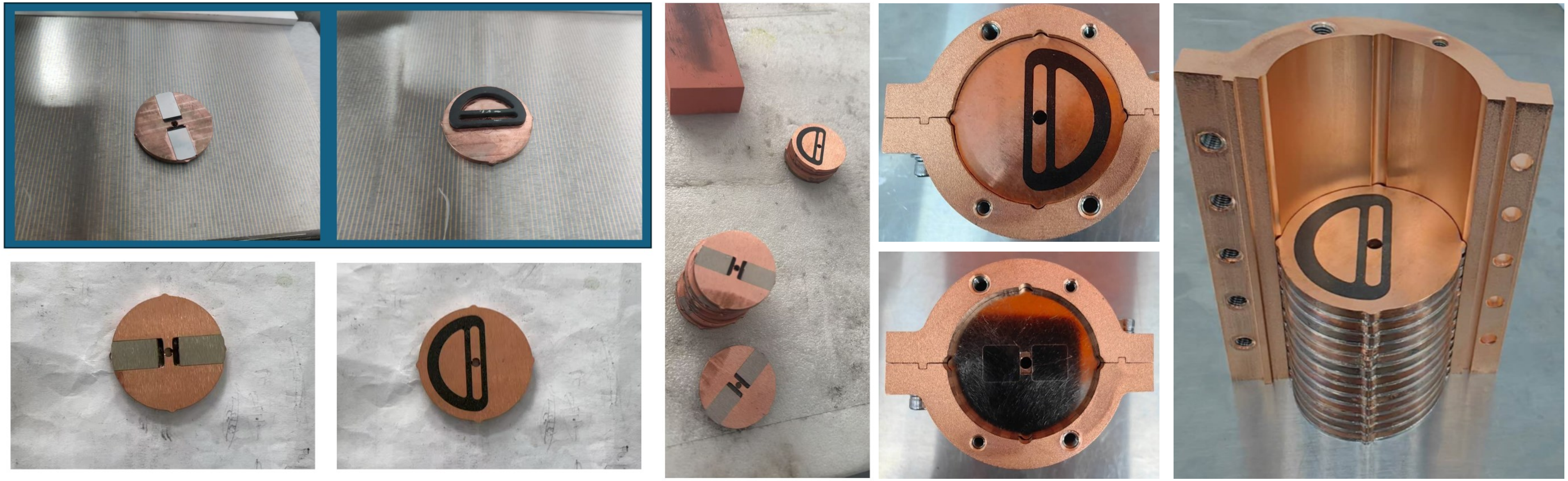
Curent density @ 10K



Simulated undulator field at 10 K

Y. M. Tong et al., IEEE Trans. Appl. Supercond., vol. 36, no. 5, pp. , 4606605, 2026

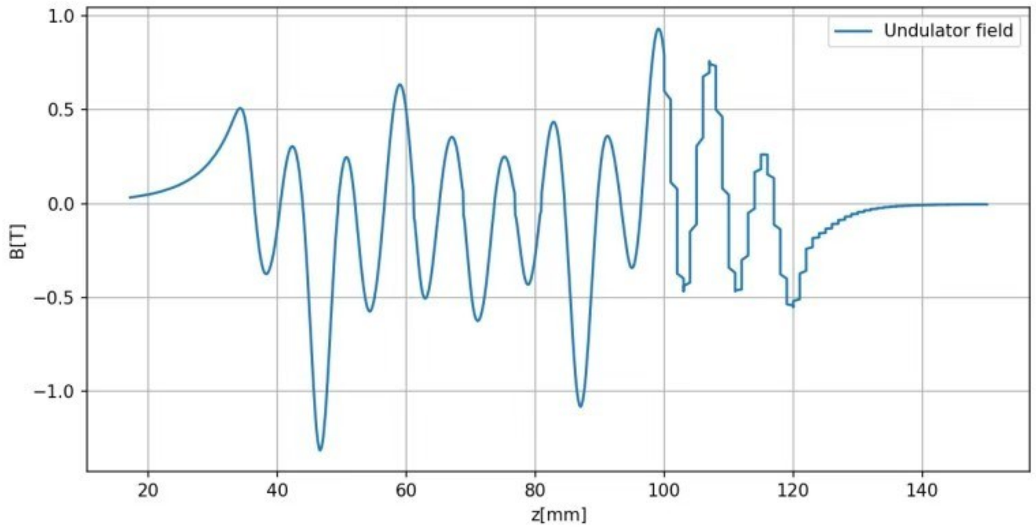
Short Model Fabrication and Assembly



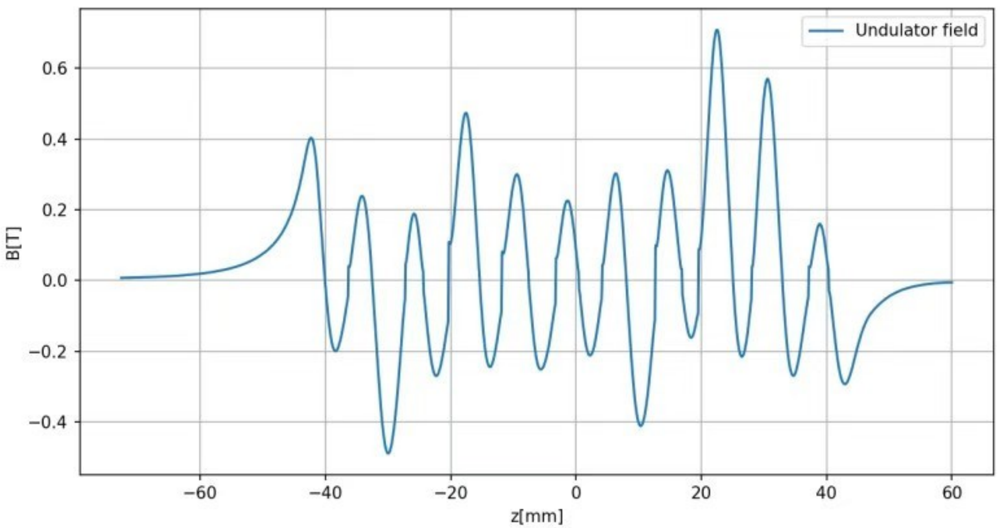
- Fabrication
  - Bulks cut with water-jet-laser
  - Bulk and Iron poles sticked with copper suppoter(EP)
  - Each silde is 3 mm think and made of a 2 mm thick hollowed Bulk, a pair of 1 mm thick CoFe coils and a copper structure to connect them.
- Assembly (11 periods)
  - An extra 1mm thick slide with a pair of CoFe poles is inserted between every 2 slides with bulks.
  - The rest pace in the shell is fulfilled with 1 mm thick copper slides.

Preliminary Experimental Results

- First results of measurement at Cambridge
  - Once under 20 K with solenoid field from 7 T to 0 T, once under 40 K from 3 T to 0 T
  - Both results have field peaks smaller and much more inhomogeneous than expected. It is probably caused by the inhomogeneity of the REBCO Bulks. The rest of the hollowed bulk has a smaller and various value of Jc than expected.
  - Test paused, a detailed examination of individual bulk pieces is planned.



FC from 7 T to zero @ 20 K



FC from 3 T to zero @ 40 K

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CONCLUSION

- Since Nov. 2025, HTSU12 has undergone more than 20 magnetization test campaigns. Among them, more than 10 quench events occurred. The quench events were attributed to multiple factors, including rapid ramp rate, large ΔBs, excessively low magnetization temperature, temperature-control delay, and other technical issues.
- HTSU12 has demonstrated an on-axis $B_0 \approx 1.8$ T for a $\lambda_u = 12$ mm and g = 4.5 at 7 K. The magnetic field non-uniformity was reduced from 3.55% to 1.3% following sorting and initial shimming. Ongoing efforts, including inverse analysis and levitation force evaluation are be conducted to further reduce the field inhomogeneity and RMS phase error.
- However, new challenges have emerged: the silver coating was observed to delaminate from the REBCO bulks following repeated thermal cycling between 77 K and 300 K.

- Three short undulator samples were fabricated and experimentally evaluated in close collaboration with PSI and Cambridge. The initial tests of the first MgB2 -based sample demonstrated promising performance, indicating that magnetic field decay can be effectively suppressed after flux freezing. Additional experimental data from the remaining two samples are expected to be collected and analyzed in the coming weeks.