Cryogenic system design for detector and accelerator superconducting magnet in colliding area

Tongxian Zhao， Shaopeng Li

Outline

- Introduction
- Cryogenic cooling schemes and Cryogenic Layout
- Cryogenic system design considerations
- The Cryostat of MDI
- Key technology
- Cost estimation
- Summary

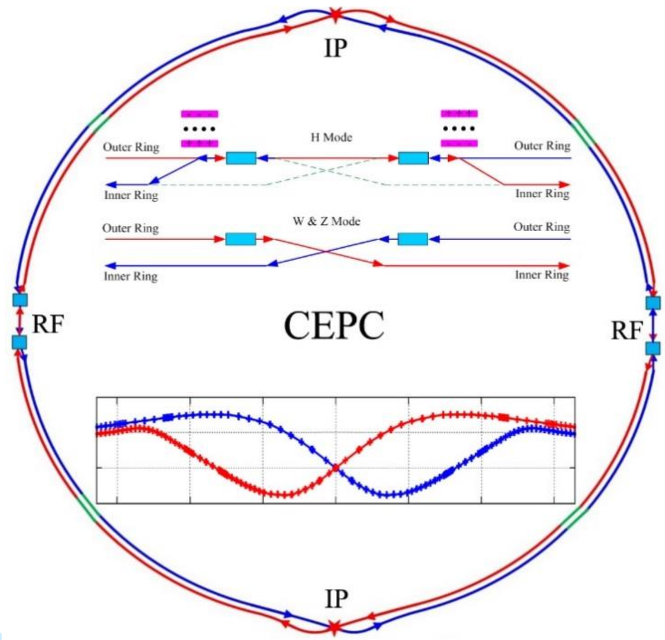
Introduction

IR magnets:

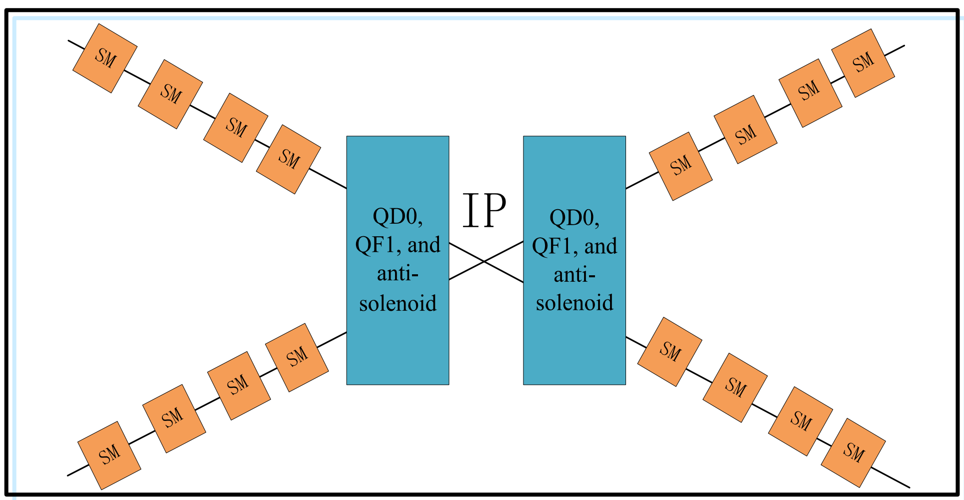
- 4 IR magnets
- 32 Sextupole magnets,
- 36 cryomodules/18 @each station
- Temperature: 4.5K (2K)

Two detectors:

- LTS Solenoid: 4.2K



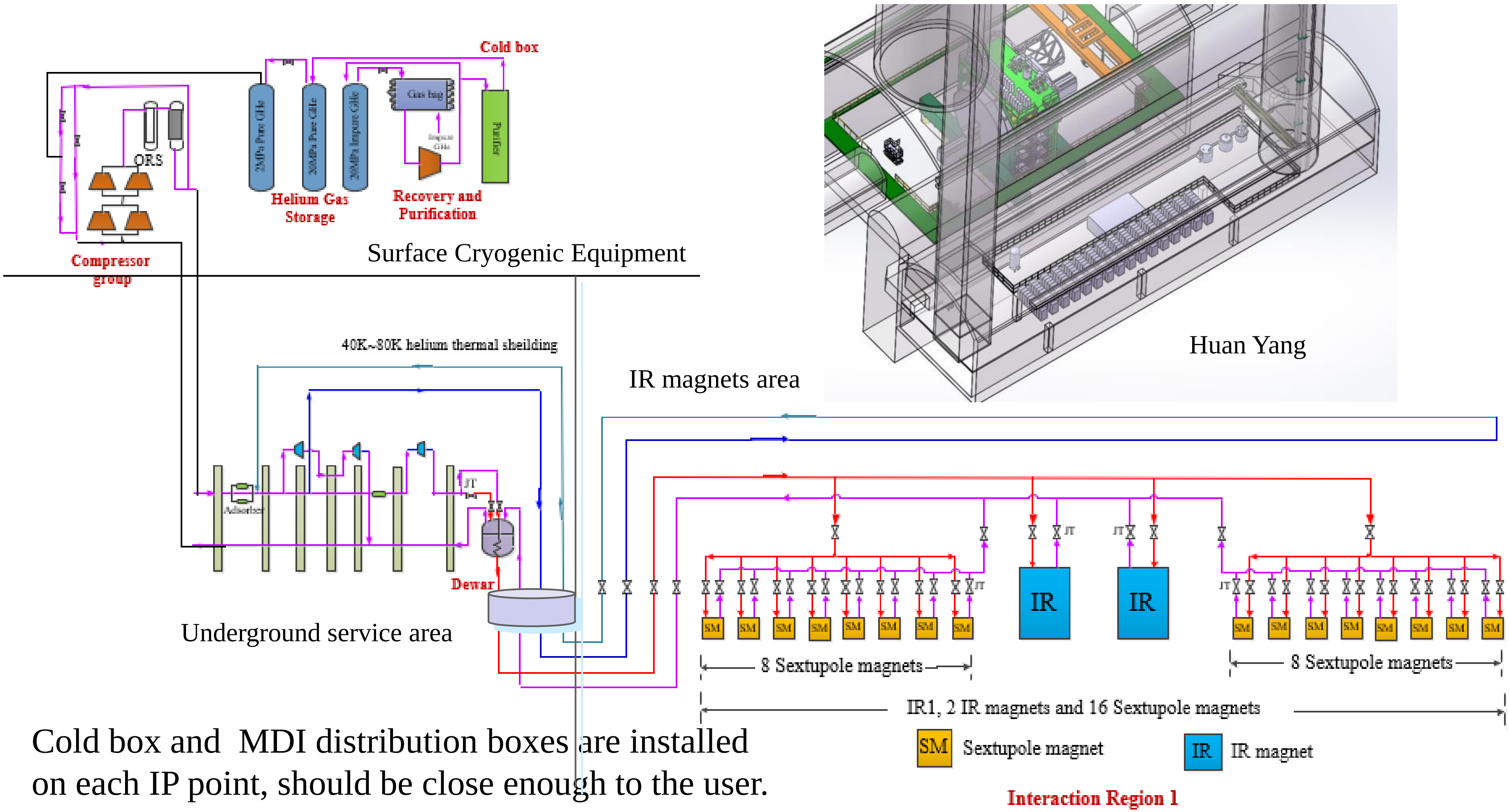
Sketch of CEPC Collider ring



CEPC MDI SC Magnets (superconducting QD0,QF1, anti-solenoid) in a helium vessel.

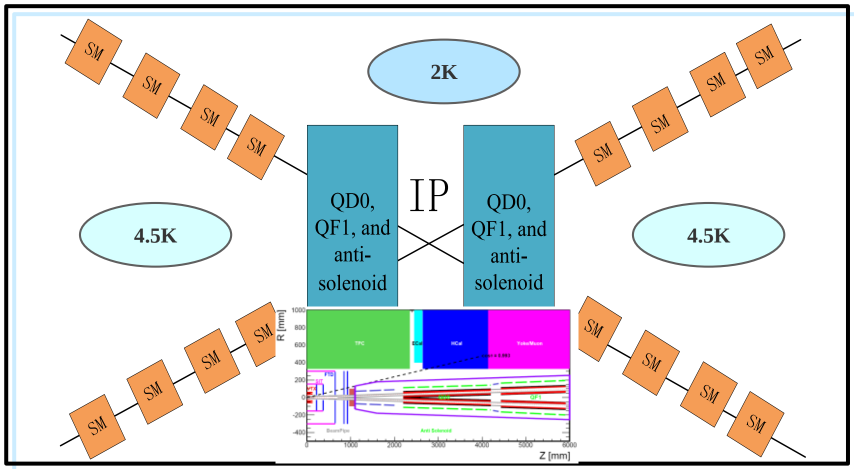
Cold Box (MDI / Detectors)
Single / more cold box

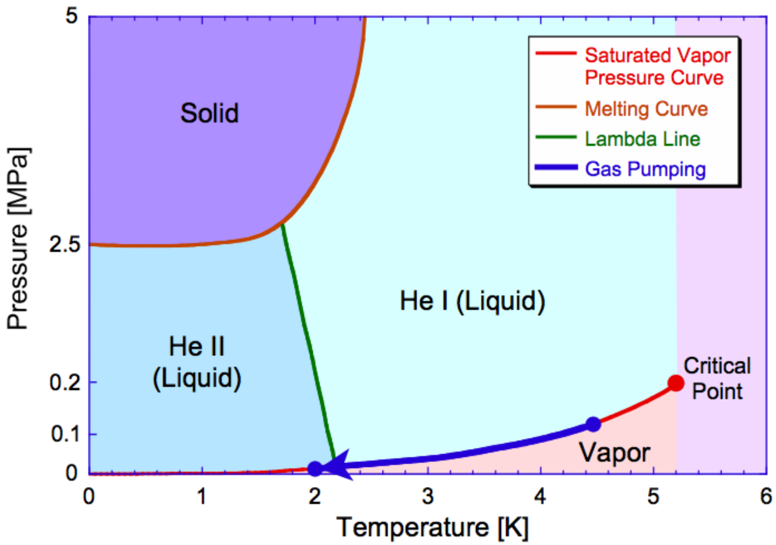
Cryogenic cooling schemes and Cryogenic Layout in the experimental Hall



Cold box and MDI distribution boxes are installed on each IP point, should be close enough to the user.
Sextupole magnets share a CB with MDI, they need to be considered together.
Refrigerator with the cooling capacity of 3kW@4.5K will be employed for each cryo-stations.

2K Cryogenic system

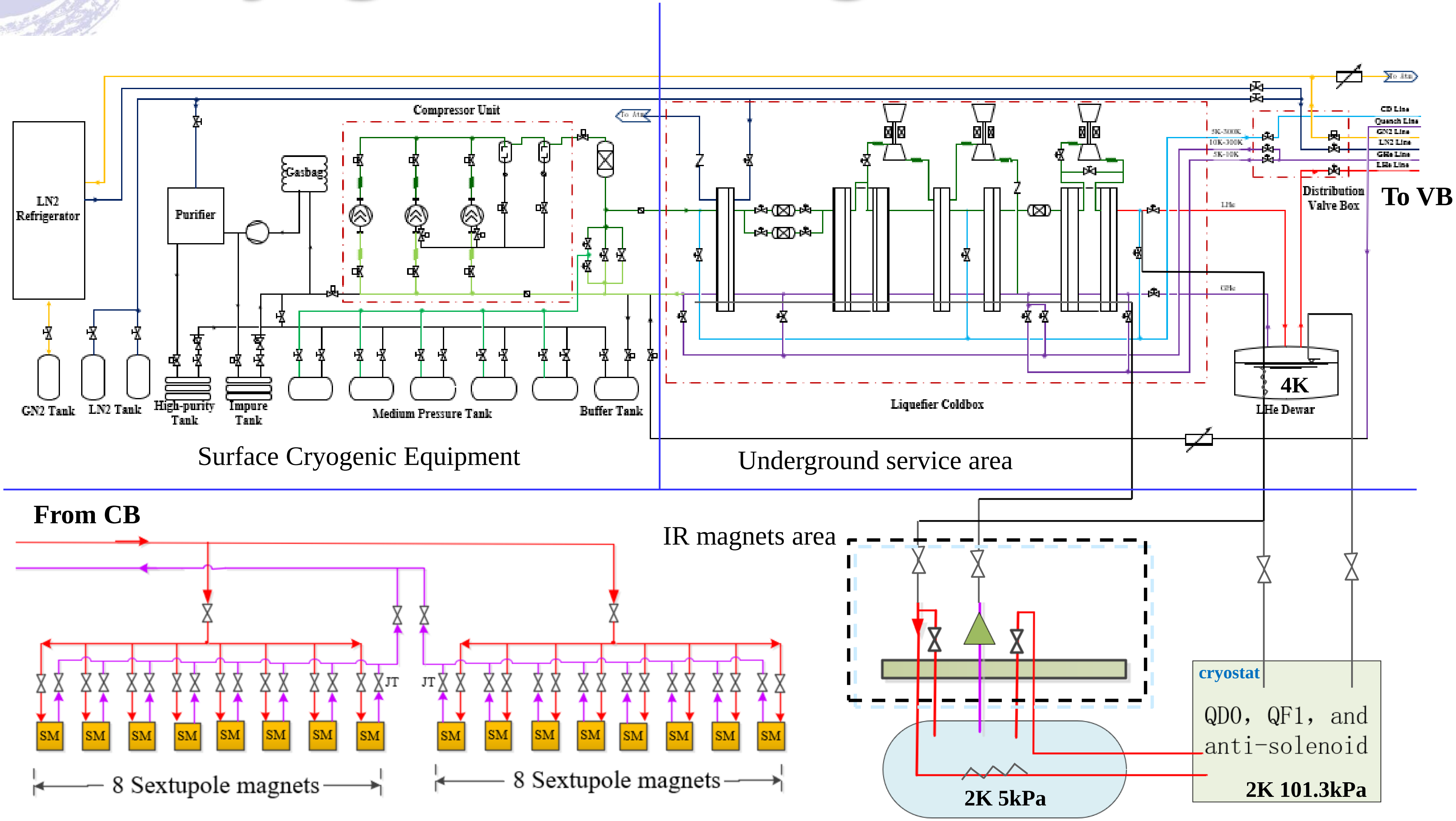




Superconducting equipment	Coolant condition	Heat Load
Sextupole magnets	4.5K(2K)	16*10W@4.5K(2K)
QD0, QF1 and anti-solenoid	Below 2K	4*30W@2K

To determine actual cooling capacity safety factor and extra heat load has to be considered. With the change of operating temperature we also have to reconsider actual thermal load for these equipment.

Cryogenic cooling schemes @2K



- The MDI cold masses will be cooled in a pressurized static superfluid helium bath at 101.3kPa and at a temperature of 2K, so we need a 2K refrigerator in the tunnel.
- The 5kPa vapor pressure is maintained by a cold compressor system
- The final operating temperature and pressure are determined by the cryogenic process calculation

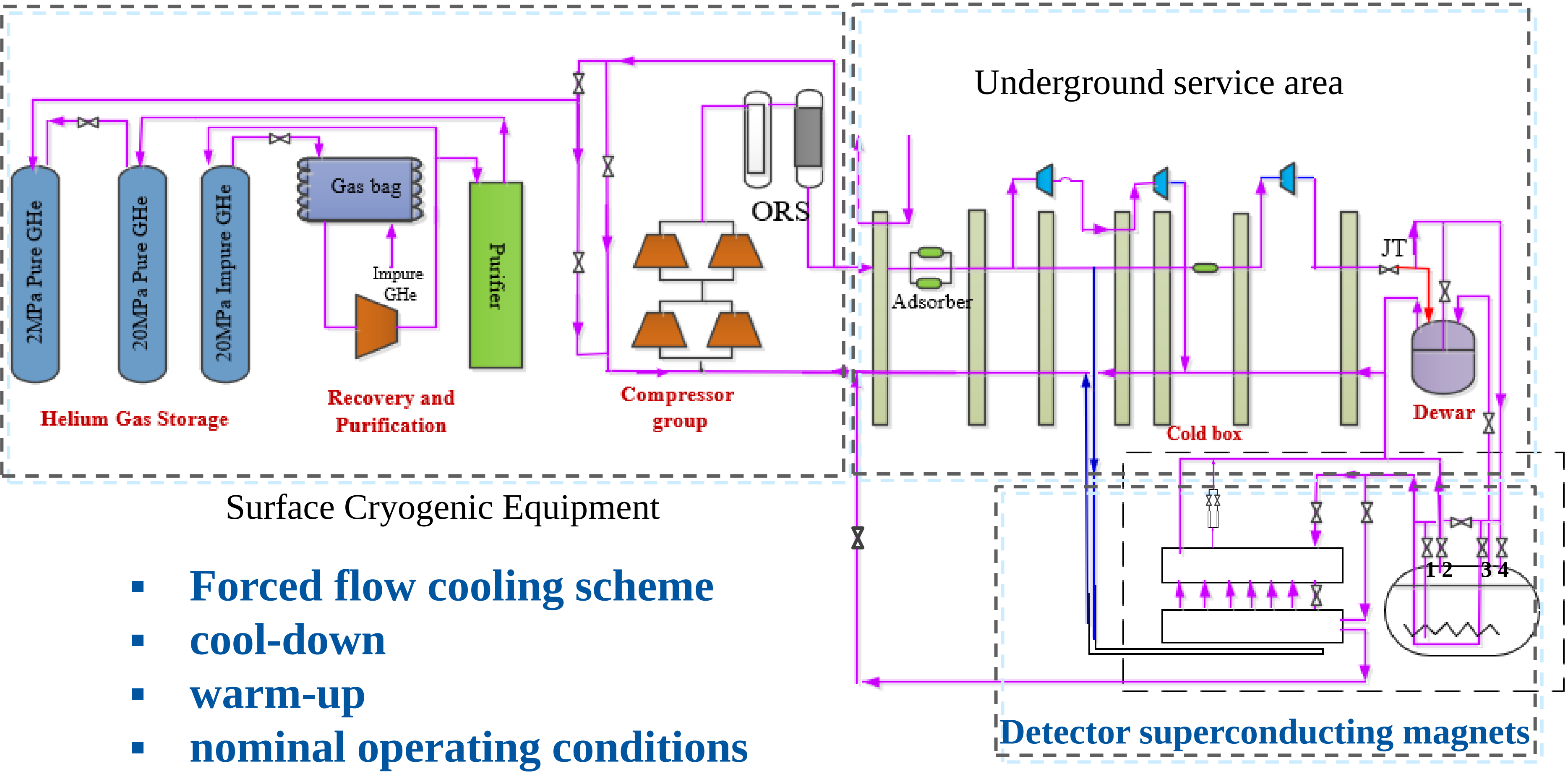
Cryogenics for detector

CEPC Detector superconducting magnets

- Solenoid located outside calorimeter
- Inner diameter 7.2 m, length 7.4 m
- Central field：3 T
- Superconductor：NbTi
- Operation temperature：4.2 K
- Thermosyphon cooling scheme
- Forced flow cooling scheme *

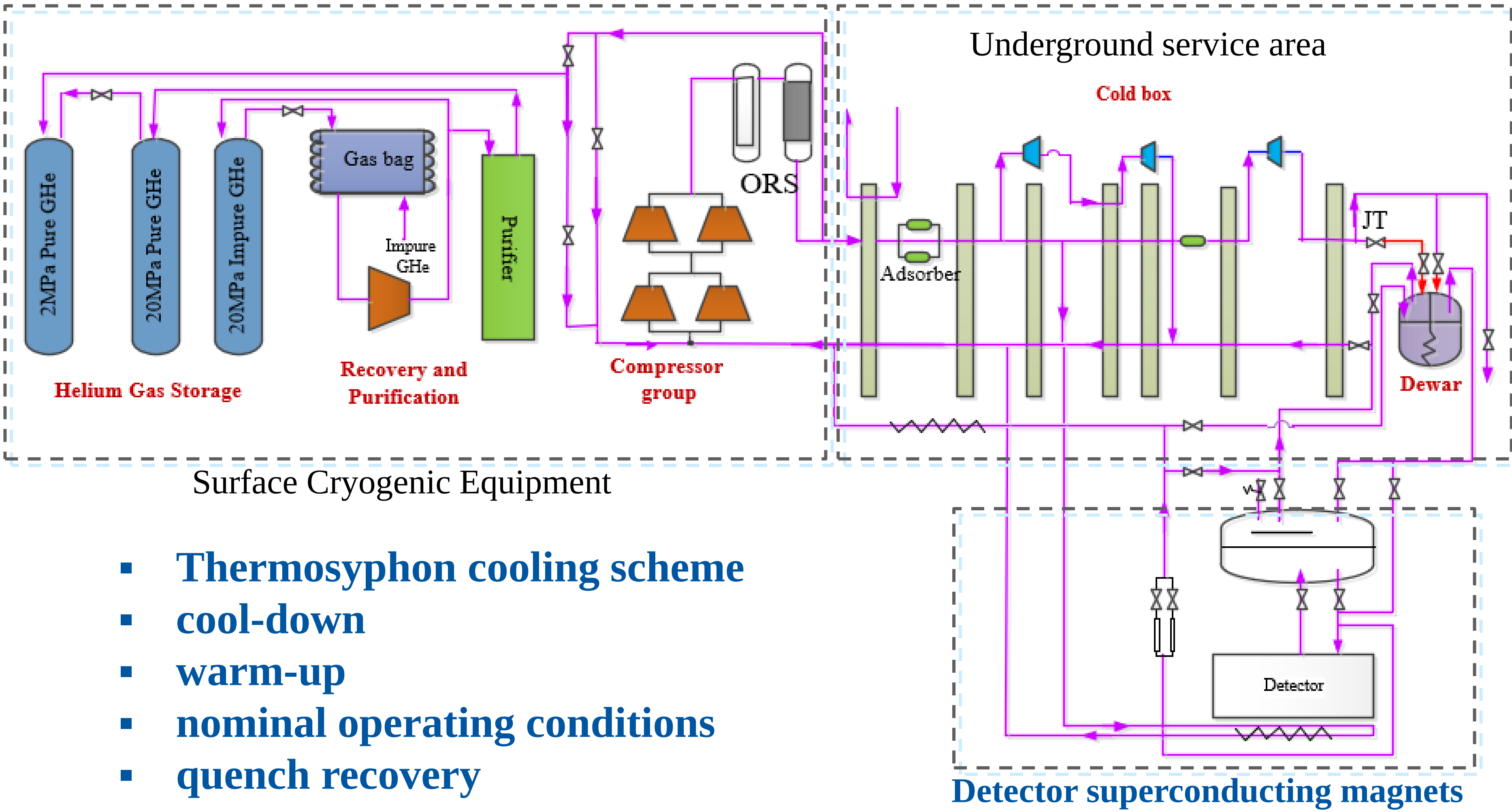
*We have two approaches to liquid cooling, natural convection and pump circulation, depending upon whether the circulation pump is employed or not.

Schematic Flow Diagram



- Forced flow cooling scheme
- cool-down
- warm-up
- nominal operating conditions
- quench recovery

Schematic Flow Diagram

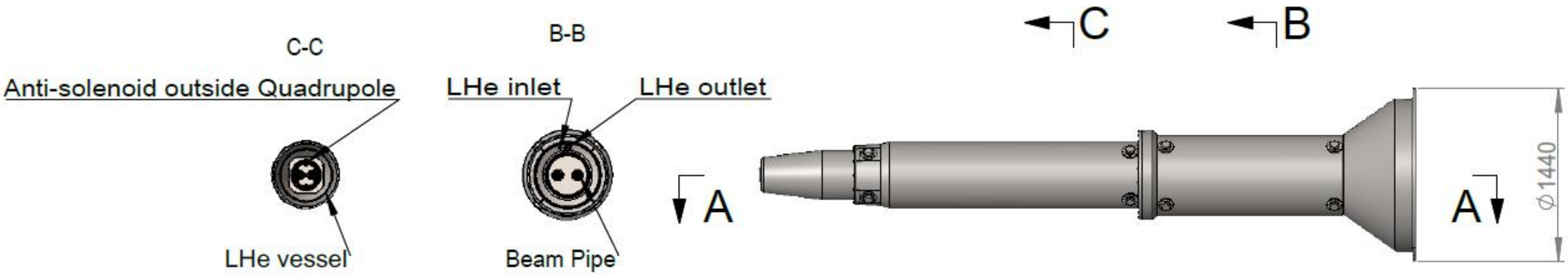


- **Thermosyphon cooling scheme**
- **cool-down**
- **warm-up**
- **nominal operating conditions**
- **quench recovery**

Cryogenic system design considerations

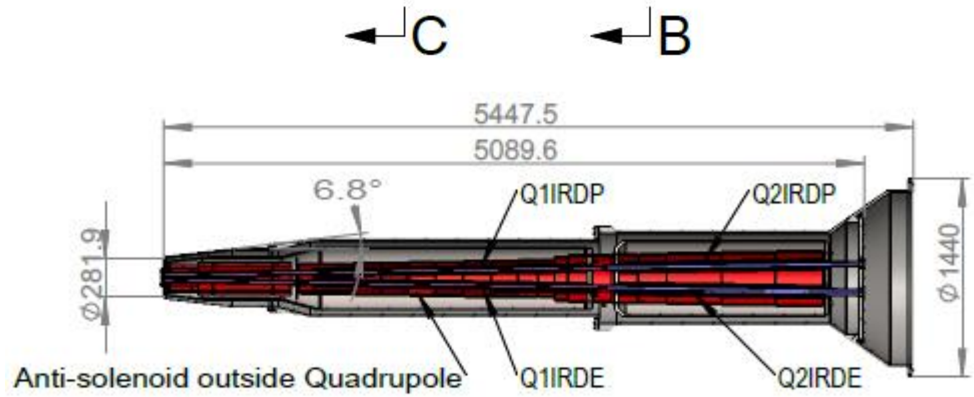
- The cryogenic systems incorporate high efficiency helium refrigeration ,produced by industry, (liquefaction) at 4.5 K, a distribution system with low heat-in leaks ,a large helium inventory (storage) and the cryogenic users (cryostat).
- The design of the cryostat and cryogenics system allowed the prior testing of the full cryogenic loop without magnet.
- CEPC cryogenic system should allow for rapid cool-down and warmup of limited lengths of the strings, e.g. for repairing or exchanging a defective unit.
- To ensure reliable operation, it should provide reasonable redundancy of functions among its components and sub-systems
- Personnel and equipment safety

The Structure of Cryostat



Magnet-cryostat design:

- superconducting magnets are assembled in the two helium vessel, respectively.
- Two beam pipes at room temperature pass completely through the helium vessel at 4K.
- Self-centered supports are designed to make the magnet positions after cool-down the nominal positon for the beam operation.
-



Magnet cryostat	Weight(Kg)
Total cold mass	1057.77
Front Lhe vessel	248.81
Rear Lhe vessel	248.96
Magnet	560

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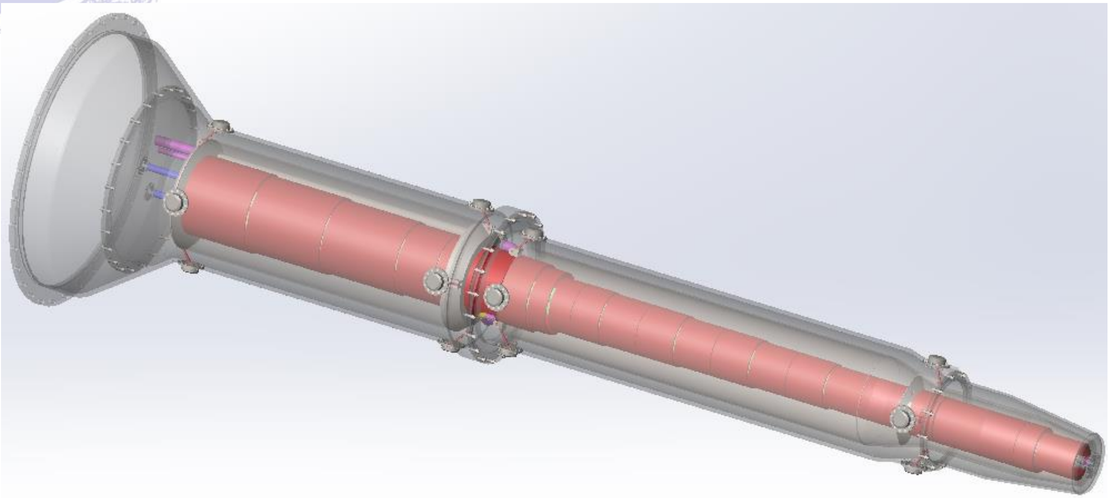
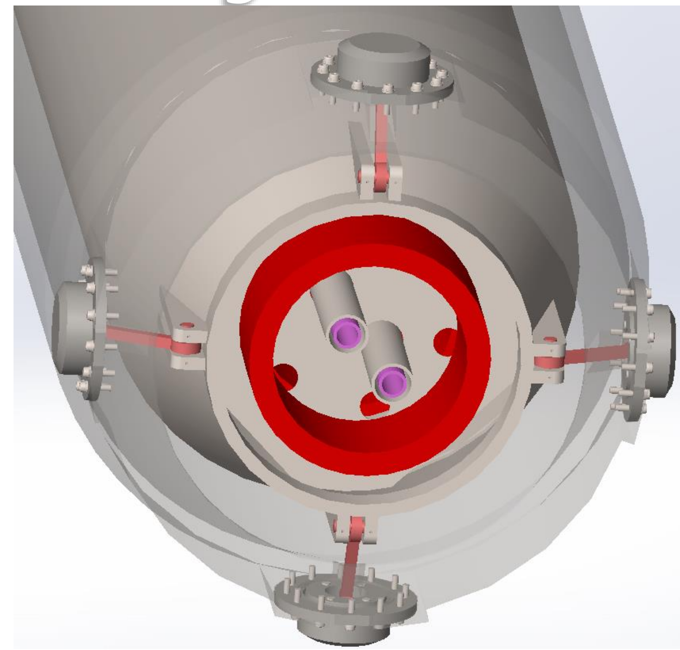
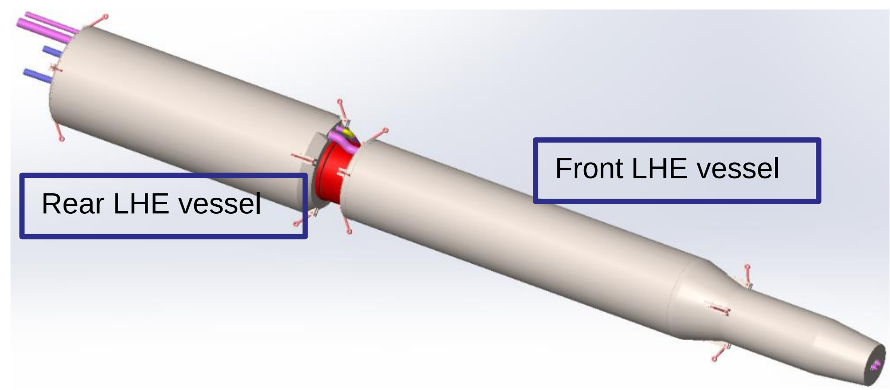
The Structure of Cryostat





- The helium vessels, in which the SC magnets are assembled, are supported by the 8 rods from the vacuum vessel.
- To be made of non-metallic materials such as Carbon fiber (CFRP, T300)
- The multilayer insulation material and it's dressing process is very important to decrease the heat load



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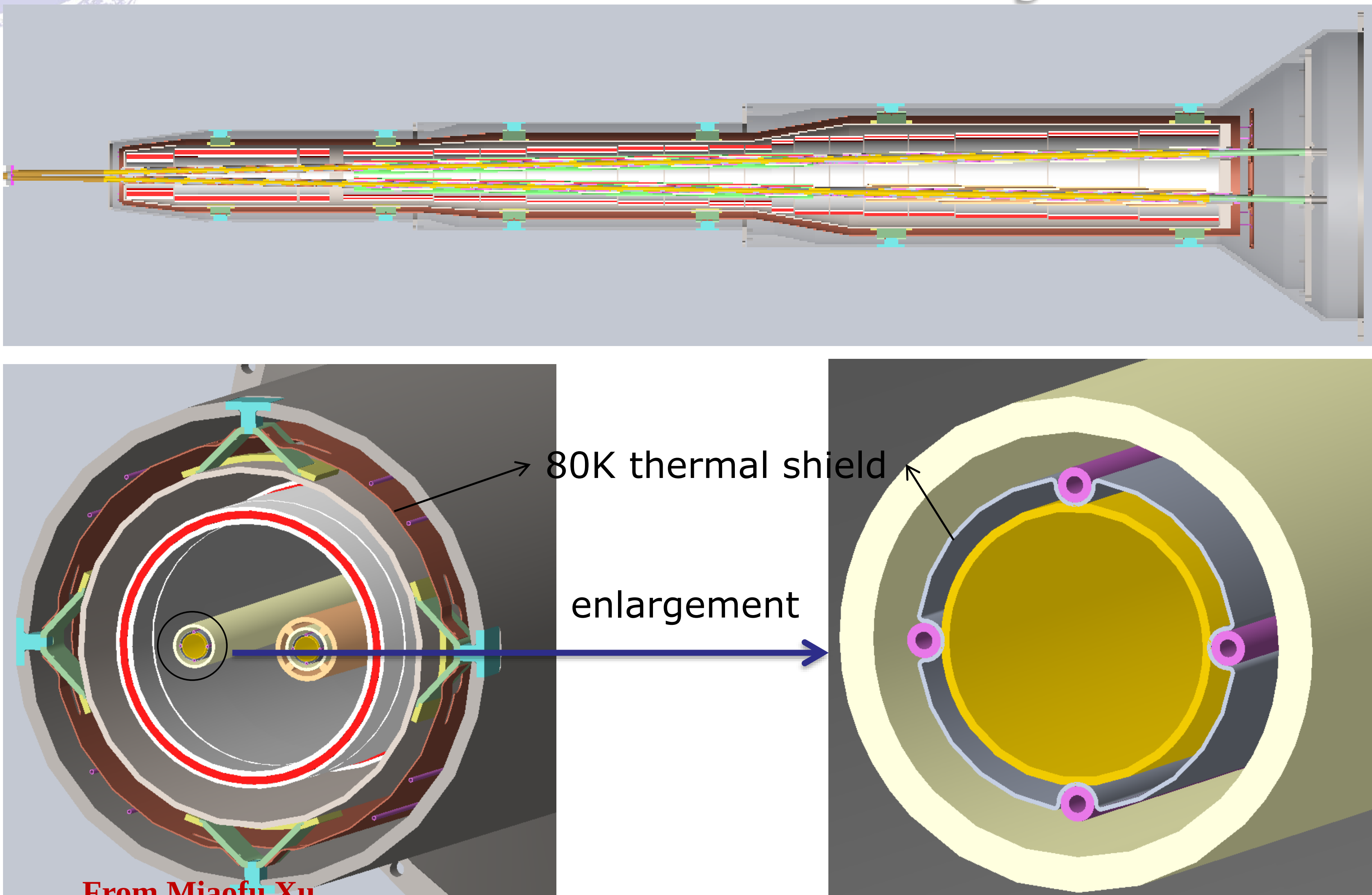
***Study on heat leak of multilayer insulation(MLI)**

The Structure of Cryostat



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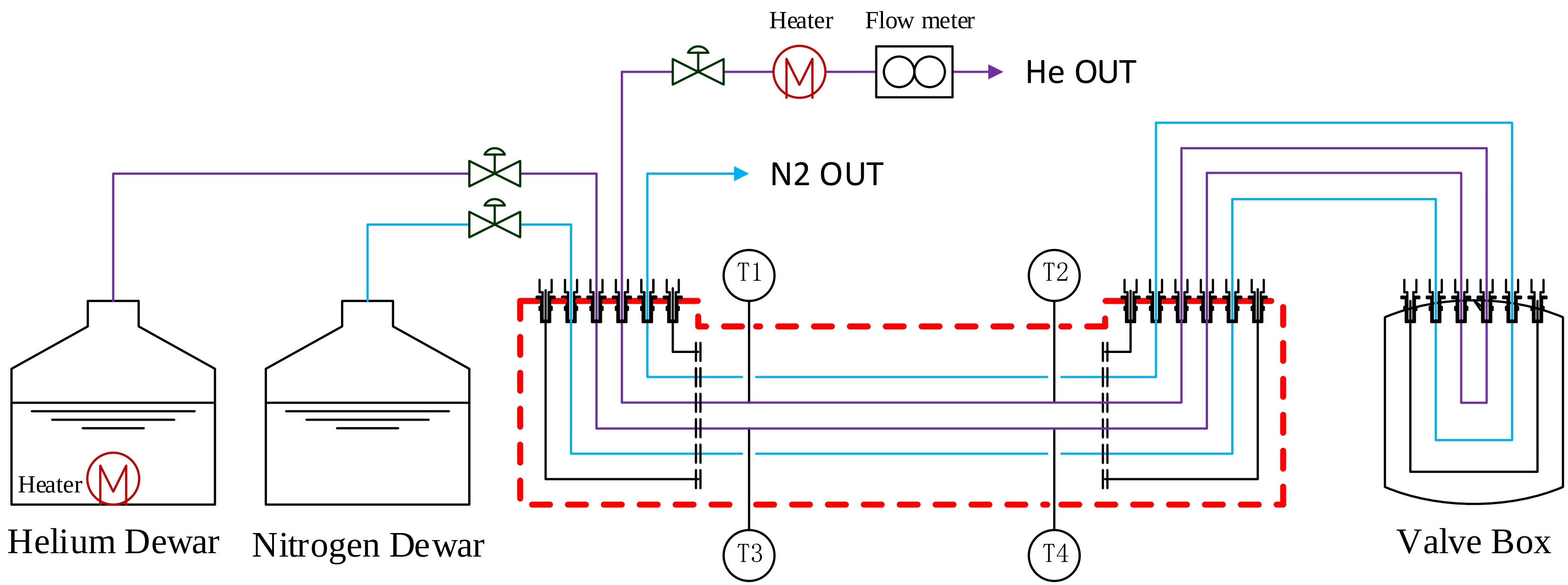
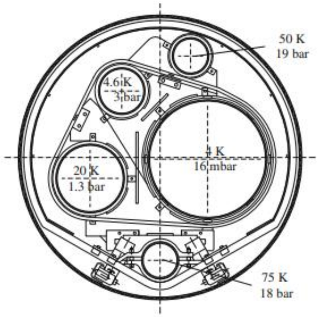
Cryostat Key technology pre-research

No	Name		Price (RMB10000)	Tatol Price (RMB10000)
1	Budget for development of cryostat prototype (without current leads)			398.90
1.1	Cryostat			341.60
1.1.1	Mechanical	1	180	180.00
1.1.2	Offline performance test of key components			18.00
	Performance test of pull rod assembly	16	0.5	8.00
	performance test of metal hose and displacement compensator	1	2	10.00
1.1.3	measurement			67.60
1.1.3.1	Temperature sensor and instrument	1	45	46.00
1.1.3.2	Liquid level meter and instrument	2	1.8	3.60
1.1.3.3	FEEDTHROUGH	1	5	5.00
1.1.3.4	multi-channel cryogenic transfer line	1	13	13.00
1.1.4	Cryogenic test			74.00
1.1.4.1	Liquid Nitrogen	1	2	2.00
1.1.4.2	Liquid Helium	4000	0.018	72.00
1.1.5	Pump system	1	20	20.00
1.2	Control Unit			12.3
1.2.1	Control PC	1.00	2.50	2.50
1.2.2	PLC	1.00	1.30	1.30
1.2.3	Cabinet	1.00	1.50	1.50
1.2.4	Software	1.00	5.00	5.00
1.2.5	Other componets	1.00	2.00	2.00
1.3	Deawr for Pressurized Lhe/ Heat exchanger	1	45	45

- **A cryostat prototype to find many unknown problems.**
- **Heat exchange for the cryostat.**
- **High-performance cryogenic transfer line.**
- **The pressurized static superfluid helium bath technology.**
- **Cold compressor station.**

Cryogenic Transfer Lines

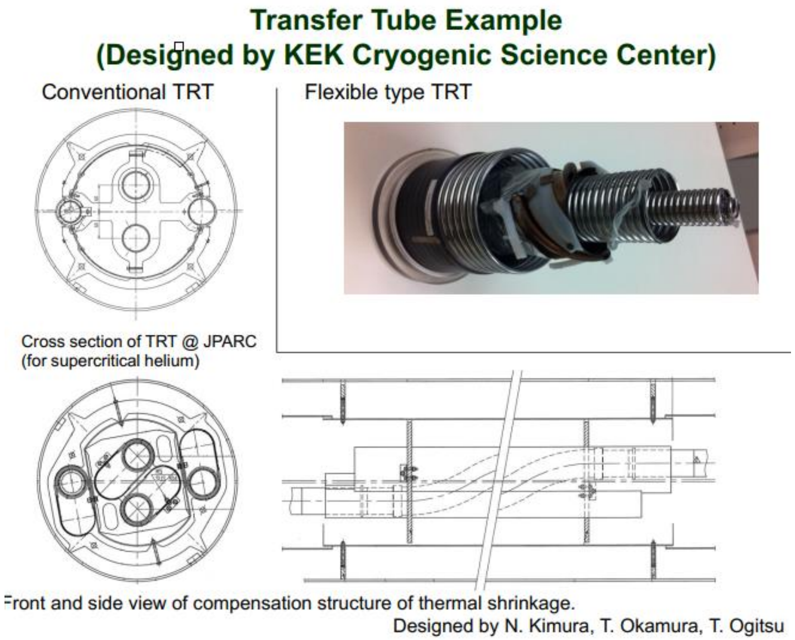




LHC/QRL CTL

Cryogenic transfer lines are typical components of almost all cryogenic systems.They are intended for transferring cryogenic fluids between two cryogenic devices. We need high-performance cryogenic transfer lines for reduce the heat leak.
We will build a test stand for the CTL heat loss measurement, design CEPC CTL.

Flexible Type TRT

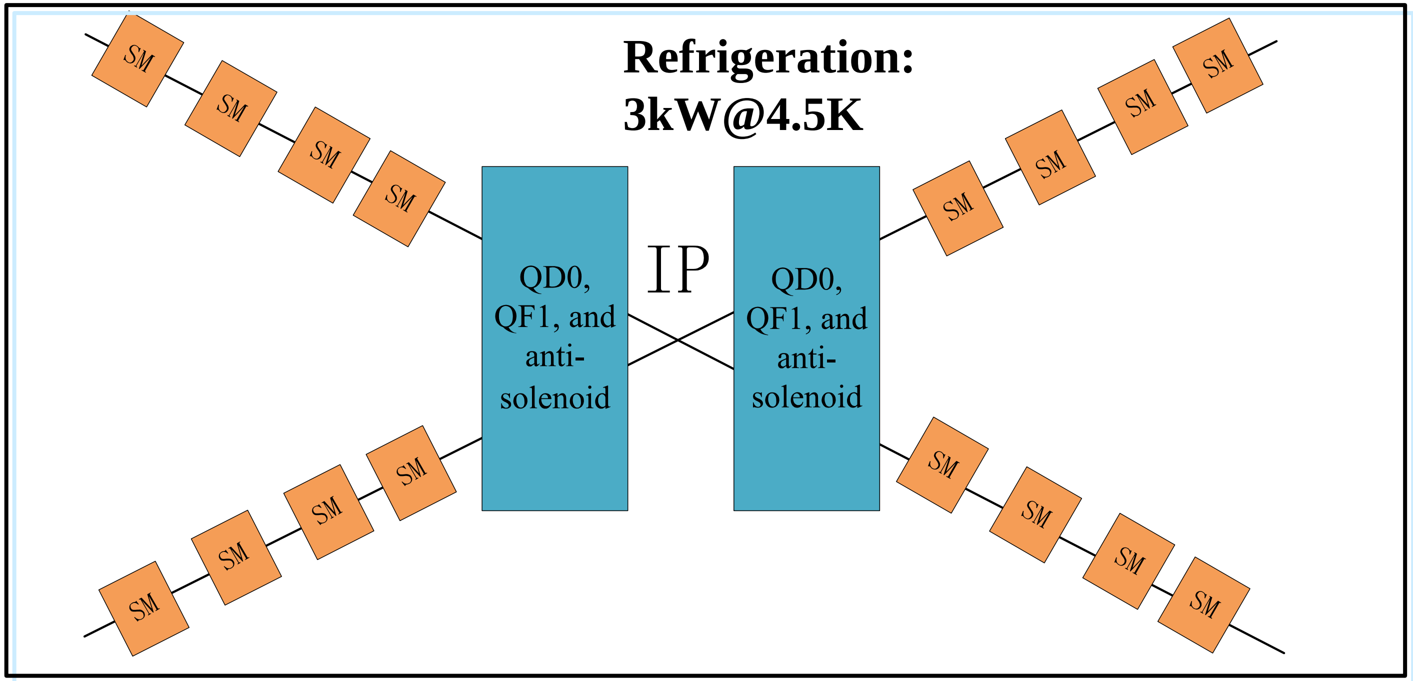


- **Flexible Type TRT maybe need between cold box and detectors for Push-pull operation.**
- **Large space for flexible TRT has to be required.**
- **bending radius of flexible TRT need to be considered**
- **Maintenance and assembly of MDI and cold box can be performed independently.**
- **Maintenance of cold box is simple because control point and equipment such as valves are not so much.**

Cryogenics for SC magnets

- **2 IPs in CEPC Interaction Region, there are 4 QD0 magnets, 4 QF1 magnets, 4 anti-solenoids and 32 sexupole magnets.**
- **There are 2 cryo-stations, each one with a refrigerator of 3kW@4.5K.**

Plan A . Large refrigerator



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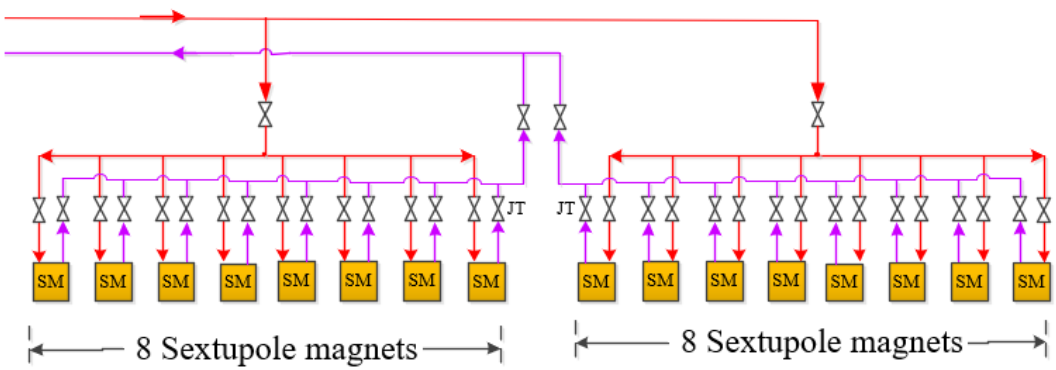
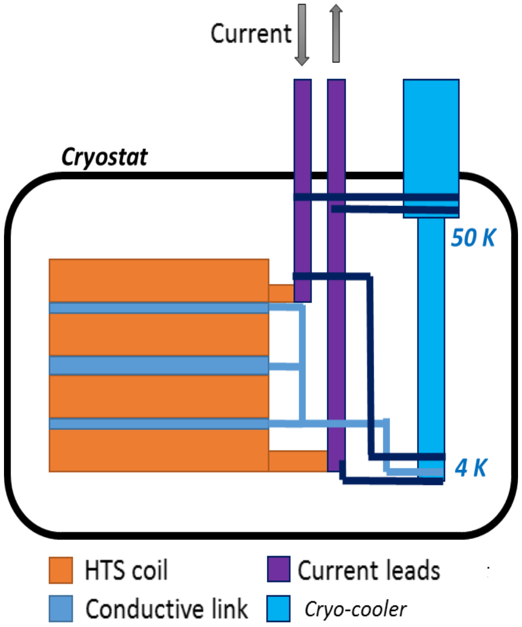
GM Refrigerator Application





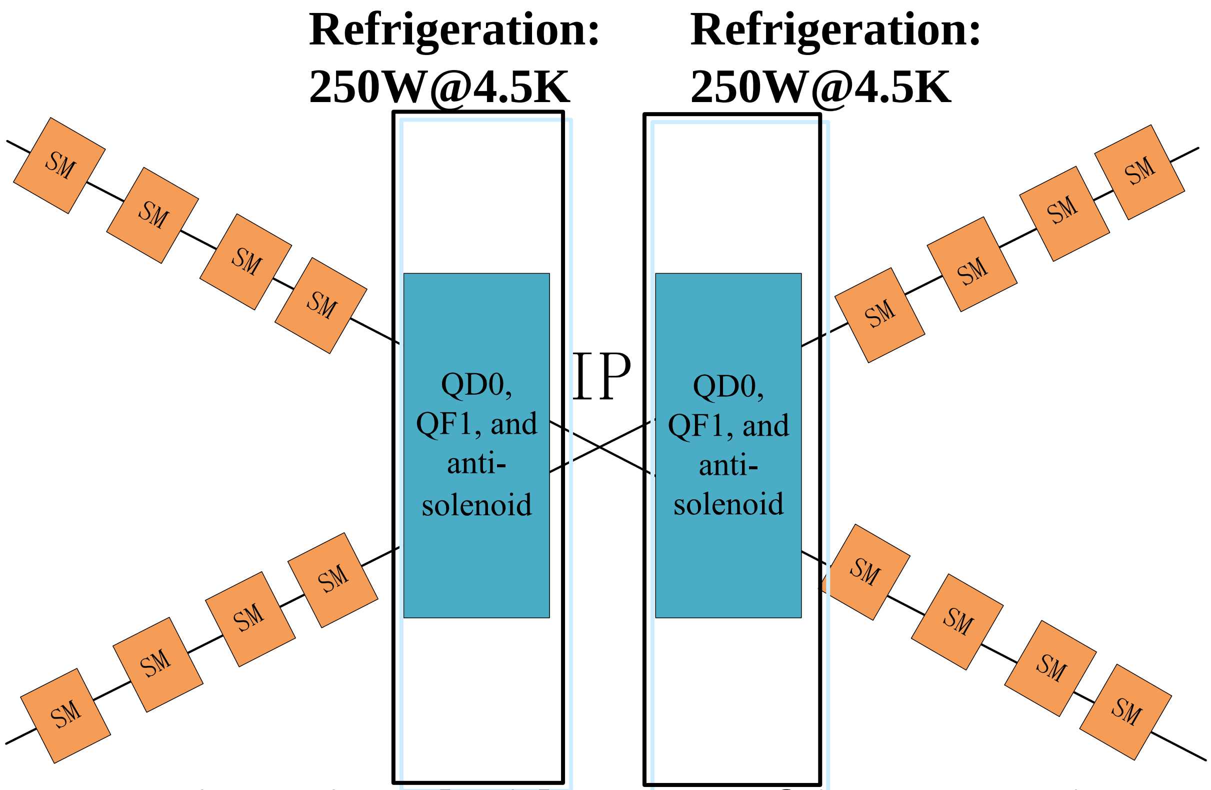
2 cryo-stations, each one with a refrigerator of 3kW@4.5K

GM refrigerators + 4*250W refrigerators

- **Replace**
- **Spare**
- **Repair**
- **emergency service**

Cryogenics for SC magnets

Plan B. GM refrigerator



Each sexupole magnet is equipped with a GM refrigerator unit, totally 32 groups. if GM refrigerator is adopted, there is no cryogenic tranfer line, but the maintenance of the GM refrigerator is more difficult.

Heat load for SC magnets

Plan A . Large refrigerator	Unit	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 of IR SC sextupole magnet	g/s	32	0.1	3.2
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	2	50	100
Cryogenic transfer-line	m	4000	0.5	2000
Total heat load				3300
Equiv. heat load @4.5K	W			3300W+5.2g/s
Equiv. heat load @4.5K with multiplier 1.5	W			3820
Cooling capacity of refrigerator@4.5K	kW			5730
Installed power (COP:300W/1W)	MW	2		1.8

There are 2 refrigerators, low cost of daily maintenance.

The CTL is long and the cost is high （214 **million**）

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Heat load for SC magnets

Plan B. GM refrigerator	Unit	No.	Heat load for each	Heat load
IR SC sextupole magnet	W	32	6	192
Cooling Capacity of Refrigerator for sextupole magnet	W	32	6	192
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	200
Total heat load				440W+2g/s
Equiv. heat load @4.5K	W			640
Equiv. heat load @4.5K with multiplier 1.5	W			960
Cooling capacity of refrigerator@4.5K	W	4	250	1000
Installed power (COP(300W/1W))	MW			0.3

Low cost（174 million）, no long-distance CTL.
128 GM refrigerators and 4*250W refrigerators, high cost of daily maintenance and high failure rate.

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Heat load for detector

Zhu Zian，Wang Meifen

Items	Parameters
Radiation heat load at 60~80K	1000W
Supports	500W
Radiation heat load	**40W**
Others(Holdings&junctions&valves&pipes)	170W （pipes 100W）
Current lead LHe mass flow rate	2.5g/s----250W
Dynamic heat loads due to field ramping	**240W**
Valve Box of Detect Solenoid Magnet	**20W**
Cryogenic transfer-line	**150W**
others	**30W**
Equiv. heat load @4.5K	**975W**
Cooling capacity of refrigerator@4.5K	**1500W**
Installed power (COP(300W/1W))	**0.45MW**

Refrigerator selection	
Liquefaction	430L/h
Refrigeration	1500W@4.5K
Liquefaction/Refrigeration	1000W@4.5K & 150L/h

Cost estimation for SC magnets

	Plan A	Plan B
Budge（million）	214	174

Plan A Budge

编号	设备名称	规格型号	单位	数量	单价（万元）	总价（万元）100公里	备注
2.3	低温系统					21360.00	
2.3.1	3KW@4.5K制冷机	3KW@4.5K	台	2	3000	6000.00	国产，研制
2.3.2	液氦储罐	3000升	台	2	100	200.00	国产，购置
2.3.3	主分配阀箱		台	2	200	400.00	国产，研制
2.3.4	连接阀箱		台	36	100	3600.00	国产，研制
2.3.5	多通道低温管线	多路	m	4000	0.8	3200.00	国产，研制
2.3.6	中压氦气储罐	16Bar，100m3	台	8	80	640.00	国产，购置
2.3.7	高压高纯氦气储罐	200Bar，25m3	组	2	350	700.00	国产，购置
2.3.8	高压不纯氦气储罐	200Bar，25m3	组	6	250	1500.00	国产，购置
2.3.9	高压氦气回收压缩机	200bar，100m3/h	台	4	230	920.00	国产，购置
2.3.10	高压氦气纯化器	100m3/h	台	2	150	300.00	国产，购置
2.3.11	纯氦气	纯度**5N9**	m3	40000	0.015	600.00	国产，购置
2.3.12	控制系统		套	2	400	800.00	国产，研制
2.3.13	隔热真空系统		套	2	300	600.00	国产，购置
2.3.14	常温管路及常温阀		套	2	300	600.00	国产，购置
2.3.15	工具，消耗品等		套	2	300	600.00	其他
2.3.16	安装施工		套	2	350	700.00	其他

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Cost estimation for SC magnets

■Plan B Budge

编号	设备名称	规格型号	单位	数量	单价（万元）	总价（万元）100公里	备注
2.3	低温系统					17420.00	
2.3.1	250W@4.5K制冷机	250W@4.5K	台	4	600	2400.00	国产，研制
2.3.2	液氦储罐	2000升	台	4	50	200.00	国产，购置
2.3.3	主分配阀箱		台	4	100	400.00	国产，研制
2.3.4	连接阀箱		台	4	80	320.00	国产，研制
2.3.5	小型制冷机	1.5W@4.5K	台	128	30	3840.00	国产，研制
2.3.6	中压氦气储罐	16Bar，100m3	台	8	80	640.00	国产，购置
2.3.7	高压高纯氦气储罐	200Bar，25m3	组	2	350	700.00	国产，购置
2.3.8	高压不纯氦气储罐	200Bar，25m3	组	6	250	1500.00	国产，购置
2.3.9	高压氦气回收压缩机	200bar，100m3/h	台	4	230	920.00	国产，购置
2.3.10	高压氦气纯化器	100m3/h	台	2	150	300.00	国产，购置
2.3.11	纯氦气	纯度**5N9**	m3	40000	0.015	600.00	国产，购置
2.3.12	控制系统		套	4	300	1200.00	国产，研制
2.3.13	隔热真空系统		套	4	200	800.00	国产，购置
2.3.14	常温管路及常温阀们		套	4	300	1200.00	国产，购置
2.3.15	工具，消耗品等		套	4	300	1200.00	其他
2.3.16	安装施工		套	4	300	1200.00	其他

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Summary

- The cryostat will be optimized follow the process of magnets.
- MDI Dynamic heating from the particle beam should be provide.
- Total cold masses
- Precision Thermometry.
- Test Stand for the CTL.
- Cryostat Prototype is necessary in the furture.
- Research on 2K cooling scheme.

Thanks for your attention