Current Development Status of Cryogen-free Conduction-Cooled 5-Tesla Wavelength Shifter Utilizing HTS Technology

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on behalf of

the PAL Leaderships and PRISM National Research Consortium

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The Roadmap of HTS-ID Development (PAL-SNU)

- (2020) **HTS-U** Proto. → (2022-) *HTS-3PW 5 T* → (2025-) HTS-MPW 4T-3λ → (2026?-) **HTS-MPW 4T-30λ** → (2027?-) **HTS-U**

- Purpose : To develop an ID technology for future light sources
  - ☐ Warm iron dominated accelerator magnet → Permanent magnet ID
    → Cryogenic PMU || LTS wiggler || **HTS wiggler**

- R&D Target : HTS-3PW
  - ☐ 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
  - ☐ Dedicated cryostat and beam pipe were assembled with the HTS magnet core
  - ☐ 30 days non-stop operation experiment & field measurement

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

λ = 14 mm, $n(\lambda)$=1.5, B_0=0.8 T

⇩

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

L_{magnet} = 0.42 m, B_0 > 5 T

⇩

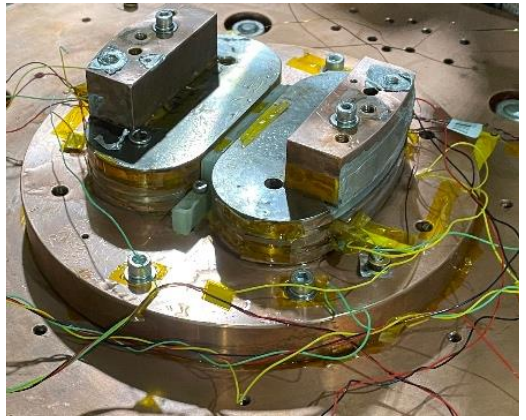
Cryogen-free Conduction Cooled REBCO Multipole Wiggler (2022 - 2026)

λ = 60 mm, $n(\lambda)$>5, B_0 > 4 T

⇩

HTS-MPW 4T-30λ

HTS-U



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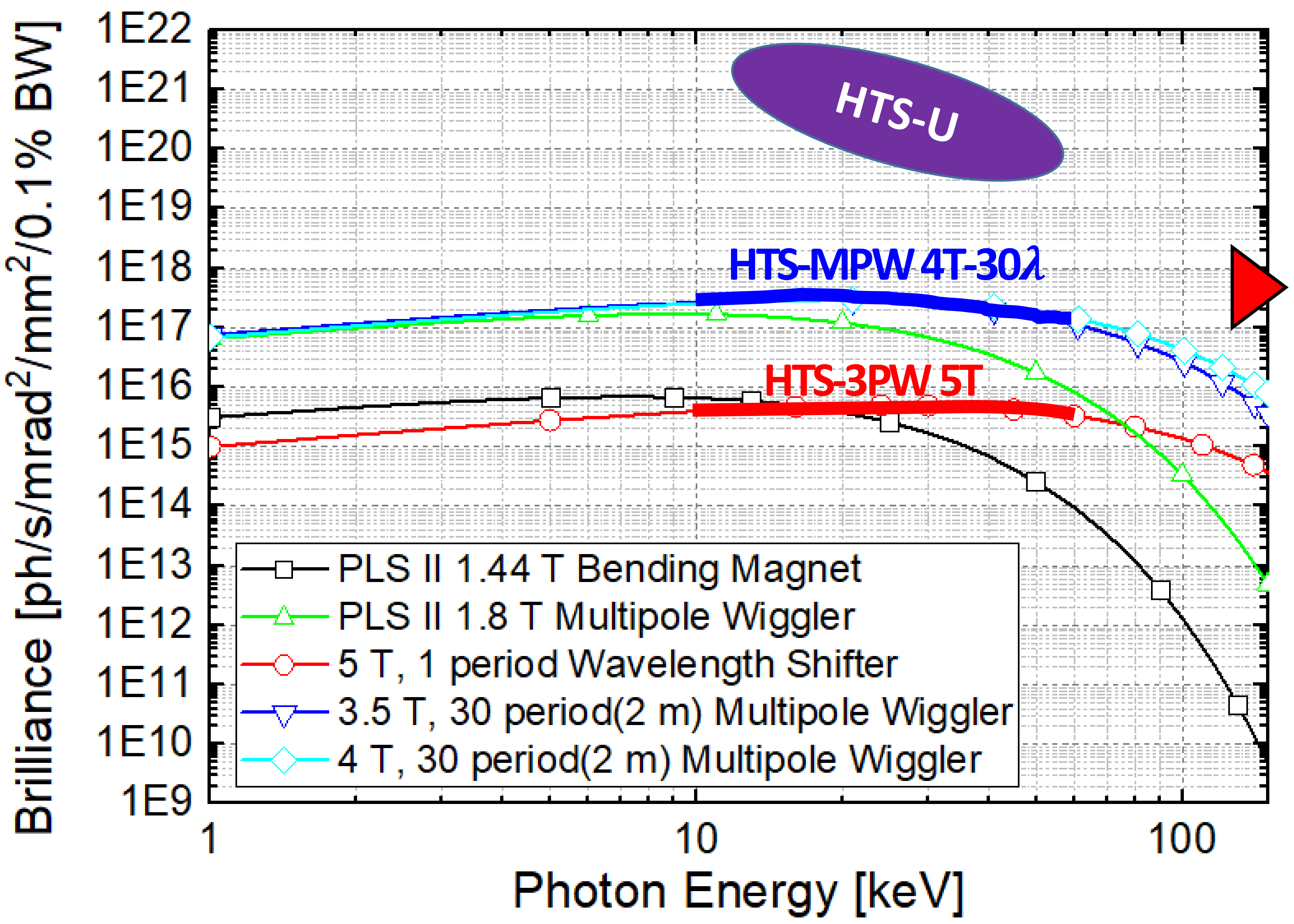

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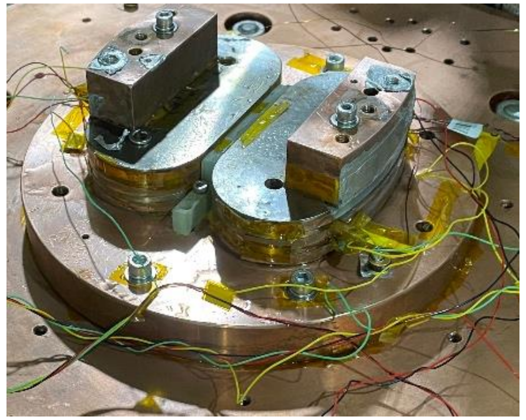
HTS-MPW 4T-30λ

HTS-U



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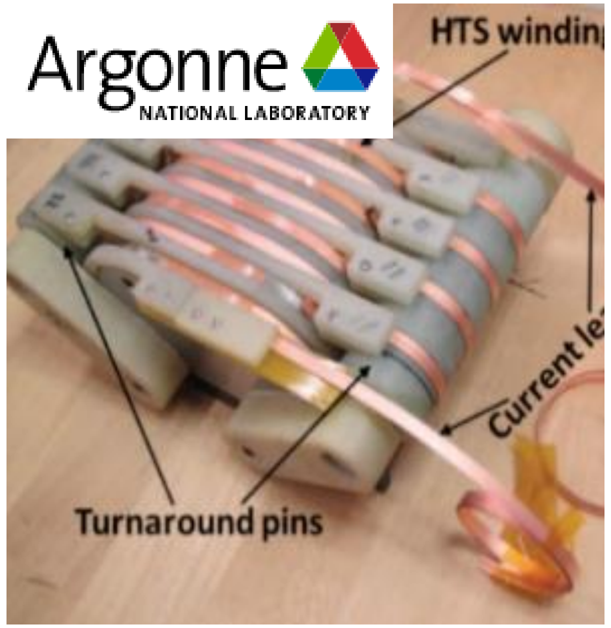
Efforts toward the development of HTS ID

- 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

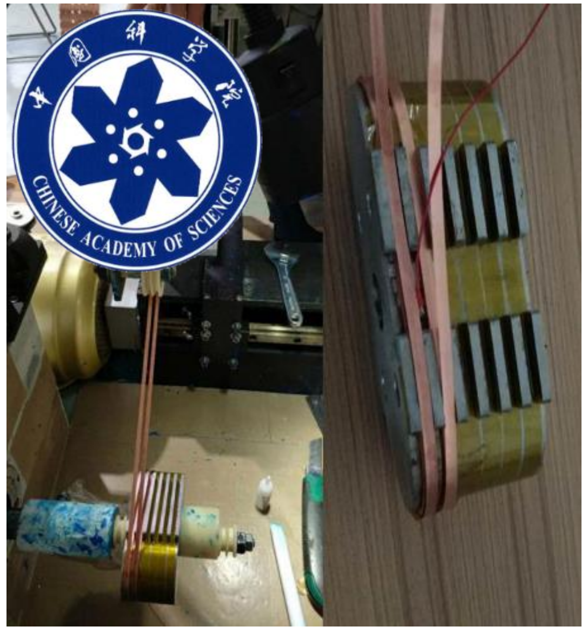
T Holubek *et al.*, "A novel concept of high temperature superconductor undulator," *Supercond. Sci. Technol., vol 30, no.11, 115002* (2017)

Argonne National University, USA



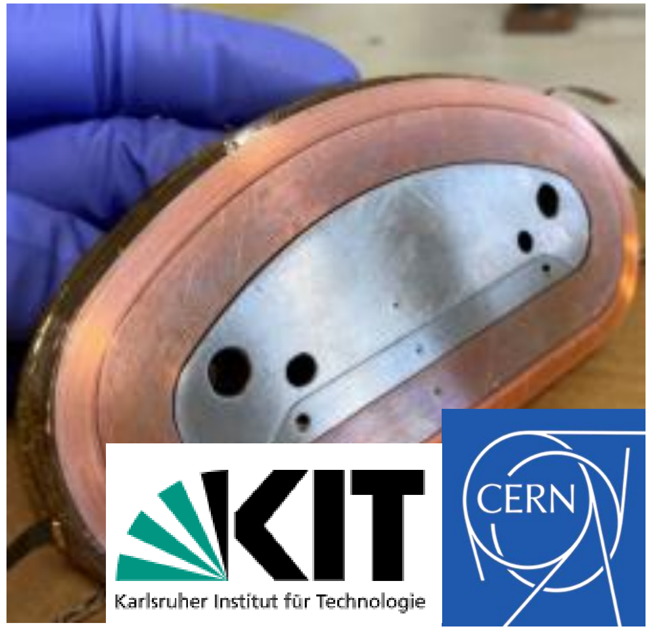
Y. Ivanyushenkov and *et al.*, "Status of the Development of Superconducting Undulators at the Advanced Photon Source," *Synchrotron Radiation News*, (2018)

Chines Academy of Sciences, China



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

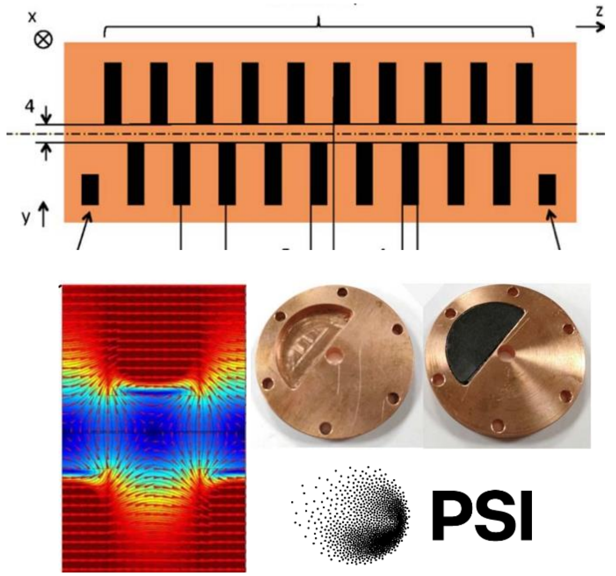
CERN, Karlsruher Institut of Technology, Europe



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)

Paul Scherrer Institute (Switzerland)

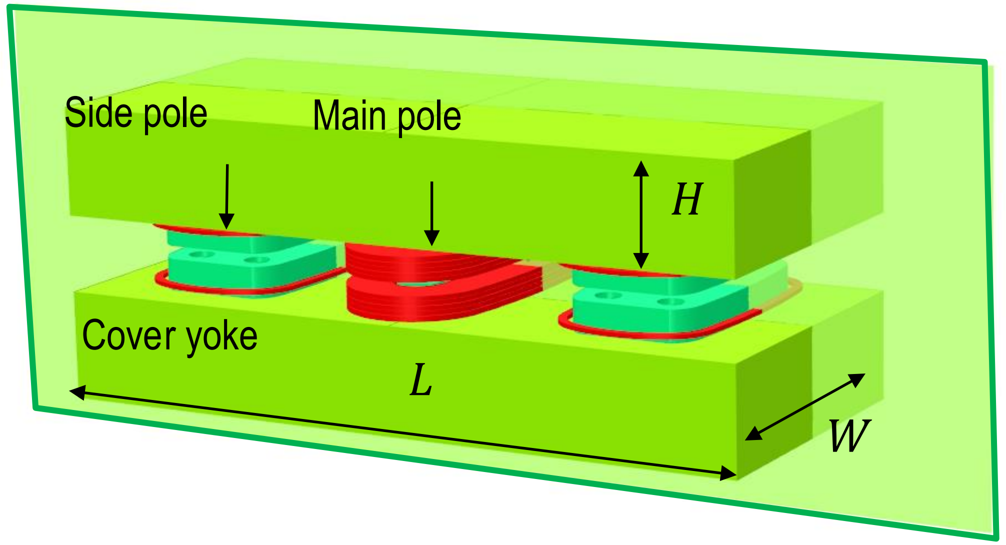
Zhang Ziang Lab. (China)

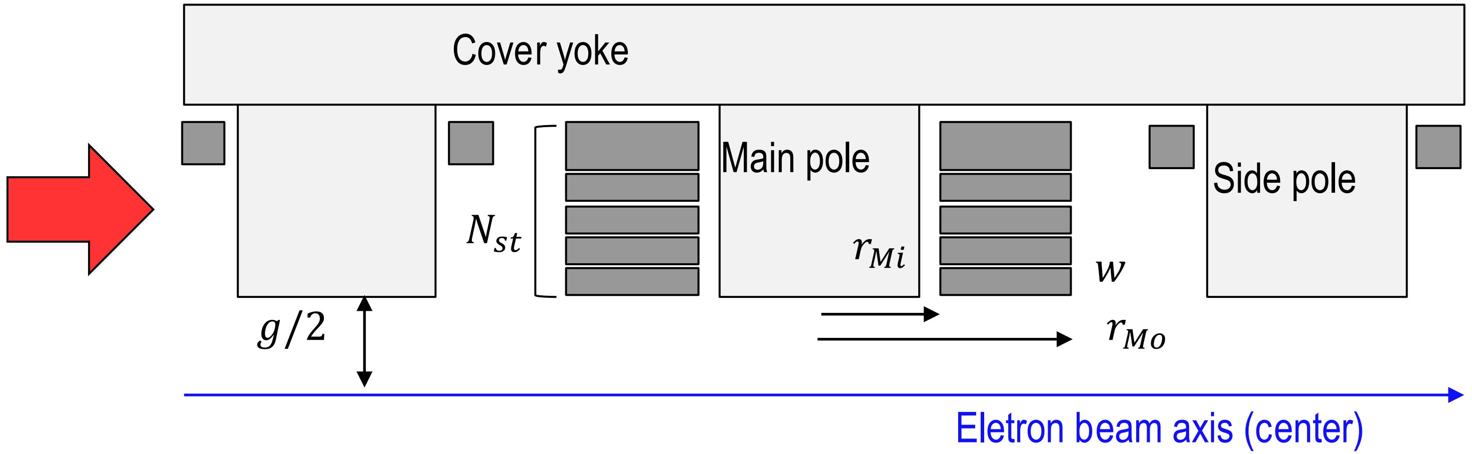


M Calvi *et al.*, "A GdBCO bulk staggered array undulator" vol 33 , 014004, Supercond. Sci. Technol. (2020)

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: N of main pole 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: ith stack width (4.1, 5.1 mm)

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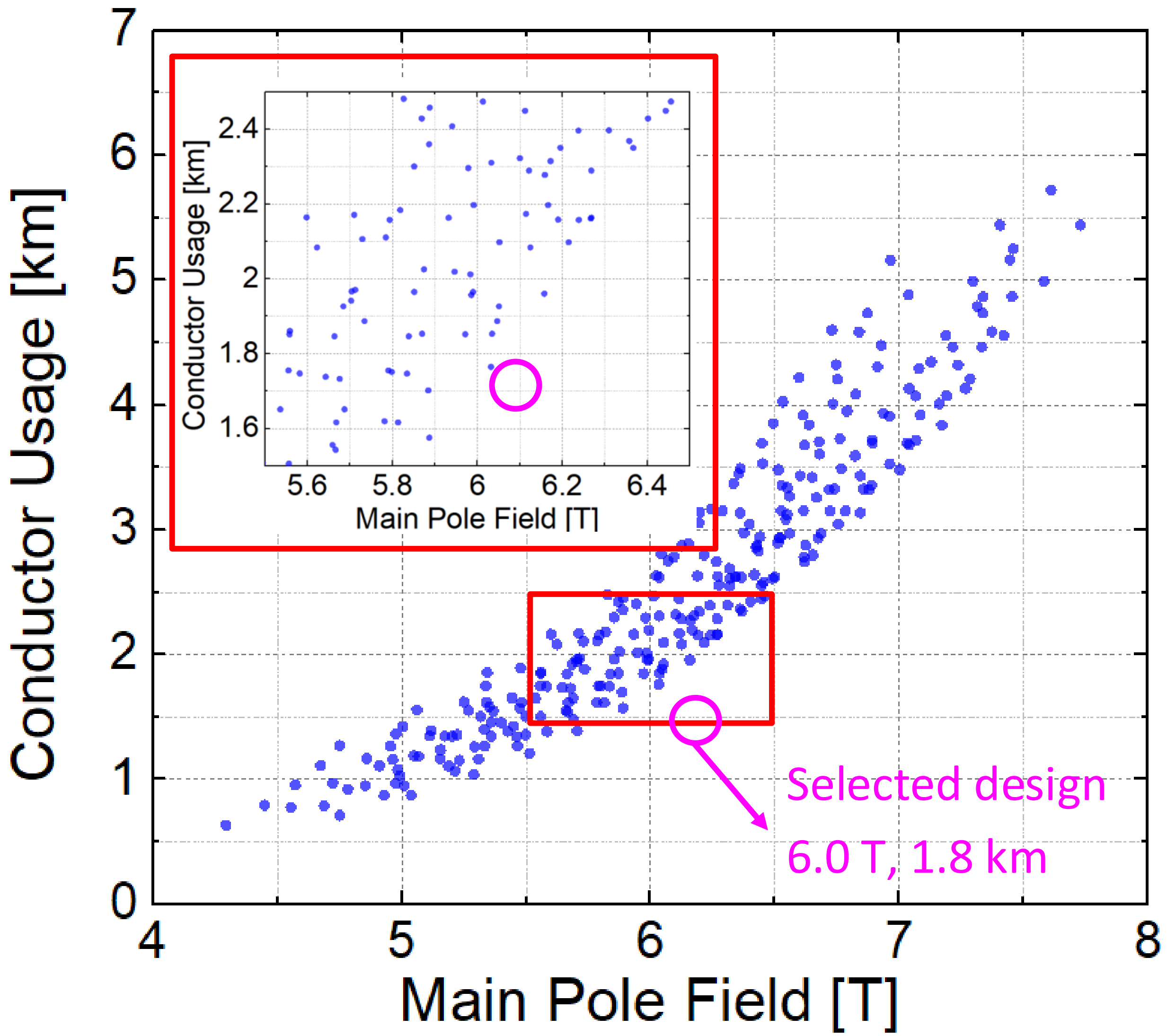
Cost Optimization

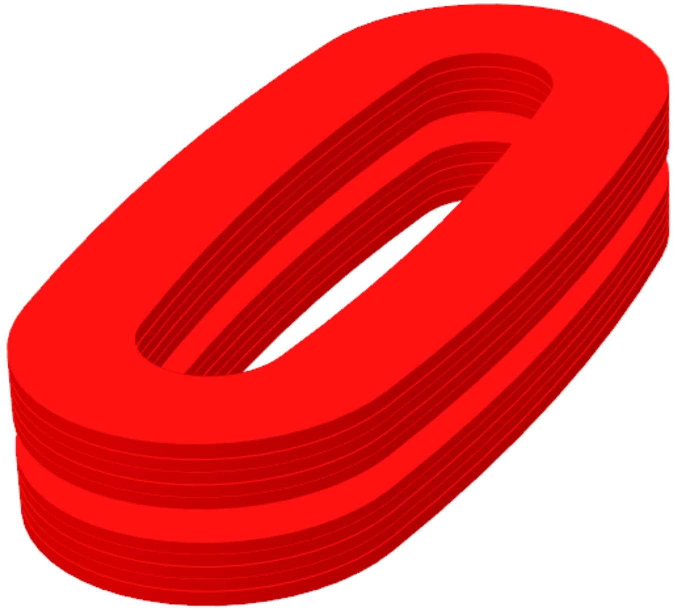
- Parameter Sweep Results
  - ☐ Final design is selected considering HTS conductor in stock (~1.8 km) ~ 43,200 KRW (24 k KRW/meter)



Selected design
6.0 T, 1.8 km

(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]

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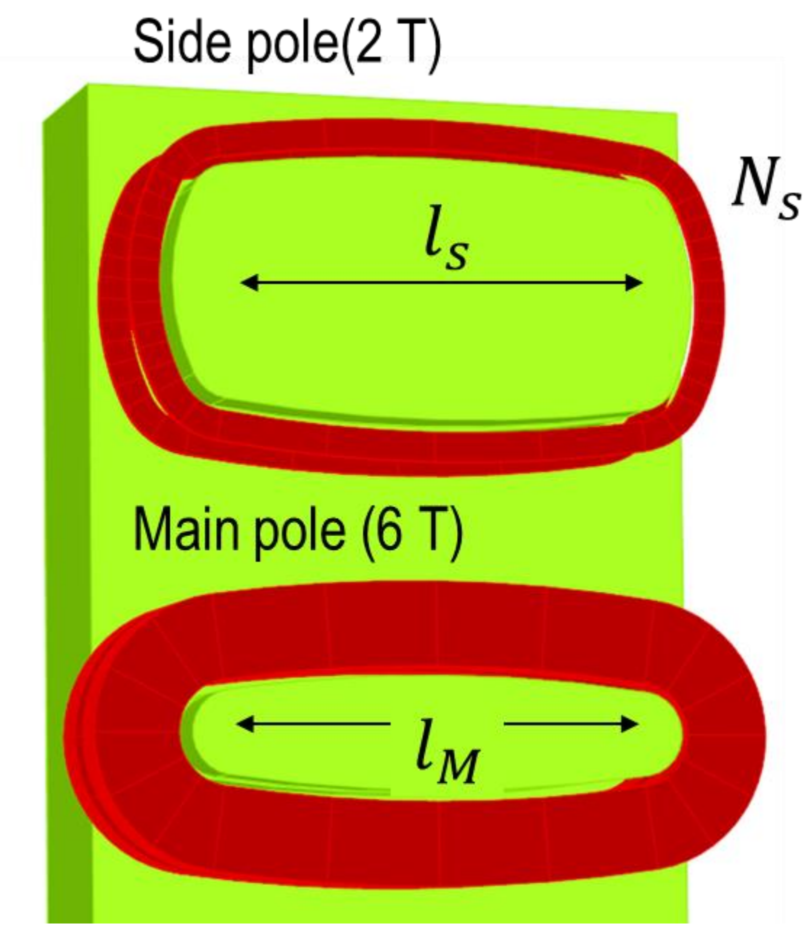
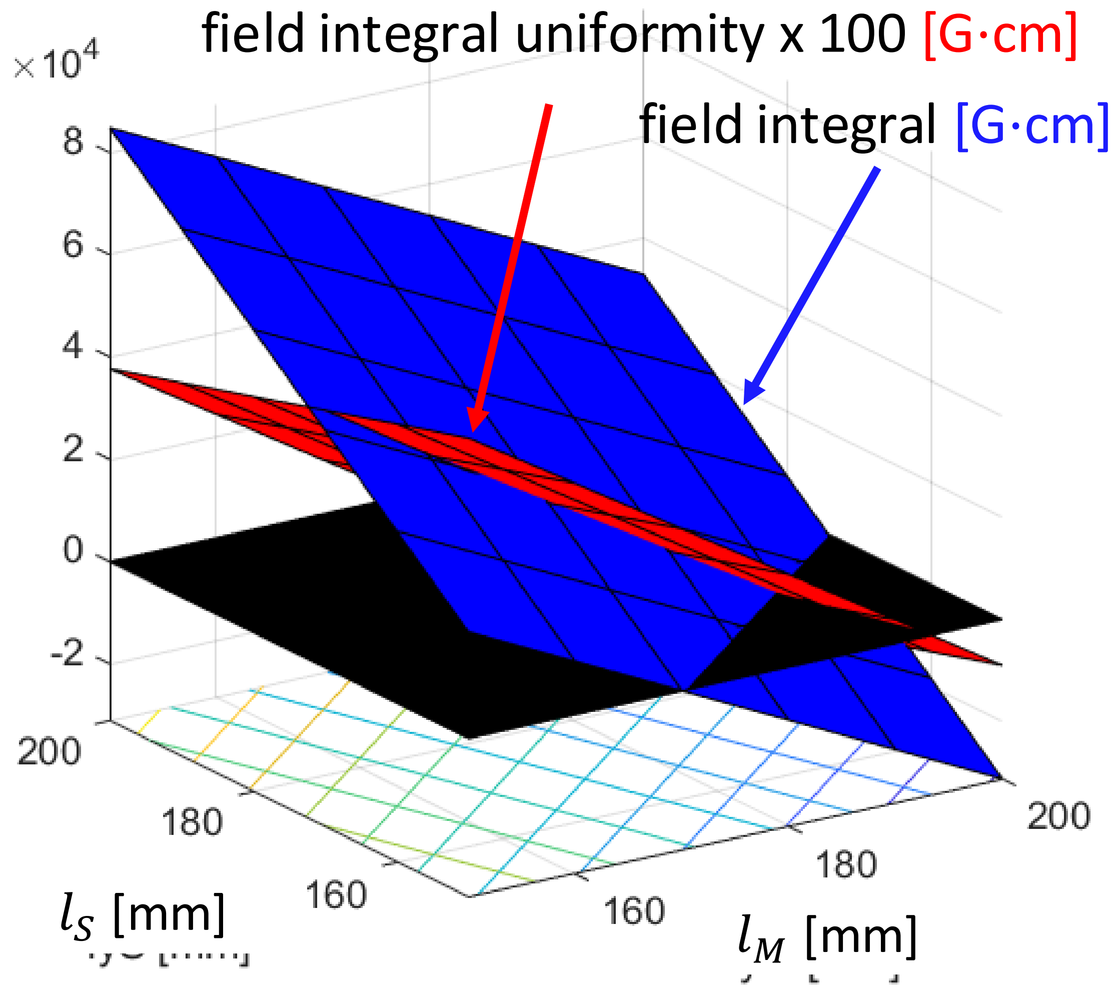
Field Quality Optimization

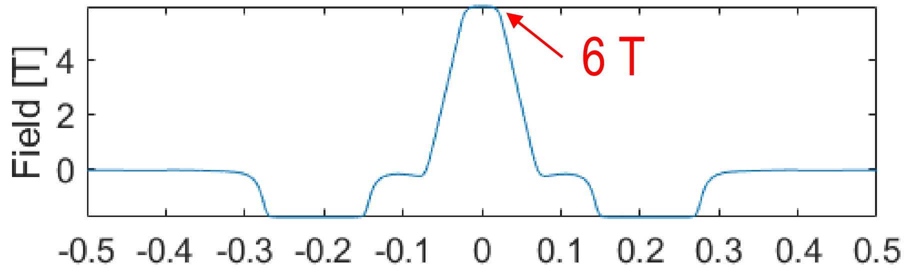
- Field Uniformity Requirements for Beam Operation
  - ☐ (1) zero field integral ($\int B_y\, dz$); (2) field integral uniformity at x=15 mm: <100 G·cm



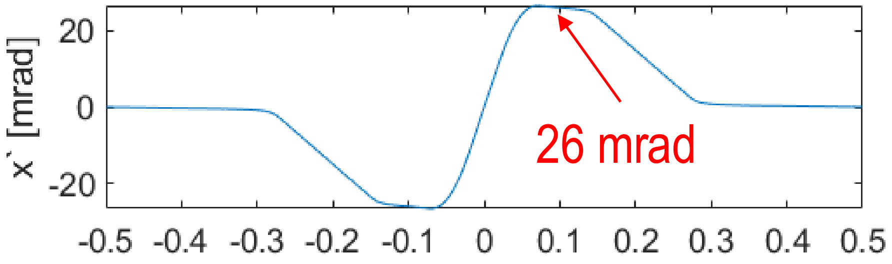
N_s: side pole turns [null]
l_M: main pole length [mm]
l_s: side pole length [mm]



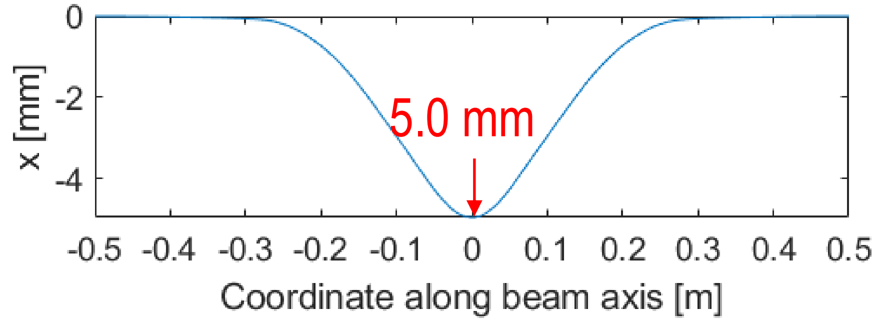
Selected dimension to minimize field integral
l_M=188 mm; l_S=166 mm; N_S=40



$$x'(z) = \frac{v_z(z)}{\beta c} = -\frac{e}{\gamma m_0 c}\int_{-\infty}^{z} B_y(z')\mathrm{d}z'$$



$$x(z) = -\frac{e}{\gamma m_0 c}\int_{-\infty}^{z}\left(\int_{-\infty}^{z'} B_y(z'')\mathrm{d}z''\right)\mathrm{d}z'$$



Stress Analysis

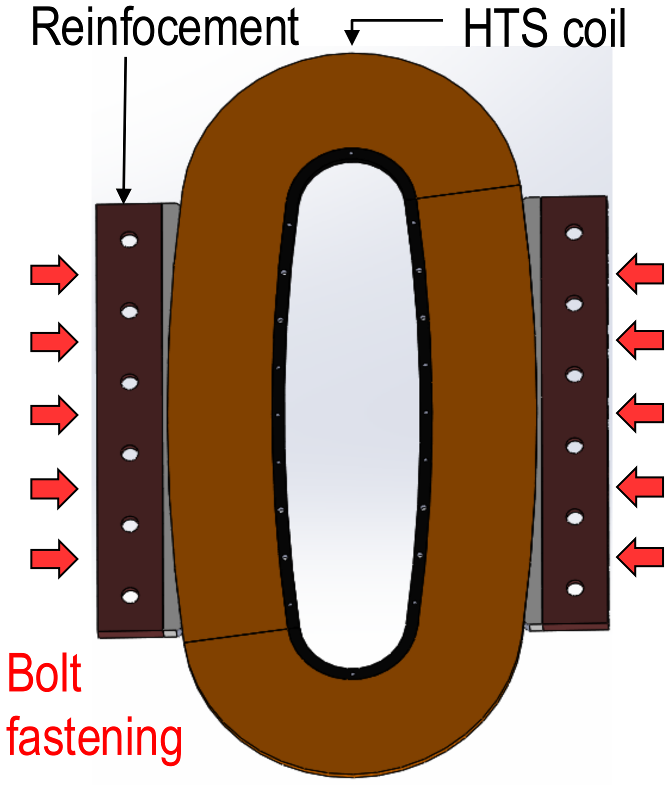
- Stress Analysis of Racetrack Shaped Mainpole Coil[11]
  - ☐ Modeling: (1) roller; (2) contact pair; (3) spring foundation
  - ☐ Maximum hoop stress of 97 MPa

Governing Equation

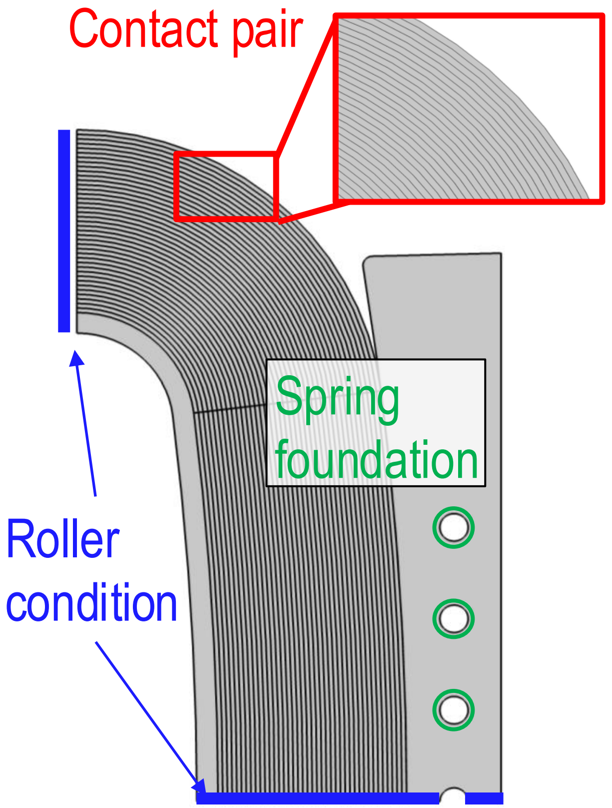
Force balance: $\nabla\sigma + \overrightarrow{f_v} = 0$

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

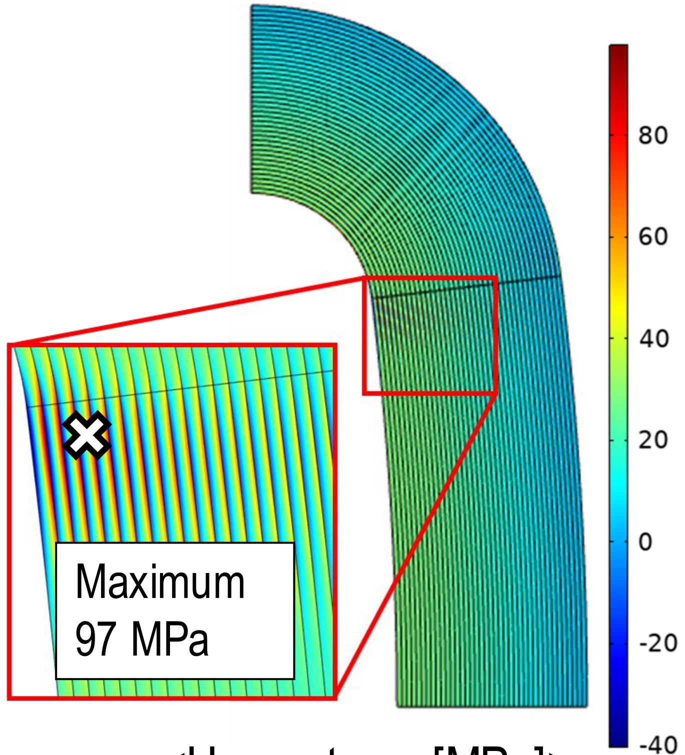
Spring foundation: $\vec{f} = -ku$



<Racetrack coil structure>



<Modeling>



<Hoop stress [MPa]>

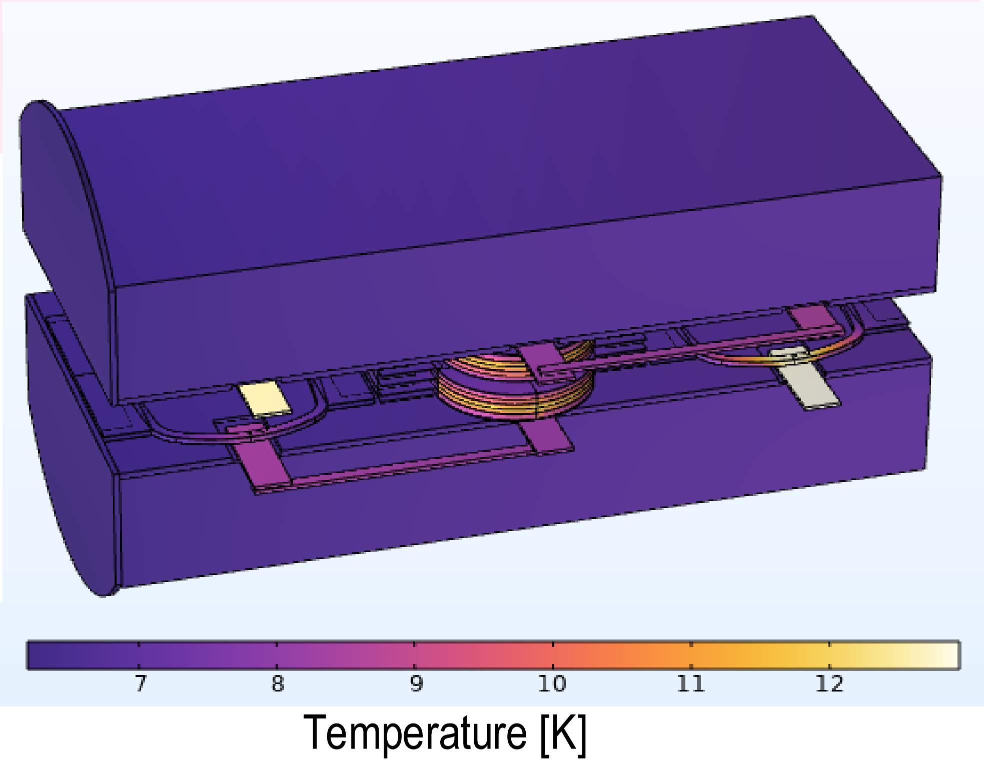
U bong *et al.*, “Numerical Studies on mechanical behavior of dry wound HTS racetrack coil,” *IEEE. Trans. Appl. Supercond.*, 30.4, 2020

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



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**

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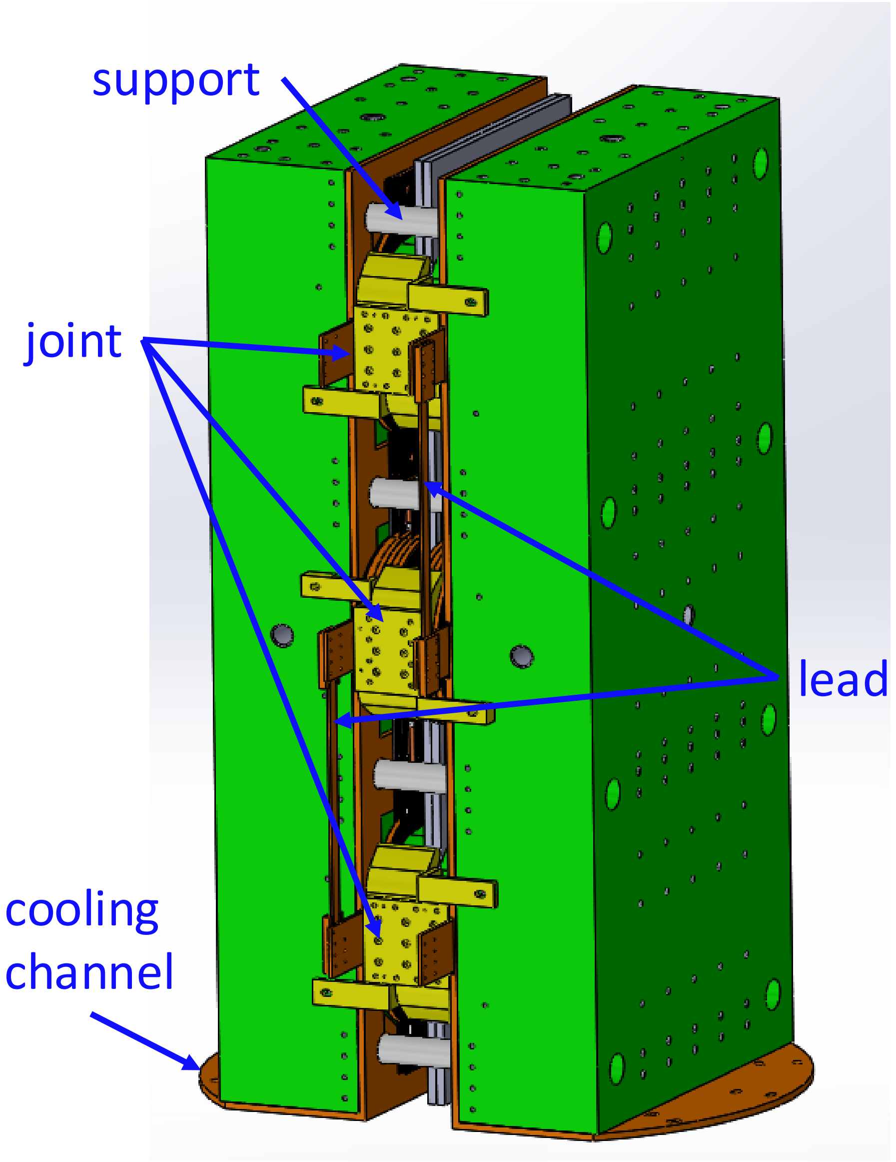
Design Result Summary

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



Glimpse of Fabrication

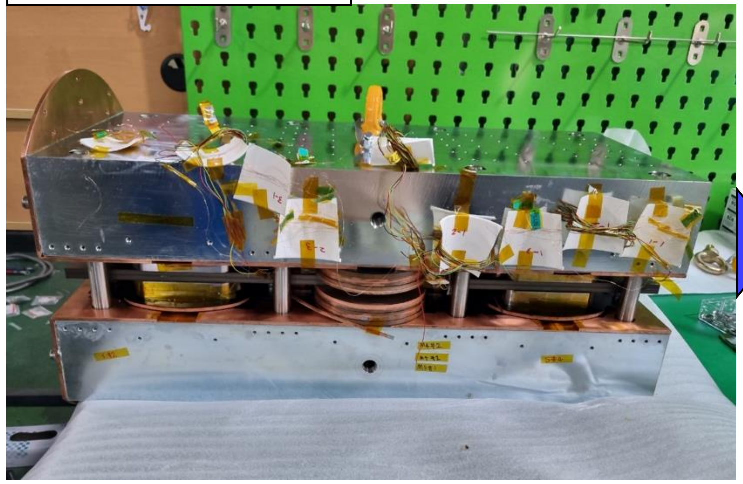
1. Winding

2. LN2 test

3. Cooling channel

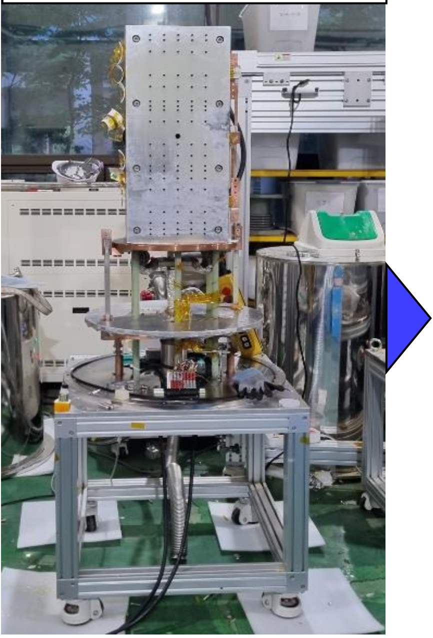
4. Stacking

5. Preload



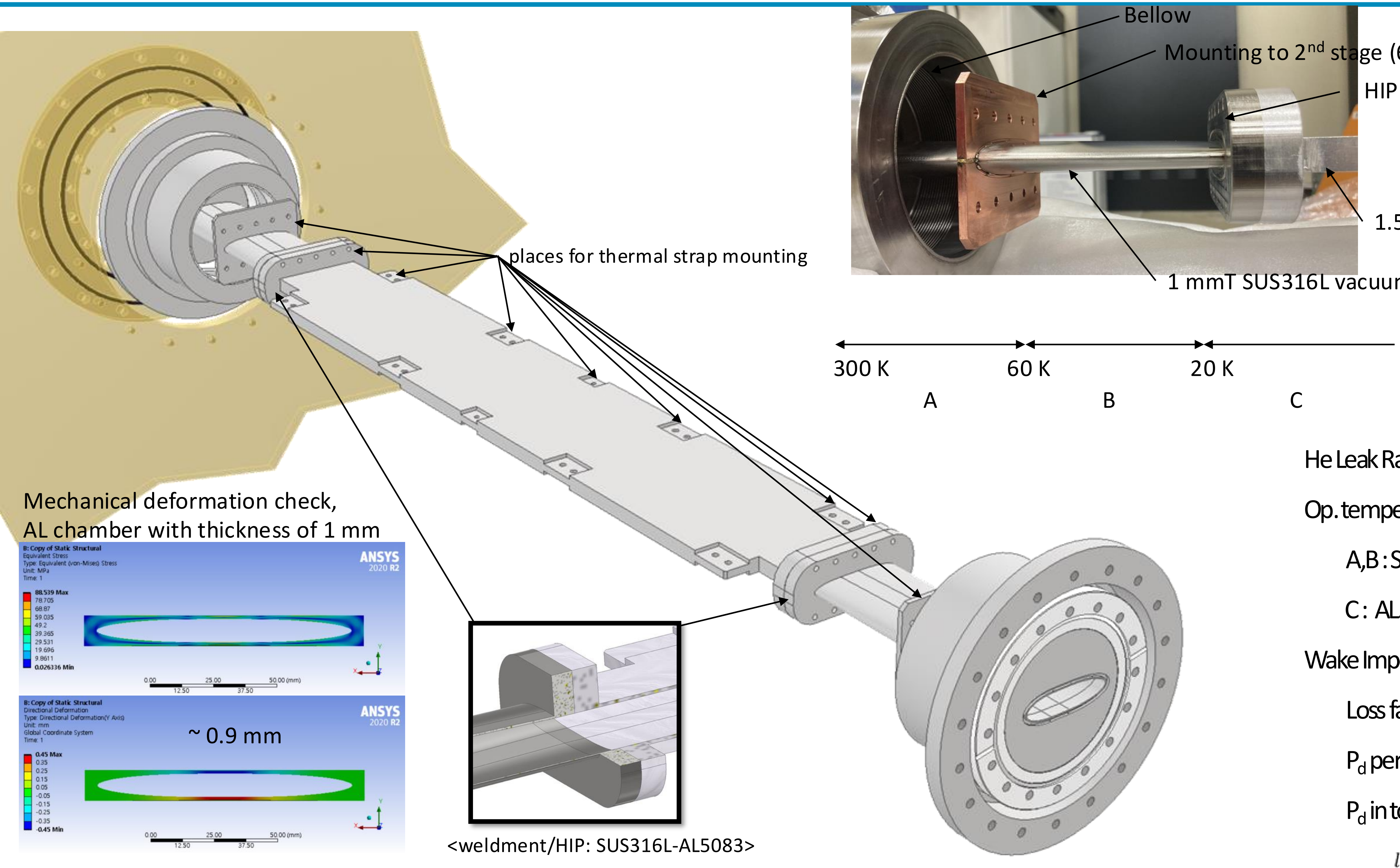
6. Joint & lead

7. Assemble



8. Operation

Vacuum Chamber



Mechanical deformation check,
AL chamber with thickness of 1 mm

<weldment/HIP: SUS316L-AL5083>

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

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

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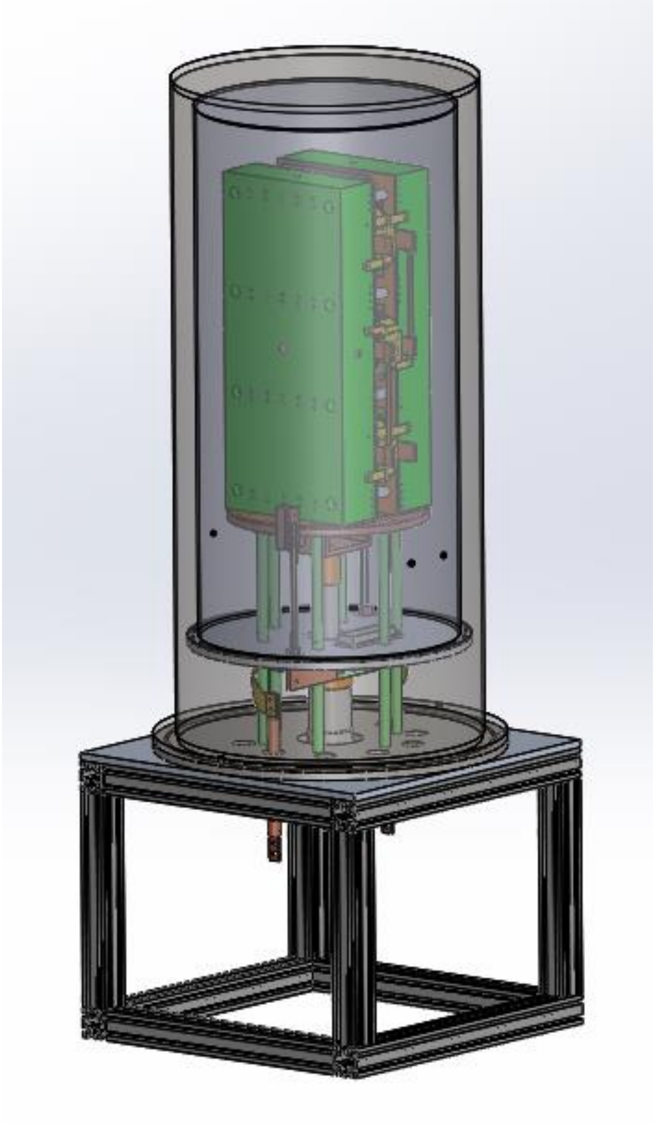
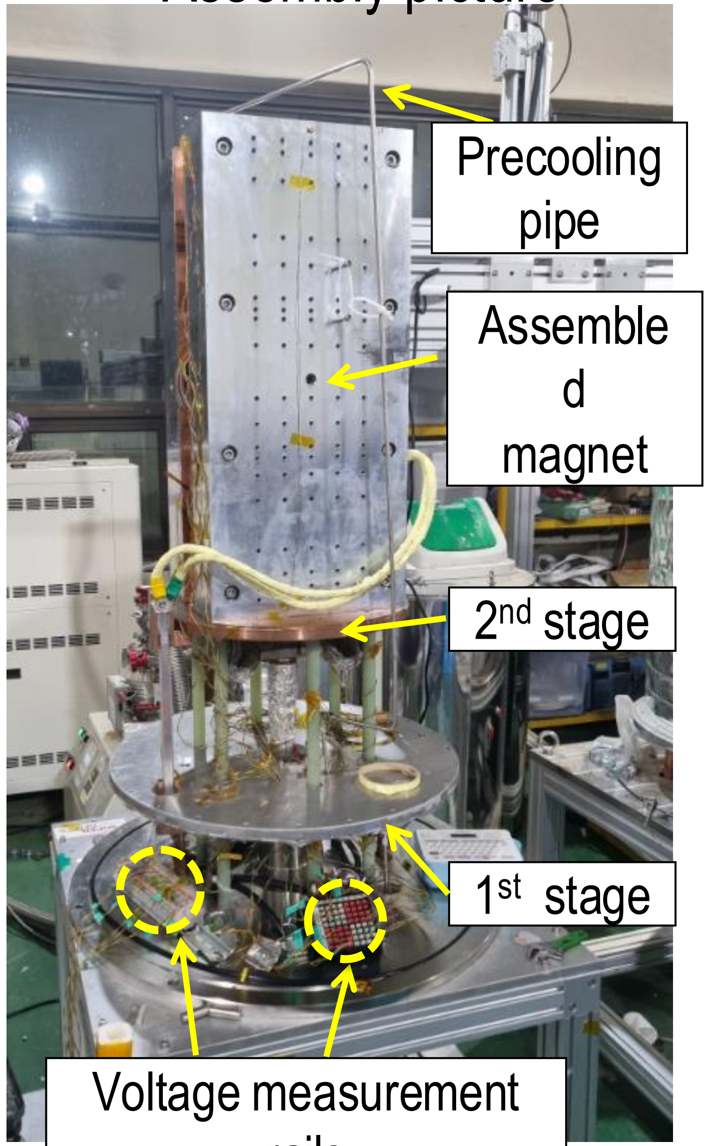
Test Environment

<CAD Drawing>



<Assembly picture>



Precooling pipe

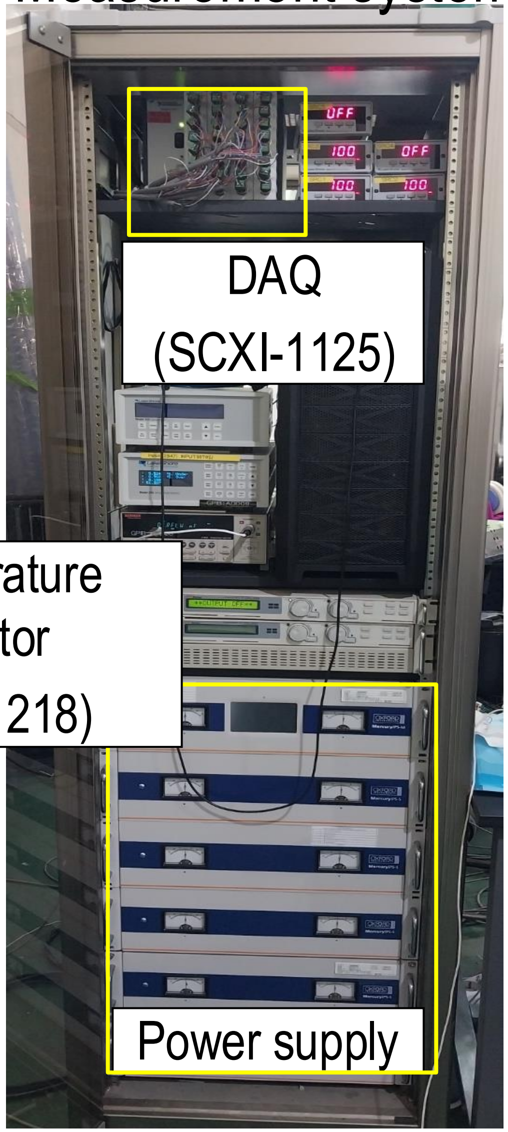
Assembled magnet

2nd stage

1st stage

Voltage measurement rails

<Measurement system>



DAQ (SCXI-1125)

Temperature monitor (Model 218)

Power supply

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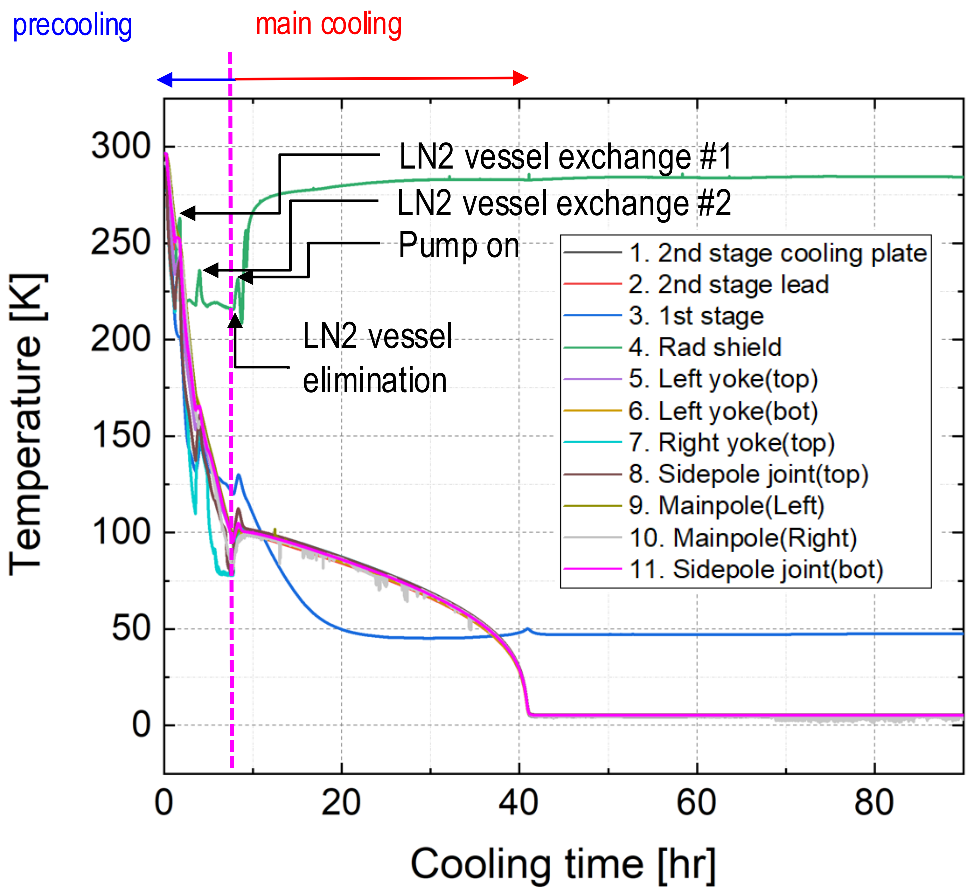
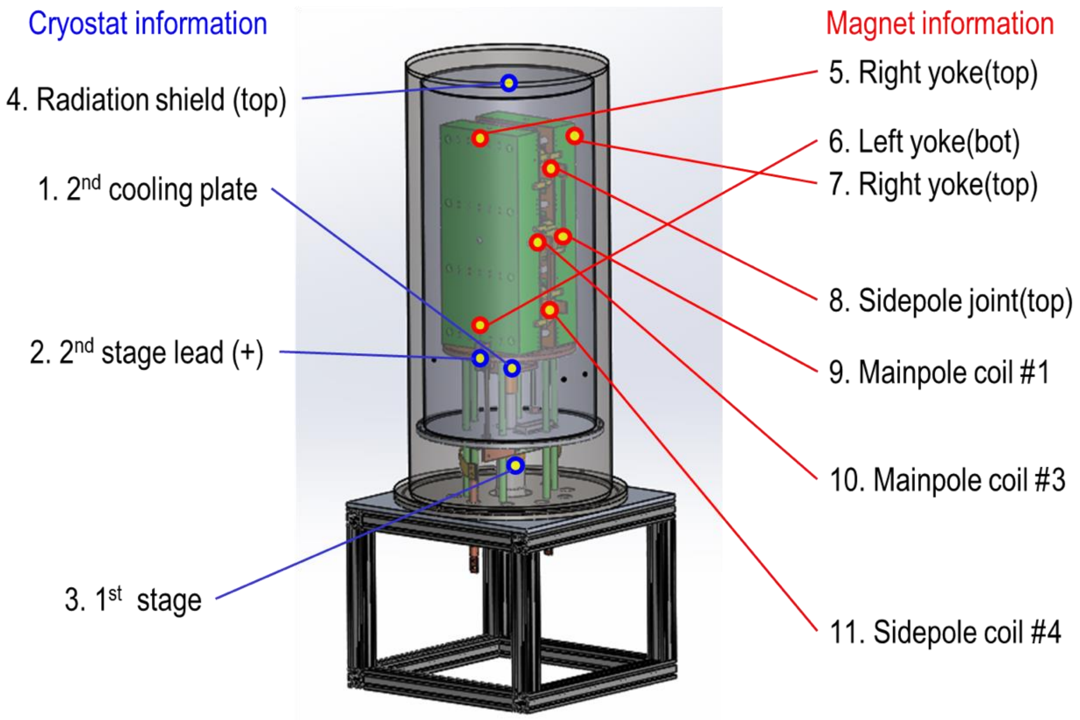
Conduction Cooling

- 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>



Cryostat information

4. Radiation shield (top)
1. 2nd cooling plate
2. 2nd stage lead (+)
3. 1st stage

Magnet information

5. Right yoke(top)
6. Left yoke(bot)
7. Right yoke(top)
8. Sidepole joint(top)
9. Mainpole coil #1
10. Mainpole coil #3
11. Sidepole coil #4

<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	

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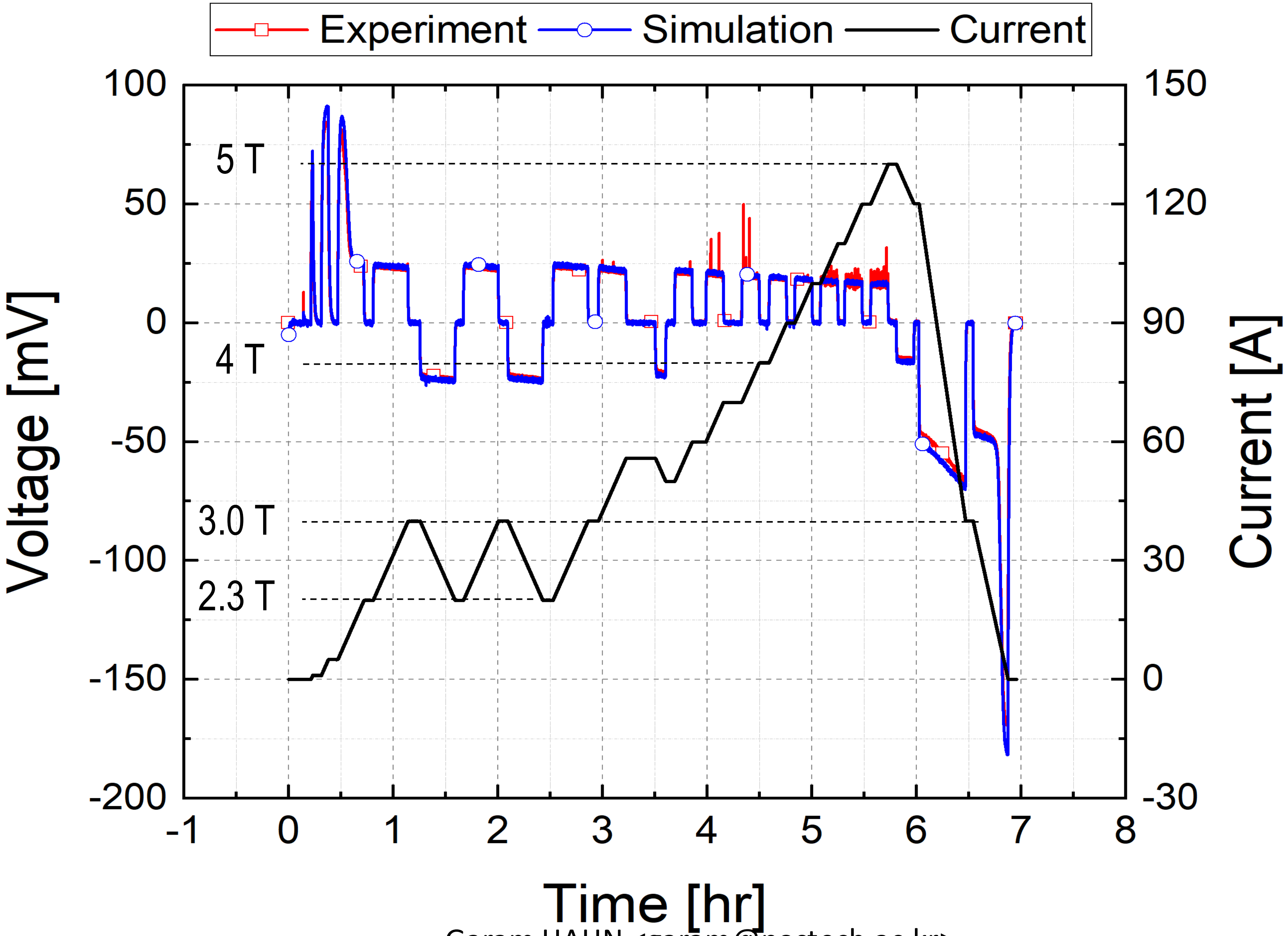
Result

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



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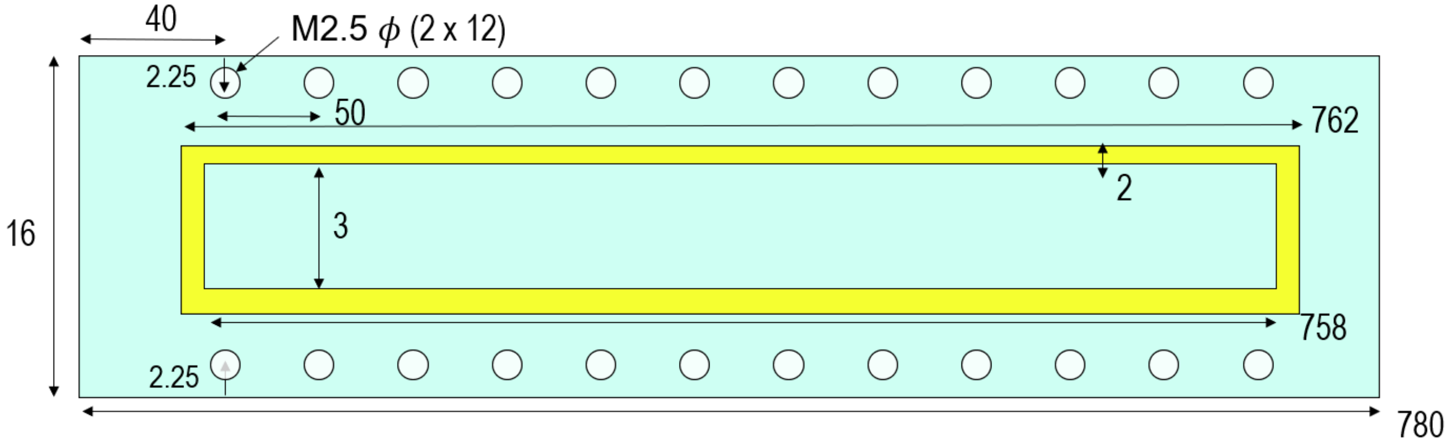
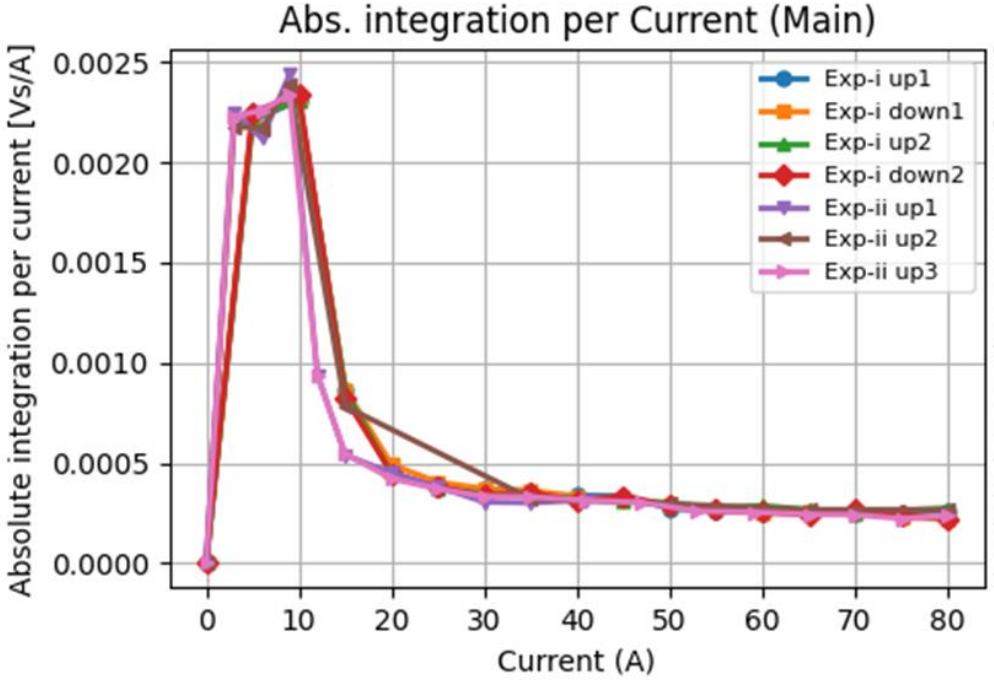
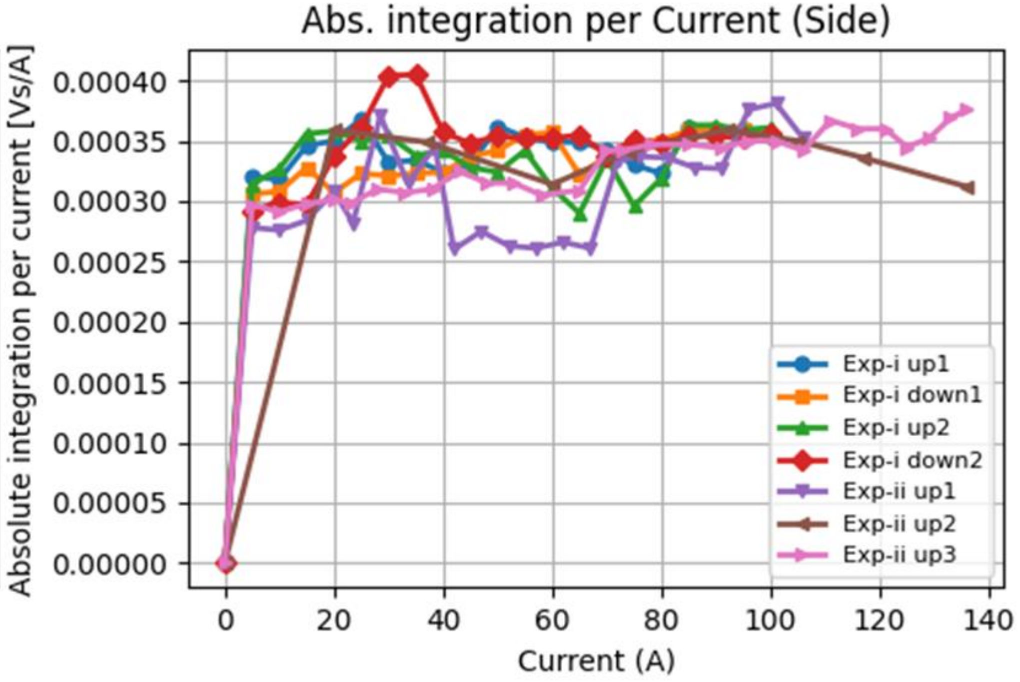
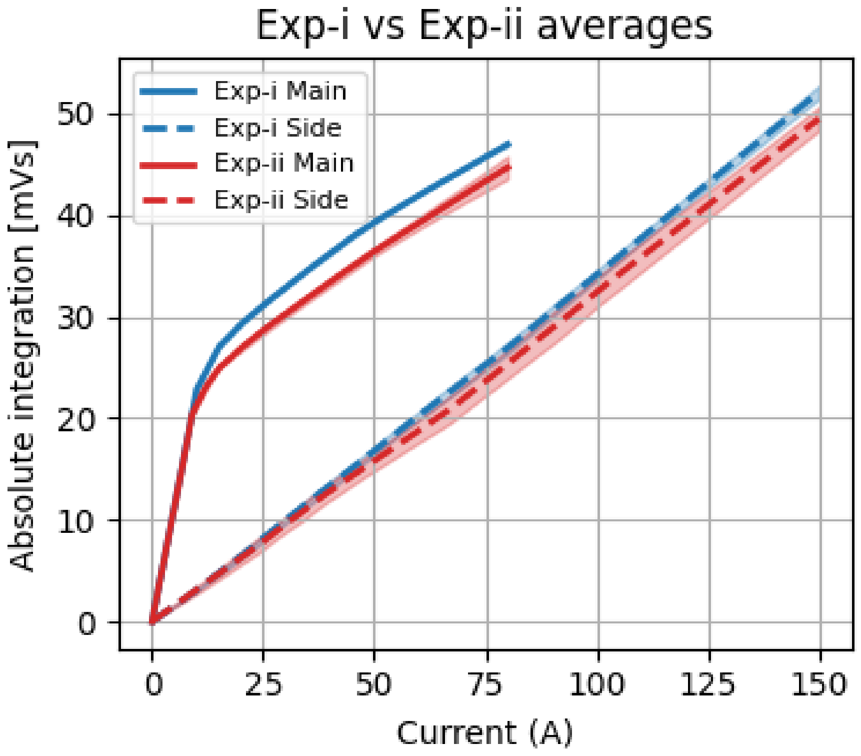
Long Coil Measurement

- Different current steps for each pole (integration ~ 0 for each step)
  - Simulation result for 4 T: Main 80 A, Side 115.2 A
  - Experiment results for 4 T: Main 80 A, Side 135.8 ± 4.2 A
- Operation currents for 1 T ~ 4 T are all estimated



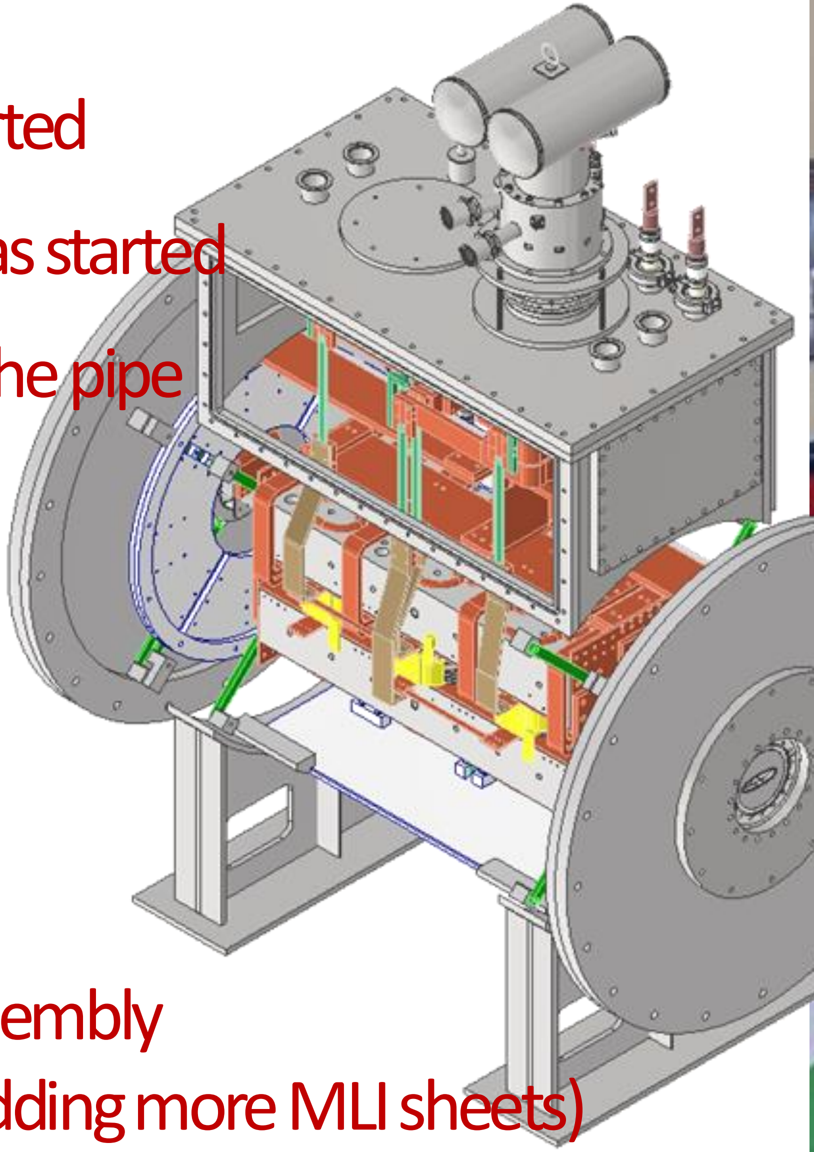

Abs. integration per Current (Main)

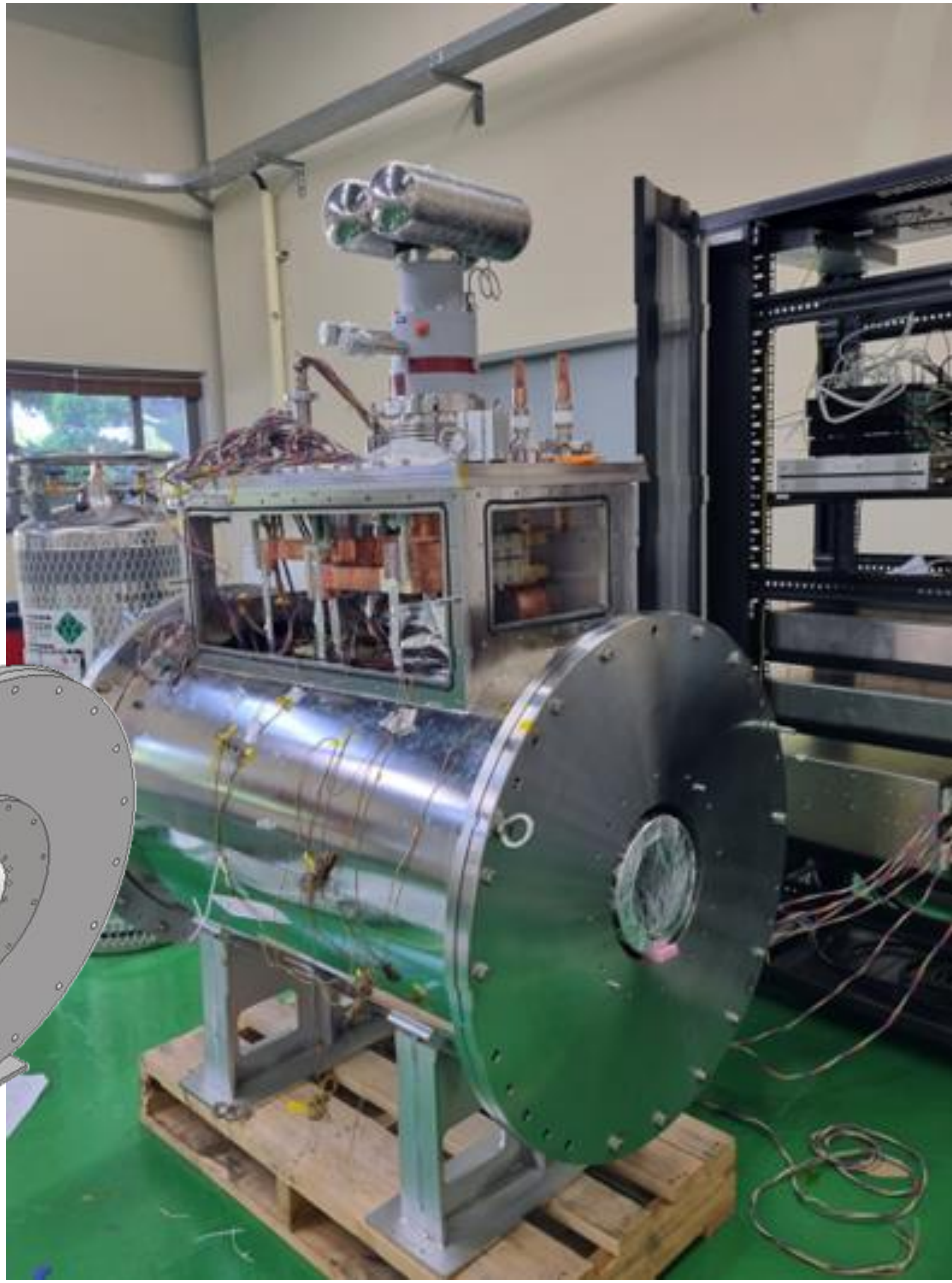

Abs. integration per Current (Side)


Exp-i vs Exp-ii averages

Assembling, Cooling, Power-on Test

- 2023.02 : HTS Magnet fabrication start
- .08 : Central field of 5 T was achieved
- .11 : Vacuum pipe fabrication was started
- 2024.02 : Dedicated cryostat fabrication was started
- .07 : Assembly of (1) the magnet, (2) the pipe & (3) the cryostat
- .08 : Disassembly of the magnet due to insulation breakdown when the power-on
- .10 : Coil-set repair & 2nd assembly
- .11 : Second power-on test and disassembly to improve thermal insulation (adding more MLI sheets)





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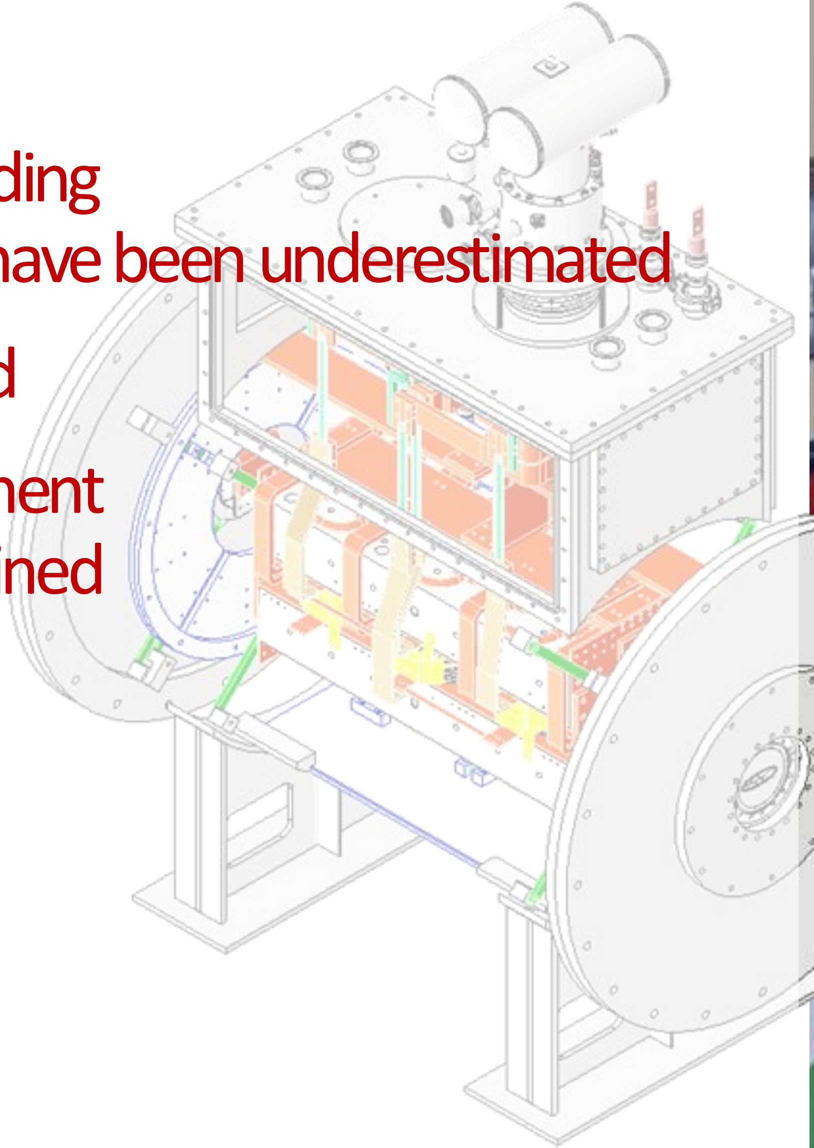
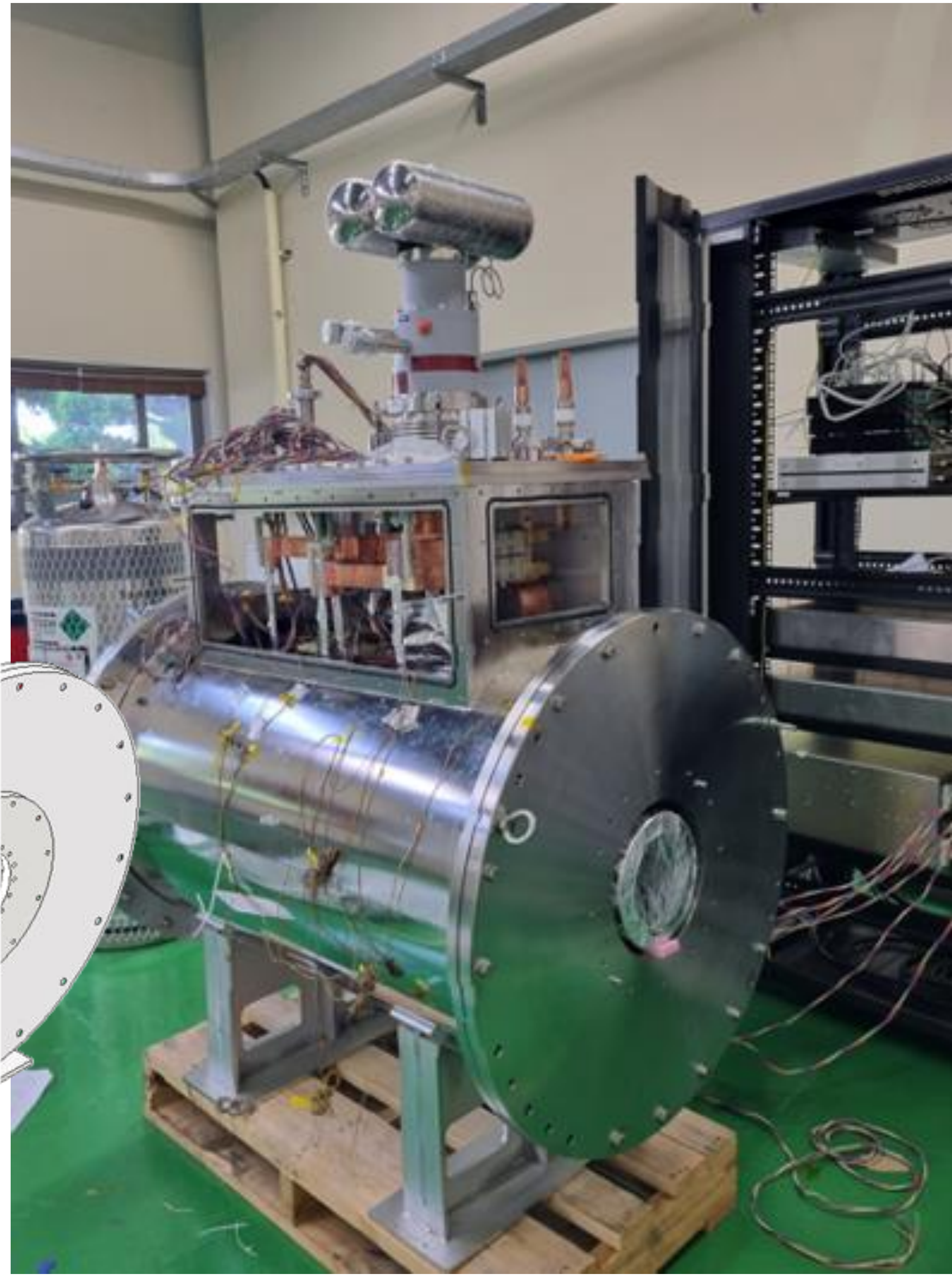
Assembling, Cooling, Power-on Test

- 2024.12 : Turbo pump was added
- 2025.01 : Powering test
- .02 : Reached 4.5 T at 20 K ...
  Cryogenic system requires upgrading
  Cooling capacity is presumed to have been underestimated
- .04 : Long-term operation test initiated
- .09 : First integral (long coil) measurement
  Operating currents were determined
- On-going work
  - 2D/3D field mapping
  - Photon energy spectrometer
- Next step
  - Machine study

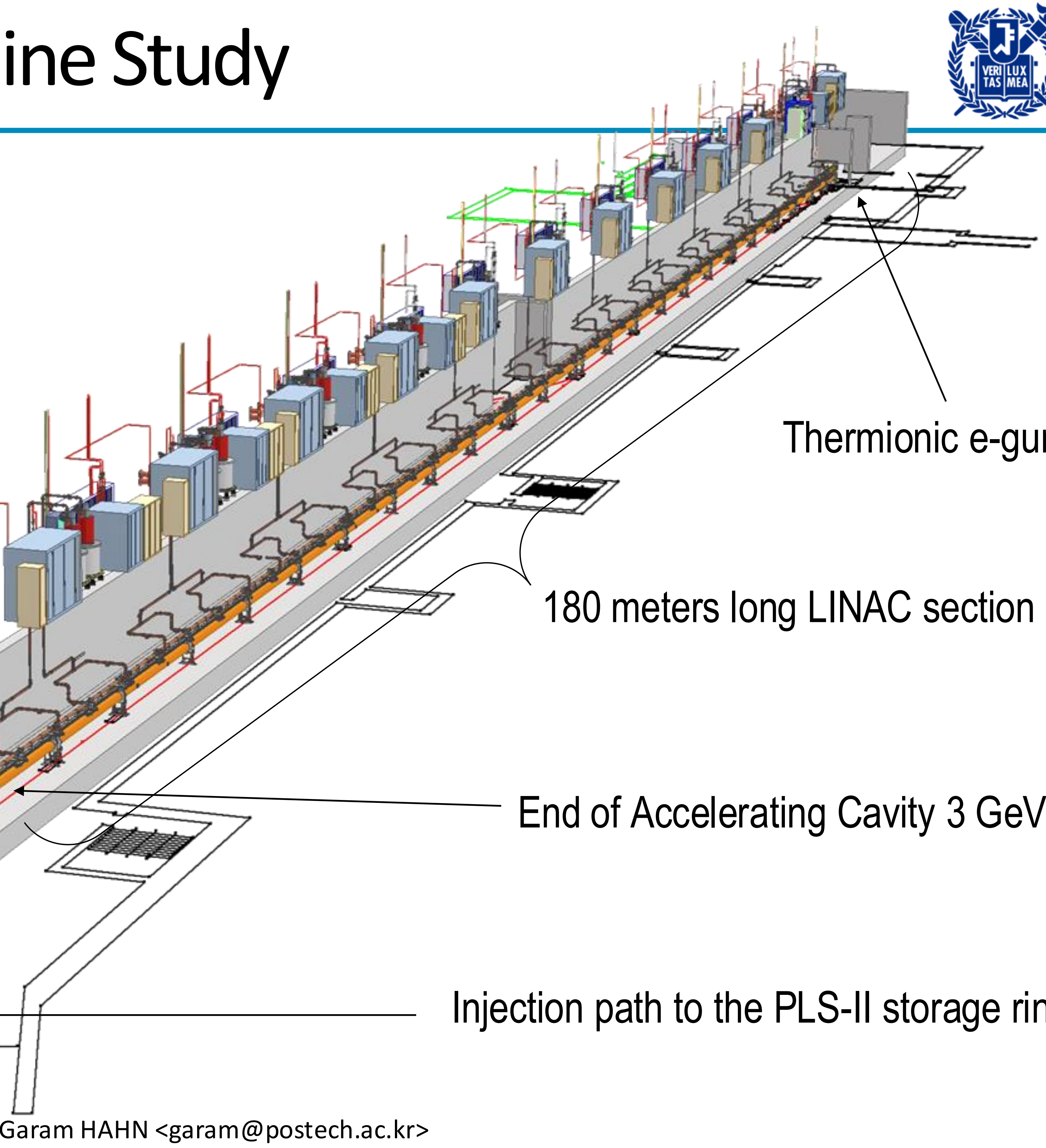




Preparing for Machine Study

PLS-II 3 GeV e^- Linear Accelerator

Figure 5. PLS-II configuration.



Thermionic e-gun 80 keV

180 meters long LINAC section

HTS-WLS test area (proposed)

End of Accelerating Cavity 3 GeV

Beam dump

Injection path to the PLS-II storage ring

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Remarks

- Since 2020, we have been conducting HTS-based magnet development research for future light source magnet technology with Seoul National University.
- 5 T HTS wiggler prototype employing LHe-free conduction cooling was successfully fabricated and tested (Aug 2023).
    - 5.02 T was experimentally vitrificated without any quench.
- The magnet was integrated with a dedicated cryogenic system and vacuum chamber (Feb–Nov 2024).
    - Two reinforcements: (1) the insulation breakdown problem and (2) thermal insulation problem
- Currently, we are preparing a precise field-mapping and a beam test

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Thank you for your attention

Proposed experiment area

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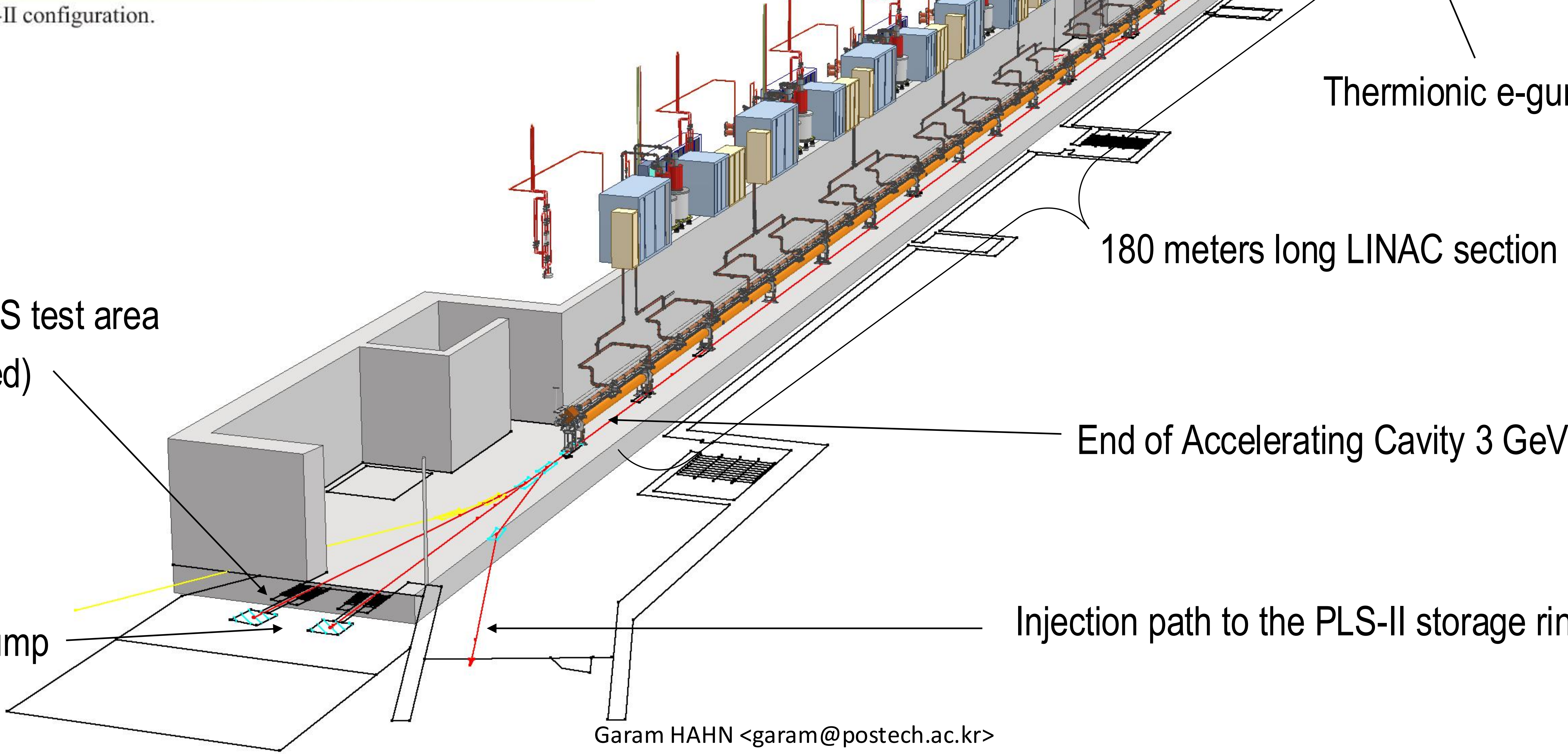
PLS-II 3 GeV e^- Linear Accelerator

Figure 5. PLS-II configuration.



Thermionic e-gun 80 keV

180 meters long LINAC section

HTS-WLS test area (proposed)

End of Accelerating Cavity 3 GeV

Injection path to the PLS-II storage ring

Beam dump

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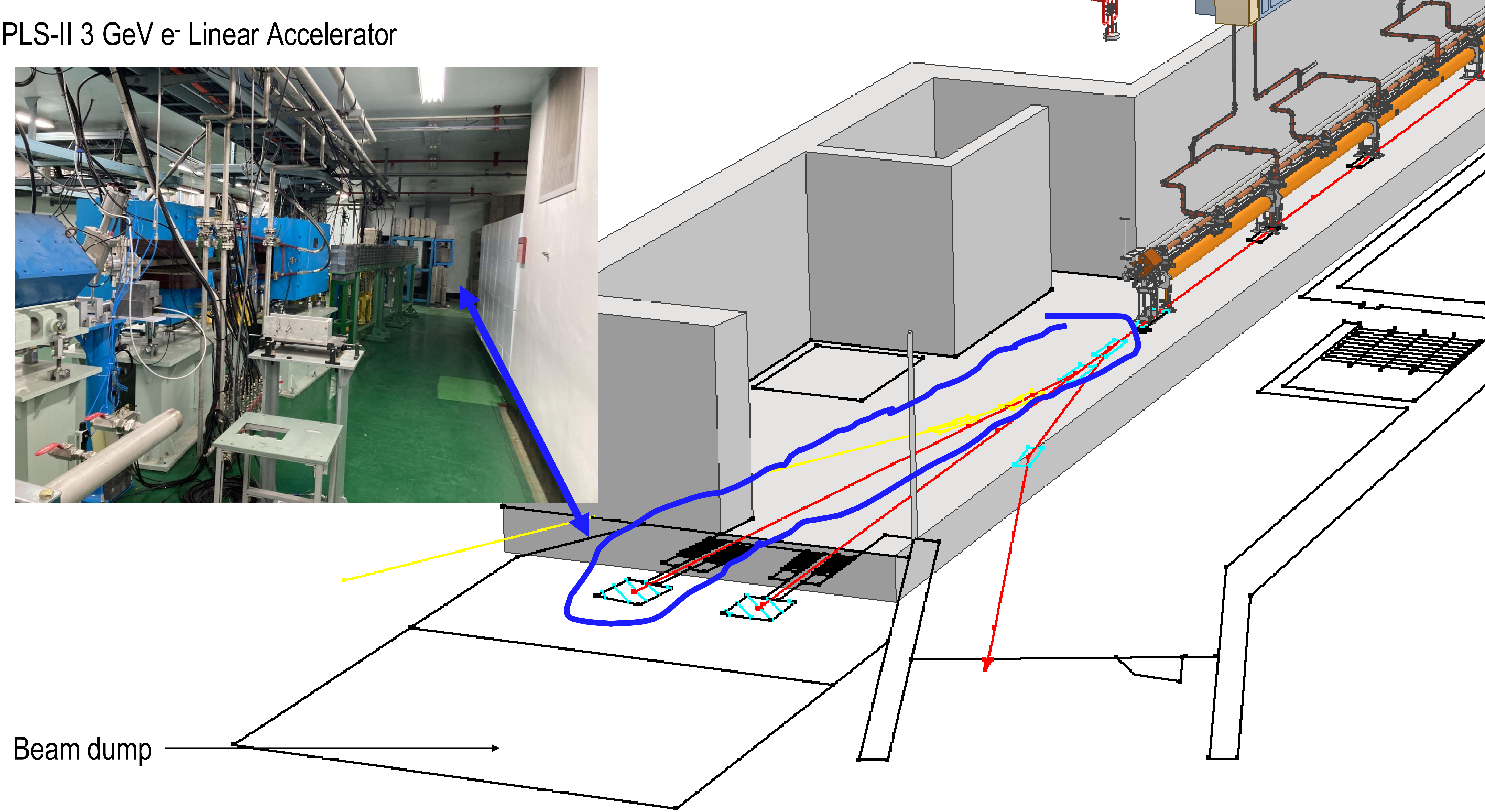
PLS-II 3 GeV e⁻ Linear Accelerator



Beam dump

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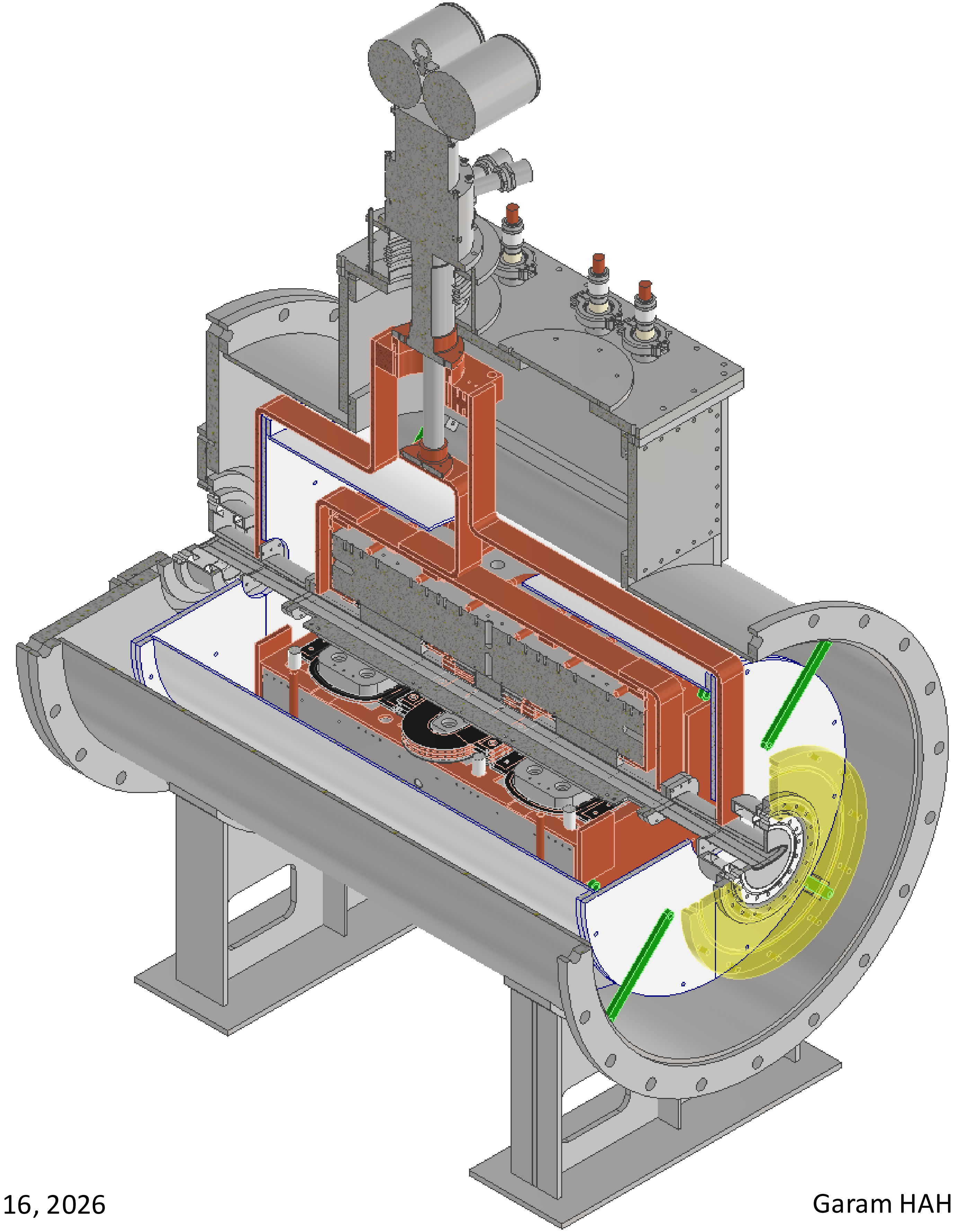

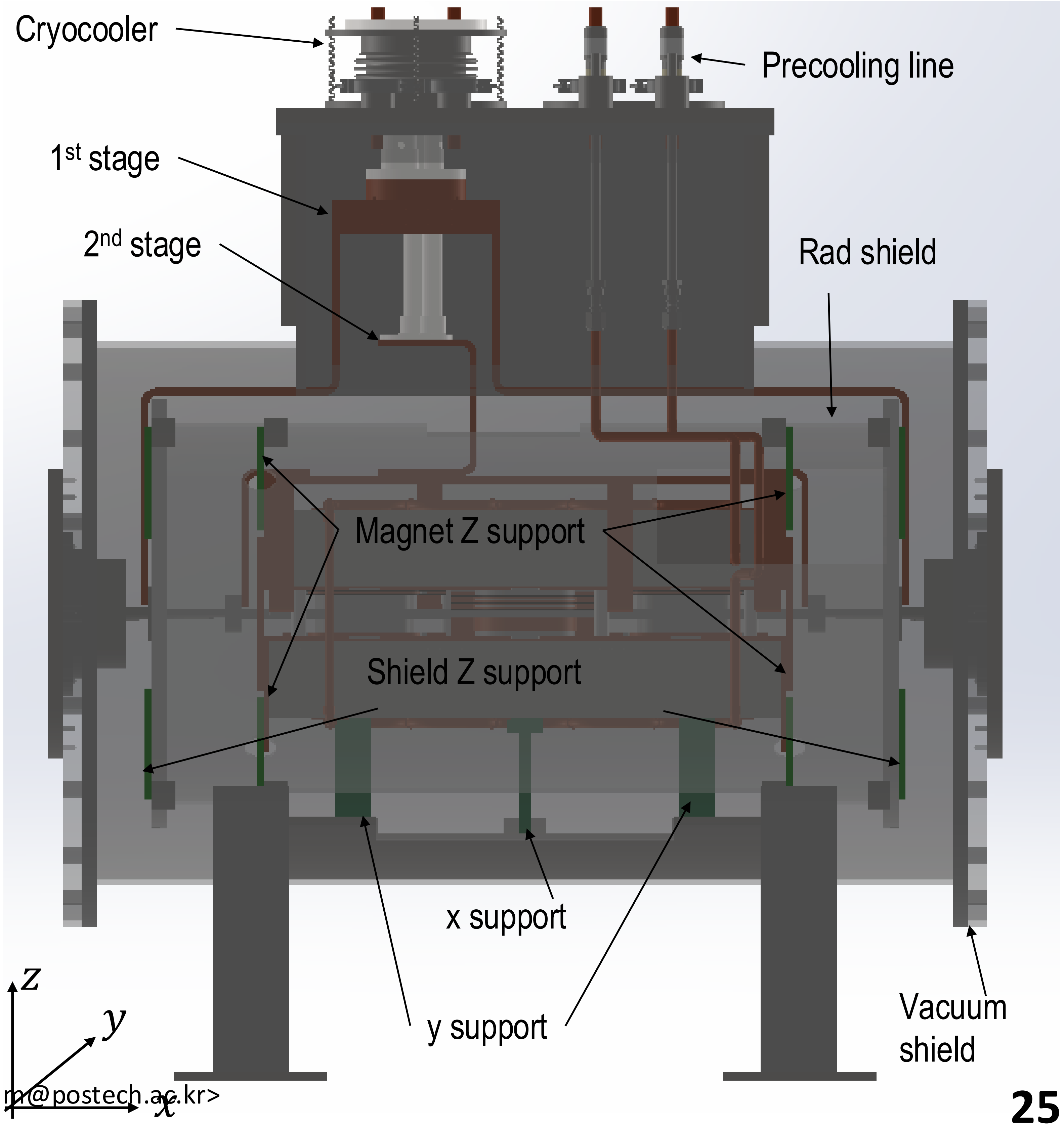
Cryocooler
Precooling line
1st stage
2nd stage
Rad shield
Magnet Z support
Shield Z support
x support
y support
Vacuum shield
z
y
x

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