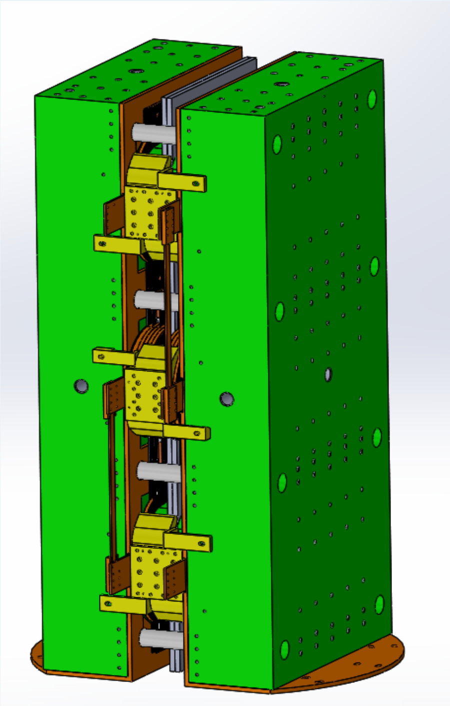
Recent Progress of 5T HTS Wavelength Shifter Development



Garam Hahn
on behalf of the magnet group in PAL
& HTS magnet research group in Seoul National University

November 13, 2023

POHANG ACCELERATOR LABORATORY

Introduction

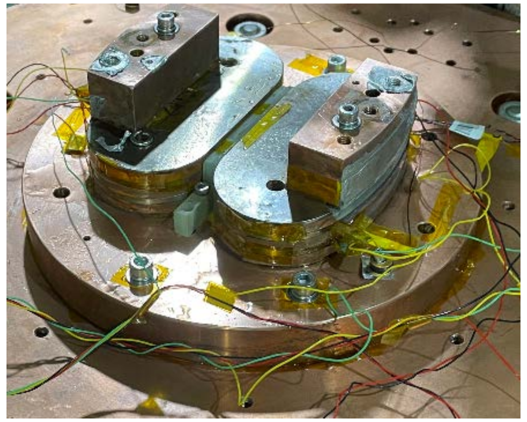
- Purpose : To develop an ID technology for future light sources
  - ☐ Warm iron dominated accelerator magnet → Permanent magnet ID → Cryogenic PMU || LTS wiggler || **HTS wiggler**
- Specific Goals
  - ☐ Magnetic field strength > 5 tesla = making higher energy photon > 100 keV
  - ☐ LHe-free cryogenic system by adopting a conduction cooling Tech. for saving operational cost
  - ☐ Enabling the above by using ReBCO conductor + NI technology Operation temperature ~ 20 K Maximize reliability (almost quench free)
- Current Status
  - ☐ Design : Yoke, HTS coil-sets, vacuum, & cryogenic system (100%)
  - ☐ Fabrication : Magnet (100%), Vacuum(100%), Cryostat (95%)
  - ☐ Core Magnet Test : Achieved 5.02 tesla, with an existing cryostat (Cond. cooled)
  - ☐ Now : Preparation of a precise field-map meas. & a beam test

- Work Plan : (2020) HTS ID prototyping → (2022-) HTS 3-pole wiggler → (2023-) HTS multipole wiggler

Cryogen-free Conduction-cooled REBCO Undulator (2020-2021)

Magnetic period = 14 mm;

Number of Period = 1.5; Pole field = 0.8 T



Cryogen-free Conduction-cooled REBCO Wavelength Shifter (2022 -)

Magnetic period = 0.42 m (no constraints);

Number of Period = 1.5; Pole field = 5.02 T

Crygen-free Conduction Cooled REBCO Wiggler (2022 -)

Magnetic length < 60 mm

Number of Period > 5; Pole field > 4 T

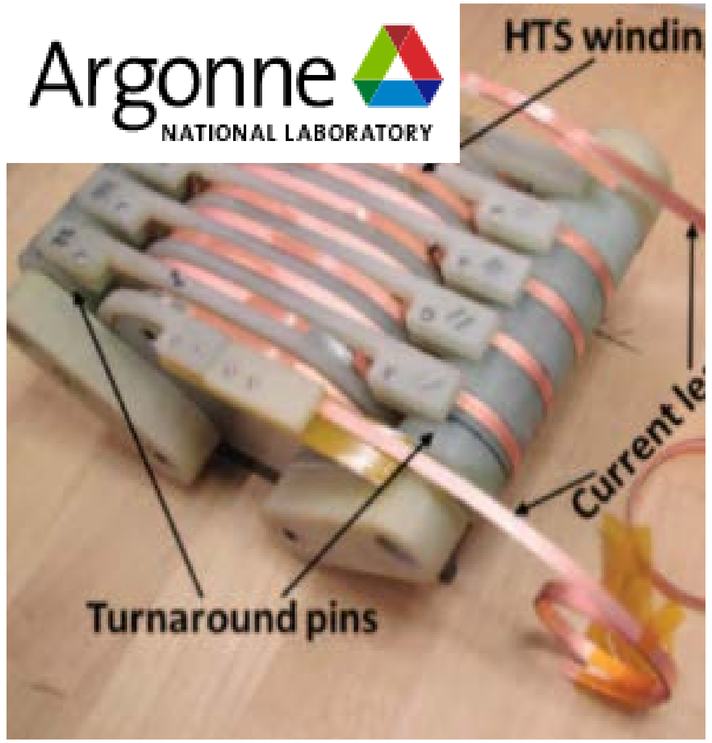
Survey

- Current status of HTS ID development of the leading groups
  - Various research is conducted by KIT, ANL, CAS, PSI, and CERN (Col. with KIT) by using LTS & HTS technology
  - Regarding HTS, a few attempts have been reported but R&D for production is mostly concentrated to LTS + LHe.

Karlsruher Institut of Technology, Germany

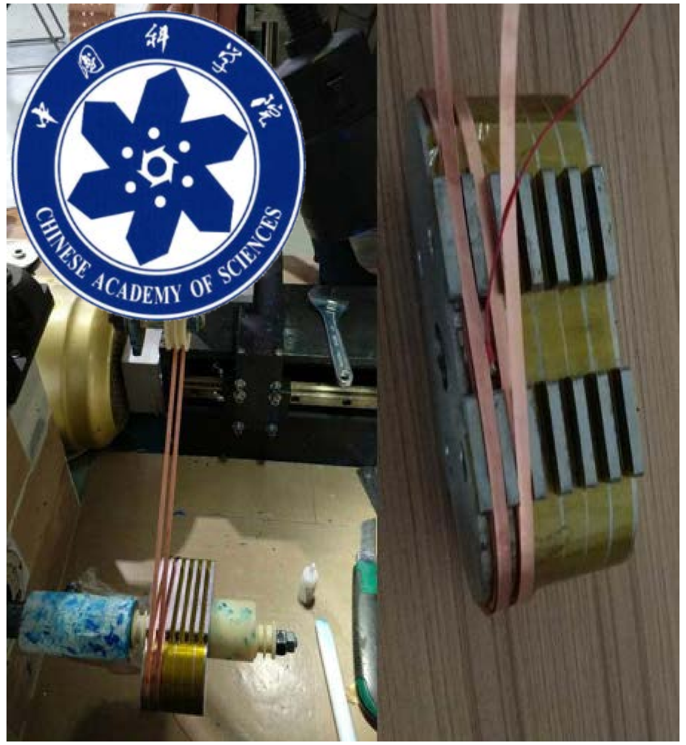
[4]: T Holubek *et al.*, "A novel concept of high temperature superconductor undulator," *Supercond. Sci. Technol., vol 30, no.11, 115002* (2017)

Argonne National University, USA



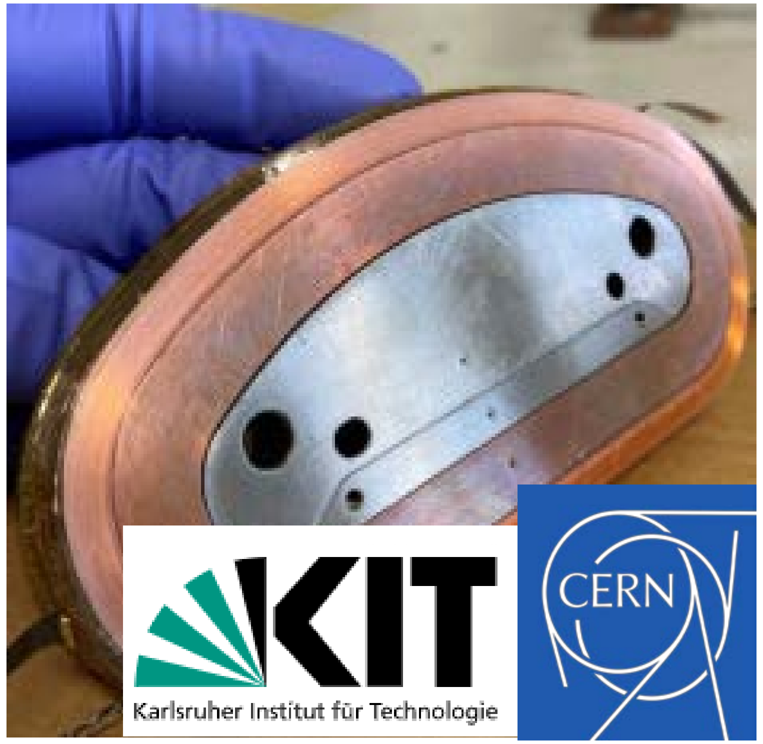
[5]: Y. Ivanyushenkov and *et al.*, "Status of the Development of Superconducting Undulators at the Advanced Photon Source," *Synchrotron Radiation News*, (2018)

Chines Academy of Sciences, China



[6]: Schichang Liu *et al.*, "Development of a Short REBCO Undulator Magnet With Resistive Joints,", *vol 29, no. 6, 4100204, IEEE. Trans. Appl. Supercond.* (2019)

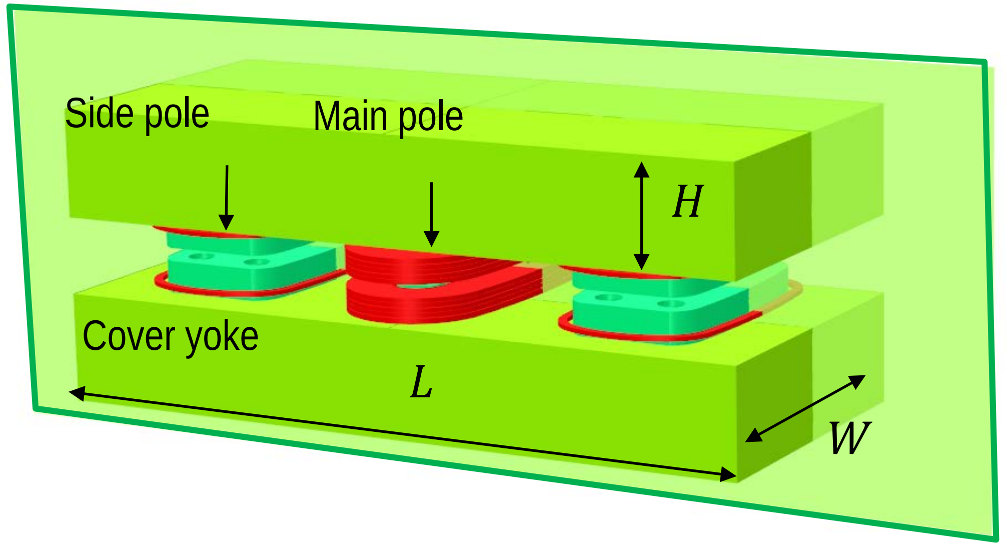
CERN, Karlsruher Institut of Technology, Europe

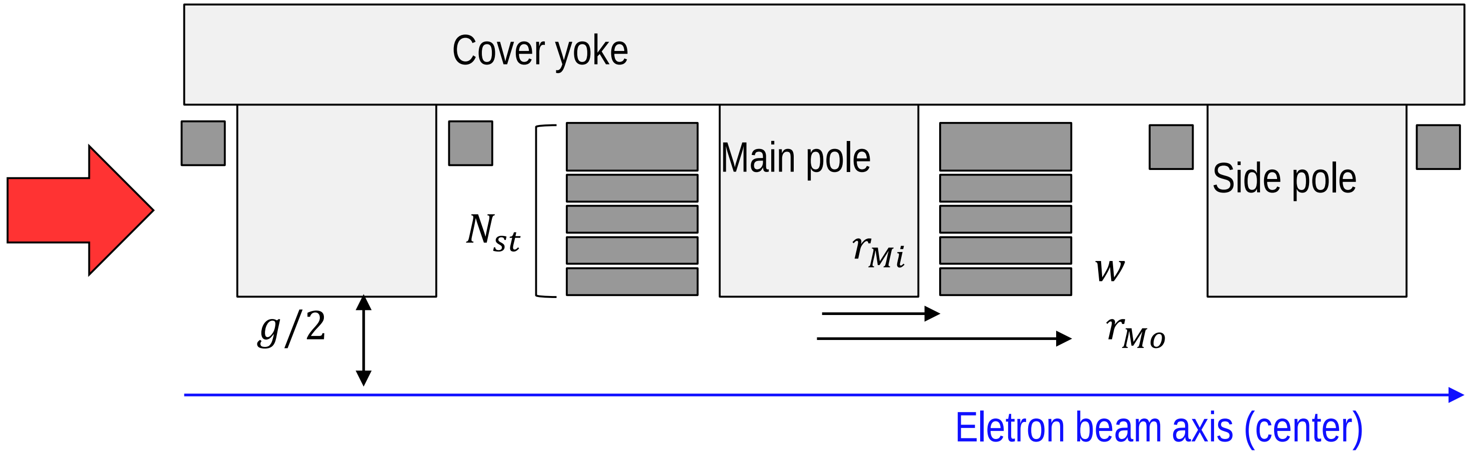


[7]: S.C. Richter *et al.*, "Progress on HTS undulator prototype coils for compact FEL designs,", *vol 32, no. 4, 4100305, IEEE. Trans. Appl. Supercond.* (2022)

EM Design

- HTS Wavelength Shifter
  - Key Design Concepts: (1) multi-width; (2) conduction cooling; (3) metal insulation
    - Multi-width: combination of 4 mm and 5 mm width REBCO conductor
    - Conduction cooling: critical current margin of >20% considering conduction cooling operation





Max. $F(x)$=$(f_1(x), f_2(x))$

$f_1(x) = B_M; f_2(x) = l_{REBCO}; x = (N_{stack}, N_M, H)$

Swept Parameters			
	Min	Max	Interval
N_{stack}	4	10	1
N_M [turns]	100	300	25
H [mm]	50	150	50

g: magnetic gap (=12 mm) N_M: Number of mainpole turns H: Yoke thcikness

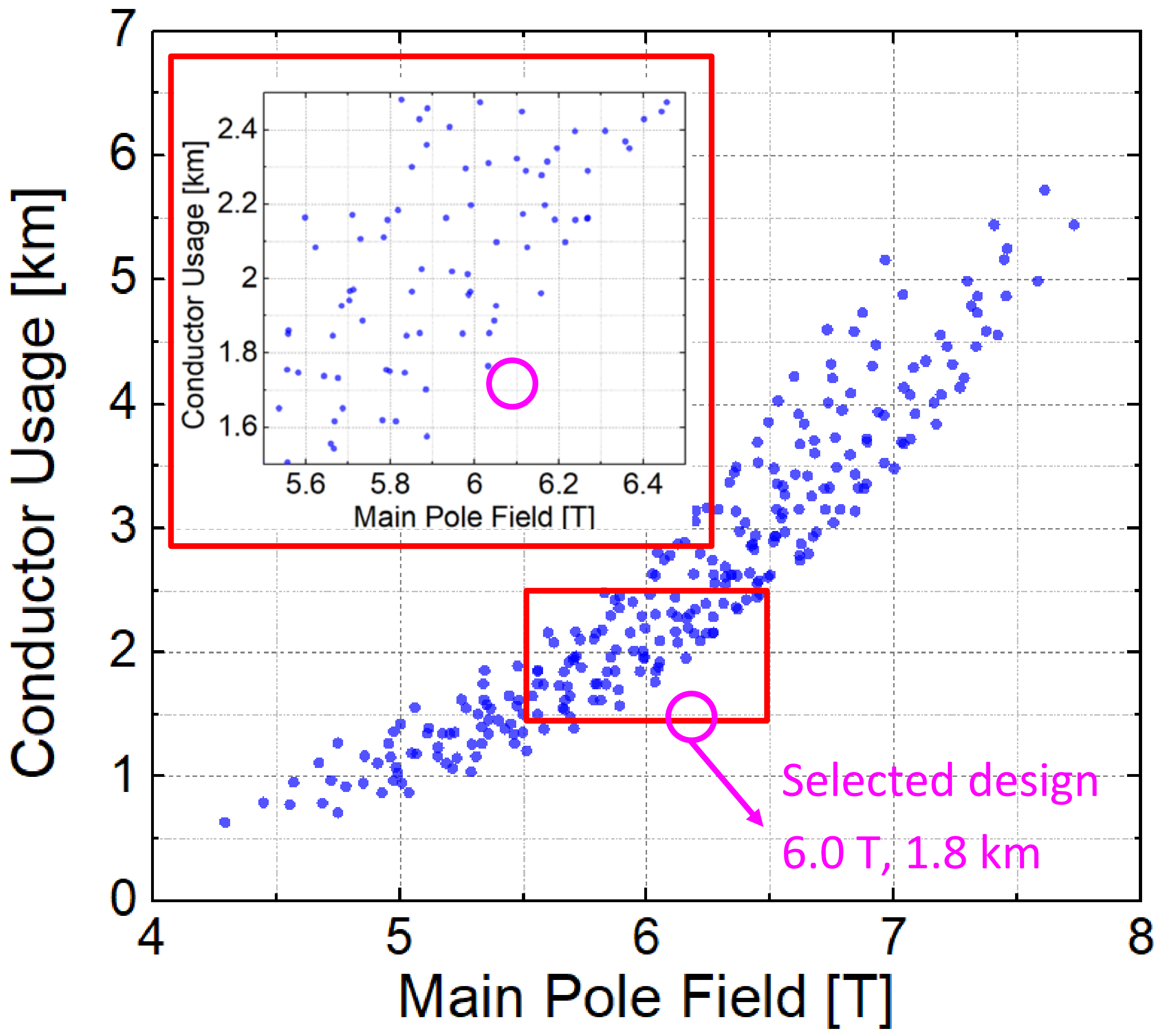
L: Yoke length (=670mm) W: Yoke width (=300 mm) N_{st}: number of stacks

r_{Mi}: Inner radius of mainpole t_{cd}: conductor thickenss (=0.2 mm)

r_{Mo}: Outer radius of mainpole (=$r_{Mi} + t_{cd}N_M$) w_i: i^th stack width (4.1, 5.1 mm)

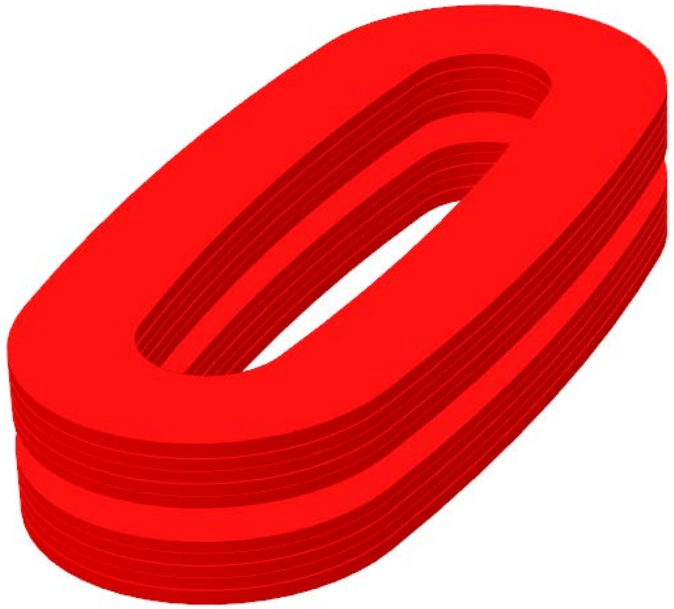
Cost Optimization

- Parameter Sweep Results
  - Final design is selected considering HTS conductor in stock (~1.8 km) ~ 43,200 KRW (24 k KRW/meter)



(N_{stack}, N_M, H)= (5, 200 ,100 mm)

l_{REBCO} = 1.8 km

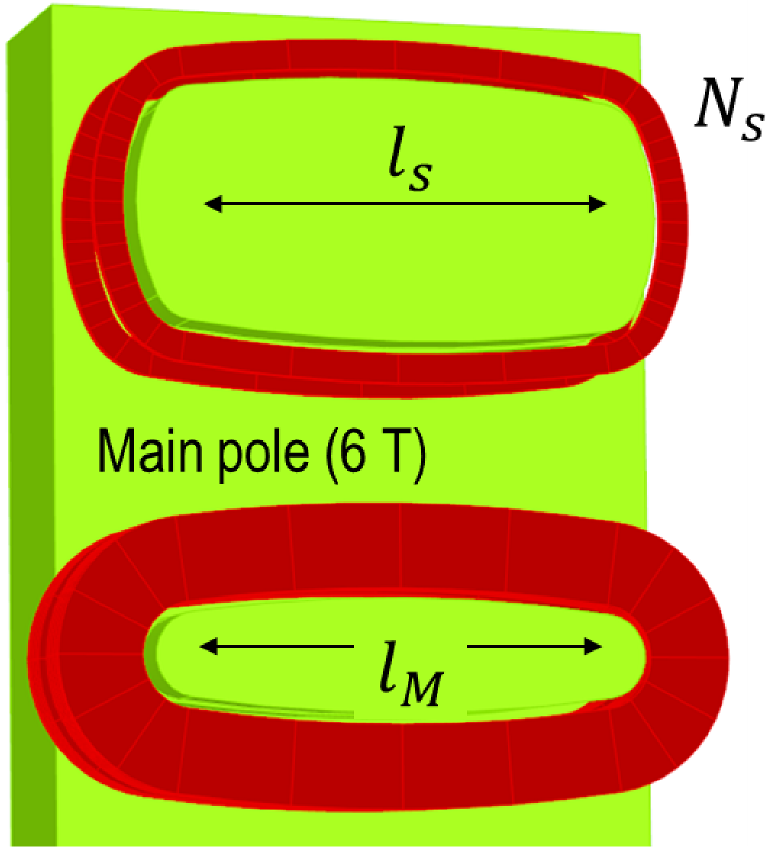


Multi-width combinations of

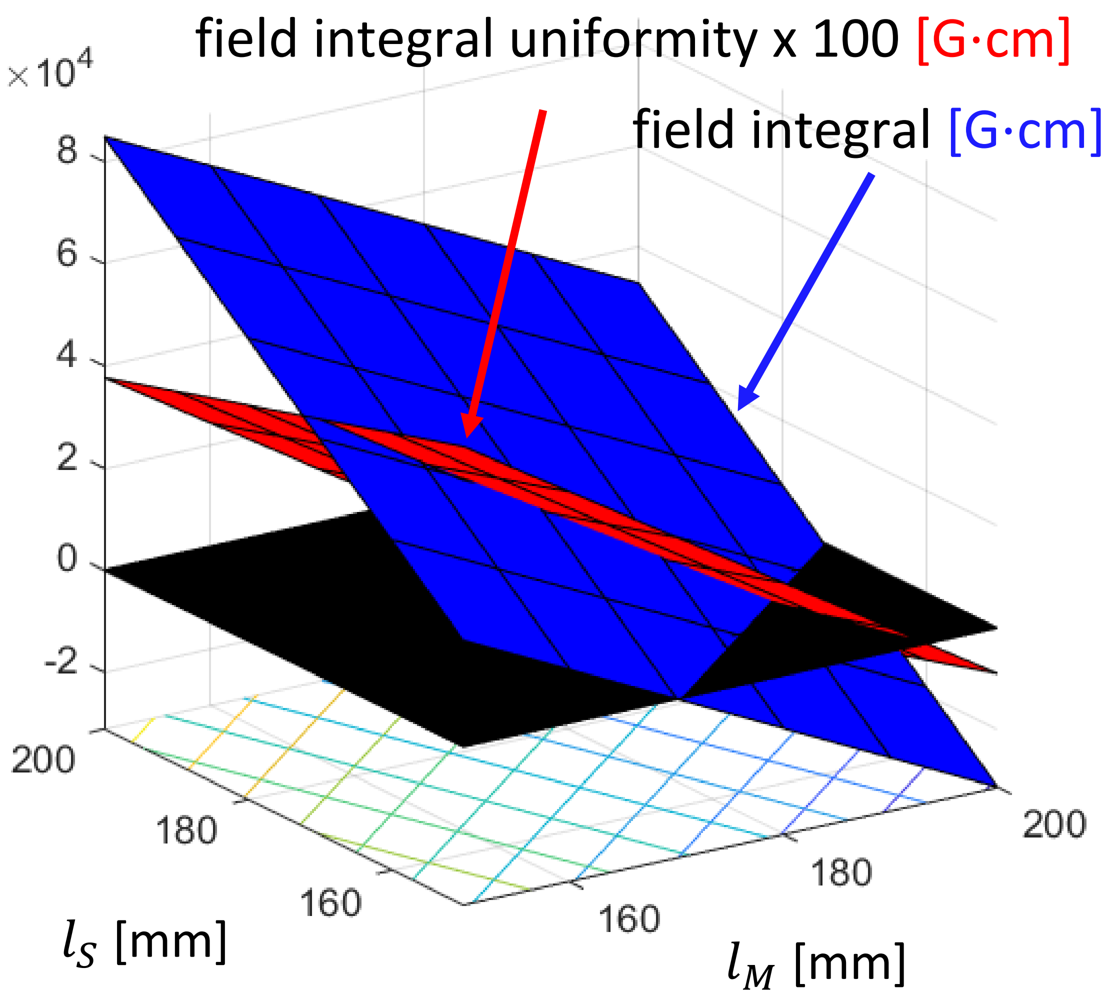
[4 mm; 4 mm; 4 mm; 4mm; 5 mm]

Field Quality

- Field Uniformity Requirements for Beam Operation
  - (1) zero field integral ($\int B_y\, dz$); (2) field integral uniformity at x=15 mm: <100 G·cm



N_s: side pole turns [null]
l_M: main pole length [mm]
l_s: side pole length [mm]



Selected dimension to minimize field integral
l_M=188 mm; l_S=166 mm; N_S=40

Stress Analysis

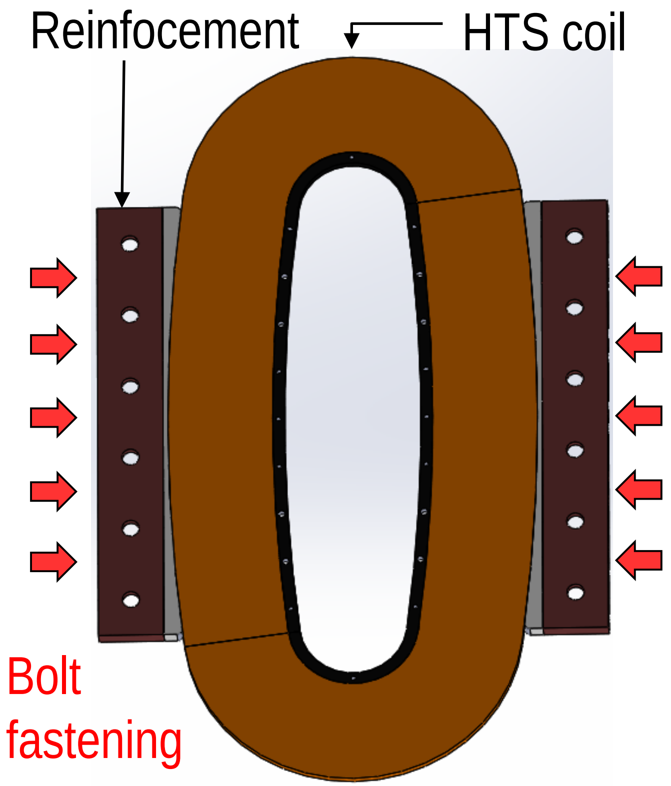
- Stress Analysis of Racetrack Shaped Mainpole Coil[11]
  - Modeling: (1) roller; (2) contact pair; (3) spring foundation
  - Maximum hoop stress of 97 MPa

Governing Equation

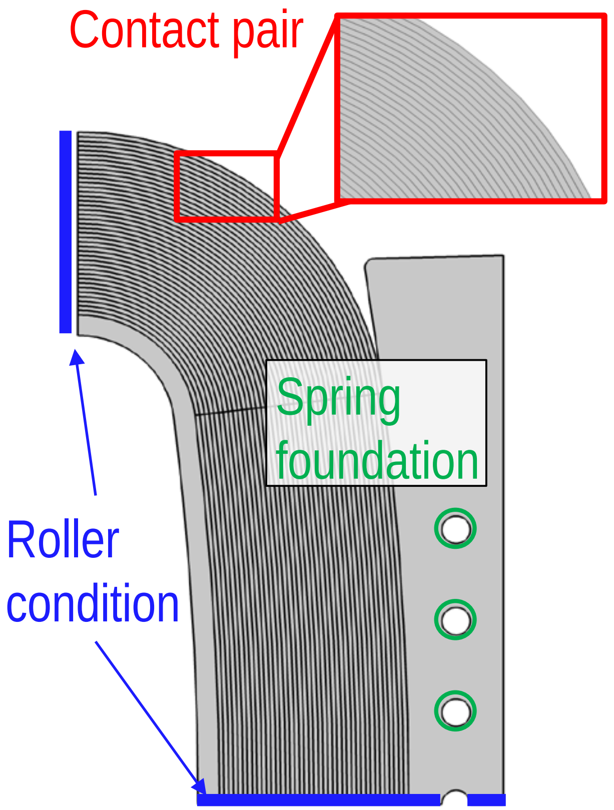
Force balance: $\nabla\sigma + \overrightarrow{f_v} = 0$

Roller condition: $\vec{u} \cdot \hat{n} = 0$

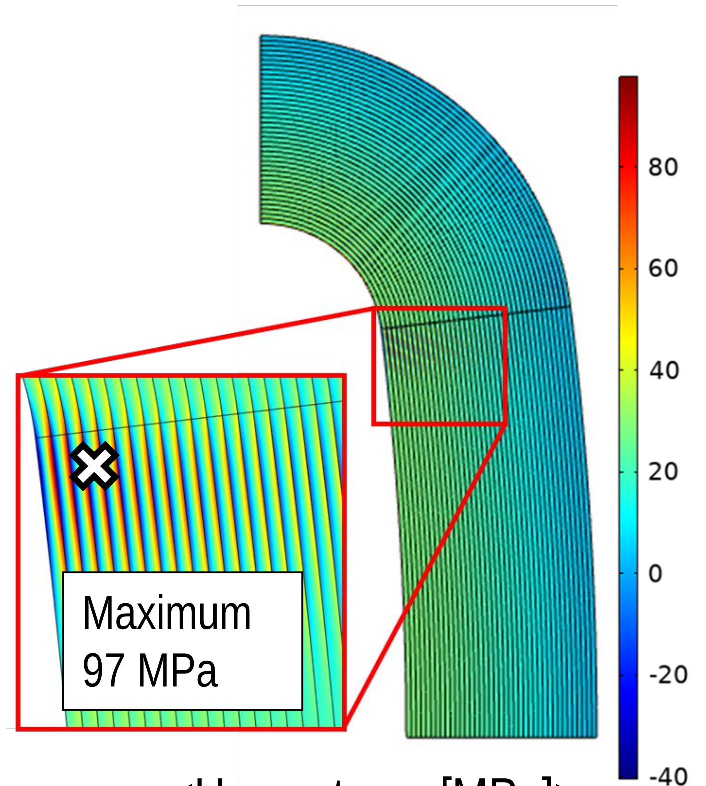
Spring foundation: $\vec{f} = -ku$



<Racetrack coil structure>



<Modeling>



<Hoop stress [MPa]>

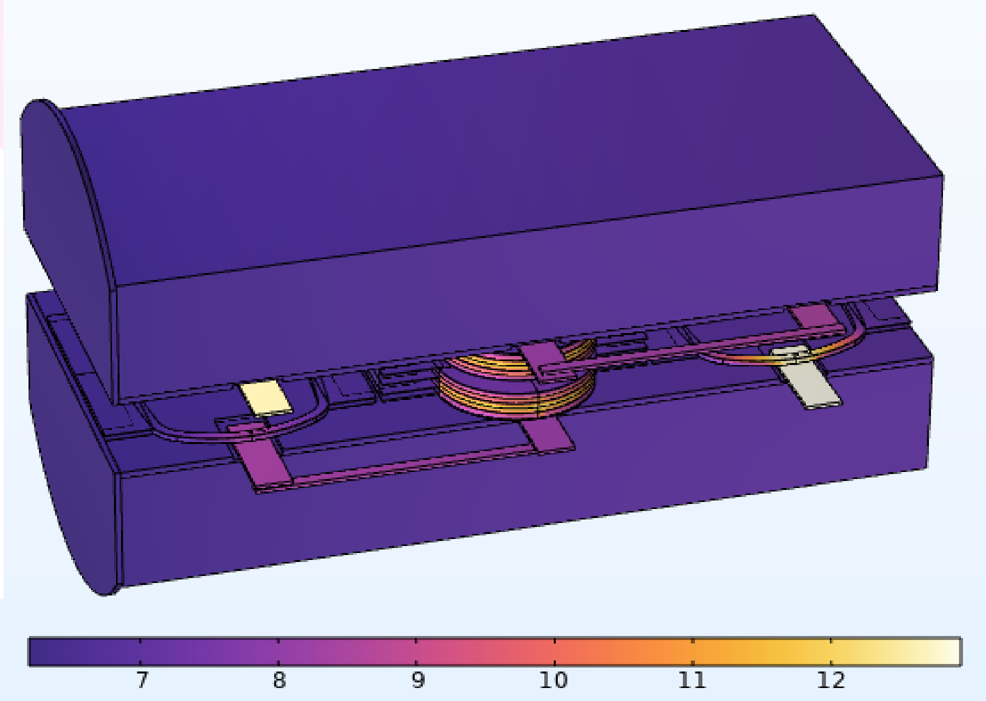
[11] U bong *et al.*, "Numerical Studies on mechanical behavior of dry wound HTS racetrack coil," *IEEE. Trans. Appl. Supercond.*, 30.4, 2020

Thermal Analysis

- Heat load and Local Temperature Analysis Results: maximum T of 13 K
  - Heat source: conduction; radiation; resistance; beam induced heat loads
  - Cooling source: cryocooler (PT815)

Governing Equation

Heat equation: $\rho C \frac{\partial T}{\partial t} + \nabla q = 0$



Temperature [K]

Heat source [W]		2nd stage	1st stage
Conduction	Magnet support	<1	<1
	Beamduct support	<0.1	<1
	Beamduct conduction	1.8	9.4
Radiation	Radiation	0.1	16.1
Resistance	Resistive joint	0.16	0
	NI leakage current	<1	0
	Current lead	0.3	33.6
Beam	Image current + Wake impedance	3.3	
	Synchrotron radiation	<1	<1
Total [W]		<10	<65.5
Cooling margin [W]		18	75

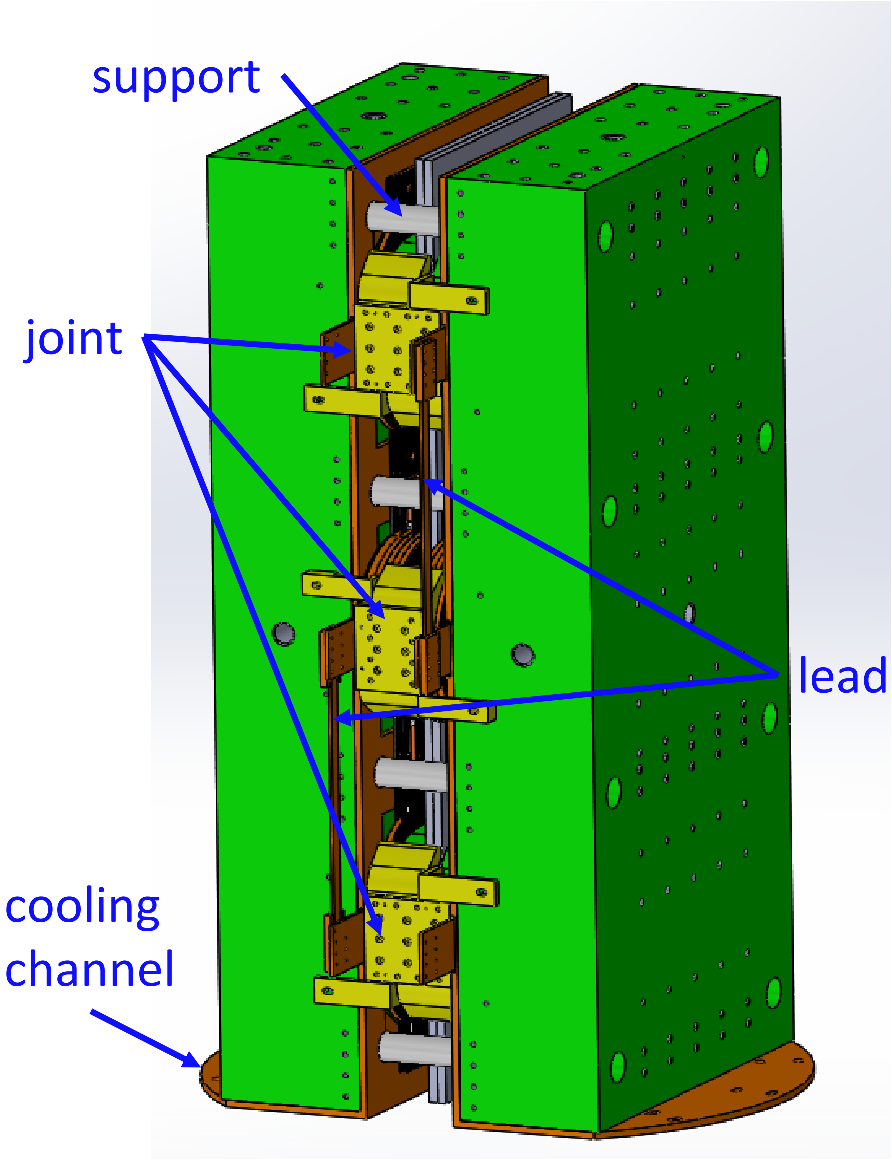
Design Result Summary

Key Design parameters

Parameters	Unit	Main pole	Side pole
REBCO tape width	[mm]	4.1; 5.1	
Tape thickness	[um]	140 (REBCO; 60 (SUS)	
Magnetic Gap, g	[mm]	12	
Overall dimension	[mm]	270 x 300 x 670	
Turn per pancake	[Turns]	200	40
Number of Stacks		5	1
Total tape length	[km]	1.8 (4 mm equivalent)	
Magnet Weight	[kg]	360	
Inductance	[H]	5.5-0.7	
Operating current	[A]	173	
Center field at Iop	[T]	6.0	1.8
Temperature, T_{op}	[K]	< 20	

Engineering Design Results

- Total of 37 parts



Design Result Summary (Cont'd)

■ Key Design parameters

Parameters	Unit	Main pole	Side pole
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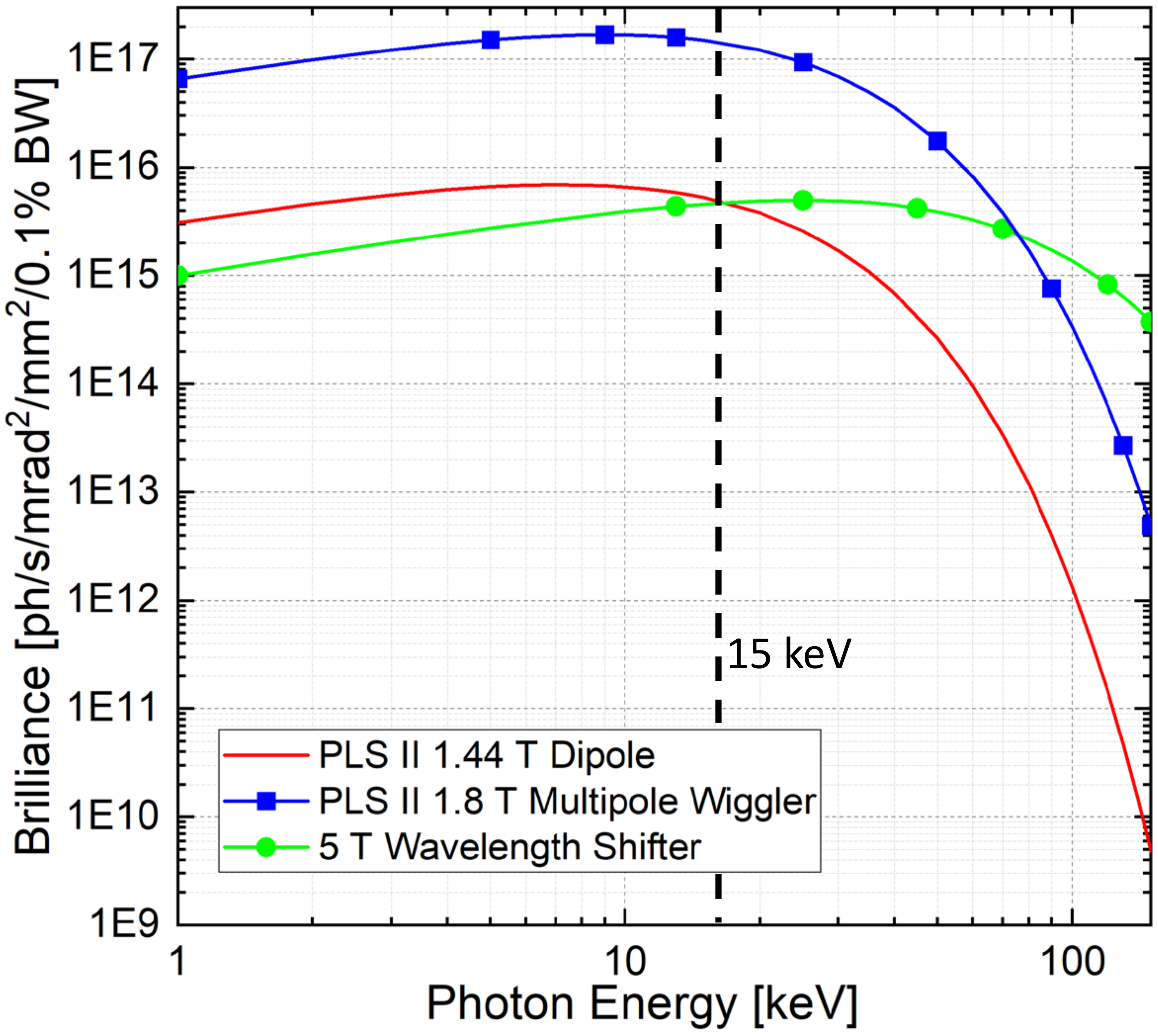
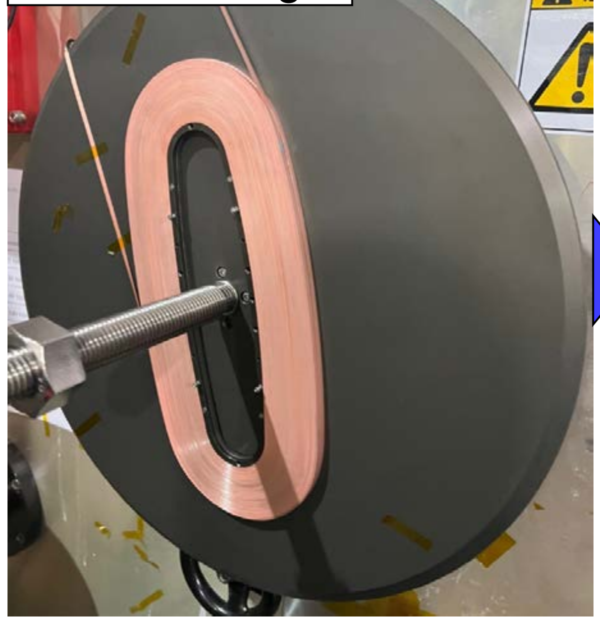
Operating current	[A]	173	
Center field at Iop	[T]	6.0	1.8
Temperature, T_{op}	[K]	< 20	



Glimpse of Fabrication

1. Winding

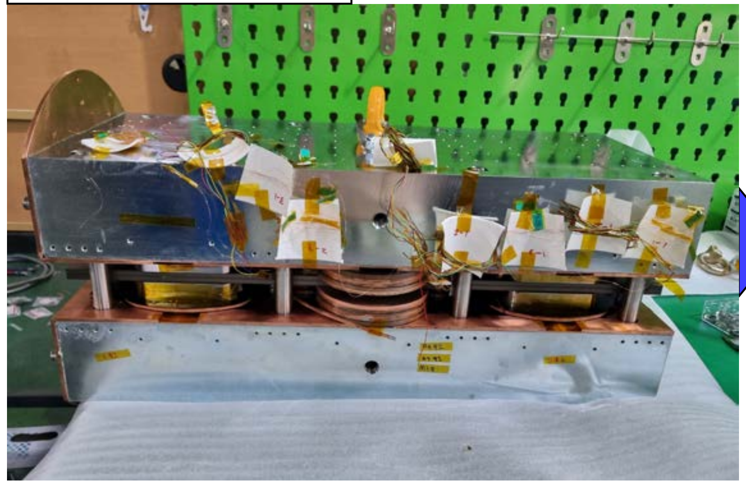


2. LN2 test

3. Cooling channel

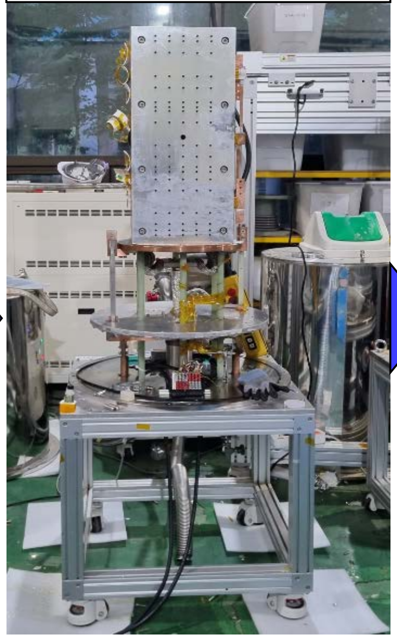
4. Stacking

5. Preload



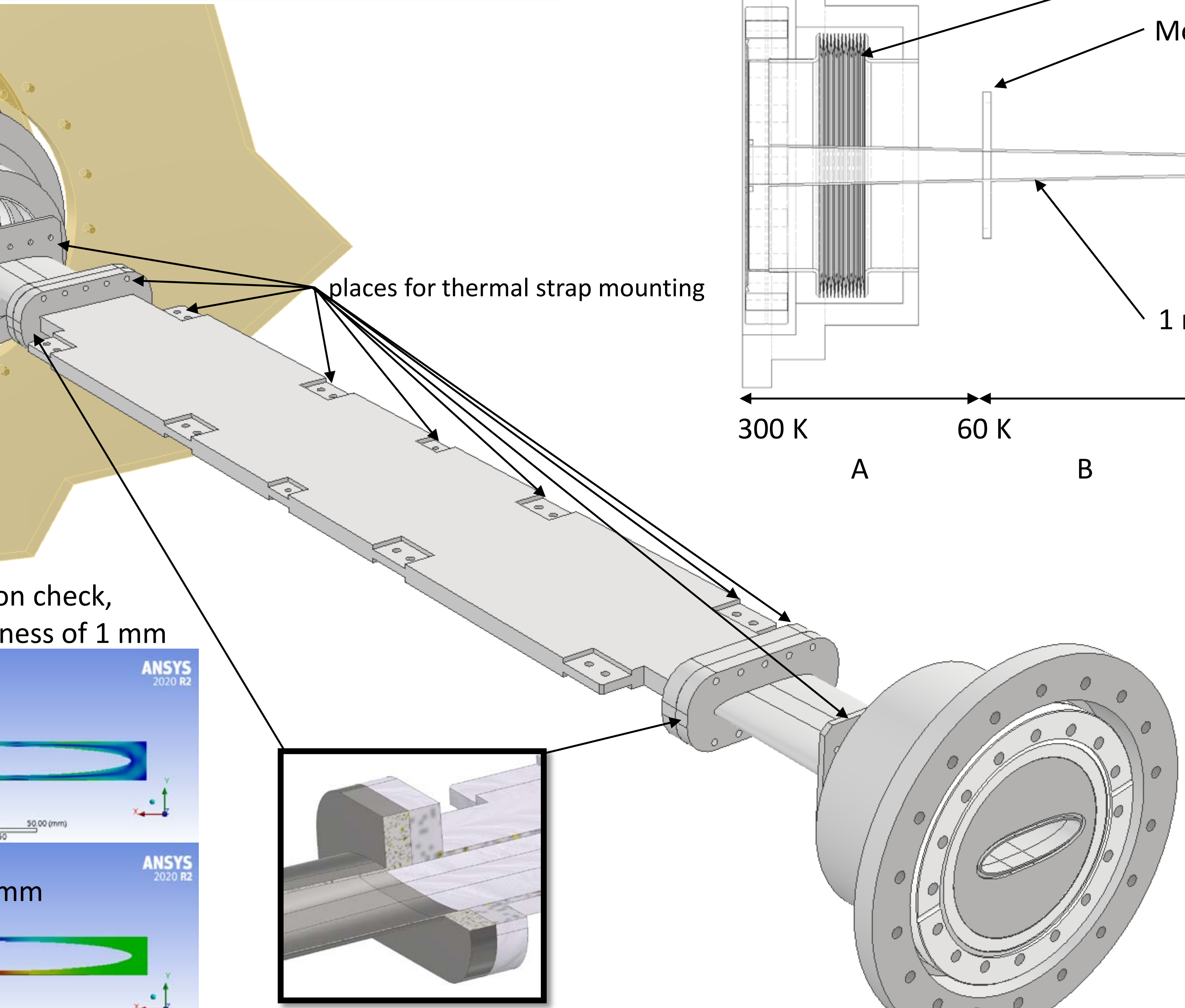
6. Joint & lead

7. Assemble

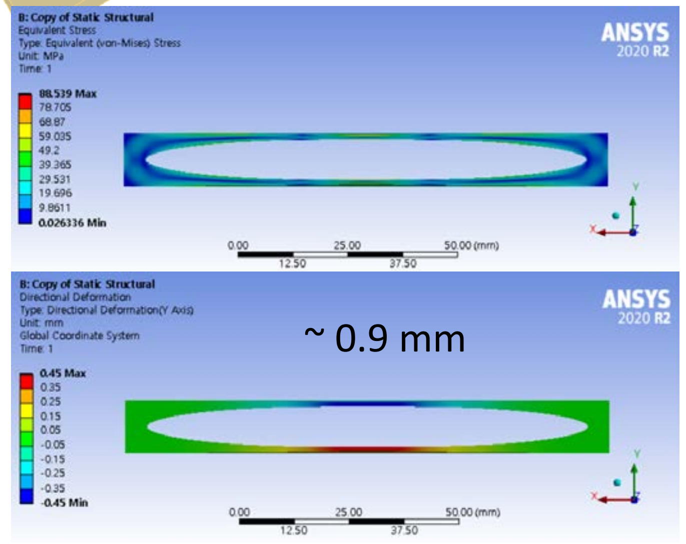


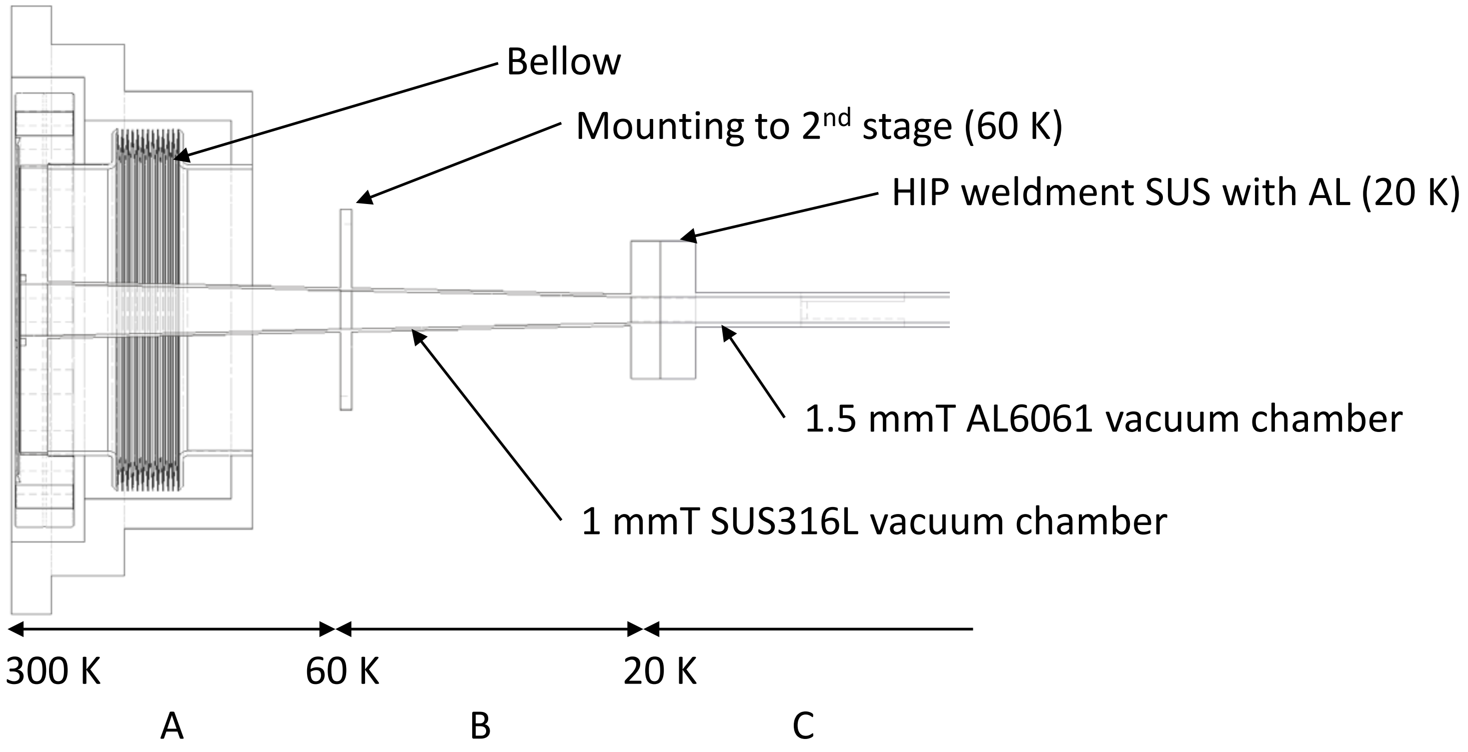
8. Operation

Vacuum Chamber



Mechanical deformation check,
AL chamber with thickness of 1 mm





He Leak Rate : < 3.0 x 10-9 mbar . l/sec

Op. temperature : 20 k , 60 k

A,B : SUS316L (Thermal transition section),

C : AL5083/AL6061 (Low temperature section),

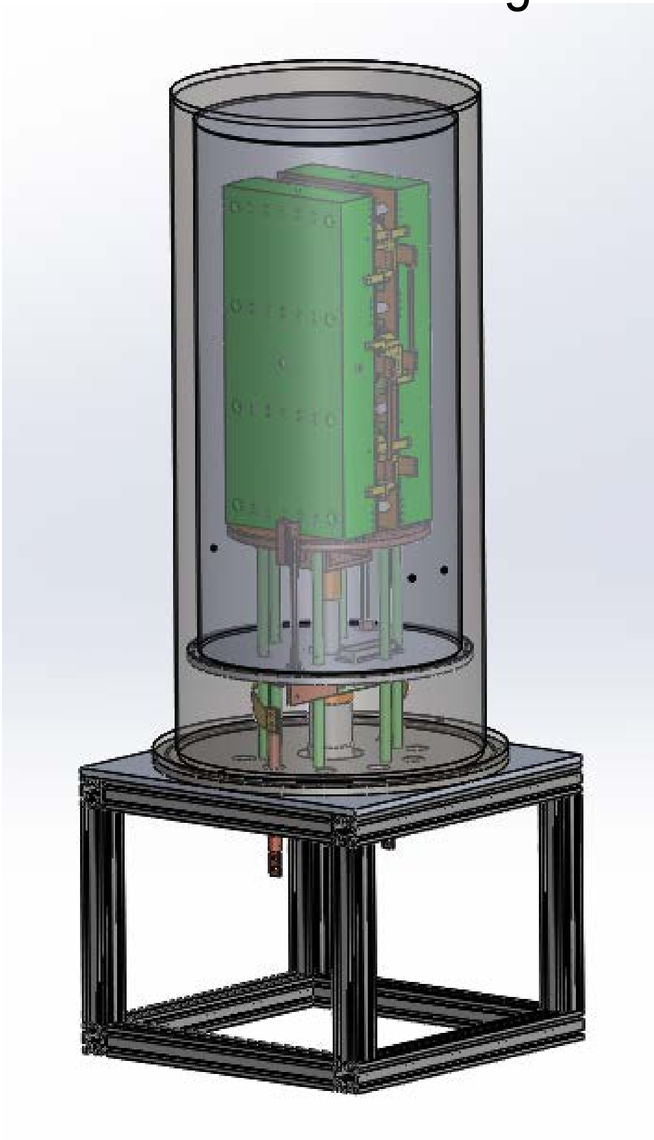
Wake Impedance (PLS-II, 400 mA operation)

Loss factor	: 7.027 mV/pC
P_d per bunch	: 12.43 mW
P_d in total	: 3.73 W

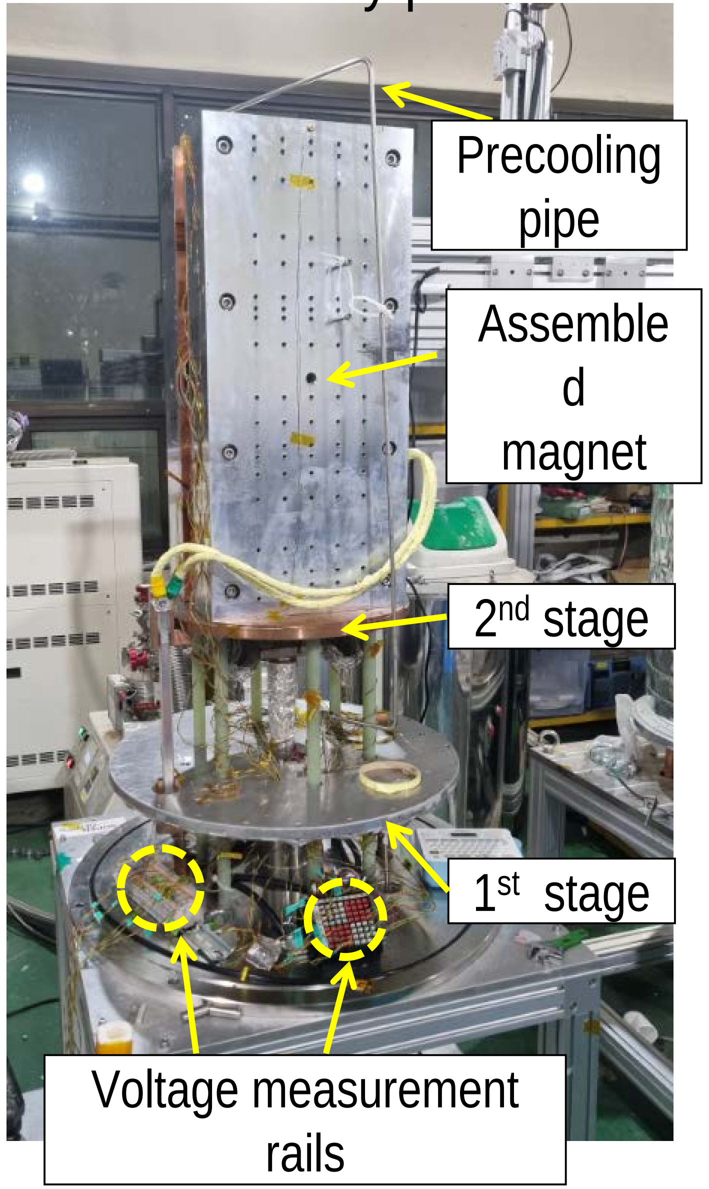
$$P = -\frac{loss(V/pC) * (1.33\,nC)^2}{10^{-6} sec}$$

Test Environment

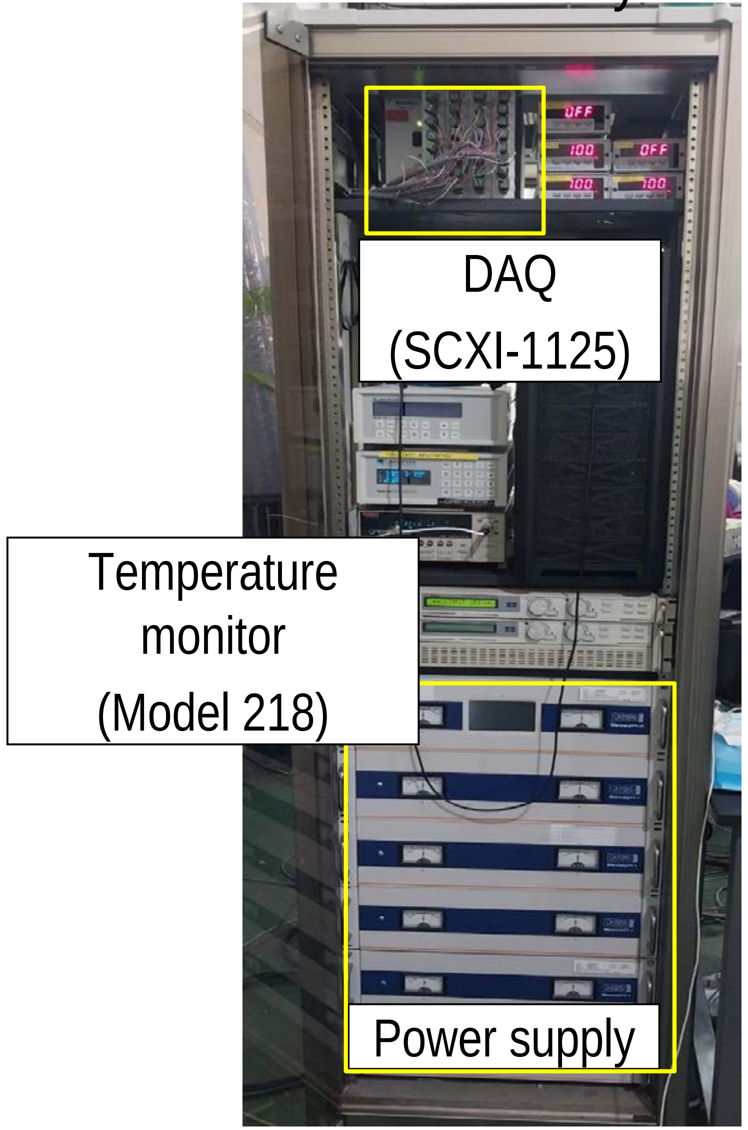
<CAD Drawing>



<Assembly picture>

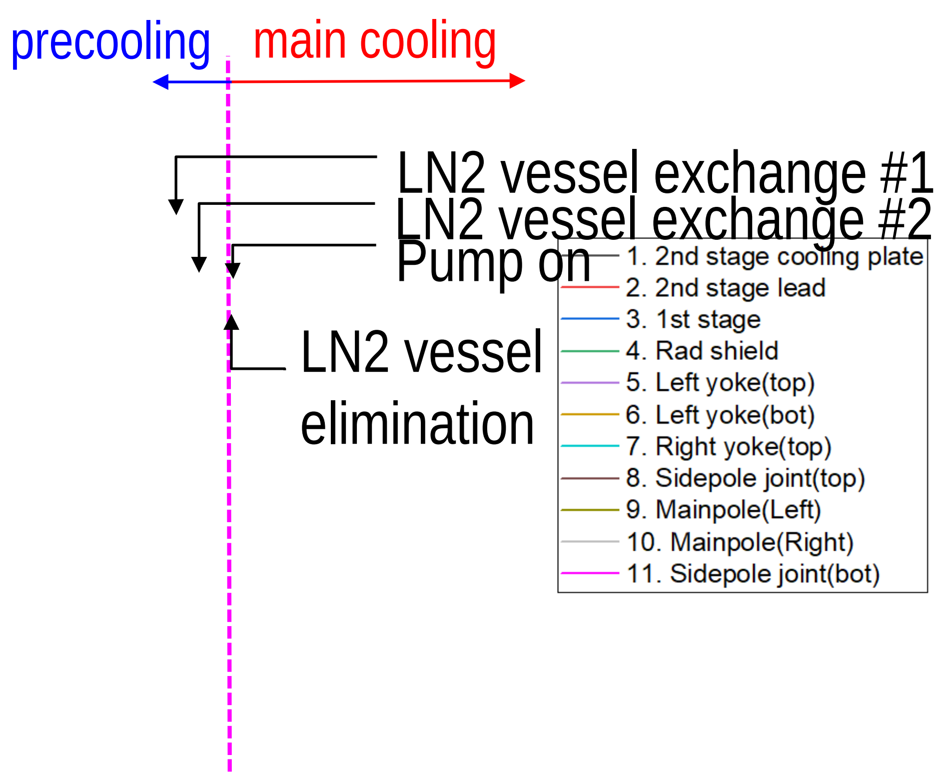


<Measurement system>

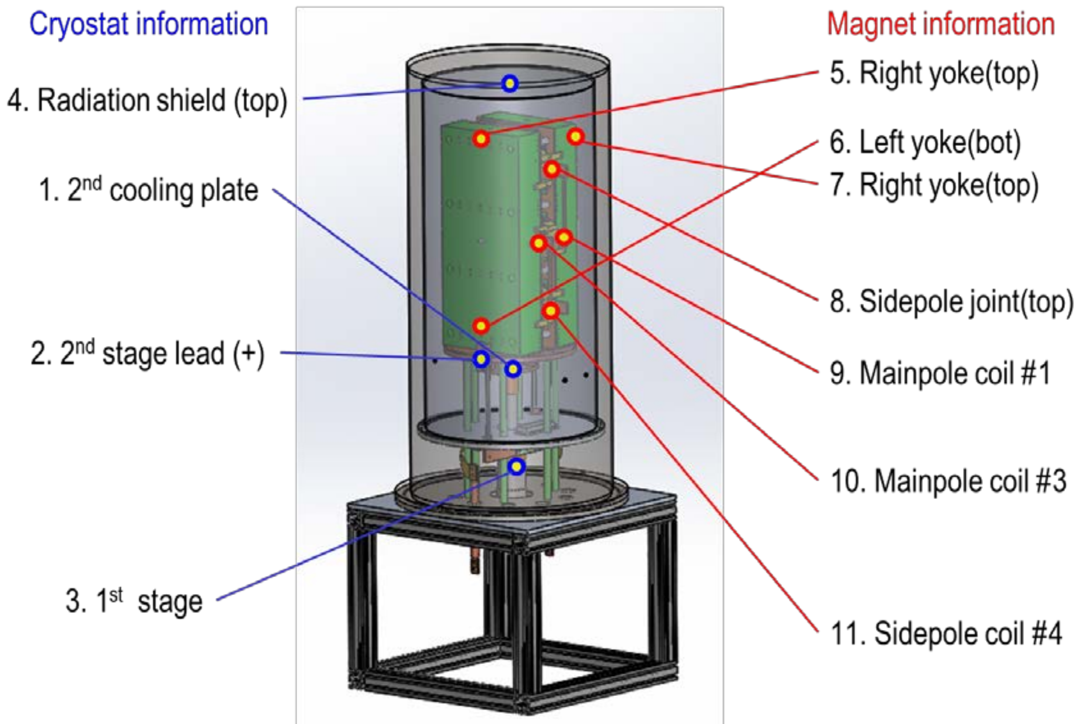


Conduction Cooling

- Initial Cooling of Magnet System
  - Liquid nitrogen usage: 110 L
    - Dump mode: 97 L; adiabatic mode: 155 L
  - Total cooling time: 42 hours



<Temperature sensor locations>

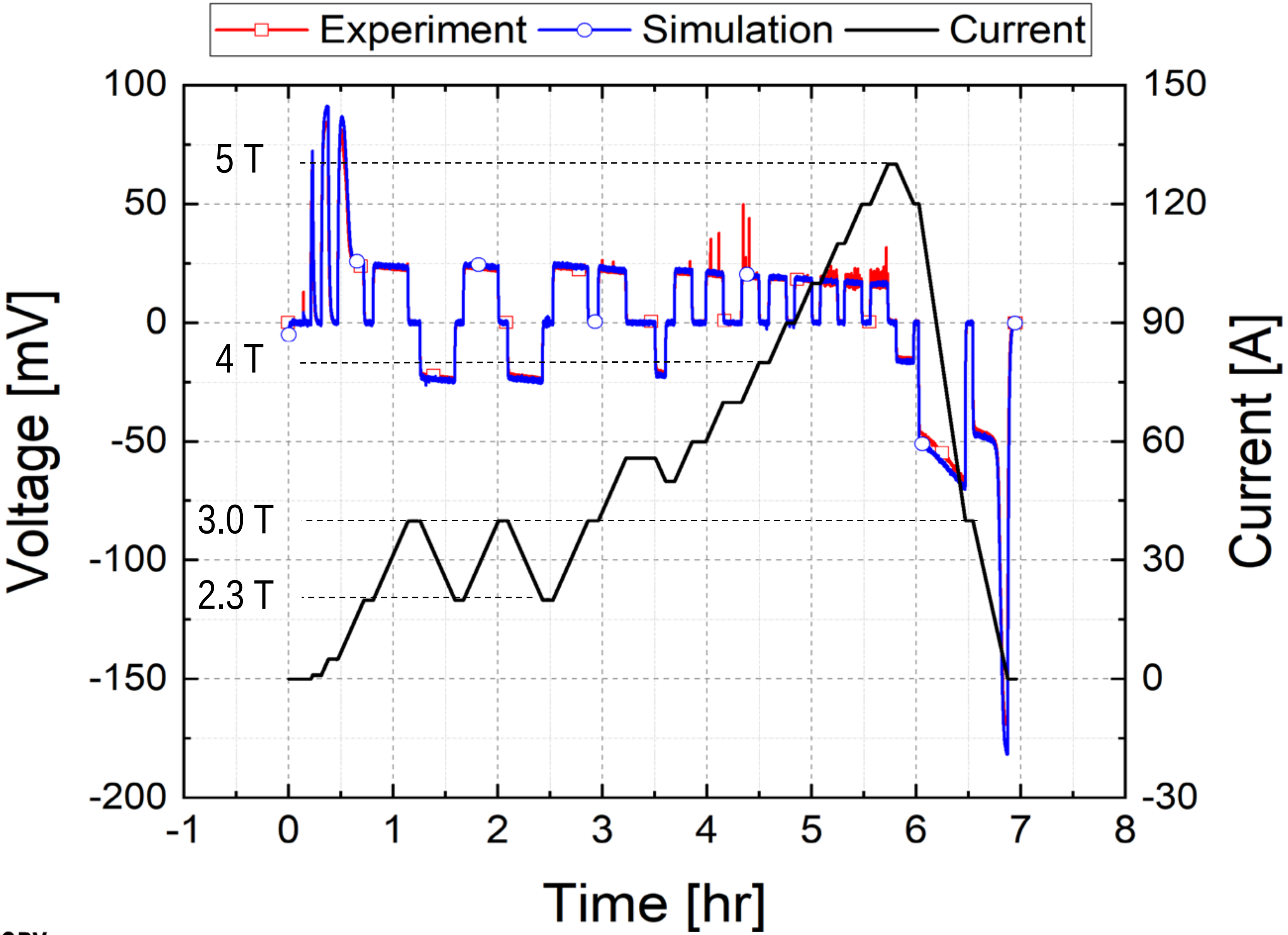


<Final temperature [K]>

#1	#2	#3	#4	#5	#6
4.5	5.4	47.6	284.4	4.6	4.8
#7	#8	#9	#10	#11	
4.9	5.5	5.1	4.6	5.3	

Result

- **World First, Coil-type HTS Wavelength Shifter.**
- **Beam experiment scheduled after a precise field measurement.**



Summary

- Since 2020, we have been conducting HTS-based magnet development research for future light source magnet technology with Seoul National University (one of the world's leading groups of HTS technology).
- The prototype of 5-tesla wiggler based on HTS with No-insulation technology and LHe-free conduction cooling was successfully fabricated and tested (Aug. of 2023).
- Central magnetic field strength of 5.02 T was experimentally vitrificated without any quench.
- The core temperature was 8.8 kelvin when the field strength was 5.02 T.
- Integral field quality error was about 0.0007 Tm, corresponding to 0.09%, which will be precisely measured in the next stage (2024-2025).
- The vacuum chamber was also fabricated and delivered after the leak test.
- Currently, we are preparing an assembly (2023-2024) with a dedicated cryogenic system, a precise field-map measurement (2024), and a beam test (2024-2025).

This work was done mainly with
Jeonghwan Park, Jaemin Kim, Geonyoung Kim, and Seungyong Hahn (Seoul National University)
Taekyun Ha, Dongeun Kim (Pohang Accelerator Laboratory)
based on the support of PAL's new director Heungsik Kang.