环形正负电子对撞机
Circular Electron Positron Collider

The 1st CEPC International Accelerator Review Committee Meeting in 2022
from Tuesday, June 7, 2022 at 15:00 to Friday, June 17, 2022 at 19:10 (Asia/Shanghai)

Cryogenic System for CEPC

Rui Ge*, Mei Li, Shaopeng Li, Ruixiong Han,
Miaofu Xu, Zhengze Chang

On behalf of the CEPC cryogenic group

June, 9th, 2022

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

OUTLINE

- Introduction
- CEPC SRF cryogenic system
- CEPC SC magnets cryogenic system
- Key technology
  - **2K JT heat exchanger R&D and test**
- Summary

CEPC Cryogenic System Brief Introduction

Booster ring:

- 1.3 GHz 9-cell cavities, 96 cavities
- 12 cryomodules
- 3 cryomodules/each station
- Temperature: 2K

Collider ring:

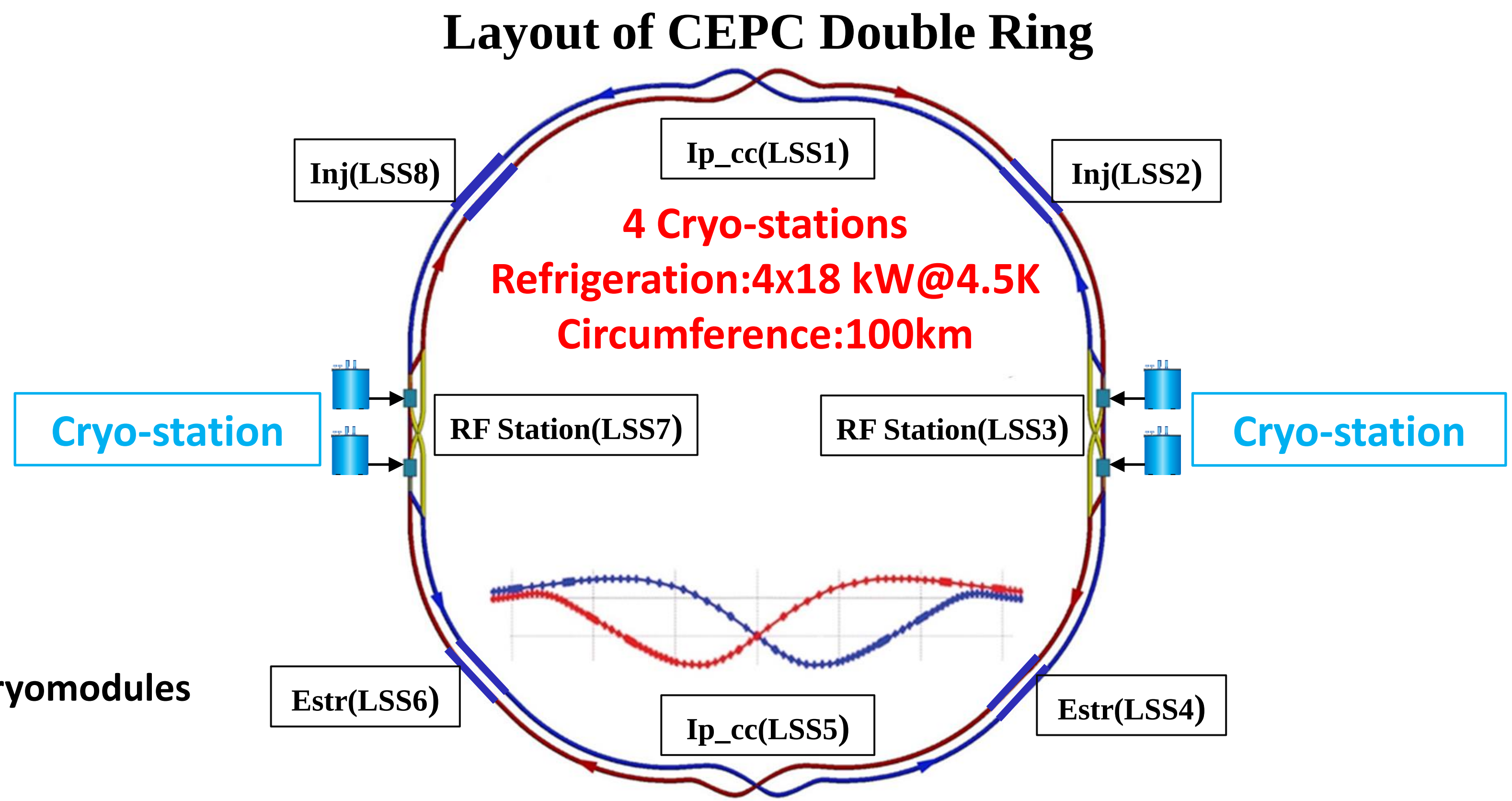
- 650MHz 2-cell cavities, 240 cavities
- 40 cryomodules
- 10 cryomodules/each station
- Temperature: 2K

IR magnets:

- 4 IR magnets, 32 Sextupole magnets, 36 cryomodules
- 18 cryomodules/each station
- Temperature: 4.5K

Detectors:

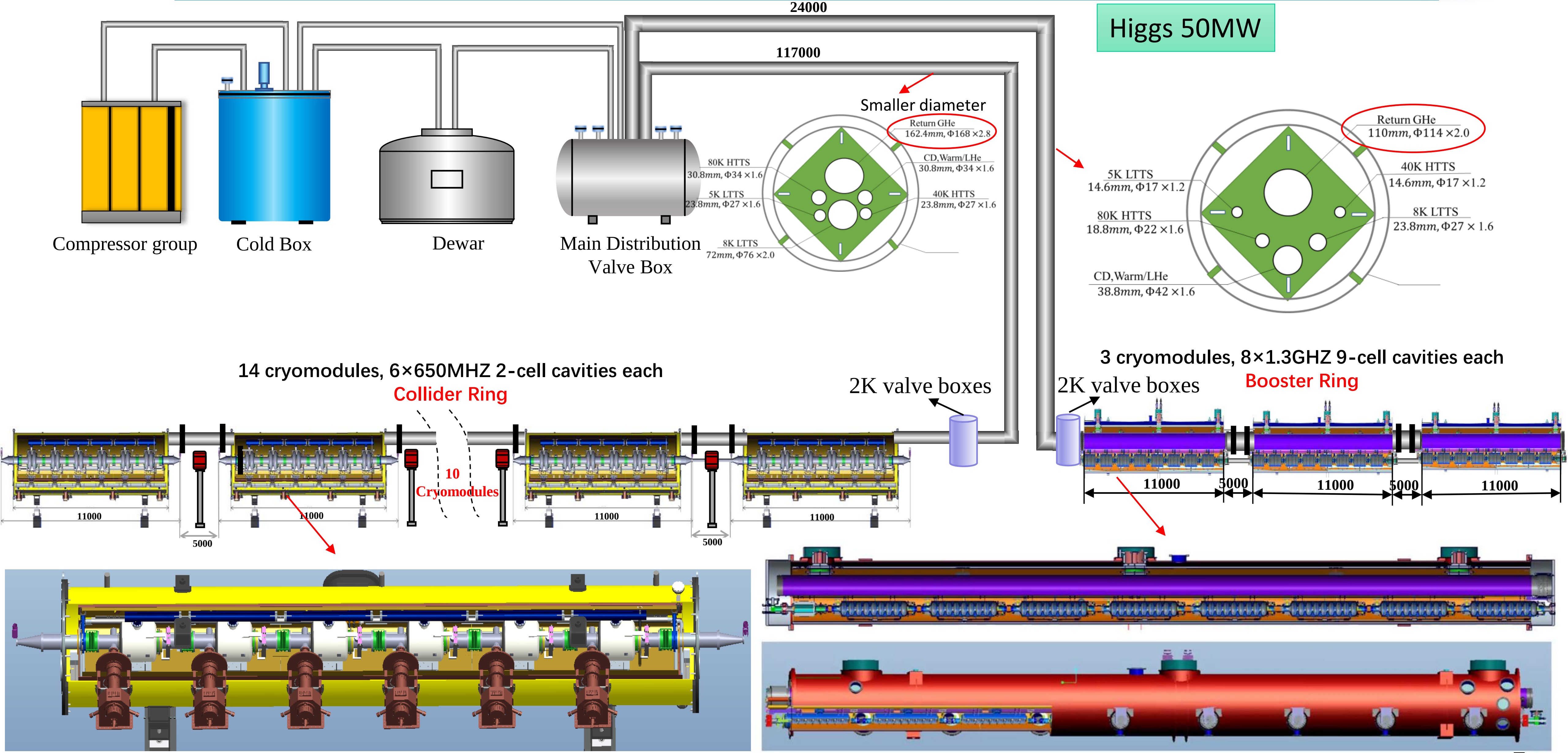
- 2 detector magnets
- Thermosiphon cooling



OUTLINE

- Introduction and Layout
- CEPC SRF cryogenic system
- CEPC SC magnets cryogenic system
- Key technology
- Summary

Flow chart of SRF Modif. Scheme



Estimated heat loads for SC cavities-Modif. Scheme

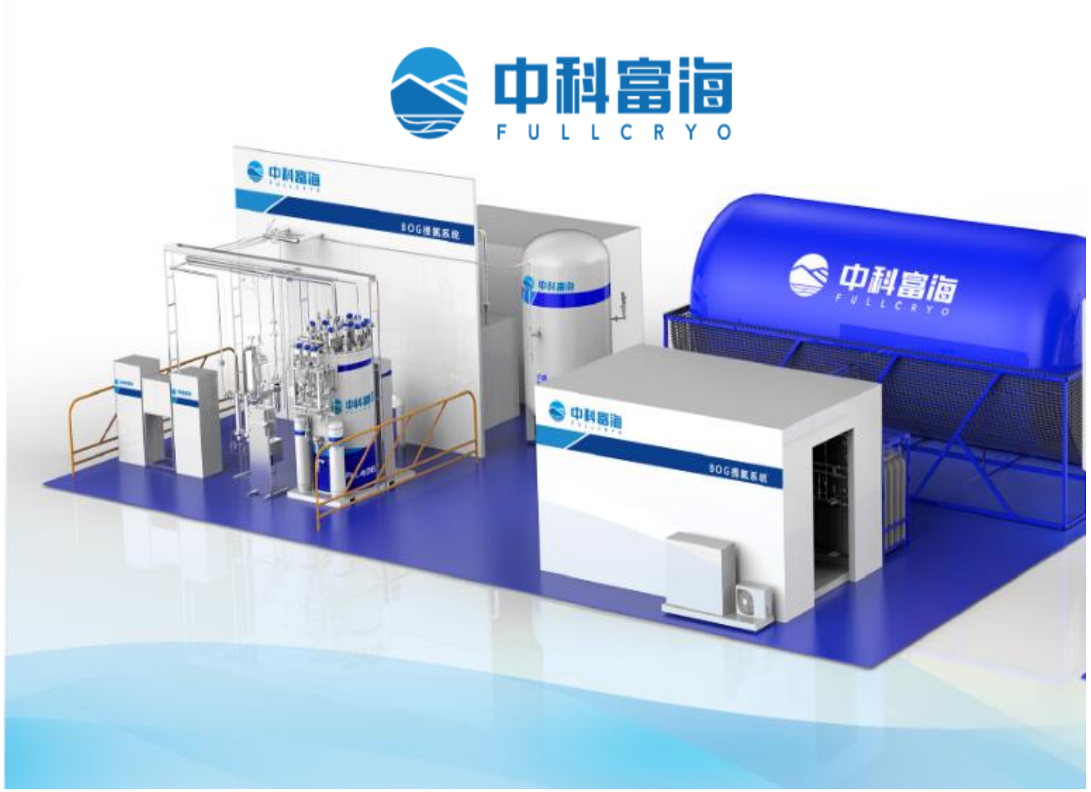
Higgs Mode 50MW	Unit	Collider			Booster		
		40-80K	5-8K	2K	40-80K	5-8K	2K
Predicted static heat load per cryomodule	W	300	60	12	140	20	3
Cavity dynamic heat load per cryomodule	W	0	0	153.59	0	0	13.98
HOM dynamic heat load per cryomodule	W	20	12	2	2	1	1
Input coupler dynamic heat load per cryomodule	W	60	40	6	40	3	0.4
Module dynamic heat load	W	80	52	161.59	42	4	15.38
Each Module total heat load	W	380	112	173.59	182	24	18.38
Cryomodule number	-	56	56	56	12	12	12
EVB heat loss	W	50	10	10	50	10	10
EVB number	-	40	40	40	12	12	12
MDVB heat loss	W	50	30	30	50	30	5
MDVB number	-	4	4	4	4	4	4
Total cryogenic transfer line length	m	728	728	728	136	136	136
cryogenic transfer line heat loss per meter	W/m	2	0.5	0.3	2	0.5	0.3
Total cryogenic transfer line heat loss	W	1456	364	218.4	272	68	40.8
Total heat load	kW	24.936	7.156	10.45944	3.256	0.596	0.40136
Total predicted mass flow	g/s	82.42	152.26	373.72	13.34	12.73	18.324
Overall net cryogenic capacity multiplier		1.54	1.54	1.54	1.54	1.54	1.54
4.5K equiv. heat load with multiplier	kW	2.89	9.97	51.56	0.37	0.83	1.98
4.5K equiv. heat load with multiplier	kW	64.41			3.19		
Total 4.5K equiv. heat load with multiplier	kW	4×16.85 kW 67.60					

•Four individual refrigerators (4 × 18kW@4.5K) will be employed for the CEPC cavity cryogenic system.

Large Helium Refrigerator Market Research

◆Domestic refrigerator / liquefier

- Institute of physics and Chemistry, CAS (FULL CRYO) has: 2kW@20K， 10kW@20K, etc.; 2.5KW@4.5K or 500W@2K Has been successfully developed;
- **10kW@4.5K or 18kW@4.5K (CEPC) has been planned with the foundation of the pilot project of Chinese Academy of Science.**
- Institute of Plasma Physics, CAS: existing 500W@4.5K or 150L / h, 2.2kW@4.5K , planned 5kW@4.5K



【中国科学报】我国研发成功-271℃超流氦大型低温制冷装备

中科院理化所 4月17日

2.5KW@4.5K or 500W@2K

传播新时代科学家精神 打造有影响力传媒品牌

中国科学報

科学网 ScienceNet.cn 构建全球华人科学社区

零下271℃、百瓦级！这项技术获重大突破

刘延柱：摩擦斜碰撞与Kane难题

走进核工业"摇篮"：见证"中国硬核"底气

李宏翰：关于结果—你就像那冬天里的一把火

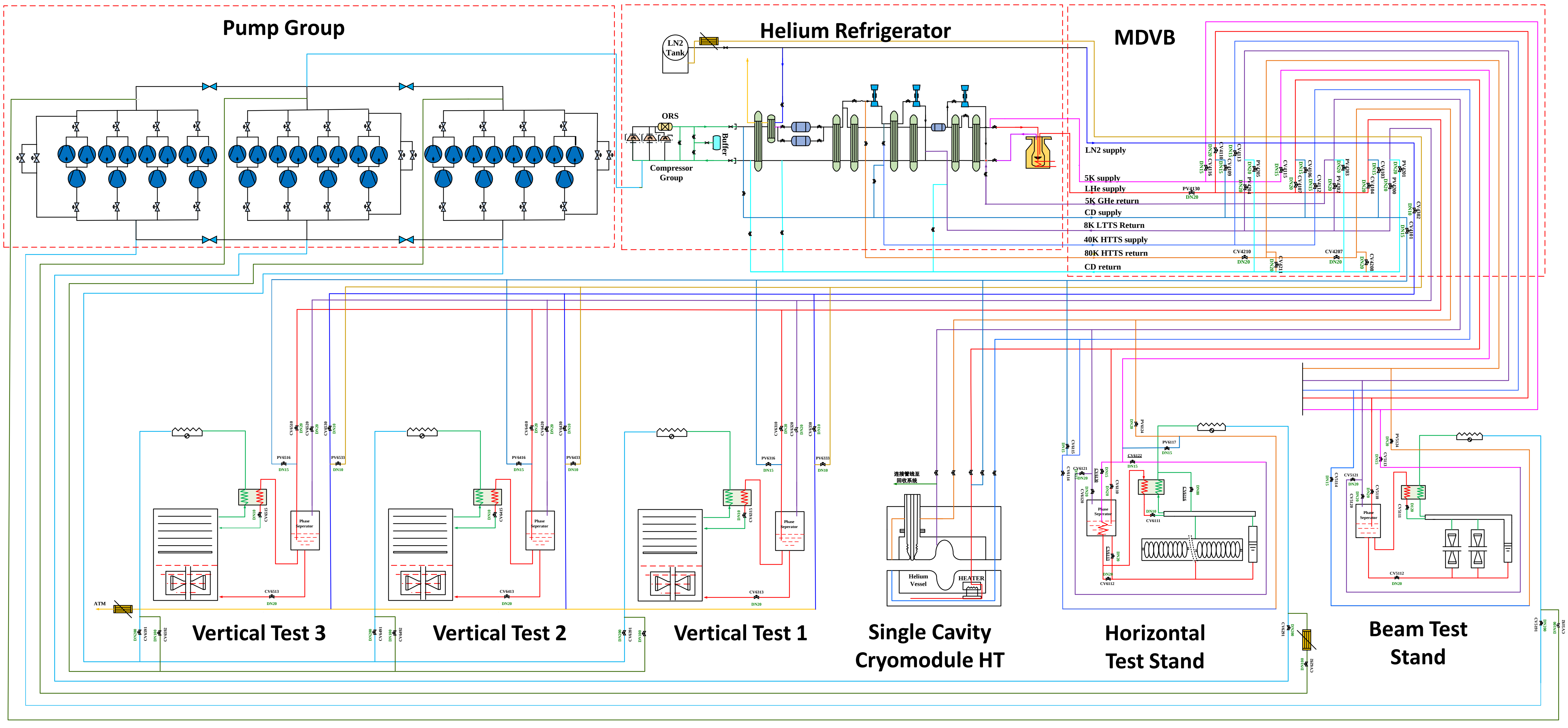
中国科大研制出一种新型软体机器人手臂

4月15日，由财政部支持、中国科学院理化技术研究所承担的国家重大科研装备研制项目"液氦到超流氦温区大型低温制冷系统研制"通过验收及成果鉴定，标志着我国打破了发达国家的技术垄断，具备了研制液氦温度（零下269摄氏度）千瓦级和超流氦温度（零下271摄氏度）百瓦级大型低温制冷装备的能力，将可满足大科学工程、航天工程、氦资源开发等国家战略高技术发展的迫切需要。

液氦温度低至-269℃，是深低温区最重要的低温源。液氦到超流氦温区大型低温制冷装备是航空航天、氢能源、国家大科学装置等战略领域不可或缺的核心基础平台。但是，越往低温推进，制冷技术难度、成本、功耗都呈几何级数上升。核心技术的缺失，使得我国大型低温制冷装备全部依赖进口，关键核心部件以及用于特殊领域的专用制冷装备国外对我禁运。

中科院理化所具有几十年低温技术的深厚积累，在洪朝生院士、周远院士带领下，通过一代代低温科技工作者的不懈努力，坚持走自主创新道路，经过五年多的拼搏奋斗，在温度（零下253度）制冷机的基础上，自主研制出了技术指标为2500W@4.5K和W@2K的大型氦制冷机。

PAPS cryogenic system for RF cavity R&D



PAPS cryogenic system for RF cavity R&D

cryogenic hall

RF hall

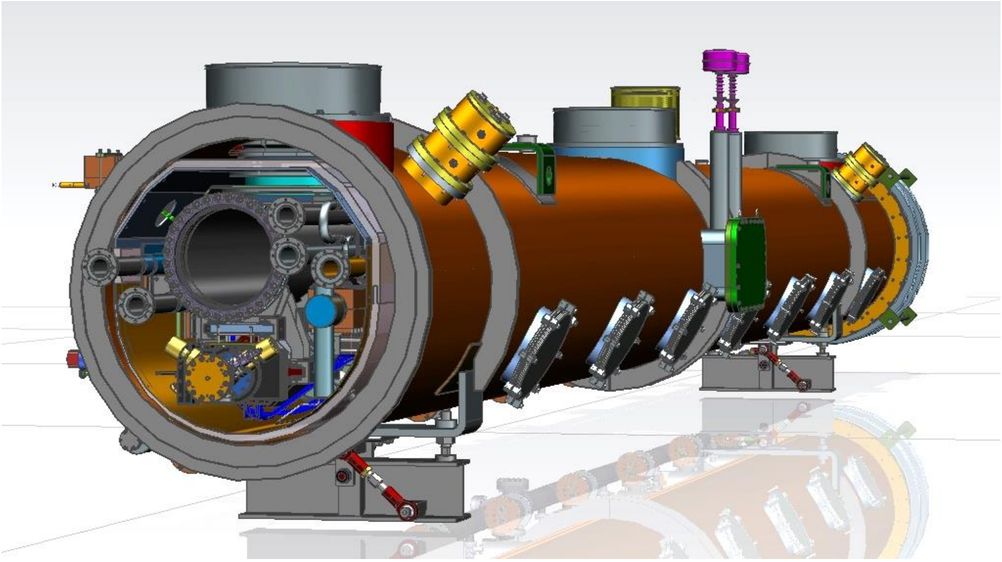
Tanks zone

VT stands

HT test stand

Beam test stand

Cryomodule for 1.3GHz 9-cell cavities

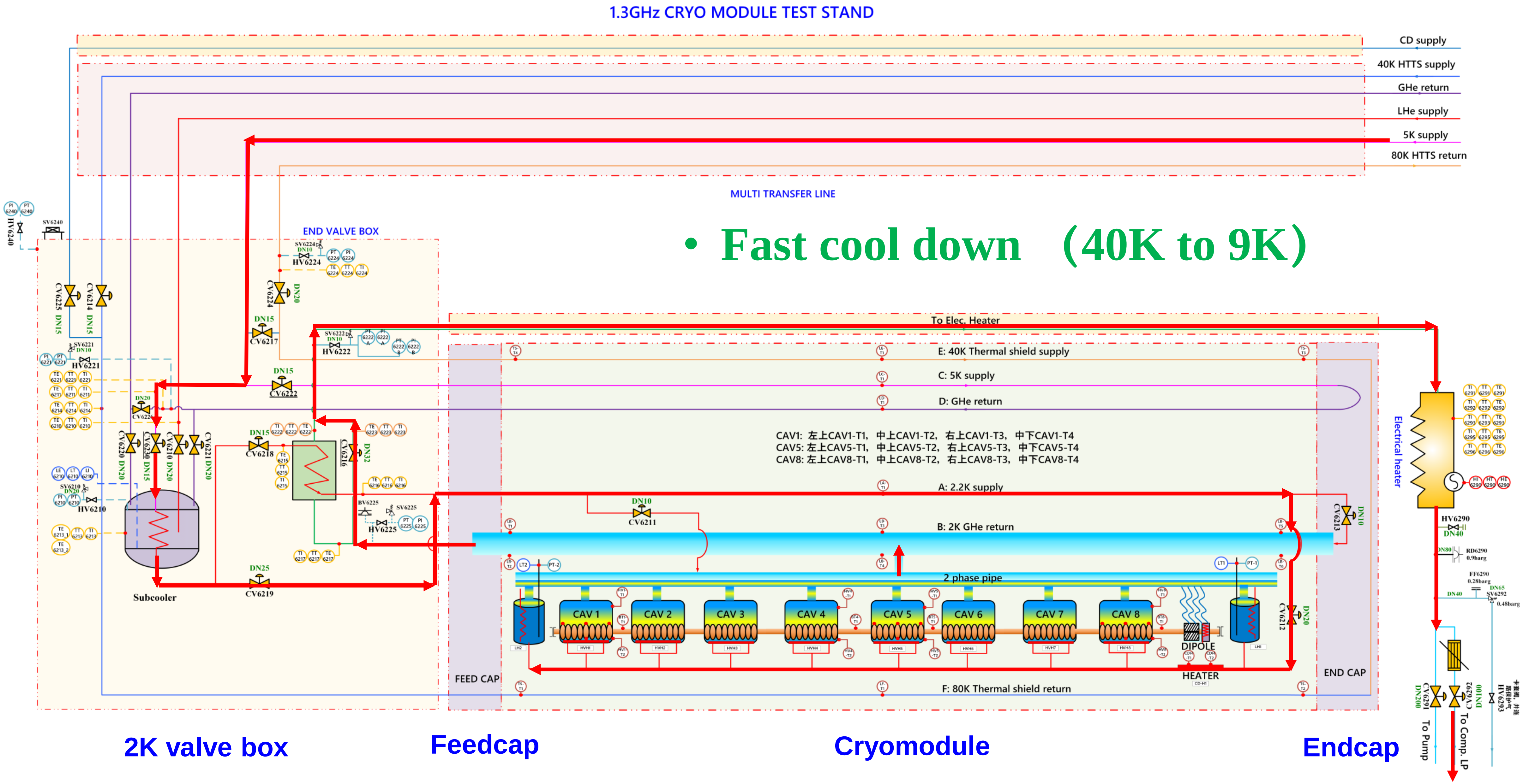


XFEL / LCLS-II type Cryomodule for High Q Cavity

Design Goals:
- **Low heat loss**
- **Fast cool down**

- Cryogenic Group in IHEP has manufactured 58 1.3GHz 9-cell Cryomodules for EXFEL cooperated with local companies.
- It's a good foundation for the optimization design for the CEPC cryomodules.

PID for 1.3GHz 9-cell cryomodule in PAPS

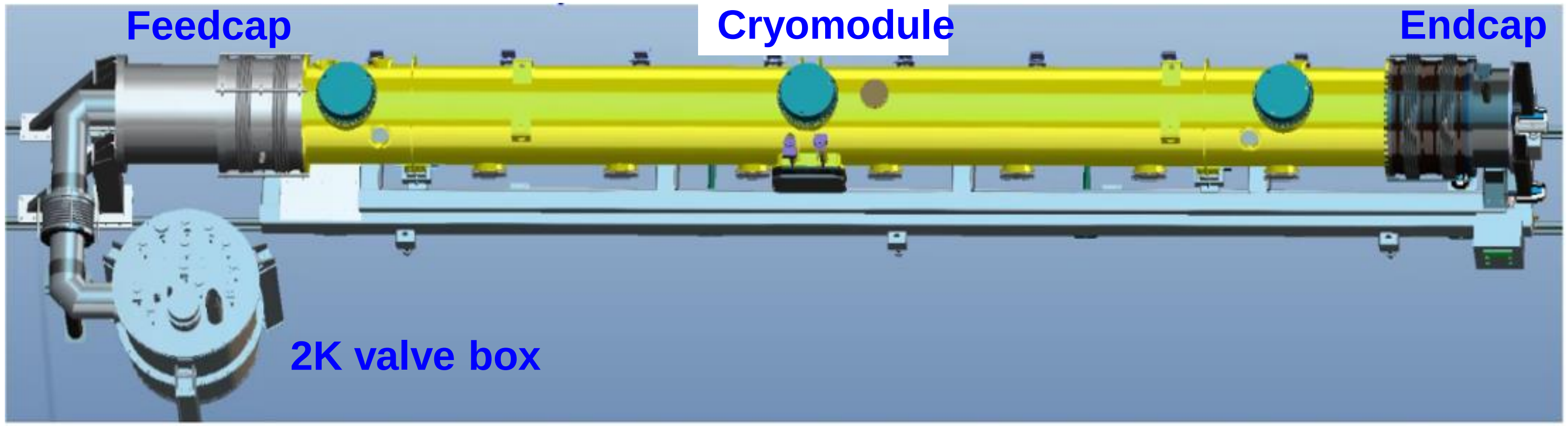


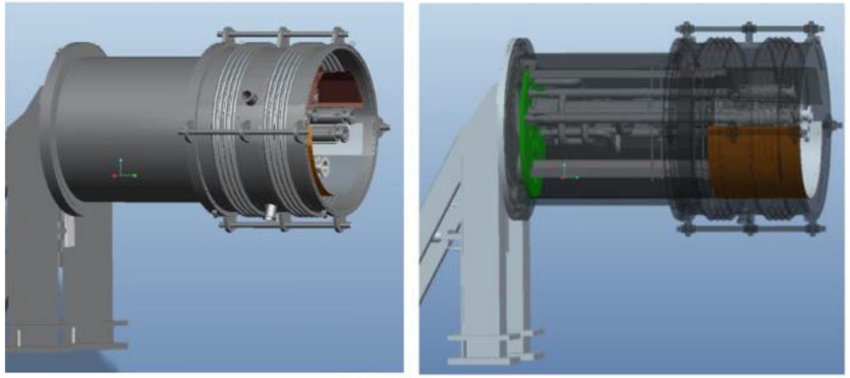
- Fast cool down （40K to 9K）

2K valve box Feedcap Cryomodule Endcap

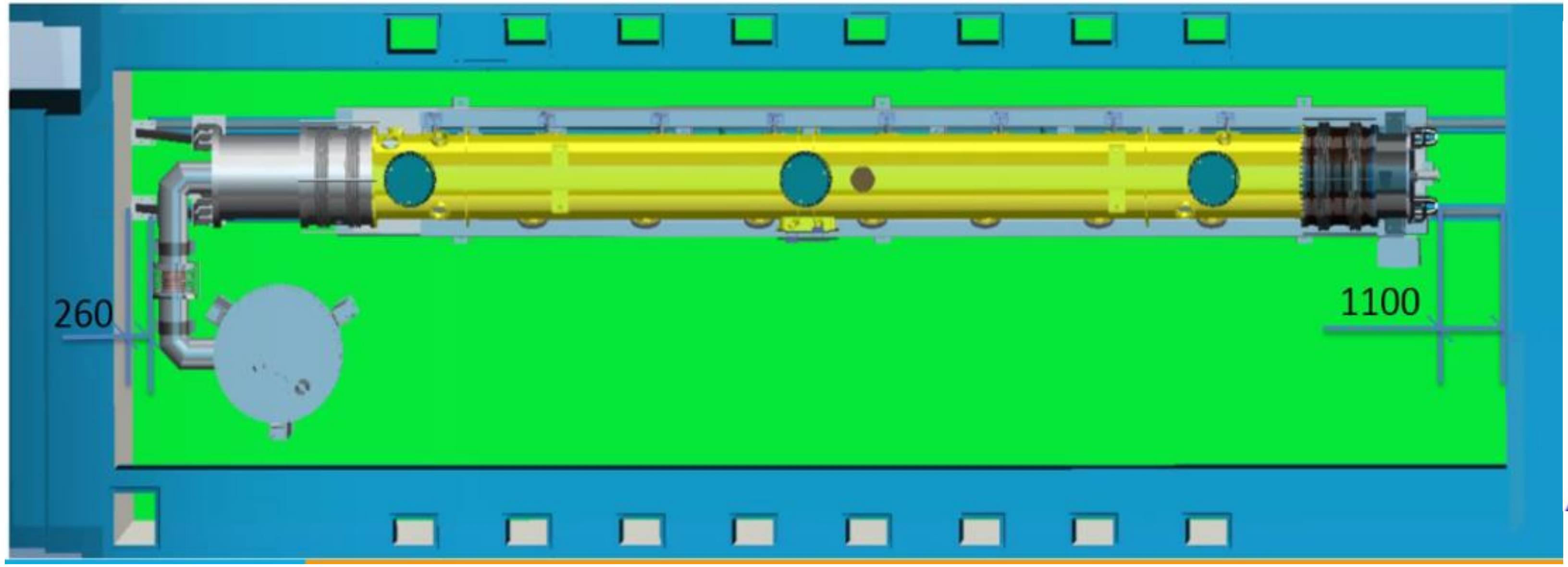
1.3GHz 9-cell cryomodule test in PAPS

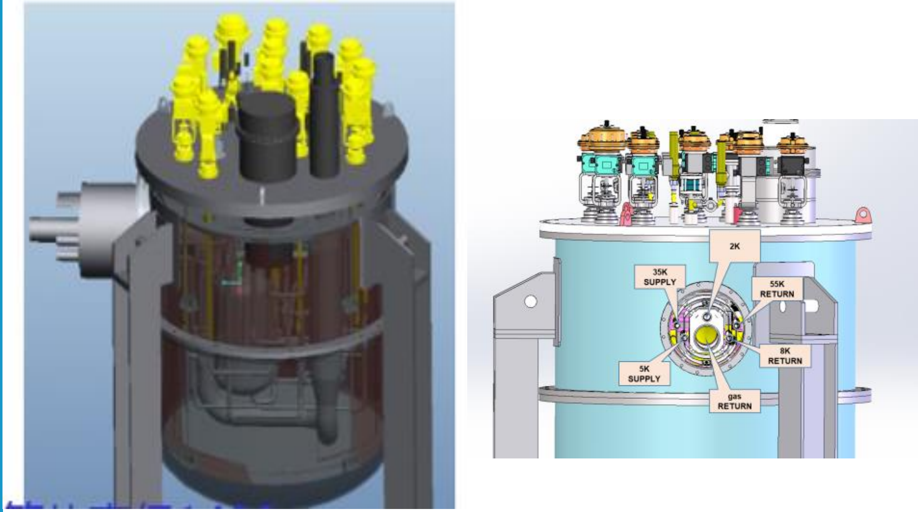
2K horizontal test will be done in PAPS in the last-half 2022 year





Feedcap

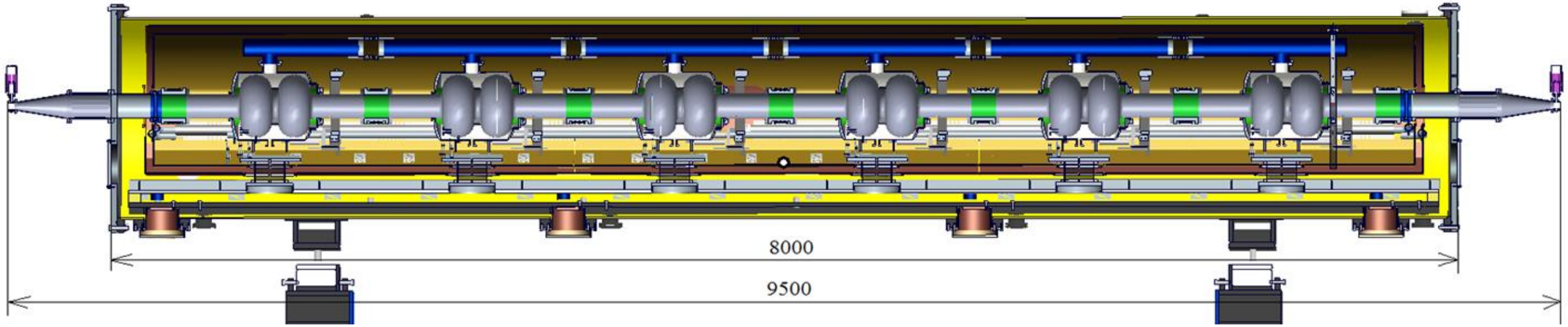




2K valve box

Cryomodule for 650MHz 2-cell cavities

- **Including six 2-cell 650 MHz superconducting cavities, six high power couplers, six mechanical tuners and two HOM absorbers**

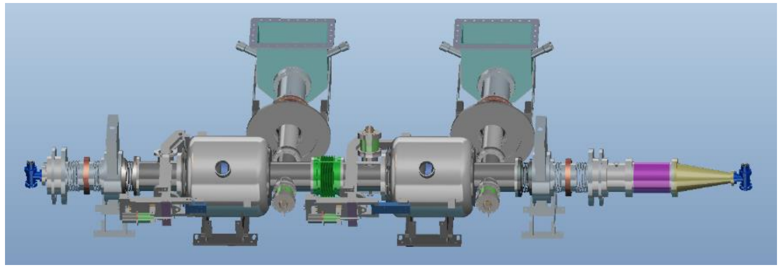


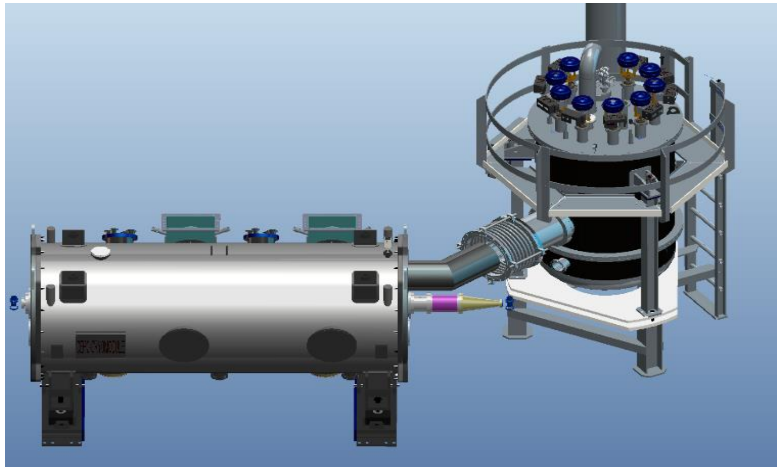
Six 2-cell Cavities Cryomodule	
Overall length(flange to flange, m)	8.0
Diameter of Vacuum vessel ,m	1.3
Beamline height from floor, m	1.5
Cryo-system working temperature, K	2
Number of 200-POST	6

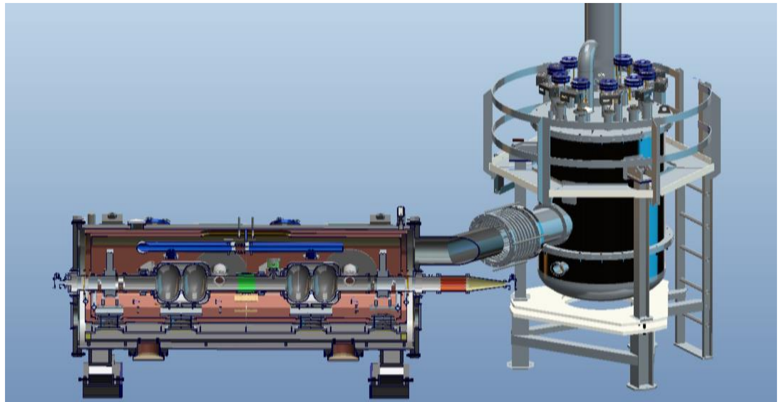
Cryomodule performance		Specification
Number of leakage	He →insulation	0
	He →beam transfer line	0
	Insulation →coupler	0
	Insulation →beam transfer line	0
	Coupler →beam transfer line	0
Alignment x/y inside (Cavities)		±0.5mm
Alignment z inside		within 2 mm
Coupler antenna design z		within 2 mm

Cryomodule for 650MHz 2-cell cavities

- A beam test cryomodule with two 2-cell 650 MHz superconducting cavities has been operated in the PAPS system beam test stand last year.

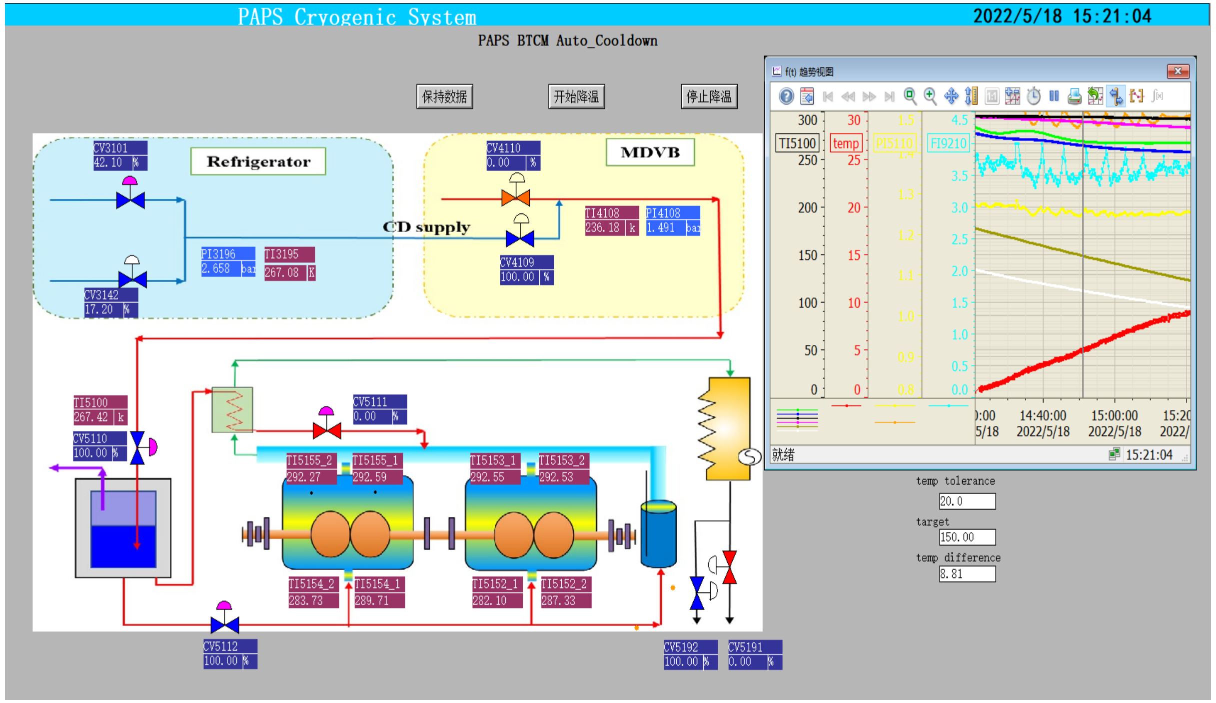


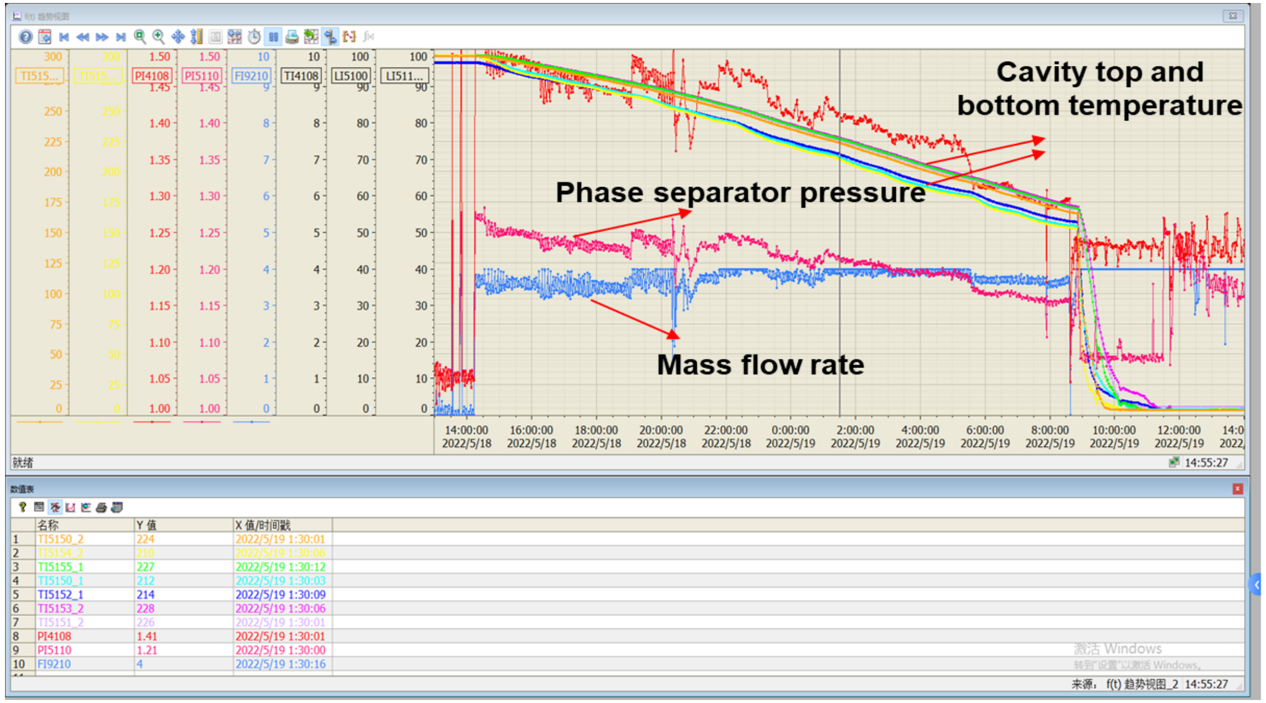




Advanced control strategy research status

- **Module automatic cooldown research progress: the MPC control method has successfully tested in PAPS BTCM cryostat** **(first time in China)**
- Designed and implemented automatic cool-down/warming-up procedure for SRF cavity cryomodule with Model Predict Control (MPC) method & Artificial Neural Network (ANN)

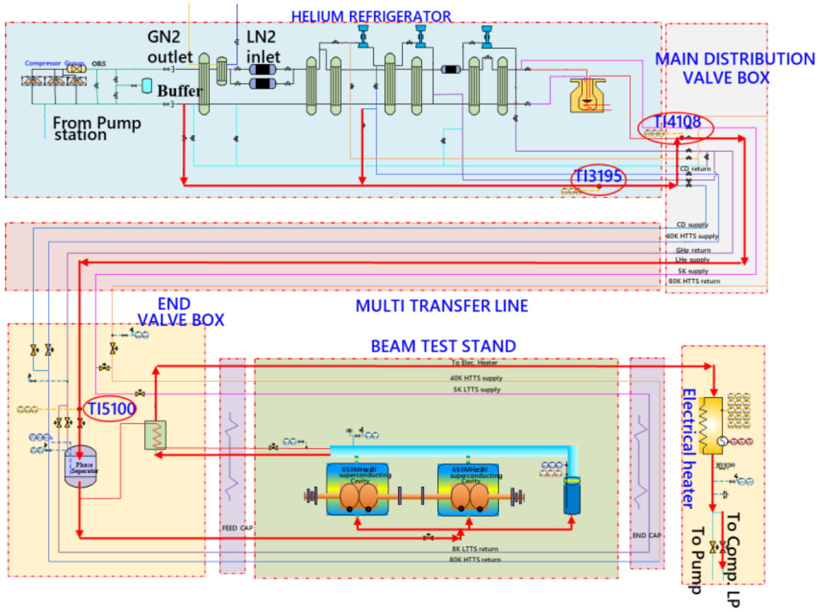




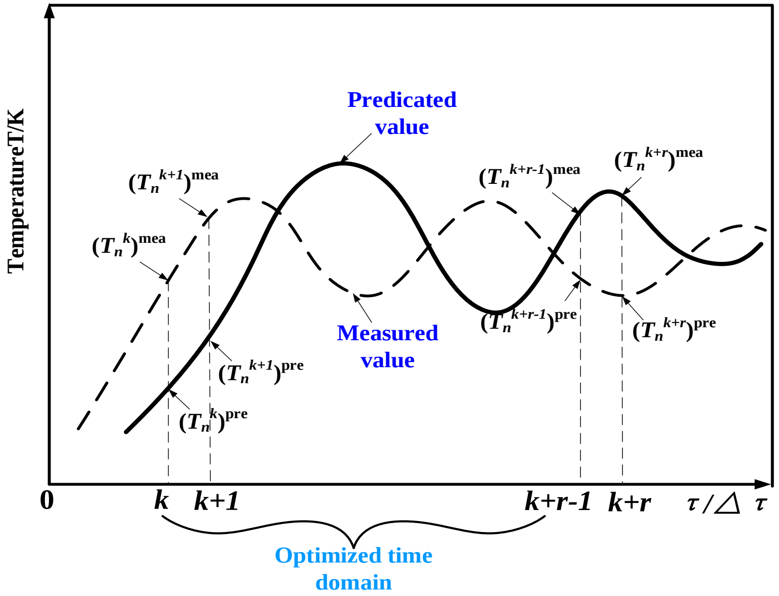
1. 300 to 150 K: < 10 K/hr. Cavity top and bottom ΔT < 20 K
2. 150 to 4.5 K: Cavity surface > 1 K/min
3. 4.5 to 2 K

Advanced control strategy research status

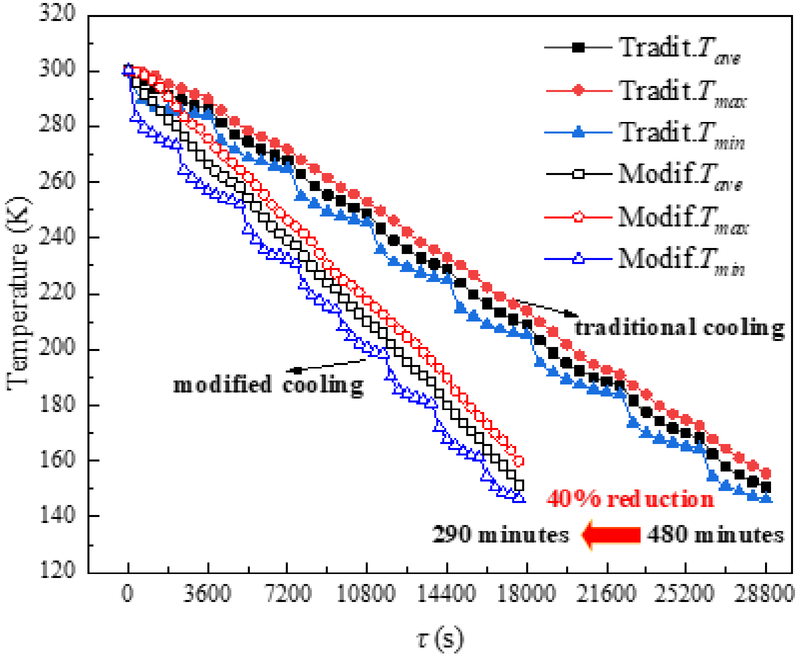
- It is verified that the **MPC method has better control stability.**
- **The foundation for a more intelligent automated control of future CEPC large cryogenic systems has been laid.**



PFD of beam test stand



Principle diagram of the MPC method



MPC method efficiently decreasing the time of CD

[1] Zheng-ze Chang*, Mei Li, ……Rui Ge*, Model predictive control of long Transfer-line cooling process based on Back-Propagation neural network, Applied Thermal Engineering, Volume 207,2022,118178,ISSN 1359-4311.

[2] Li M, Chang Z, Zhu K, et al. Unsteady numerical simulation and optimization of 499.8 MHz superconducting cavity cooling process at the High Energy Photon Source (HEPS)[J]. Thermal Science and Engineering Progress, 2021, 26: 101100

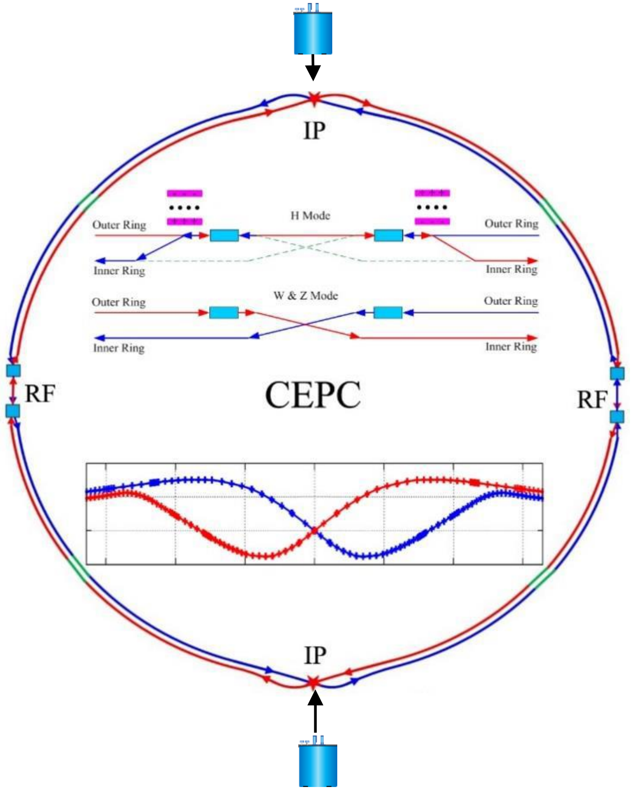
OUTLINE

- Introduction and Layout
- CEPC SRF cryogenic system
- CEPC SC magnets cryogenic system
- Key technology
  - **2K JT heat exchanger R&D and test**
- Summary

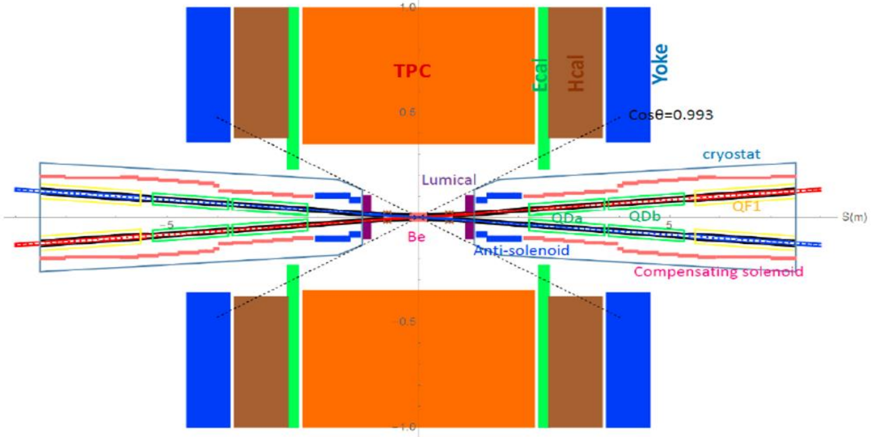
SC magnets cryogenic system overview

the detectors are installed at two interaction points (IPs)

SC magnets
Cryo-station

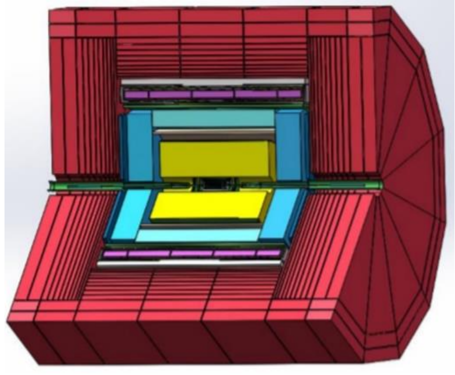


SC magnets
Cryo-station

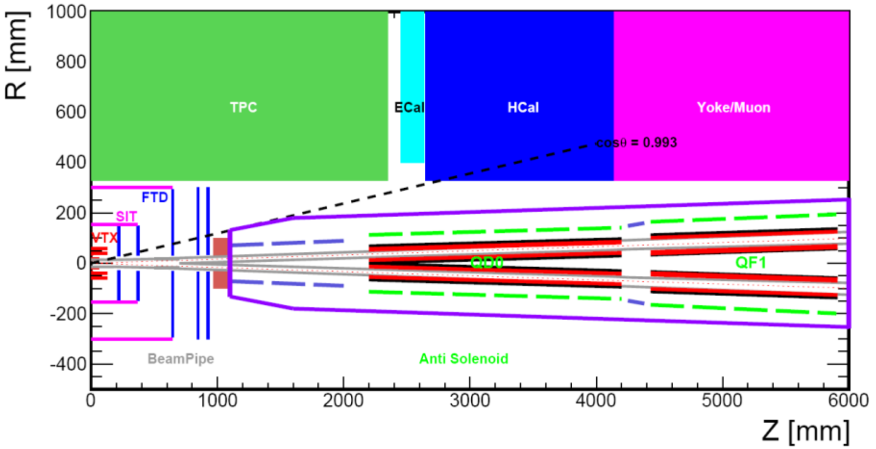


Schematic layout of QD0, QF1, and anti-solenoid

IR SC magnet (QD0,QF1, and anti-solenoid)

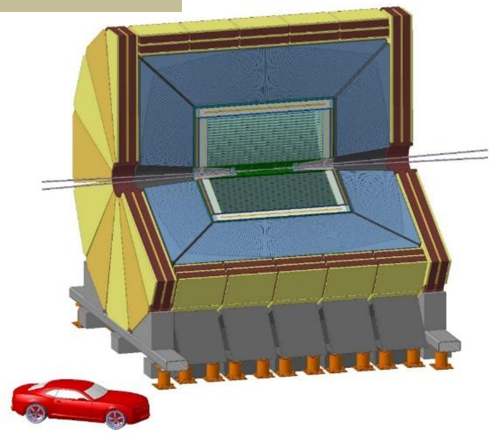


LTS Solenoid：
- Solenoid located outside calorimeter
- Inner diameter 7.2 m, length 7.4 m
- Central field：3 T
- Superconductor：NbTi
- Operation temperature：4.2 K



From Zhu Ying-shun

IDEA detector



HTS Solenoid：
- Solenoid located inside calorimeter/less material
- Inner diameter 4 m, length 6 m
- Central field：2 T
- Superconductor：YBCO
- Operation temperature：20 K

Zhu Zian，Wang Meifen

Estimated heat loads for SC IR magnets

		4.5K main loop			Thermal Shielding 40~80K		
Name	Unit	No.	Heat load for each	Heat load	No.	Heat load for each	Heat load
IR SC sextupole magnet	W	32	10	320			
Valve Box of IR SC sextupole magnet	W	32	20	640			
Current lead heat load of IR SC sextupole magnet	W	32	——	——			
IR SC magnet	W	4	30	120			
Valve Box of IR SC magnet	W	4	30	120			
Current lead of IR SC magnet	g/s	4	0.5	2			
Main distribution valve box	W	4	50	100			
Cryogenic transfer-line	W	4000	0.3	1200	3424	1.5	5136
Total heat load @4.5K	W			2500			5136
Total heat load @4.5K	W			2500W+2g/s			5136
Total heat load @4.5K	W			2523.45			5136
Coefficient				1			0.05
Total heat load @4.5K	W			2523.45			**256.8**
Total equiv. heat load @4.5K	W	2780.25					
Total equiv. heat load @4.5K with multiplier 1.5	W	4170					
Cooling capacity of refrigerator@4.5K	W	**2**	**4kW@4.5K**	**8kW@4.5K**			

•Two individual refrigerators (2 x 4kW@4.5K) will be employed for the CEPC SC magnets cryogenic system.

Basic Parameter of SC Magnet

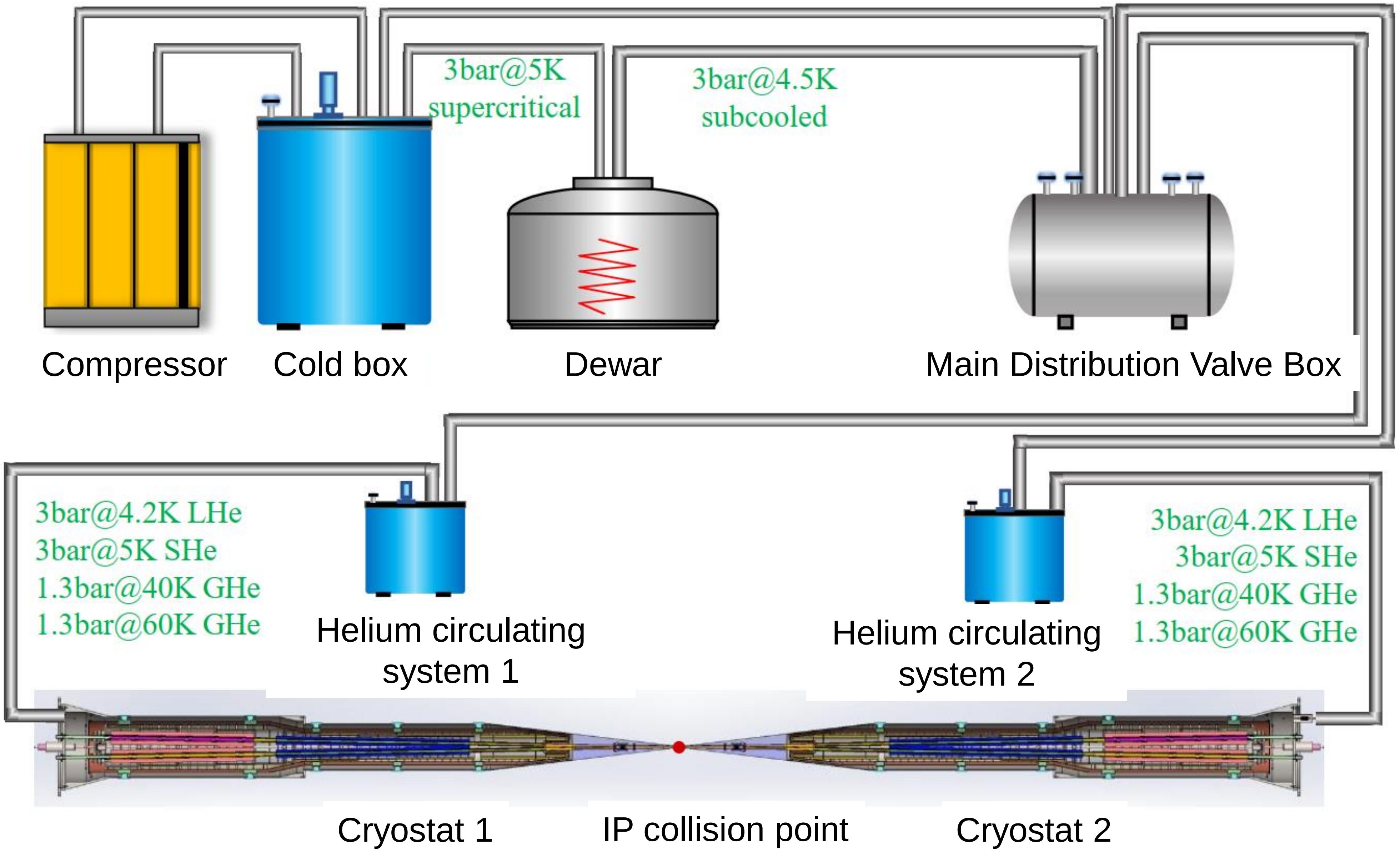
- The requirements of the Final Focus quadrupoles(QD0 and QF1) are based on the length of 2.2 m, beam crossing angle of 33 mrad in the interaction region

ITEM	QD0	QF1	Anti-Solenoids
Central field gradient (T/m)	136	110	
Cooling type	LHe	LHe	LHe
Operating current (A)	2080	2300	1000
Magnetic storage energy (KJ)	25	30.5	715
Operating temperature（K）	4.5K	4.5K	4.5K
Magnet length (m)	2	1.48	1.1+2+1.7
X direction Lorentz force/octant(KN)	68	110	?
Y direction Lorentz force/octant(KN)	-140	-120	?

The total weight of magnet is about 1T, the total energy release to cryogenic system when magnet quench is about 400KJ in 2 second

From Yingshun Zhu

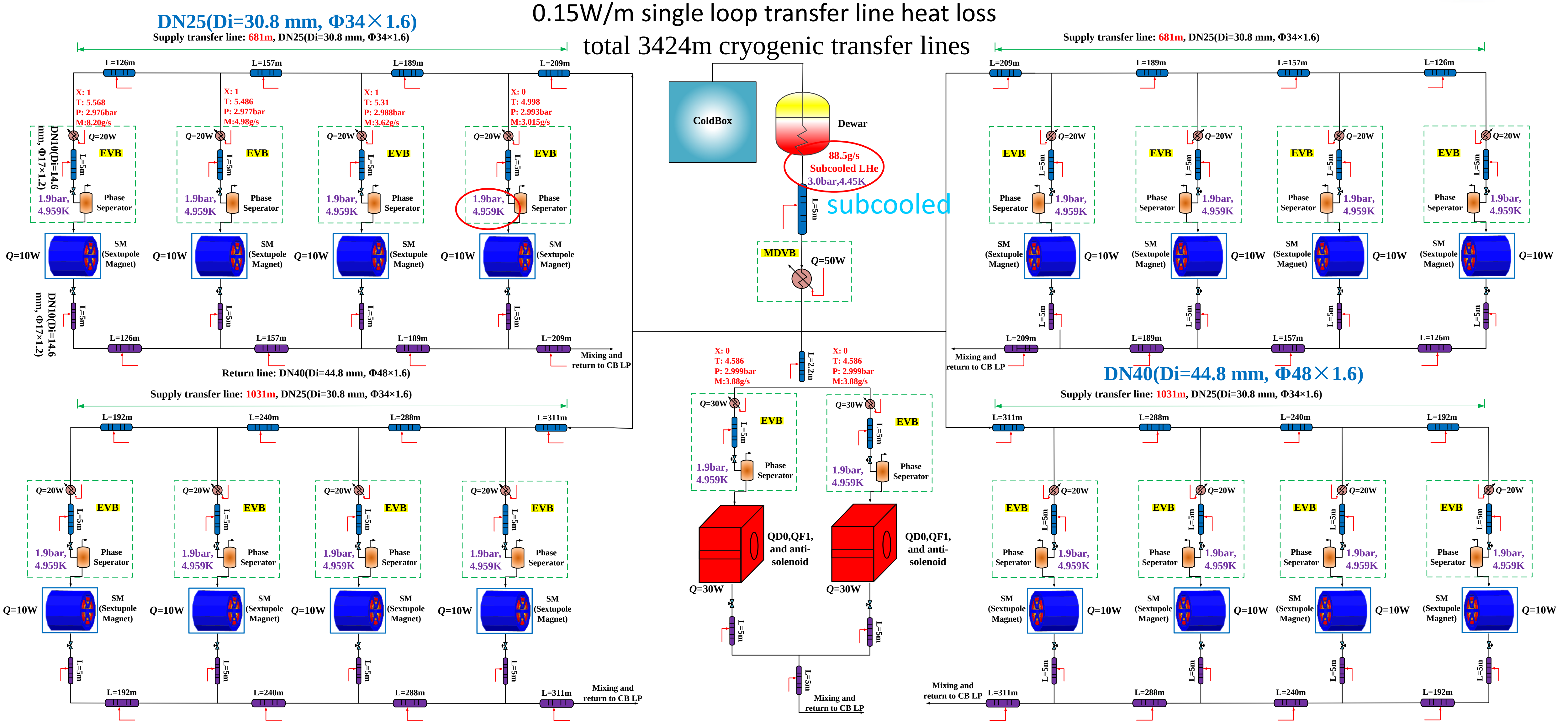
Detailed Flow Chart for CEPC MDI Cryostat (one site)



SC magnets Process calculation

0.15W/m single loop transfer line heat loss

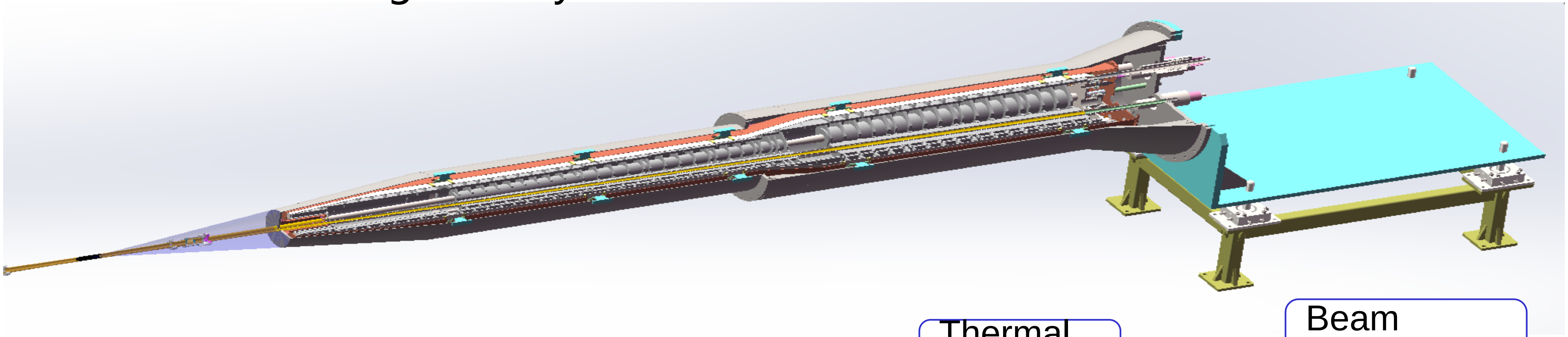
total 3424m cryogenic transfer lines

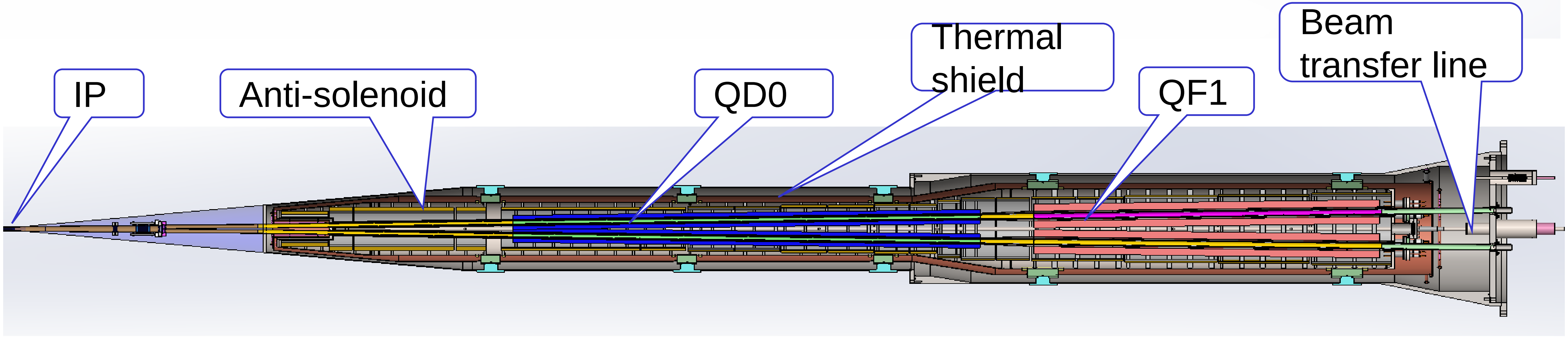


- Cooling method: subcooled supercritical helium.
- 3.0 bar@4.45K subcooled liquid helium is transferred, throttling at local equipment valve box, then return to the dewar.

Mechanical Design of CEPC MDI Cryostat

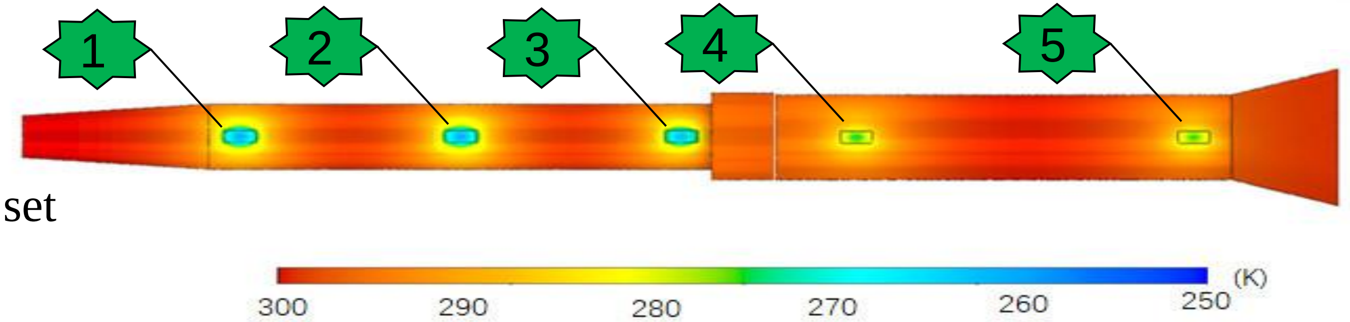
- The total weight of cryostat is about 2.5 T





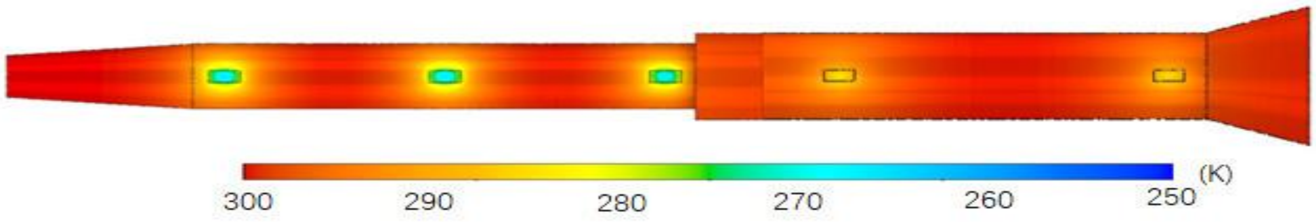
Vacuum chamber---temperature field

5 [W m^-2 K^-1]



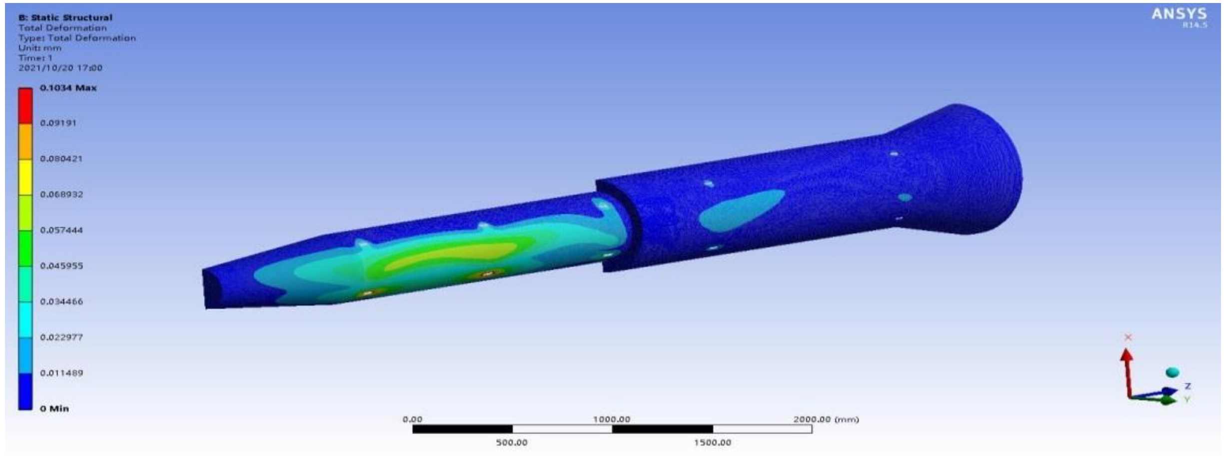
Calculation conditions: the outermost layer is set as convective boundary condition, the surface that the support structure contacts with the helium pool is set as 5K, and the surface that contacts with the cold screen is set as 60K

8 [W m^-2 K^-1]

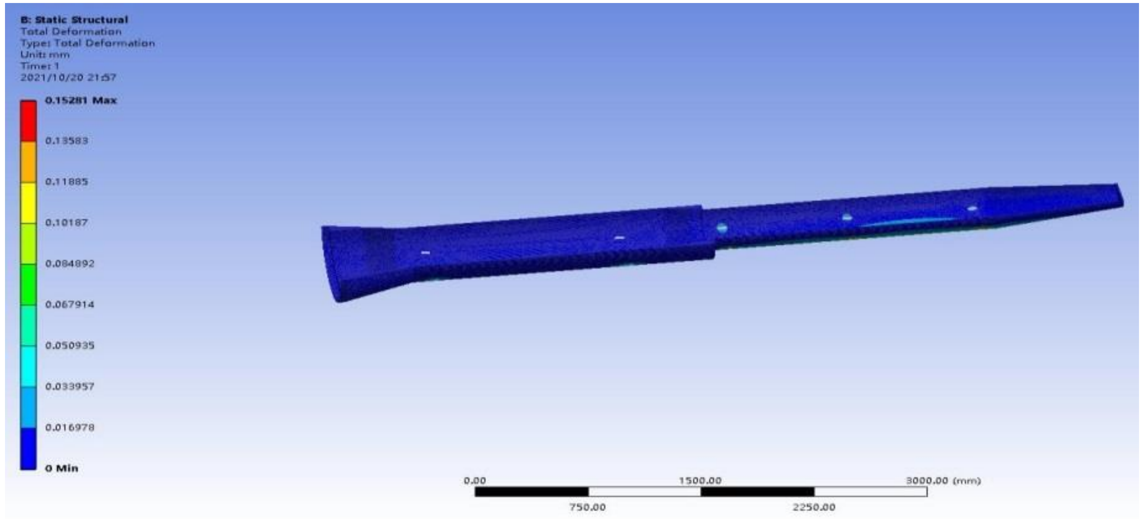


Support numbers					
convective heat transfer coefficient	1	2	3	4	5
5W m^-2 K^-1	268.97 K	268.98 K	270.52 K	282.76 K	283.32 K
8W m^-2 K^-1	273.14 K	273.14 K	274.09 K	285.34 K	286.65 K

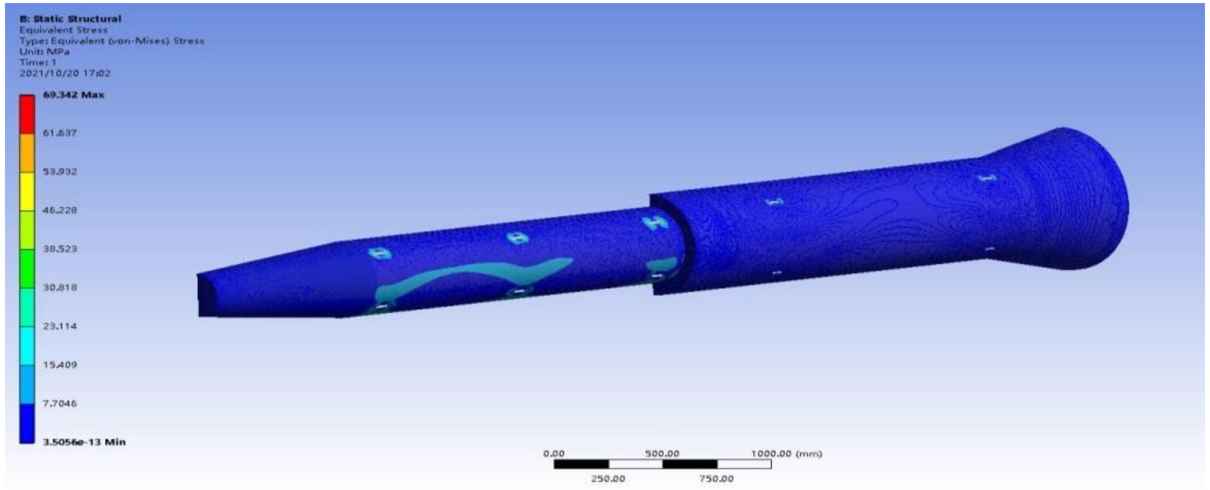
Vacuum chamber---stress analysis



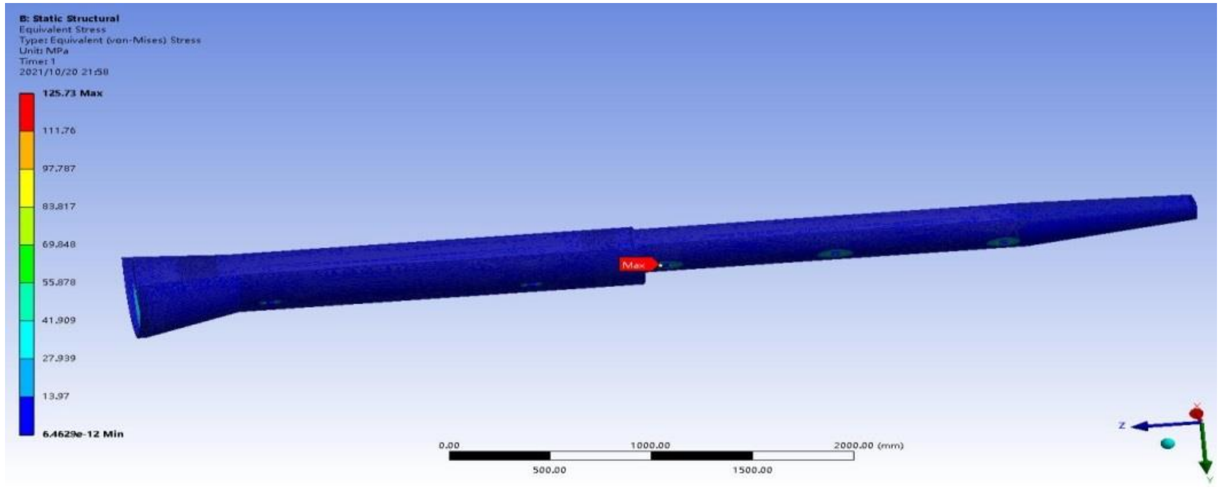
Maximum deformation 0.1mm@external pressure 1Bar



Maximum deformation 0.15mm@internal pressure 1.2Bar



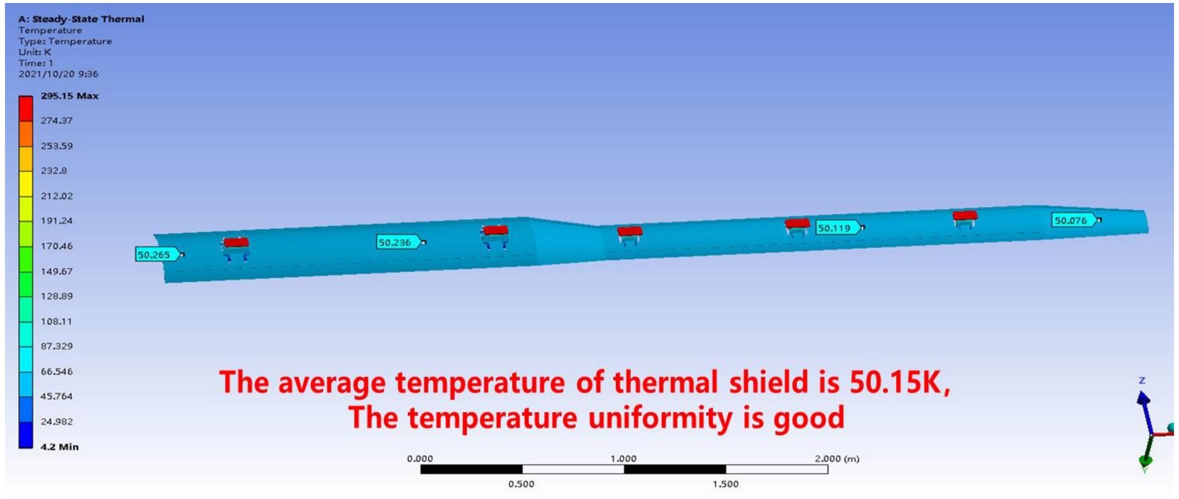
Maximum stress 69.343MPa@external pressure 1Bar



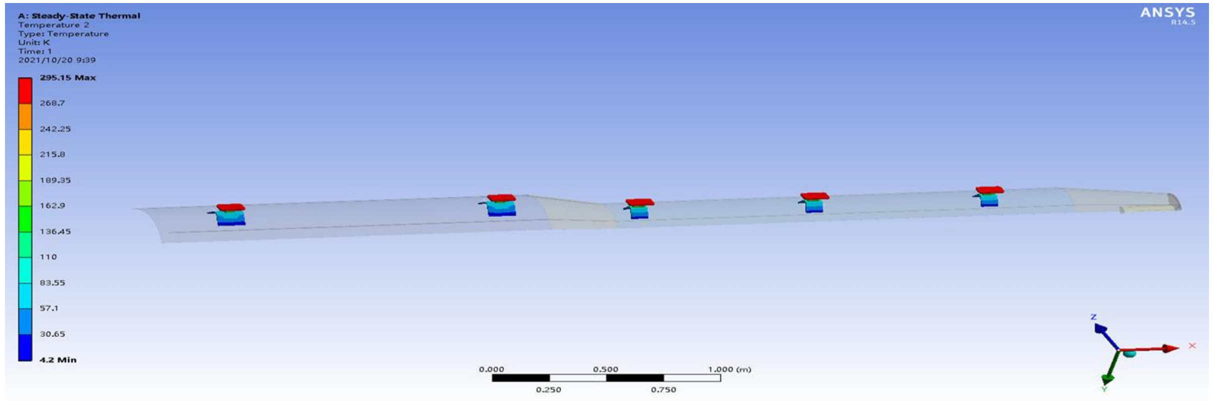
Maximum stress 125.73MPa@ @internal pressure 1.2Bar

Thermal shield and supports--temperature field

Thermal shield: inlet 40K cold helium; outlet 70K cold helium. Set the temperature of cold screen coil is 50K

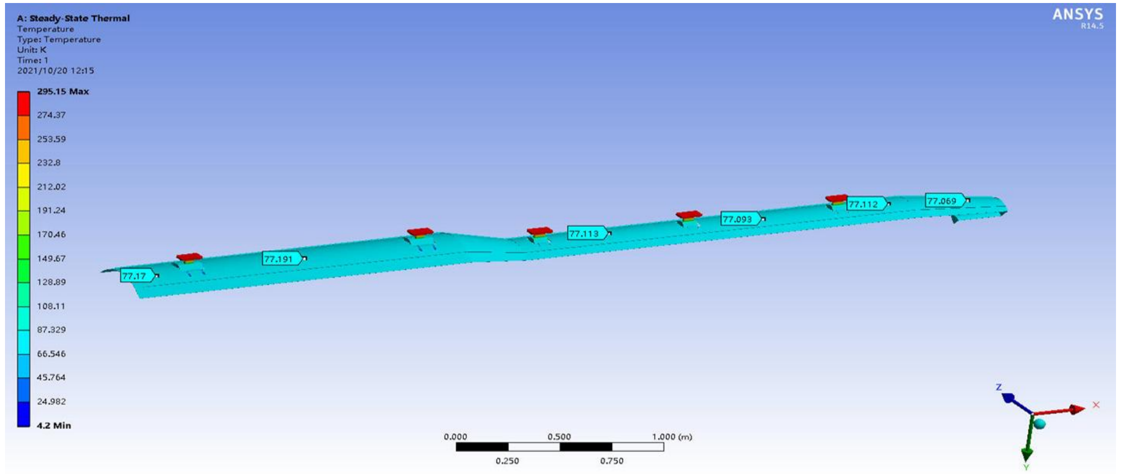


Boundary conditions: T_{INLET}=40K cold helium gas, T_{OUTLET}=70K; Set thermal shield coils temperature is 50K.

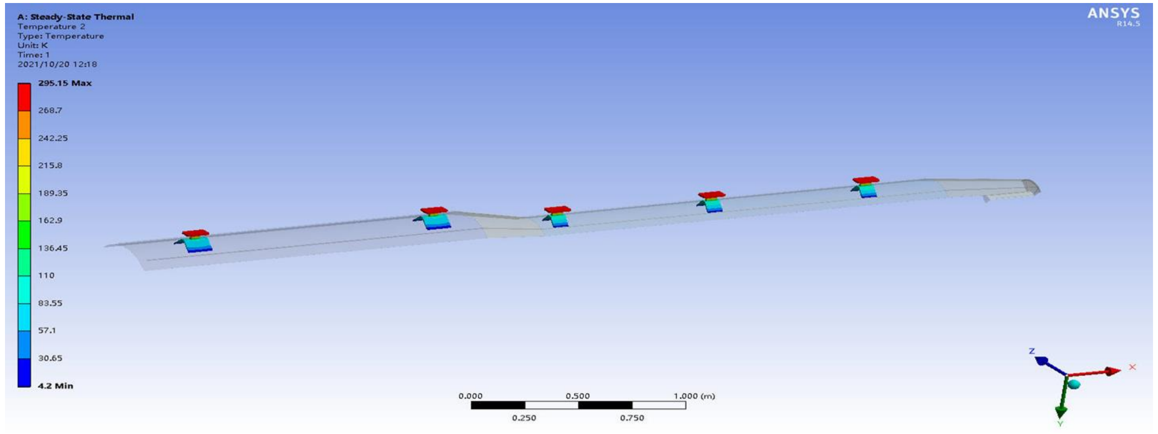


Heat load of thermal shield: 7.12*4=28.48W@50K
Heat load for 4.2K temperature zone: 2.01*4=8.04W@4.2K

Thermal shield cooled by liquid nitrogen, Set thermal shield coils temperature is 77K



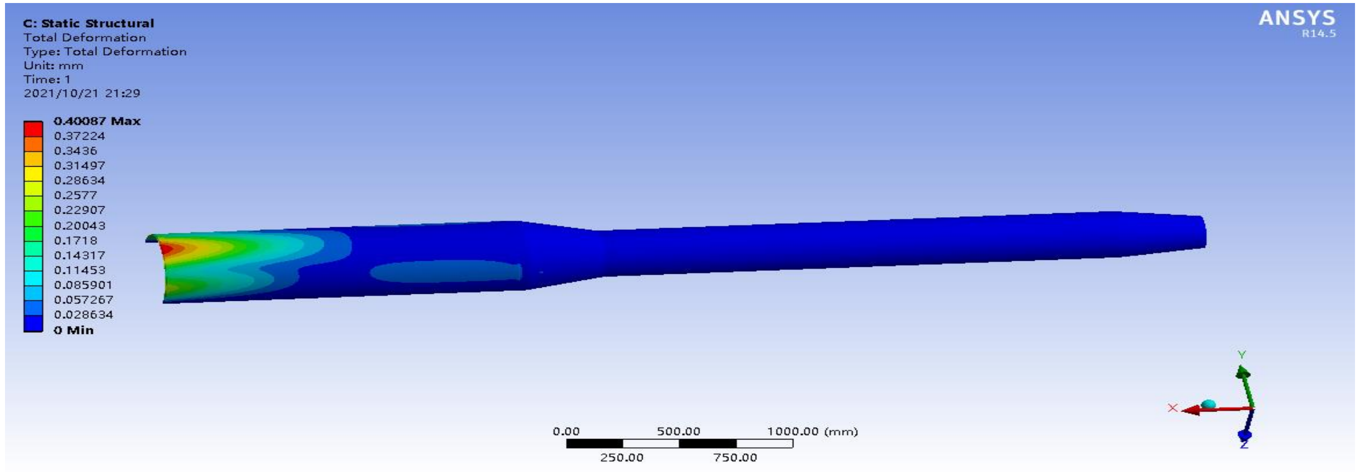
Thermal shield cooled by liquid nitrogen, Set thermal shield coils temperature is 77K



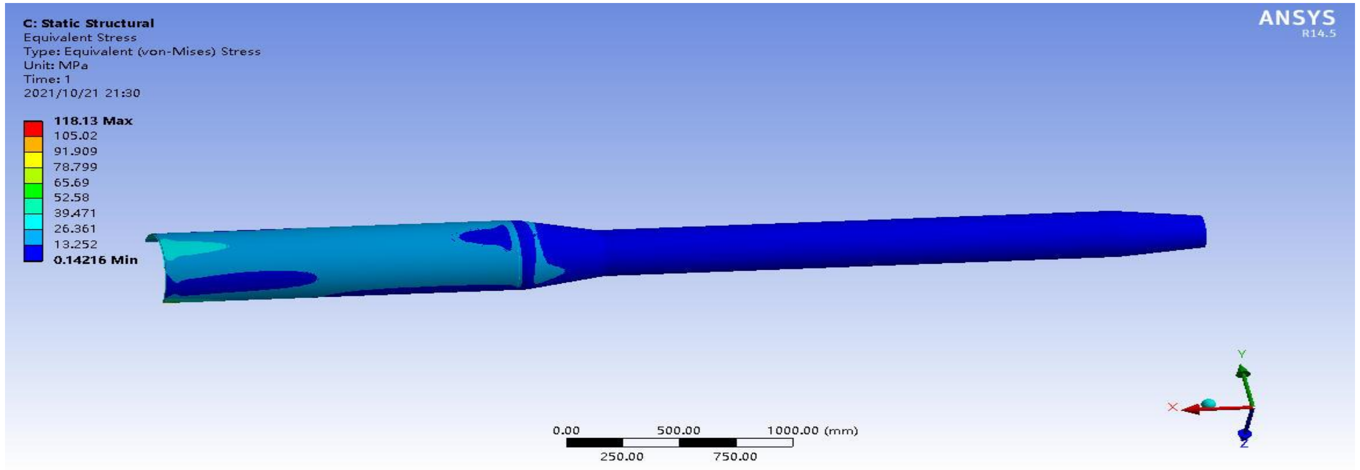
Heat load of thermal shield: 5.35*4=21.4W@77K
Heat load for 4.2K temperature zone: 3.42*4=13.68W@4.2K

Stress analysis of helium tank

Material:316L，E=1.93E11Pa，Poisson’s ratio: 0.27，$[\sigma_{allow}]$=120.3MPa



Maximum deformation为 0.4mm@P_{IN}3Bar



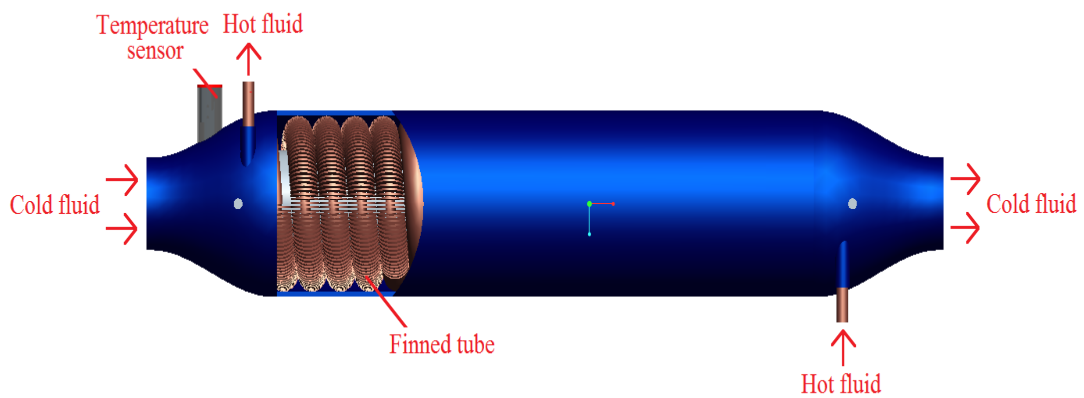
Maximum stress 118.13MPa@P_{IN}3Bar

OUTLINE

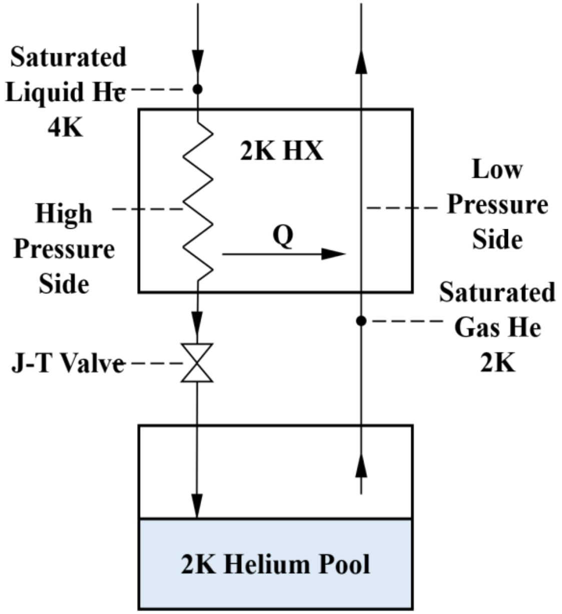
- Introduction and Layout
- CEPC SRF cryogenic system
- CEPC SC magnets cryogenic system
- Key technology
  - 2K JT heat exchanger R&D and test
- Summary

2K JT HX

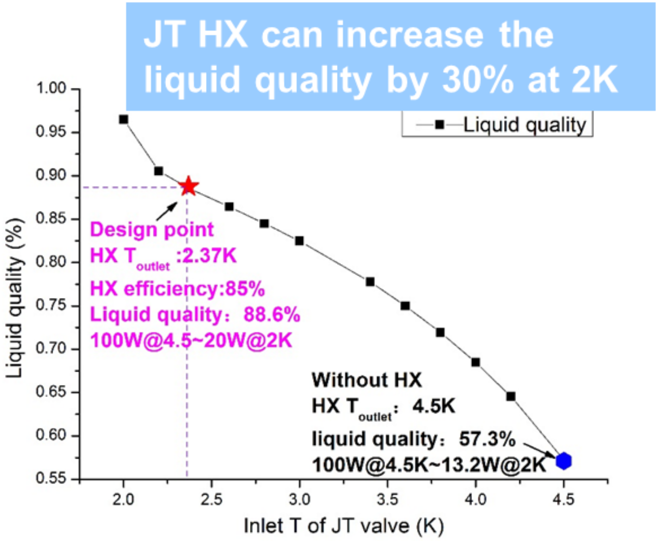
- **Function**： key component of the 2K cryogenic system； Increase the liquid quality by 30% at 2K
- **Indicators**： $\varepsilon = \frac{H_{h,in} - H_{h,out}}{H_{h,in} - H_{in}^{*}}$ Effectiveness of HX   ***GHe ΔP*** Pressure drop of the gas helium side



Structure of Coiled Finned-tube HX

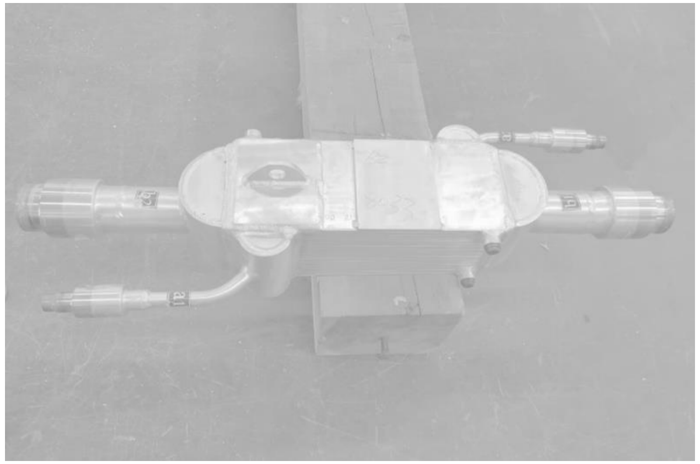


Working Flowchart of 2K HX



Currently, 2K JT heat exchangers have been gradually developed and tested for high flow rates (10g/s → 50g/s → 130g/s (CEPC demands, kilo watts level) → >200g/s)

2K JT heat exchanger R&D and test



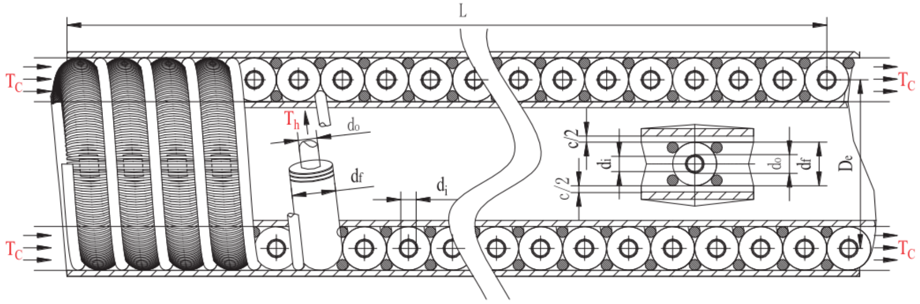
Stage1. Single Layer Coiled Finned-Tube HX

- Low mass flow rate ≤5g/s
- 2K HX test Dewar's design & construction

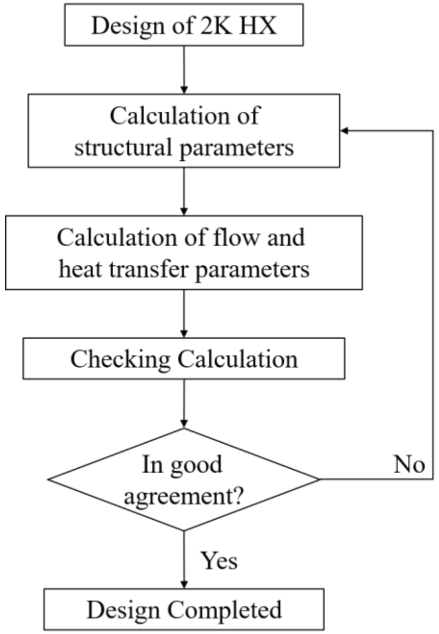
2K JT heat exchanger R&D and test

Stage1. Single Layer Coiled Finned-Tube HX

- **Design**

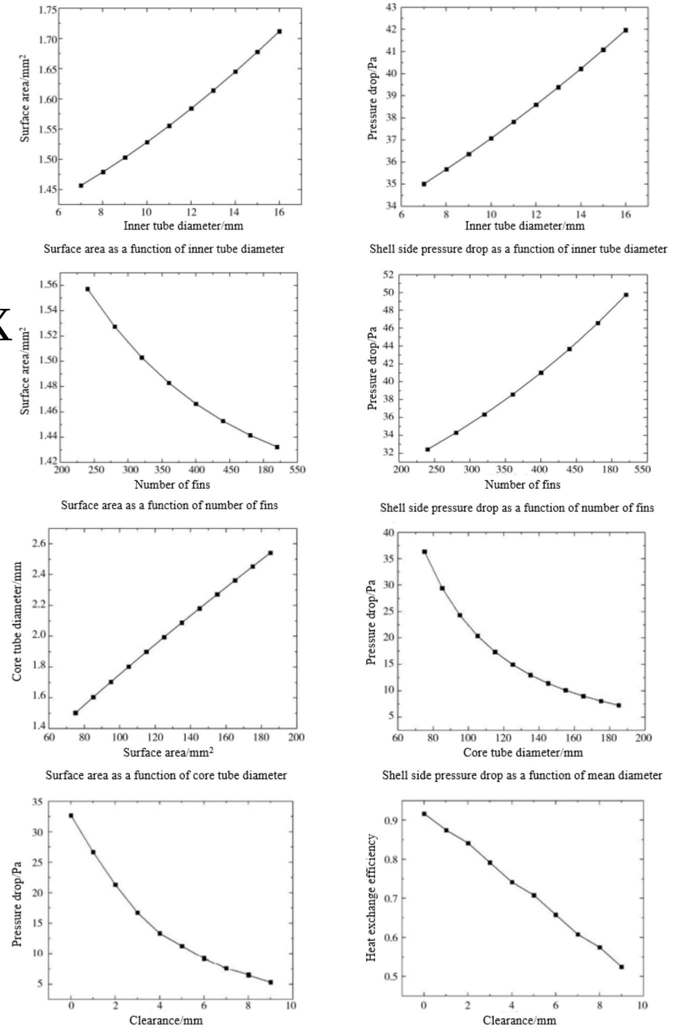


Structure of Single Layer Coiled Finned-tube HX



Flowchart of the design process

- **Optimization**



Surface area as a function of inner tube diameter

Shell side pressure drop as a function of inner tube diameter

Surface area as a function of number of fins

Shell side pressure drop as a function of number of fins

Surface area as a function of core tube diameter

Shell side pressure drop as a function of mean diameter

Surface area as a function of clearance

Heat exchange efficiency as a function of clearance

Optimal design parameters

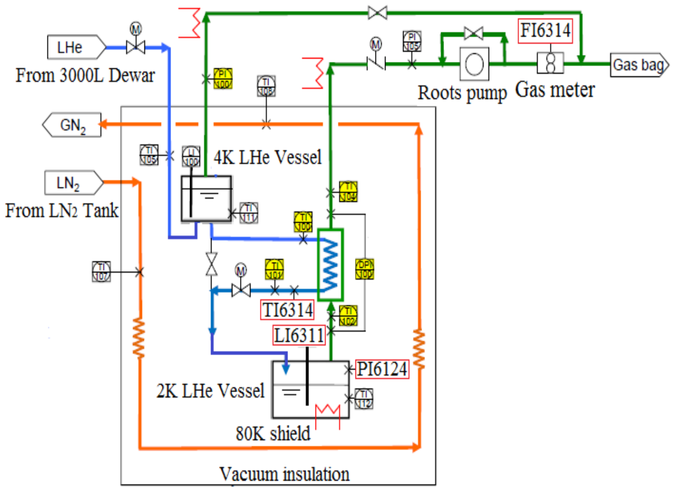
Parameter	Value
Core tube	435mm×φ70mm
Finned-tube inner diameter	10mm
Fin height	5mm
Fin pitch	2.101mm

- **Manufacture**

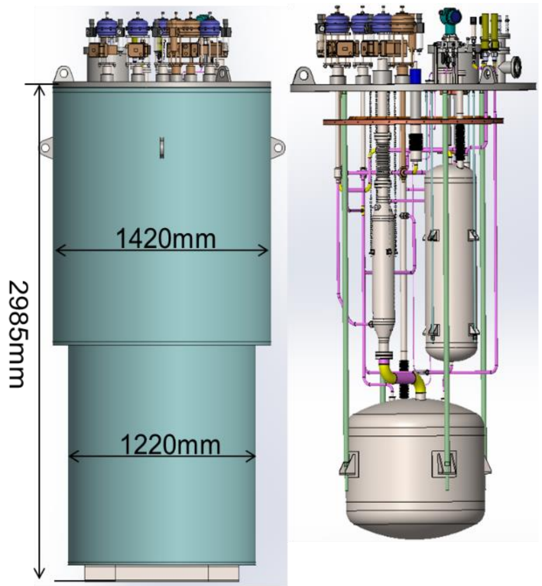
Photo of the manufactured Single Layer Coiled Finned-tube HX

2K JT heat exchanger R&D and test

- **Test Dewer Construction**

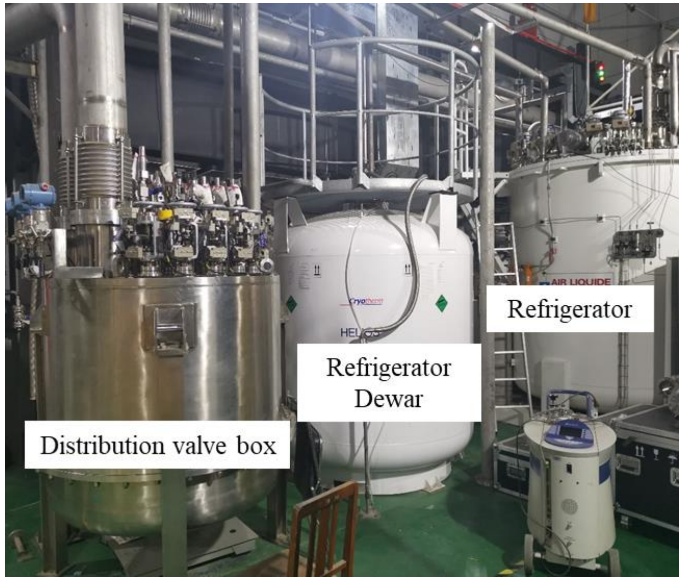


Flowchart

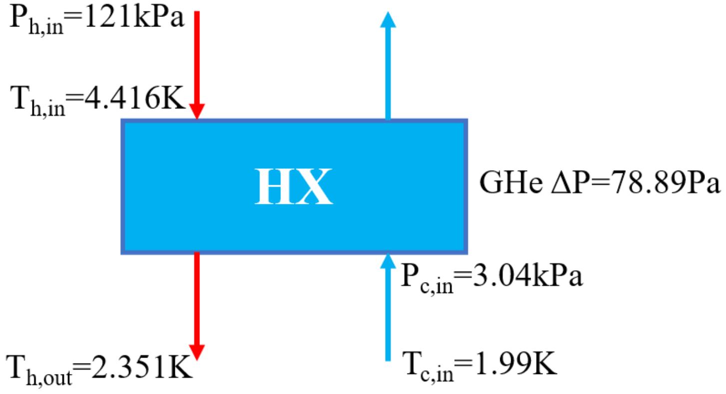


Test Cryostat

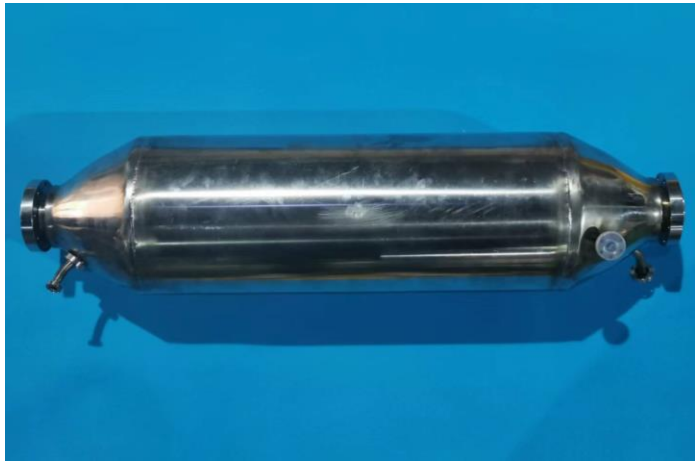
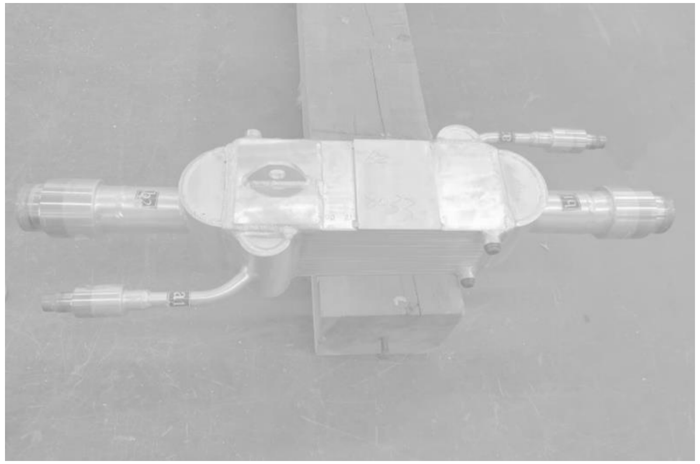
Photo of test cryostat



- **Test Results**
- design mass flow rate : **5g/s**
- Effectiveness : **80.3%**
- Pressure drop :**78.89Pa**



Test Result of the Single Layer Coiled Finned-tube HX

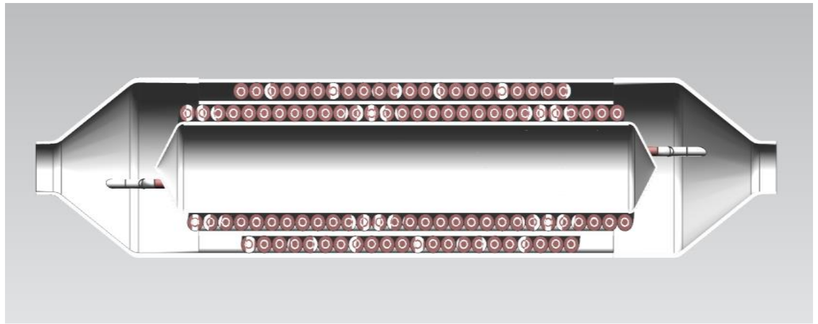




Stage2. Double Layer Coiled Finned-Tube HX

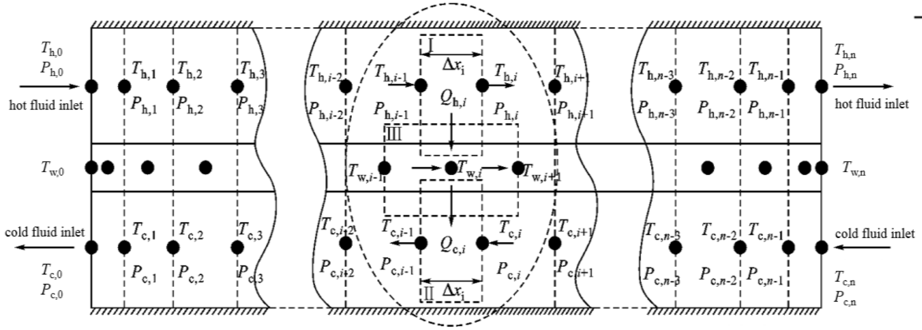
- Medium mass flow rate for 10g/s
- Distributed parameter differential method

Stage2. Double Layer Coiled Finned-Tube HX

• Design



Structure of Double Layer Coiled Finned-tube HX



Distributed parameter differential method

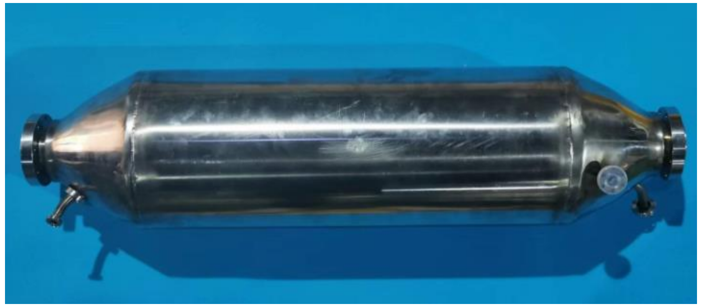
• Optimization

Optimal design parameters

Parameter	Value
Inner layer core tube	614mm×φ114mm
Outer layer core tube	573mm×φ169mm
Finned-tube inner diameter	8mm
Fin height	4.8mm
Fin pitch	3.125mm

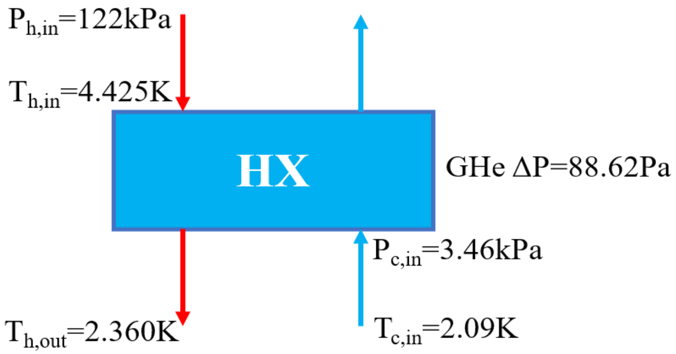
Double Layer Coiled Finned-tube HX

• Manufacture



• Test Results

- design mass flow rate : **10g/s**
- Effectiveness : **84.9%**
- Pressure drop : **88.62Pa**

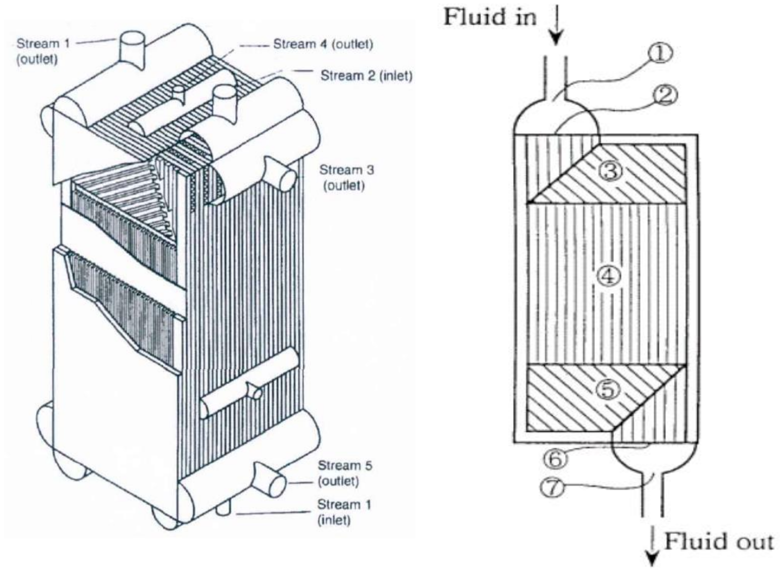


Stage3. Plate Fin HX

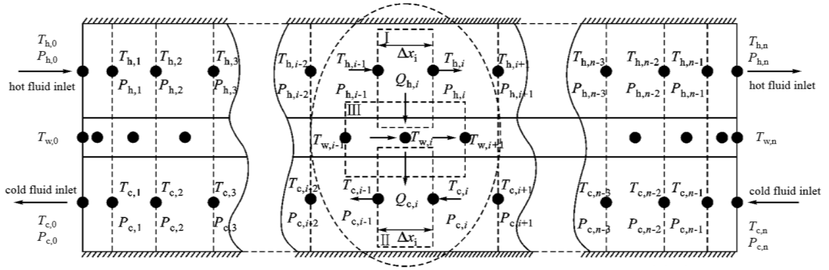
- Large mass flow rate for > 10g/s
  - Multi-objective Optimization

2K JT heat exchanger R&D and test

- **Design Calculation**

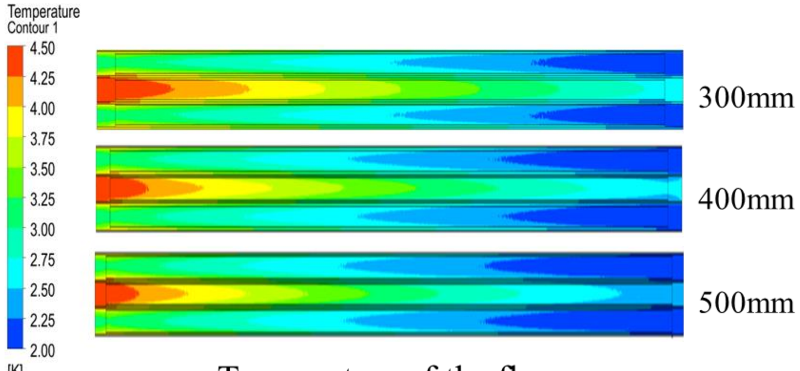


Structure of Plate Fin HX



Distributed parameter differential method

- **Check Calculation**

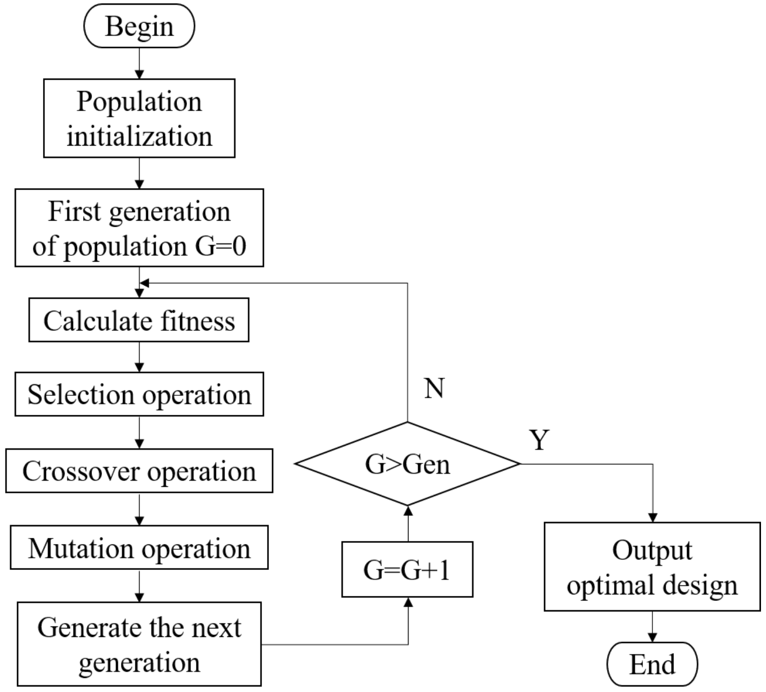


Temperature of the flow

Result comparison

Length	CFD Result		Calculated Result	
	$T_{c,out}$	$T_{h,out}$	$T_{c,out}$	$T_{h,out}$
300mm	3.13K	2.95K	3.17K	3.05K
400mm	3.16K	2.76K	3.19K	2.88K
500mm	3.22K	2.58K	3.29K	2.79K

- **GA Multi-objective Optimization**



Flowchart of GA Multi-objective Optimization

$$\mathrm{Fit}(x_1, x_2, x_3 \cdots x_n) = \mathrm{k}_1 \cdot \frac{Nu}{f^{1/2}} - \mathrm{k}_2 \cdot V - \mathrm{k}_3 \cdot Rt - \mathrm{k}_4 \cdot Pc + \mathrm{k}_5 \cdot \varepsilon$$

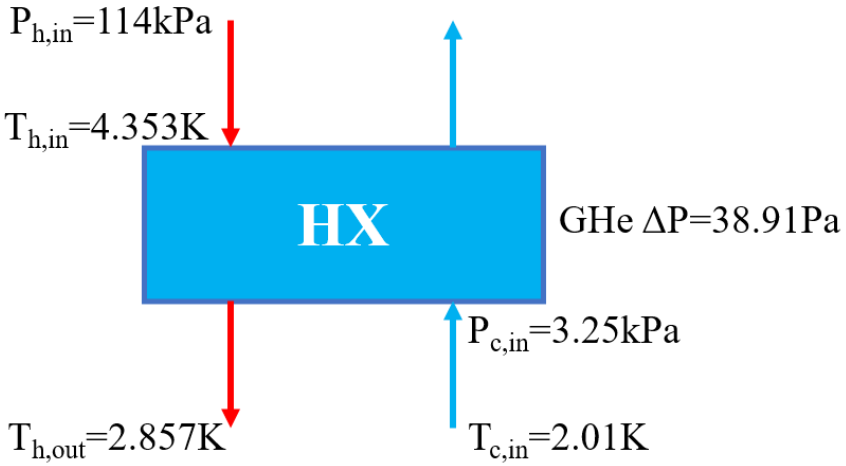
2K JT heat exchanger R&D and test

• Manufacture

Manufacture process of Plate Fin HX

• Test Results

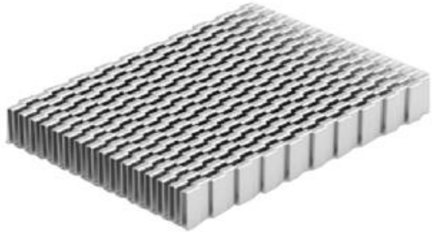
- design mass flow rate : **10g/s**
- Effectiveness : **65.2%**
- Pressure drop : **38.91Pa**



Test Result of the Single Layer Coiled Finned-tube HX

Upcoming research work

- **Research of various types of fins**
- Fins with different shapes and structures will be studied in order to realize the simulation of thermal and pressure drop performance of PFHE with different fin designs.



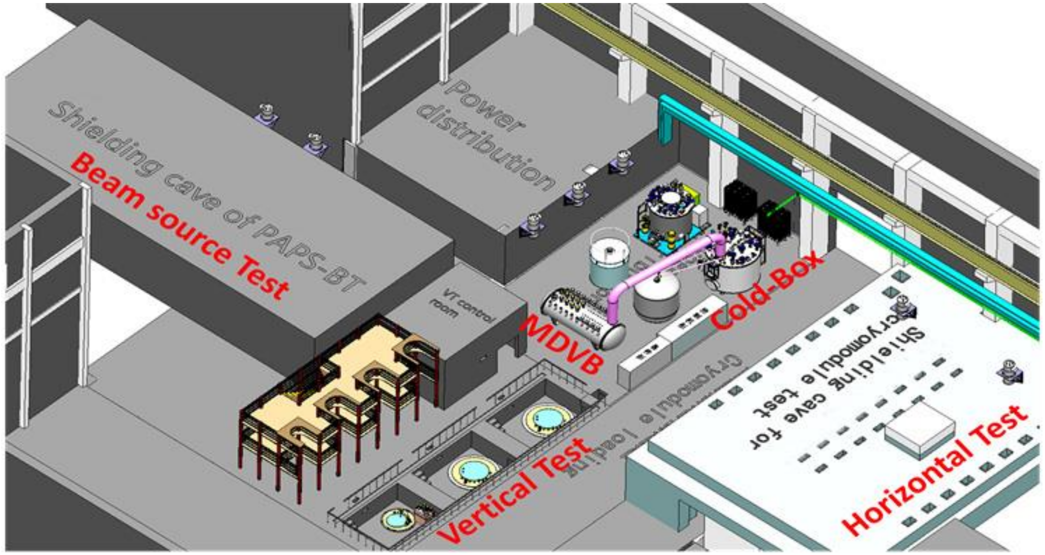
serrated fin

perforated fin

plain fin

wavy fin

- **Construction of test Dewar for plate fin heat exchanger (PFHE) in kilowatt scale**
- Based on the cryogenic system of PAPS, the 2K heat exchanger test Dewar will be designed and constructed to meet the experimental requirements of PFHE in kilowatt scale.



Summary

- Previous CDR and TDR works have laid a good foundation for the further design.
- For the CEPC cryogenic system TDR design, relevant aspects have been considered , including process scheme, layout, and key equipment design.
- We still need to work together to greatly push forward the work, and complete the TDR design on time.

Thanks for Your Attention !