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Investigation on the zero liquid helium consumption cryostat for a superconducting undulator

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Content

1. Introduction

☐ Superconducting undulator（SCU）

- **Synchrotron Radiation Facility(SRF)**

Four generations: The first generation is based on a particle collider and the light is from a bending magnet; The second generation has specialized storage ring; The light depends on insertion devices(IDs), including wigglers and undulators, in the third generation; The fourth is defined by its quite low emissivity, for instance, the HEPS.

- **Insertion device (ID)**

Undulators are divided into in-ambience undulator(IAU), in-vacuum undulator(IVU), cryogenic permanent magnet undulator(CPMU) and so on. They are all based on permanent magnets, of which the magnetic field has been close to the limitation. Therefore, new technologies to enhance the magnetic field must be explored.

- **Superconducting undulator (SCU)**

One of the most potential insertion devices; Many incomparable advantages, for instance, higher peak field, higher photon energy, higher brightness, tunability of radiant energy, possibility of developing new forms of inserts.

However, there exist many challenges, for instance, superconducting coils cooling, development of the cryostat. This investigation is focused on the zero liquid helium consumption cryostat.

1. Introduction

Institute	Research and development history
APS/ANL	Staring form 1999; Since 2012, SCU0, SCU1 and SCU1 have been fabricated and commissioned in the storage ring.
ANKA/KIT	Staring form 1999; SCU14 and SCU15 have been installed in the storage ring.
BINP	It has been investigating the zero liquid helium consumption cryostat for superconducting insertions for about 40 years, especially the wigglers.
DLS	Starting from 2005; The superconducting magnet was developed. There was no beam test.
STFC	Starting from 2005; The magnet development and the cryogenic test have been finished.
ALS/LBNL	Corporate with the APS.
NSLS	Some design and calculation works.
LCLS-II	Starting from 2014; Based on pulse tube cryocooler; 5m long cryostat, 29, which depend on large helium liquefier.
ESRF	Starting from 2004; Few references.
TLS/TPS	Starting from 2005; Based on large helium liquefier.
SSRF	Starting from 2013; SC magnet and horizontal test is finished. It has been installed in the storage ring.

- There are many institutes who study superconducting undulators. However, only the APS and ANKA succeed. Many failures are caused by cryostats.

1. Introduction

Advanced Photon Source(APS); Affiliated to the ANL

Research process：

1999，Concept design of the SCUs;

2002-2009，R&D of the SCU0 and SCU1;

2009-2012，Fabrication and assembly of the SCU0;

2012-2013，SCU0 was installed in the storage ring of the APS；

2014-2015，Design, fabrication, commissioning of the SCU1（SCU18-1）;

2014-2016，SCU0 was replaced by SCU18-2;

2016-2017，Design, fabrication, commissioning of the HSCU1;

Since 2018，Research on SCUs made of Nb_3Sn and HTS.

Table1 Key parameters of SCUs in APS

	SCU0	SCU18-1/2	LCLS R&D SCU	HSCU
Period length	16 mm	18 mm	21 mm	31.5 mm
Gap	9.5 mm	9.5 mm	8.0 mm	/
Magnet Length	0.33 m	1.1 m	1.5 m	1.2 m
Peak field	0.64 T	0.97 T	1.67 T	0.4 T
Total length	2.063 m	2.063 m	2.063 m	1.85 m

- It corporated with the BINP to complete the design of the cryostat. SCU0, SCU1 and LCLS SCU share the same cryostat scheme.

1. Introduction

ANgstrom source Karlsruhe(ANKA) , KIT
Research process :

1998, Concept design ;

2005, SCU14 was developed and installed in the storage ring;

2007, the test platform CASPER was developed;

2010-2011, the dynamic heat load was studied;

2011, the CASPERII was developed for 2m long magnet;

2006-2015, SCU15 was designed, fabricated and tested;

Since 2016, SCU20 has been studied.

Table 2 Key parameters of SCUs in ANKA

	SCU14	SCU15	SCU20	SCUW	CASPER II
Period	14 mm	15mm	20mm	18mm/54	/
Gap	Variable	5-8 mm	/	5-8mm	/
Length	1.54m	1.5m	1.5m	/	2m
Peak field	0.77T	0.73-1.33T	/	0.77-1.46T	/
Total length	2.5 m	2.7m	/	/	/

- Helium-free cryostat; The superconducting magnets are cooled through heat conduction. The current was approximately 150 A.

1. Introduction

Shanghai Synchrotron Radiation Facility(SSRF)，SINAP

Research process:

2009，Measurement device of heat load;

2013，Study of key technologies;

2015，Development of a SCU prototype;

2016，Cryostat was tested alone successfully ;

2018，Many difficulties were faced when the cryostat was assembled with the magnet;

2021，with the electron beam.

Period	16 mm
Gap	9.5 ~11.5 mm
Length	0.8 mm
Peak field	0.67 T
Current	400 A
Total length	1.8m

1. Introduction

- Three types of cryostats:

Type	Institutes	Advantages
Zero liquid helium consumption	APS、STFC、SSRF、BINP	More uniform temperature
Heat conduction cooled	ANKA、ESRF、TLS	Helium free
Large helium liquefier	LCLSⅡ、TPS	Smaller gap; Larger capacity

- Many profound lessons have validated two experiences：

1、The superconducting magnet and vacuum box should be separated. And both should be thermally insulated.

2、Do not just focus on the taking away of the heat load at lowest temperature, but also on the prevention of heat load.

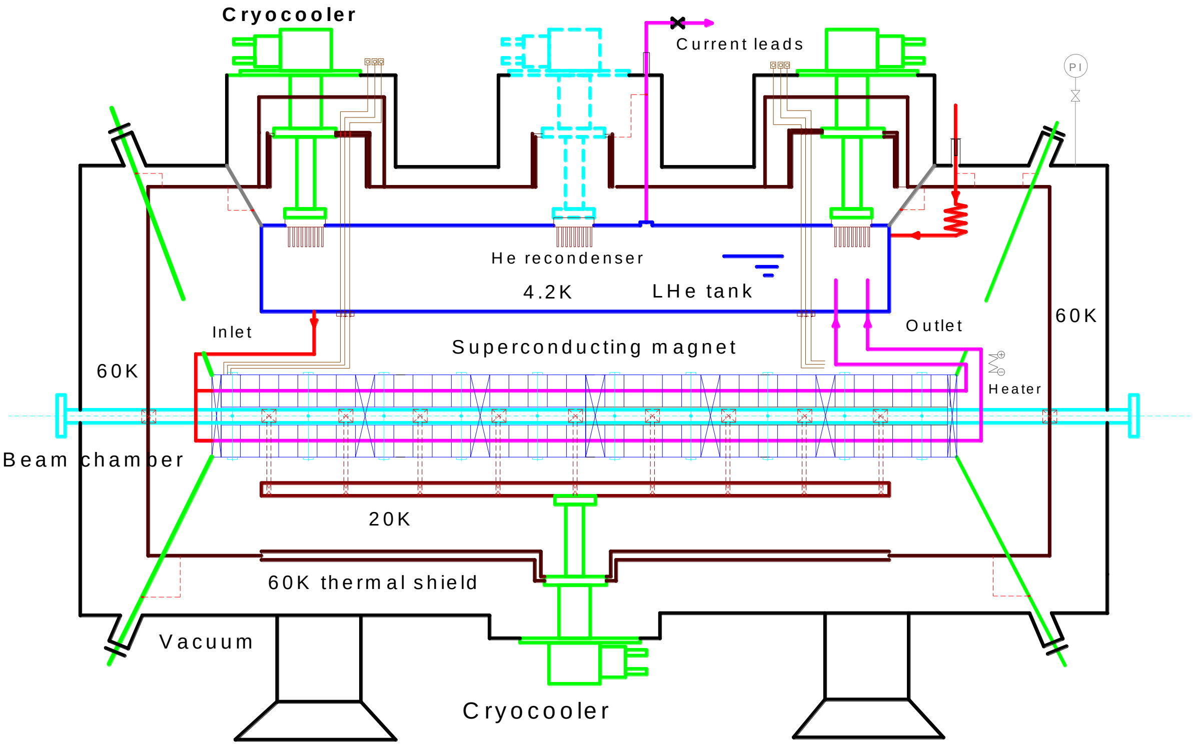
- Problems:

Insufficient effective cooling capacity; Complex mechanical structure;...

2. Experimental setup

Scheme

- Based on the thermodynamic and heat transfer theory, a new refrigeration distribution is proposed, which is based on the technologies of zero liquid helium consumption and thermosiphon circulation.

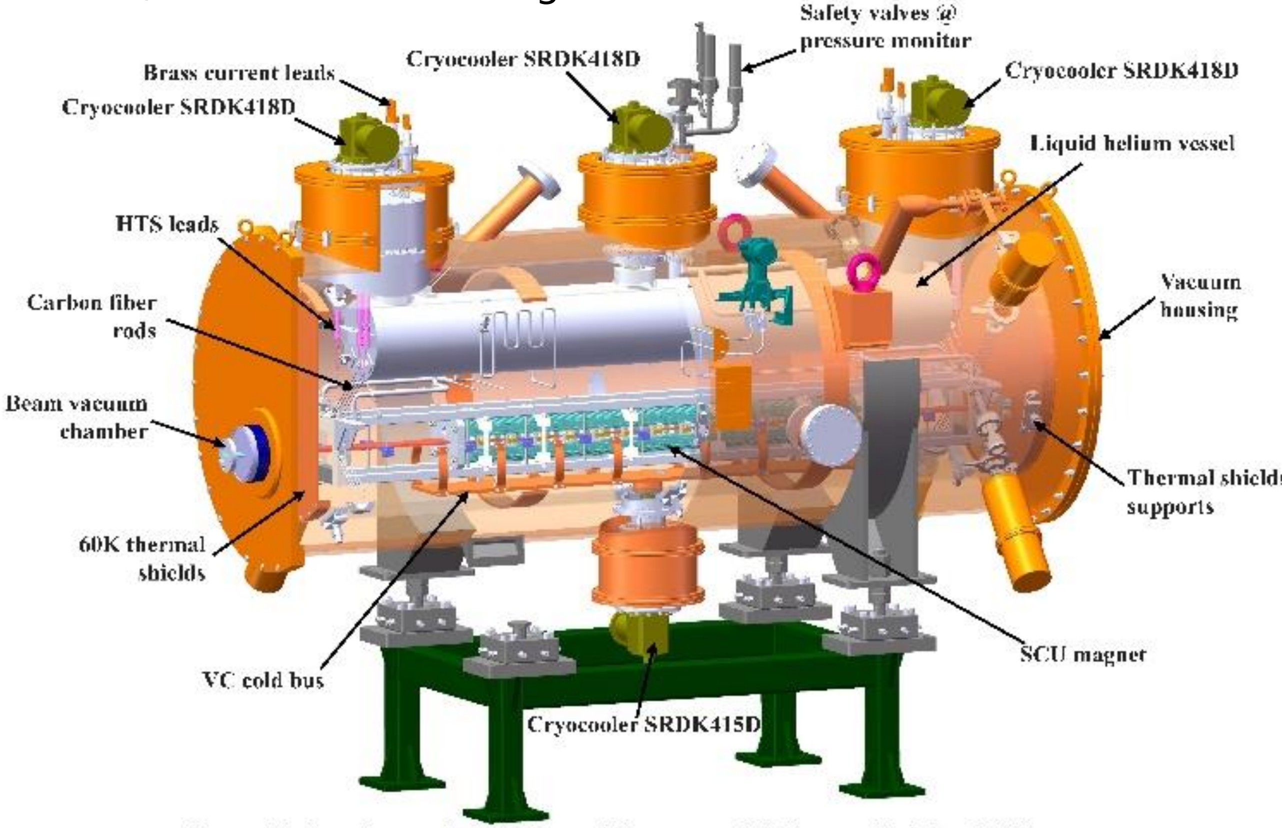


- **Cold source**: GM Cryocoolers, 4.2 K
- **Shield**: Single; At 60 K
- **Helium tank**: 100 liters; No discharge.
- **Condenser**: Finned exchanger;
- **Magnet cooling**: Circulation loop based on thermosiphon effect;
- **Beam chamber**: Adiabatic supports; At 20 K
- **Current lead**: Binary current lead made of high temperature superconductor
- **Magnet support**: Carbon fiber rods combined with thermal interruption
- **Refrigeration layout:** Three 4.2 K cold heads for the magnet; One cold head for the beam chamber; Four first stages for the thermal shield and current leads.

2. Experimental setup

Structure

- Based on the scheme, 3D structure of the cryostat is completed, which is 2.9 m long, 1.8 m high and 1.0 m wide. The height of the beam is approximately 1.2 m.
- The geometric parameters are optimized through thermal analysis so that the total heat load is decreased. Moreover, the mechanical strength is ensured.



Overall size: Length-2992mm; Diameter-1028mm; Height-1800mm

2. Experimental setup

Binary current leads

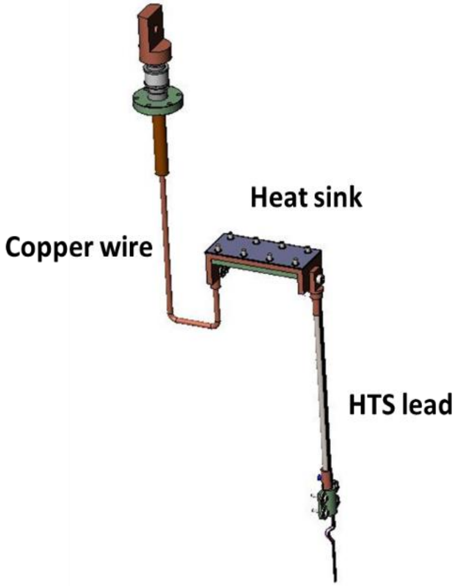
- High temperature superconductor is used. A couple of 400 A leads and two couples of 50 A are needed.
- Thermal analysis and optimization of the copper part are performed to minimize the heat load at 60 K.
- The heat load consists of heat conduction and Joule heat. The optimal geometry of copper lead and the minimum heat load can be calculated theoretically.

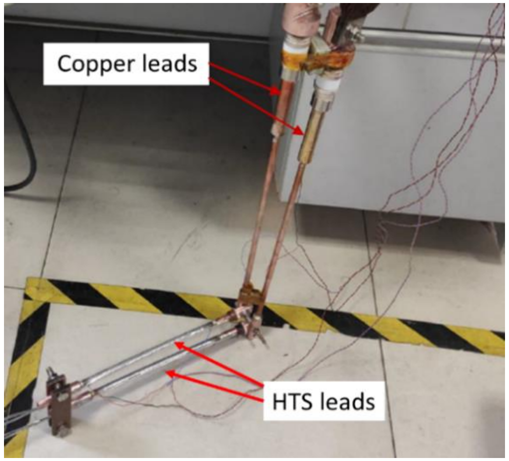
$$\frac{L_{\mathrm{Cu}}}{A_{\mathrm{Cu}}} = C = \int_{T_{\mathrm{L}}}^{T_{\mathrm{A}}} \frac{\lambda_{\mathrm{Cu}}(T)}{\sqrt{2I^2 \int_{\mathrm{T}}^{T_{\mathrm{A}}} \rho_{\mathrm{Cu}}(T)\lambda_{\mathrm{Cu}}(T)\mathrm{d}T}} \mathrm{d}T$$

$$Q_{\min} = \sqrt{2I^2 \int_{T_{\mathrm{L}}}^{T_{\mathrm{A}}} \rho_{\mathrm{Cu}}(T)\lambda_{\mathrm{Cu}}(T)\mathrm{d}T}$$

- The heat load at 4.2 K is only from heat conduction of the HTS part.

$$Q_{4\mathrm{K}} = \frac{A_{\mathrm{HTS}}}{L_{\mathrm{HTS}}} \cdot \int_{4.2}^{T_{\mathrm{J}}} \lambda_{\mathrm{HTS}}(T)\mathrm{d}T$$

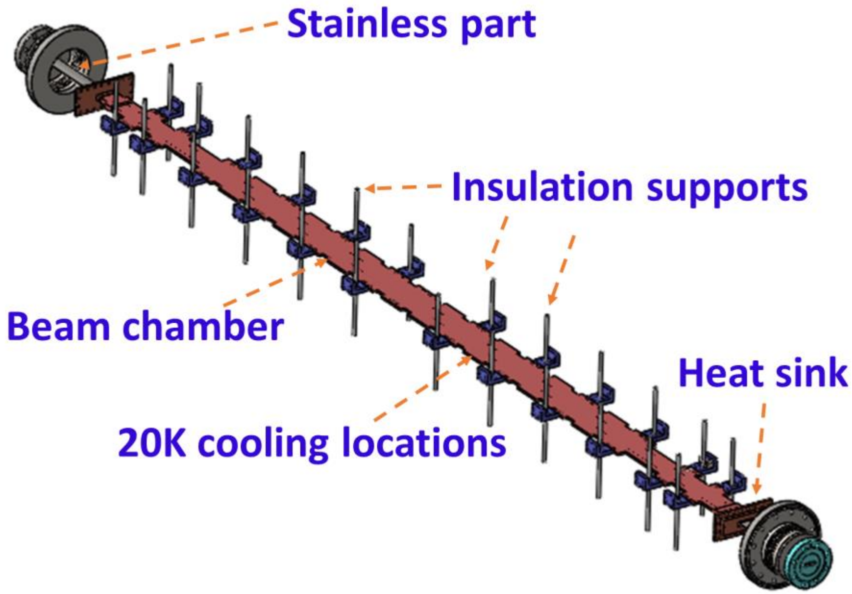




2. Experimental setup

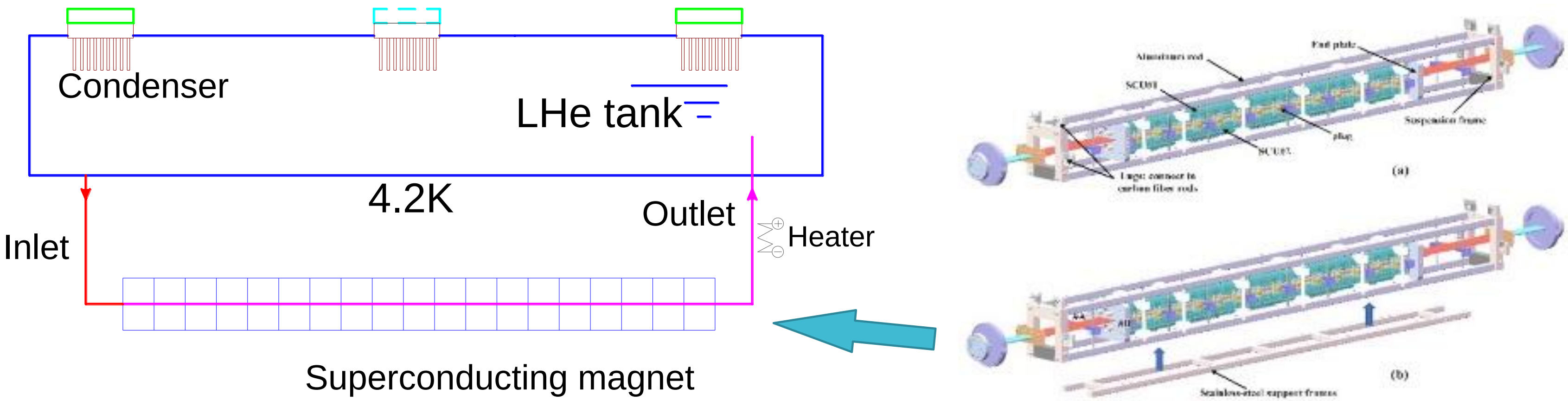
Beam chamber

- The beam chamber is cooled to 20 K, at which the cryocooler has a large cooling capacity and the chamber has little effect on the superconducting magnet.
- The beam chamber is installed on the frame by insulation supports. A cold bus is set parallel to the chamber, and some heat links are installed to connect them.
- At the two ends of the chamber, two heat sinks are set to prevent the heat from the ambience. In addition, the part from the sink to the ambience is made of stainless steel which has low thermal conductivity.



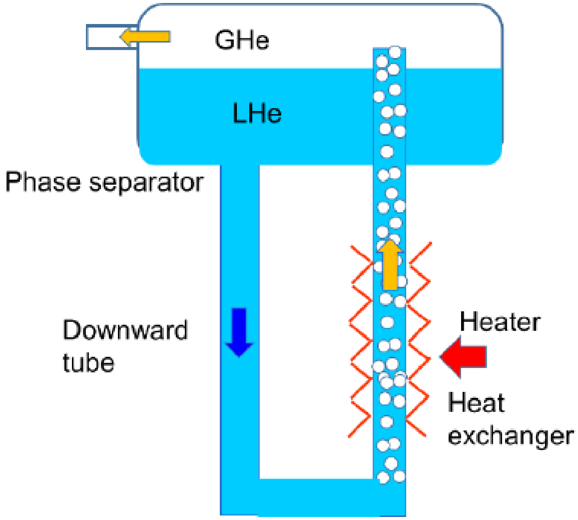
3. SC magnet cooling

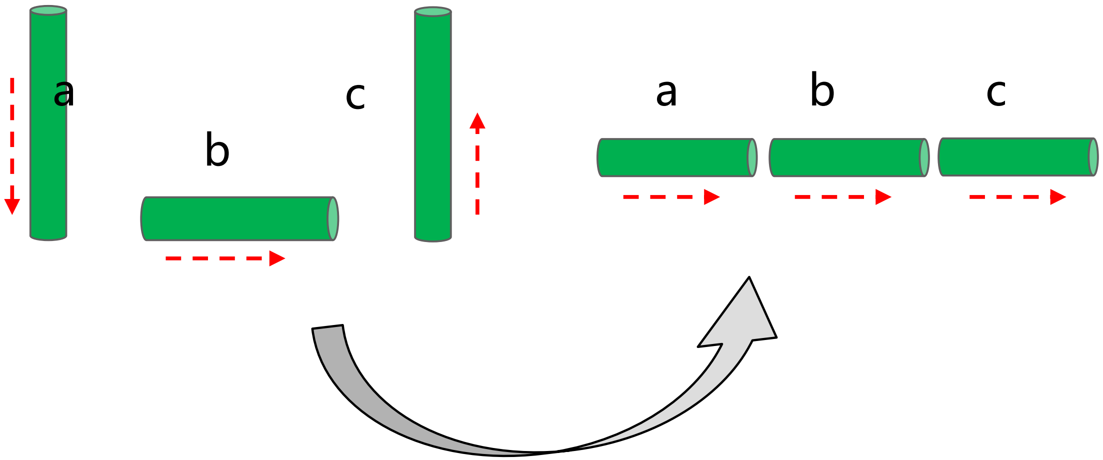
- If the magnet is not cooled by liquid helium immersion, How is the cooling capacity transferred to the superconducting magnet ?



- The circulation based on thermosiphon effect is suitable, which is driven by the density difference.
- A liquid helium pump is avoided, which has so large heat load that the cryostat will be failed.
- The circulation is composed of LHe tank, condenser, SC magnet, and heater. The heater vaporizes some liquid phase to gas phase to change the density. The condenser re-liquefies the helium.
- The heat load from the magnet is very little. Therefore, as long as the liquid helium flows, the heat will not accumulate at some point.

3. SC magnet cooling

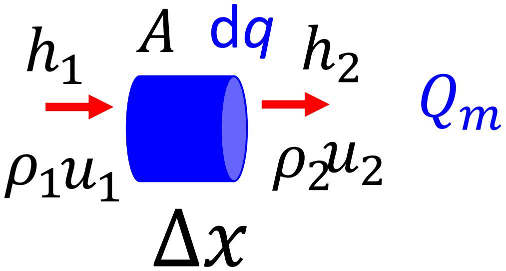




$$\frac{\mathrm{d}(\rho u A)}{\mathrm{d}x} = 0 \qquad (1)$$

$$(\rho u A)\mathrm{d}u = -A\mathrm{d}p - \left(\frac{\mathrm{d}p}{\mathrm{d}x}\right)_{f+\delta} \cdot A dx + (\rho g)_\theta A \mathrm{d}x \qquad (2)$$

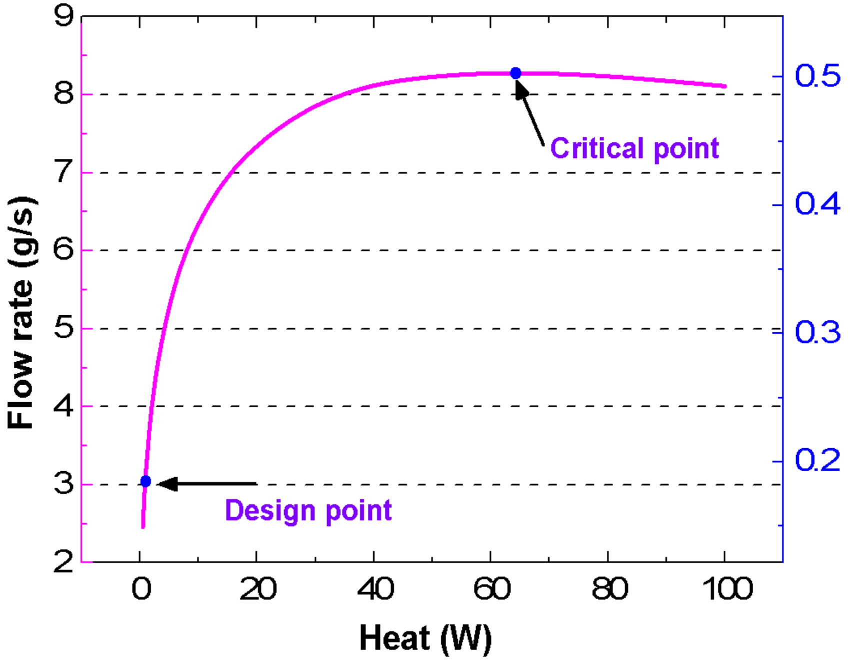
$$dq = (Q_\mathrm{m})\mathrm{d}(h + \frac{u^2}{2} + (gx)_\theta) \qquad (3)$$

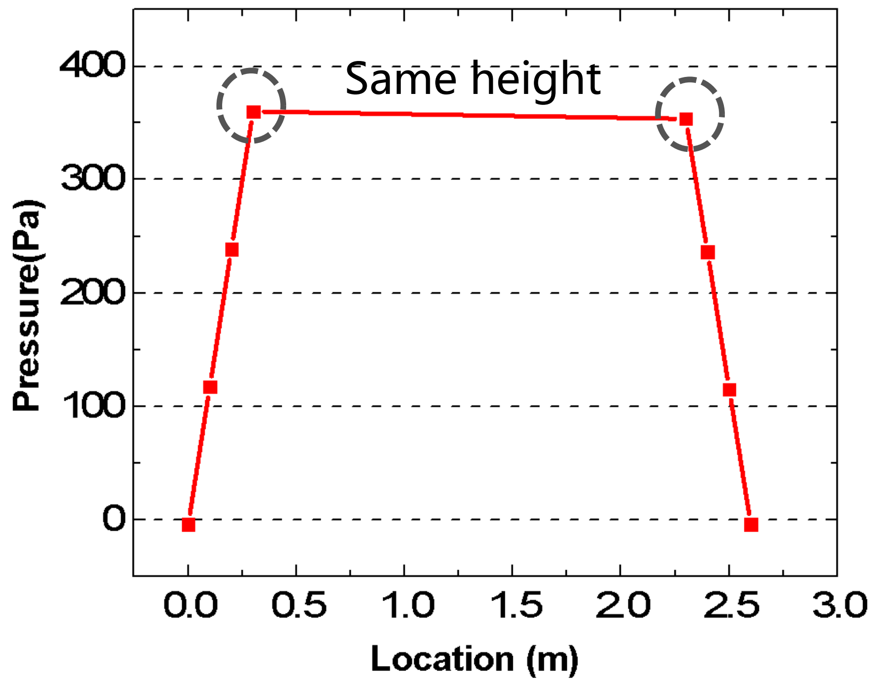


- The combination of the fundamental law equation and the physical property equation completes the closure of the equations, which can be solved to get the unknown parameters.

3. SC magnet cooling

- Initially, the flow rate increases rapidly. However, a critical point is reached, after which the flow rate decreases. This occurs because the driving force increases at a slower rate than the flow resistance.
- The gravity item is the essential driving force of the thermosiphon flow, and the density difference is the key condition.





3. SC magnet cooling

Condenser

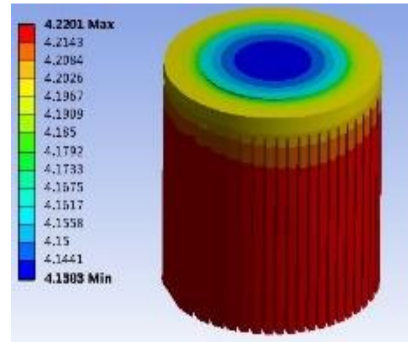
- In order to achieve high condensation efficiency of helium, a finned-type exchanger should be installed on the cold head.
- The heat convection on the surface can be described by the model of vertical convective heat transfer.

$$\bar{h}_L = 0.943[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{\mu_l(T_{sat}-T_s)L}]^{1/4}$$

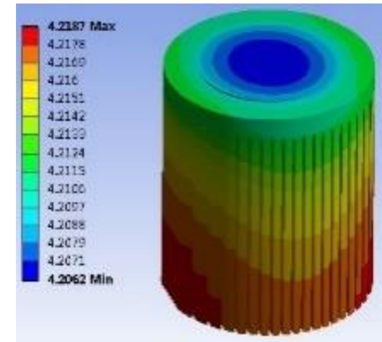
$$h'_{fg} = h_{fg} + 0.68c_{p,l}(T_{sat}-T_s)$$

$$Q = A\cdot\bar{h}_L\cdot(T_{sat}-T_s) = 2\cdot S\cdot L\cdot\bar{h}_L\cdot(T_{sat}-T_s)$$

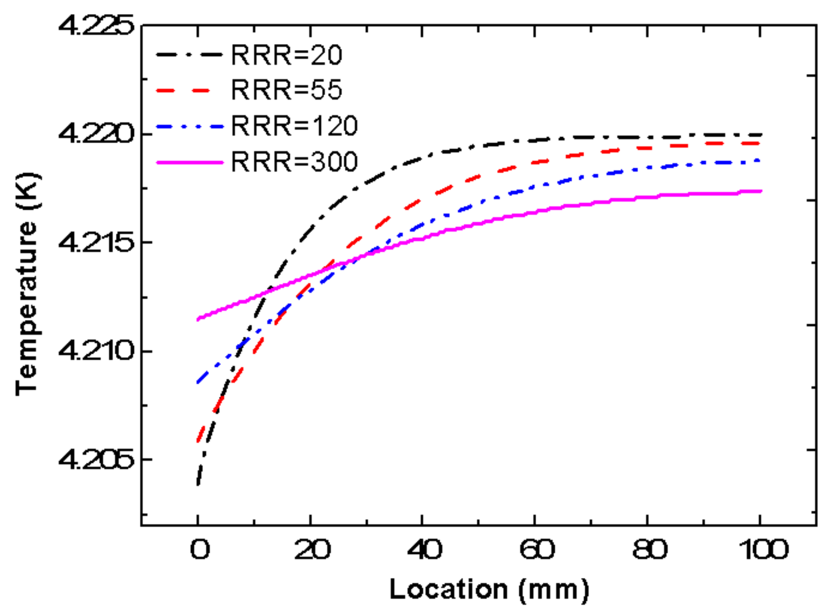
- The condenser is made of oxygen-free copper, with a Residual Resistivity Ratio (RRR) greater than 100. It can maintain a temperature difference as low as 0.05 K while transferring 2 W of heat.



RRR 20



RRR 300



4. Thermal analysis

Fundamental theory

- The governing equation of the heat transfer in solid.

$$\rho c(T)\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right)+S$$

- Two types of boundary conditions: constant temperature; constant heat flux.
- The temperature field and the flow can be obtained by the numerical method.
- If the geometry of a component is simple, the heat load can be calculated directly.

$$Q_{\mathrm{T}}=\sum_j\left[\frac{A}{L}\cdot\int_{T_2}^{T_1}\lambda\, dT\right]_j$$

- The Joule heat:

$$Q_J=\sum_m R_m\cdot I^2+\sum_n r_n\cdot i^2\approx M\cdot\overline{R_{\mathrm{I}}}\cdot I^2$$

- Multilayer insulation:

$$q=\frac{C_{\mathrm{S}}\overline{N}^{2.56}T_{\mathrm{m}}}{N_{\mathrm{S}}+1}\cdot(T_{\mathrm{H}}-T_{\mathrm{C}})+\frac{C_{\mathrm{R}}\varepsilon_{\mathrm{RT}}}{N_{\mathrm{S}}}\cdot\left({T_{\mathrm{H}}}^{4.67}-{T_{\mathrm{C}}}^{4.67}\right)$$

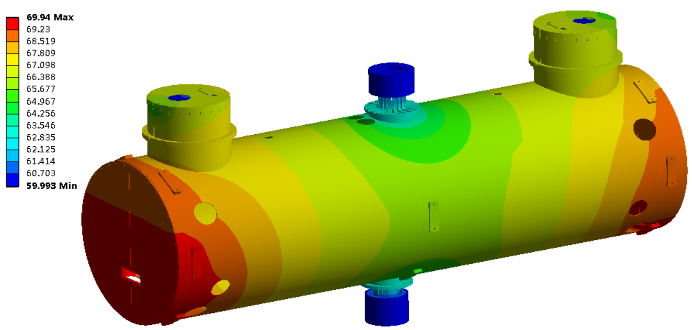
- Current lead:

$$Q_{\min}=\sqrt{2I^2\int_{T_{\mathrm{L}}}^{T_{\mathrm{A}}}\rho_{\mathrm{Cu}}(T)\lambda_{\mathrm{Cu}}(T)\mathrm{d}T}$$

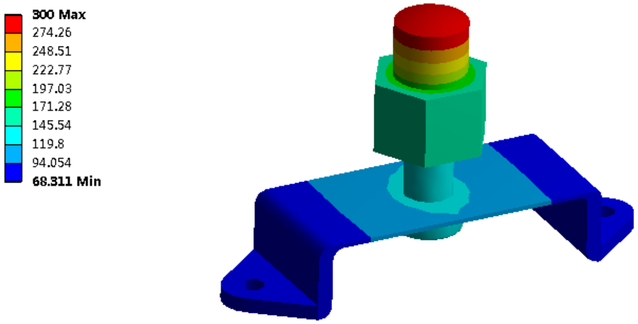
4. Thermal analysis

◻ 60 K temperature field

The maximum temperature difference of the thermal shield is less than 5 K, and it has minimal impact on the performance.



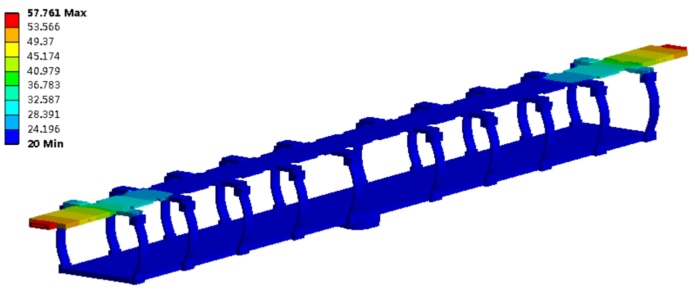
Thermal shield



Support of the shield

◻ 20 K temperature field

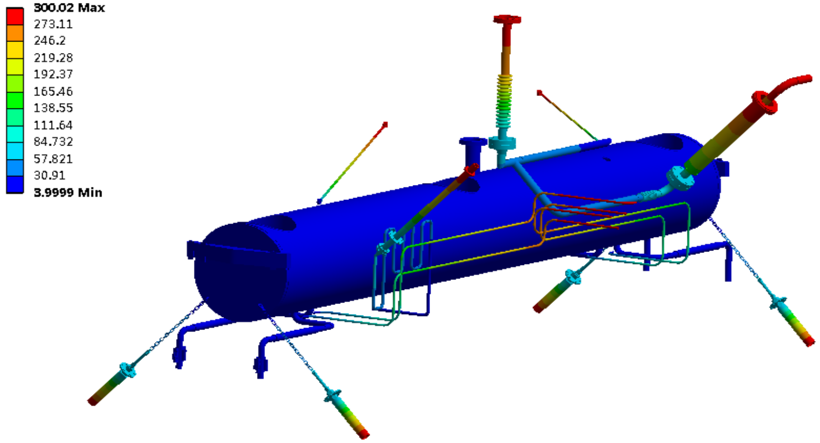
The temperature gradient exists at both ends. The static heat load comes from heat conduction.



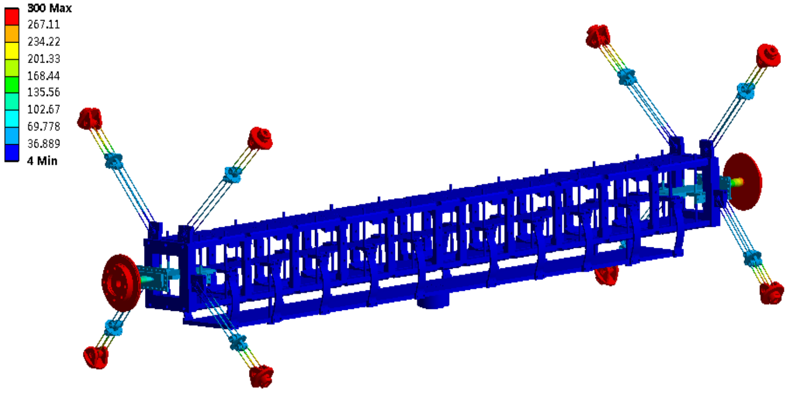
Beam chamber

4. Thermal analysis

- 4.2 K temperature field
  - For a lower heat load, many thermal interruptions are used, which are connected with the 60 K shield.
  - The carbon fiber material has a larger conductivity when the temperature is higher than liquid nitrogen temperature. Therefore, the thermal interruption can decrease the heat significantly.



Helium tank assembly



Superconducting assembly

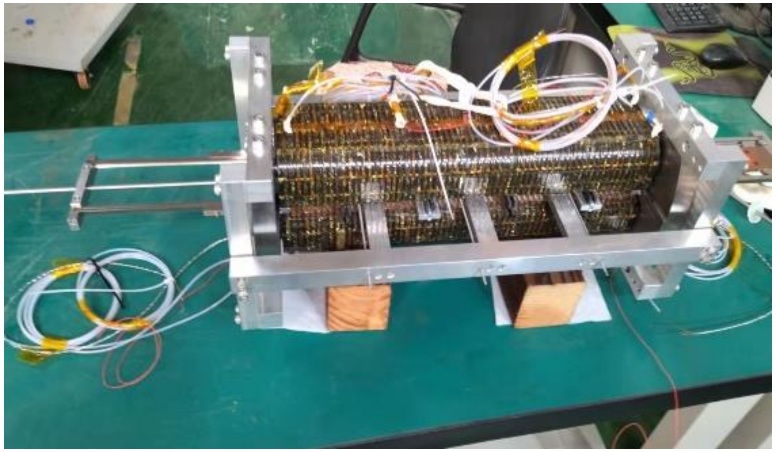
4. Thermal analysis

- Based on the optimization calculations of the cryostat, the results of the heat loads are summarized.
- The heat loads are divided to three temperature zones, 60 K, 20 K, and 4 K for each specific component.
- The 4.2 K heat load is less than the cooling capacity, which is the theoretical basis for the cryostat to realize zero consumption of liquid helium.

Category	60 K	20 K	4.2 K	4.2 K static	No magnet
Liquid helium tank	9.695	/	0.758	0.758	0.758
Superconducting Magnets	3.032	/	0.781	0.781	/
Current leads	51.6	/	0.6	0.48	0.48
Beam chamber	1.1	4.96	0.125	0.125	/
Thermal shield	28.63	/	/	/	/
In total	94.1	4.96	2.36	2.14	1.24
Cooling capacity	161	20	5.4	5.4	5.4
Excess capacity	66.9	15.0	3.04	3.26	4.16

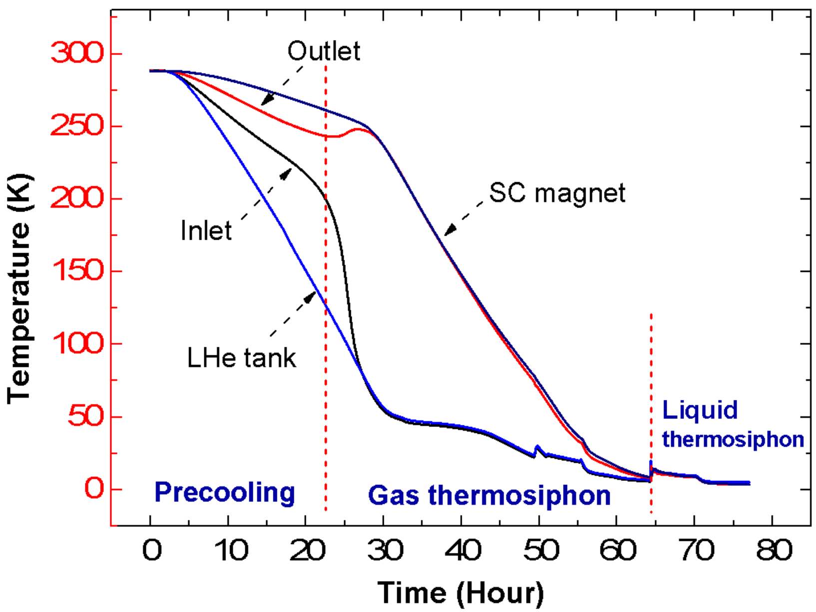
5. Test results

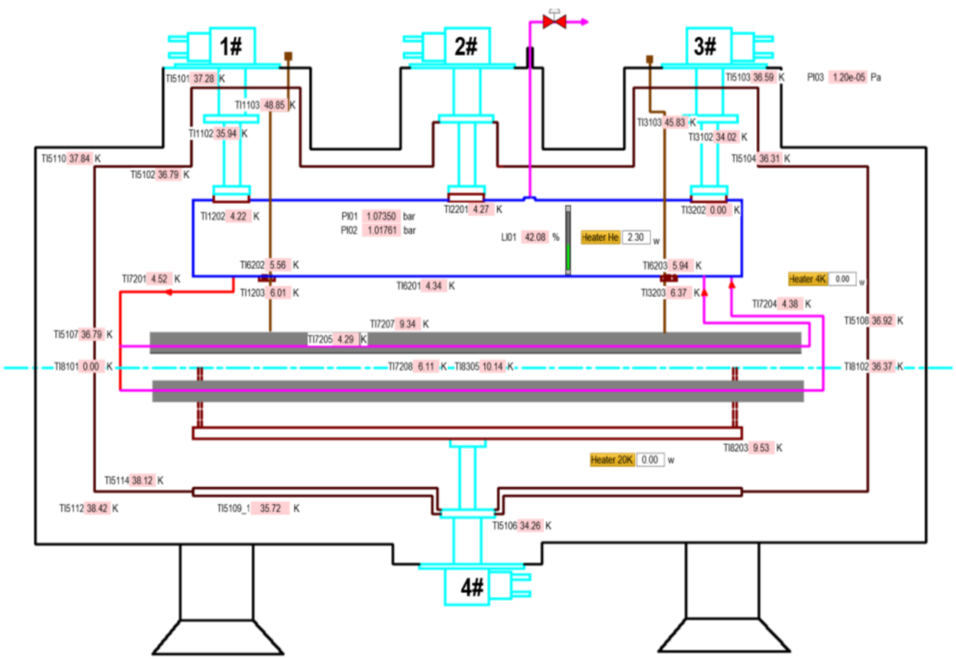
- The experiment was divided into two stages. The first is the test of 0.5 m long superconducting magnet. The second stage is the 1.5 m long full scale superconducting magnet. These pictures were about assembling of 0.5 m magnet.



5. Test results

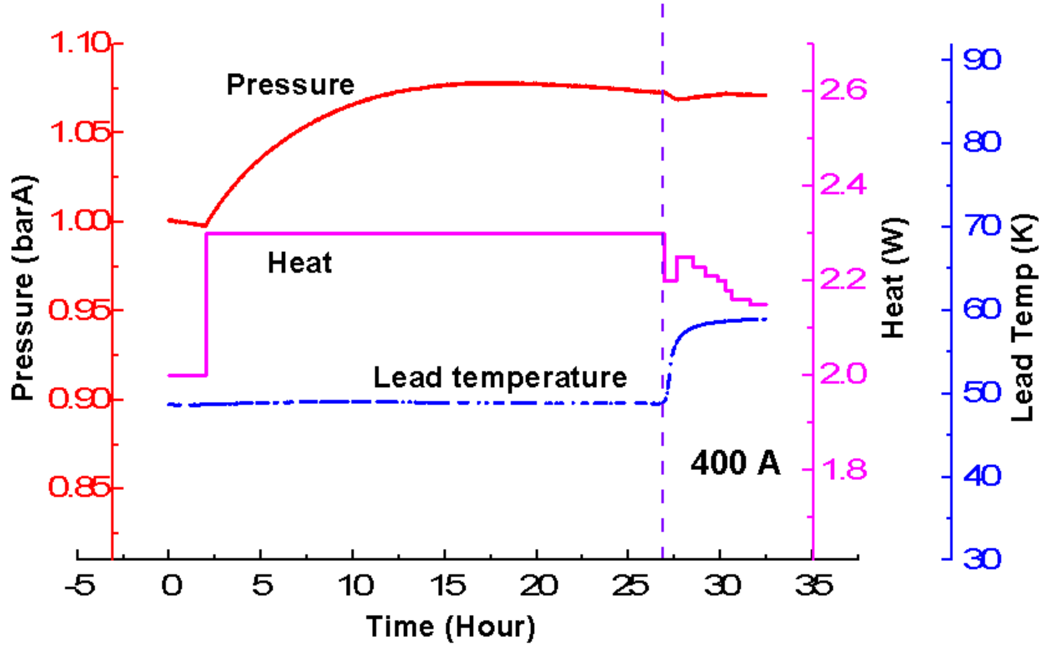
- It took three days to cool down the magnet from the ambient temperature to 4.2 K. When the temperature of the helium in the tank got close to 100 K, the thermosiphon circulation of the helium gas was established gradually.
- The temperatures of the thermal shield, current leads, helium tank, beam chamber and tank were measured. The shield was below 40 K, the magnet was 4.2 K, and the beam chamber was 10 K.





5. Test results

No.	Parameter	Result
1	LHe consumption	Zero
2	Magnet T	3.5~4.2 K
3	Excess capactiy	2.2 W
4	Total load	2.6 W
5	Insulation Vac	1.2*10^{-6}Pa



- The measurement of the cooling capacity depends on the heater. A thermal balance can be established where the helium pressure is below 1.1 barA.

$$Q_\mathrm{C} = Q_\mathrm{H} + Q_\mathrm{L}$$

where Q_C is the total cooling capacity, Q_H is the heater power, and Q_L is the total heat load. The heater power is equal to the excess cooling capacity.

- The process of establishing the thermal balance is shown in Figure. The final result is 2.2 W.

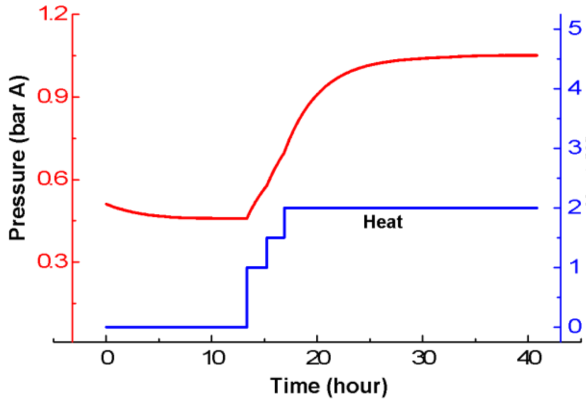
5. Test results

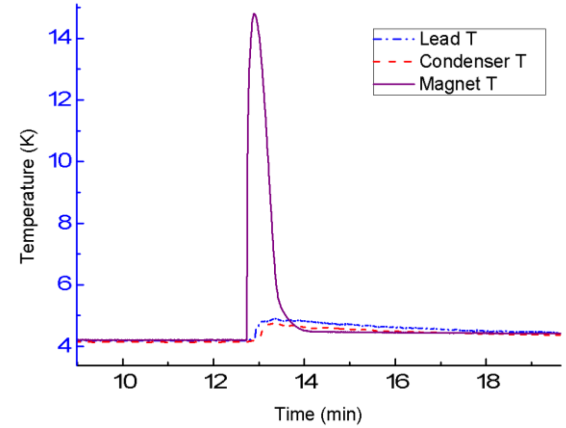
- The pictures were about assembling of 1.5 m superconducting magnet and the cryostat.
- It is approximately 2.8 m in length. Additionally, the weight of the magnet is approximately 300 kg.

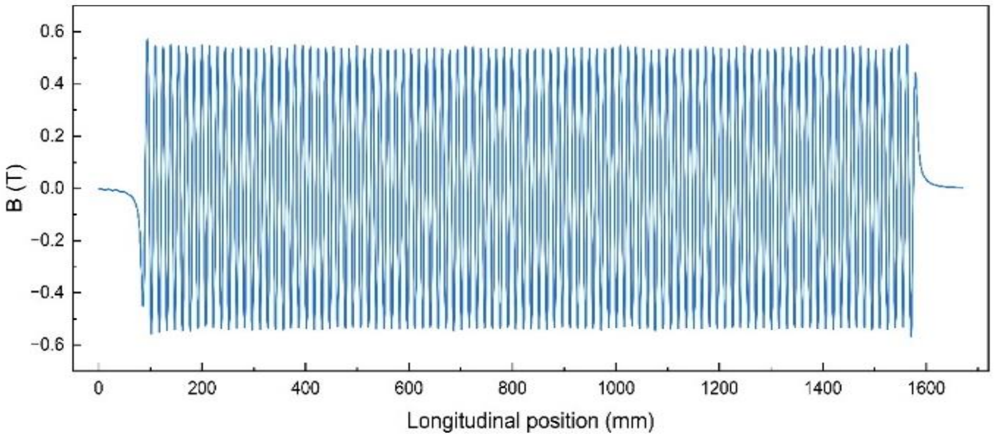
5. Test results

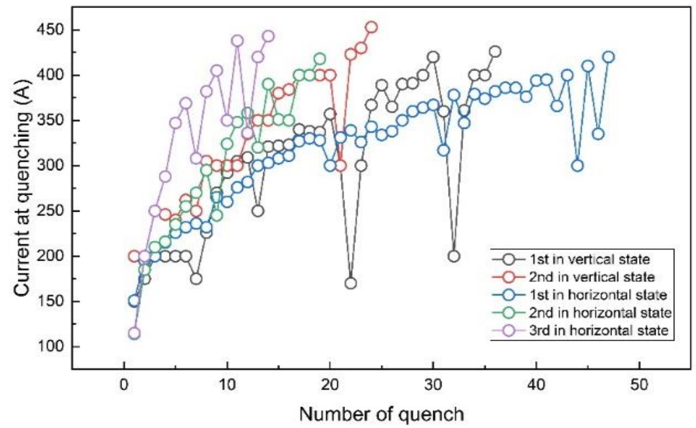
- The zero liquid helium consumption was achieved with an excess cooling capacity of 2.0 W.
- The superconducting magnet reaches a current of 450 A. There is no discharge when a quench occurs.
- Approximately six optimizations were performed to decease the phase error to 7°@400A .

No.	Parameter	Result
1	LHe consumption	Zero
2	Magnet T	4.2 K
3	Excess capactiy	2.0 W
4	Total load	2.8 W
5	Insulation Vac	$1.2*10^{-6}$Pa









6. SUMMARY

- The refrigeration distribution scheme is feasible for superconducting undulators cooling.
- There is no liquid helium consumption for the cryostat. The cryostat has an excess cooling capacity of 2.0 W.
- The cryostat has a single thermal shield, simplifying the mechanical structure.
- The full-scale superconducting magnet reaches a current of 450 A.

Thanks for you attention !