

CEPC Cryogenic System EDR Status

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On behalf of CEPC cryogenic system

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- 3.2 Safety System

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CEPC Cryogenic System Brief Introduction

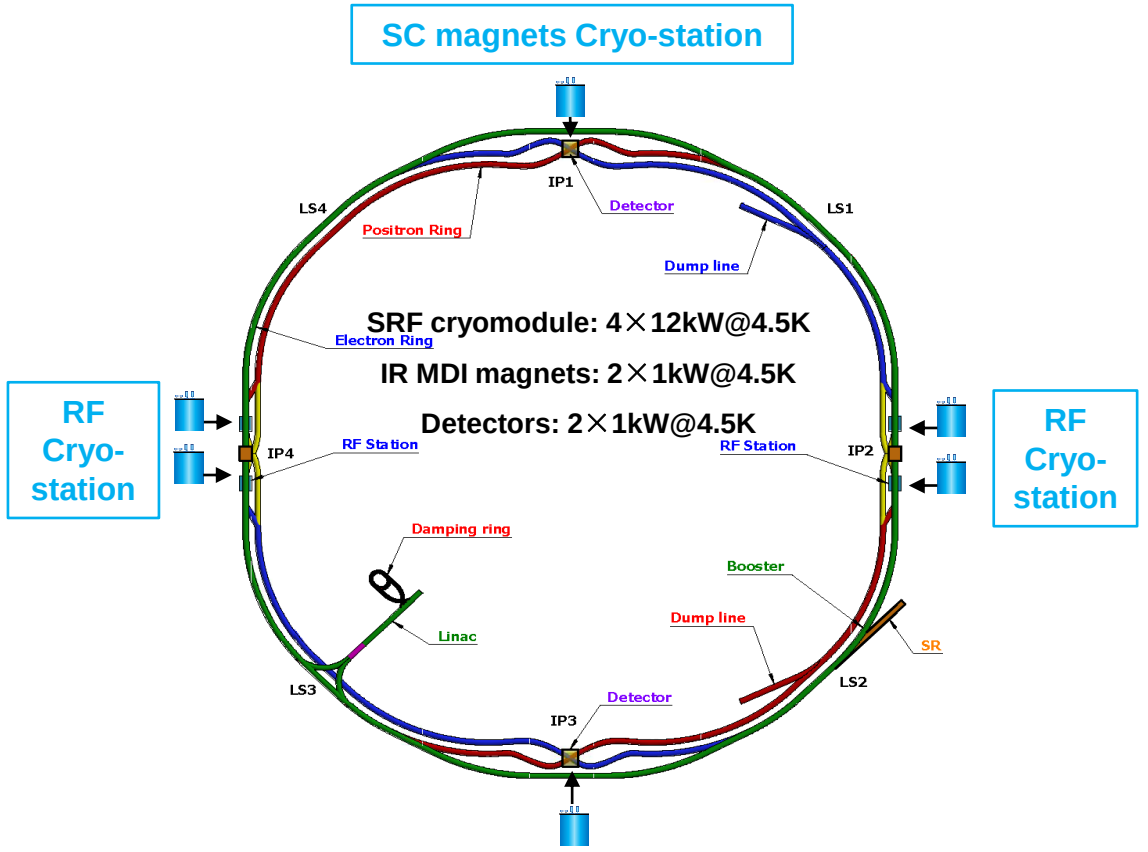
- CEPC is a positron and electron collider, and the beam is accelerated to 30 GeV by linear acceleration section, and then further accelerated to 120 GeV by RF cavities in the Booster and Collider ring.
- Cryogenic system is designed to provide a reliable and stable cooling environment (4.5K or 2K) for RF cavities and magnets.

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
- 32 cryomodules for Higgs 30MW, 56 for Higgs 50MW
- 8 or 14 cryomodules/each station
- Temperature: 2K



Overview of the CEPC cryogenic system

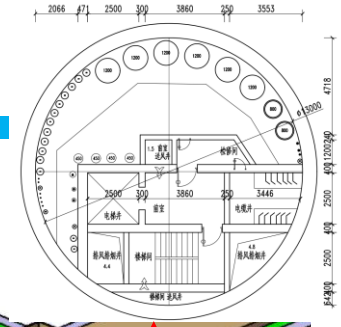
MDI IR magnets:

- 4 IR magnets, 4 cryostats
- Temperature: 4.5K/2K

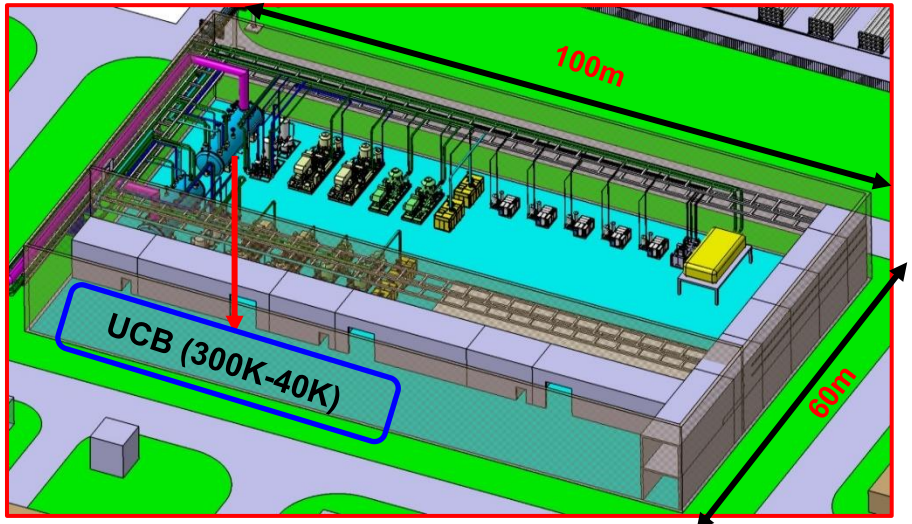
Detectors:

- 2 detector magnets
- HeI/Thermosiphon cooling

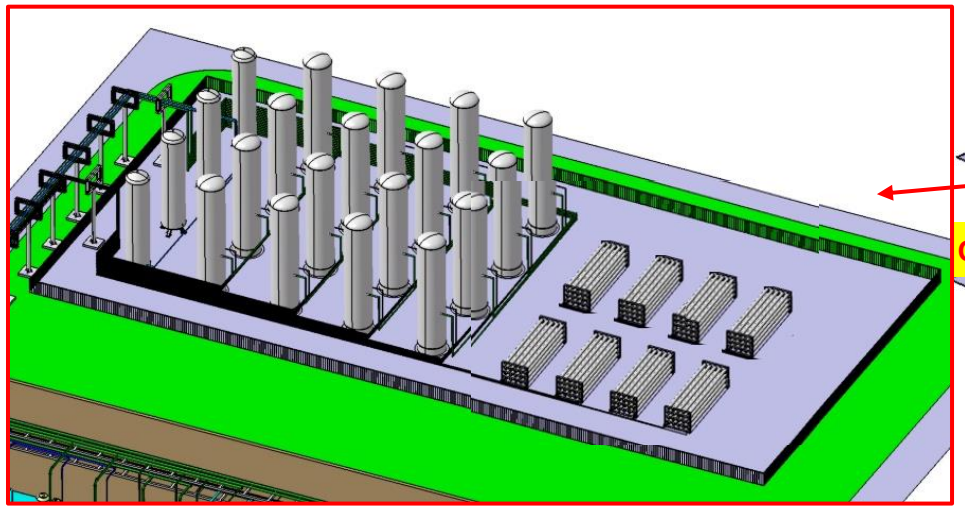
CEPC SRF Civil Engineering Cryo-Layout



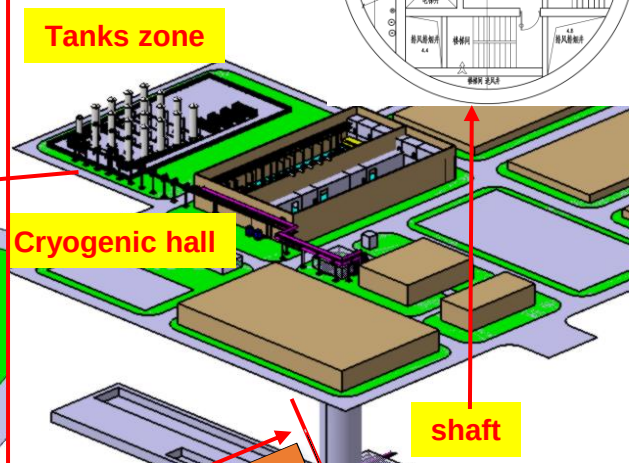
SRF Cryogenic System: 4×15kW@4.5K

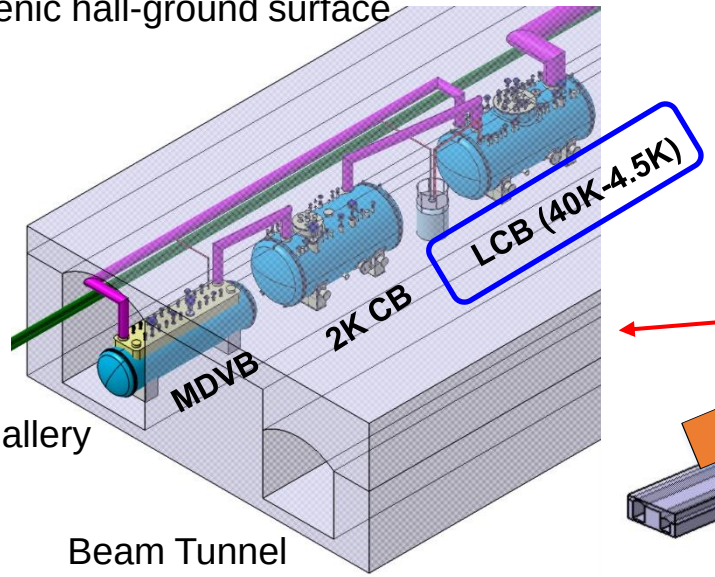


Cryogenic hall-ground surface



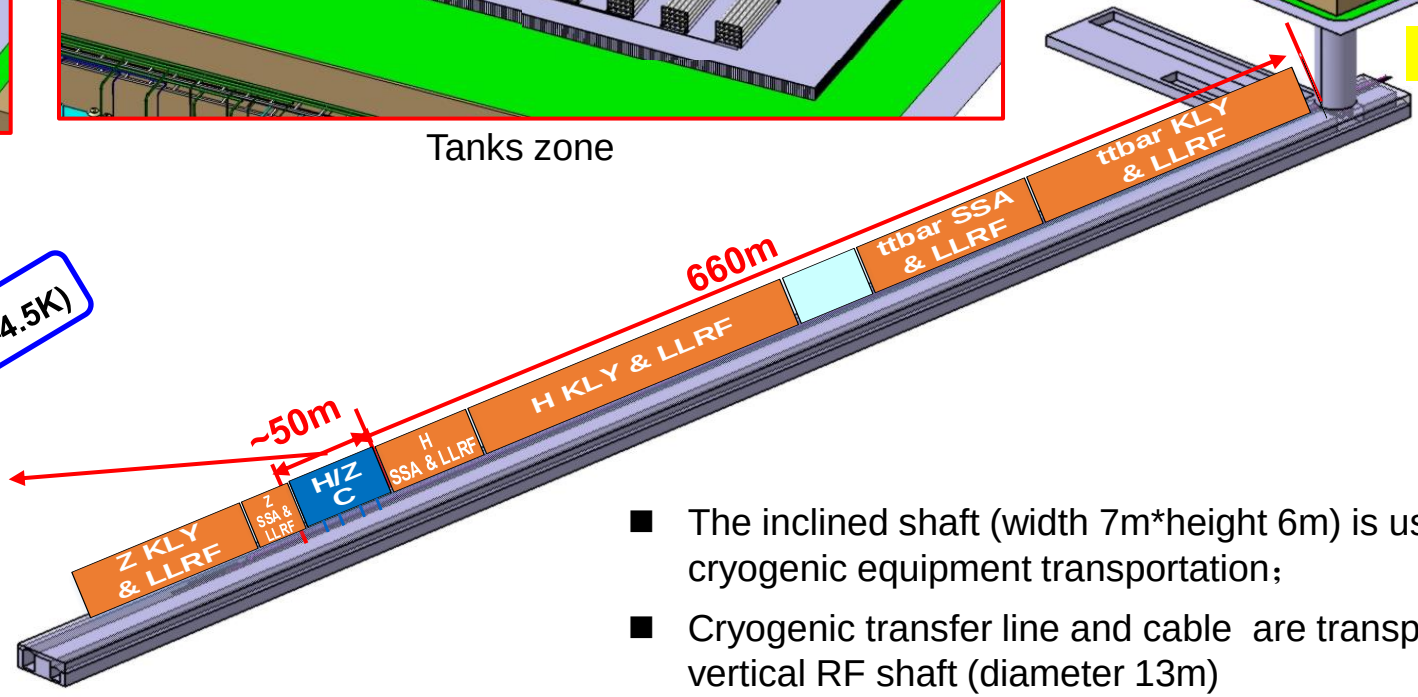
Tanks zone





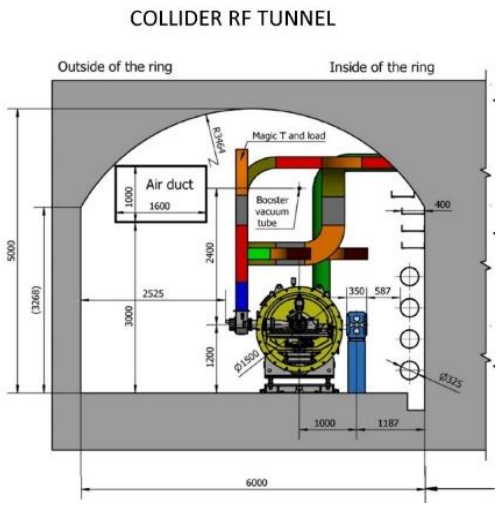
Auxiliary gallery

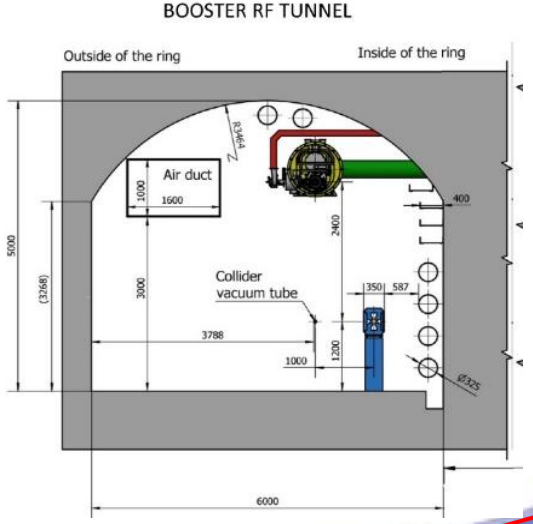
Beam Tunnel



- The inclined shaft (width 7m*height 6m) is used for cryogenic equipment transportation；
- Cryogenic transfer line and cable are transpoted through vertical RF shaft (diameter 13m)

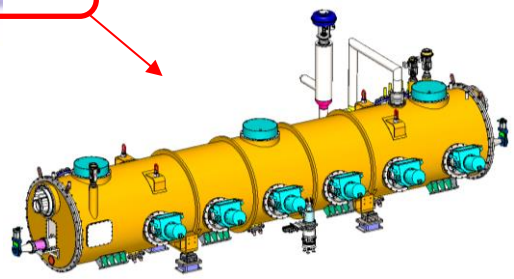
CEPC SRF Beam Tunnel Cryomodule Layout

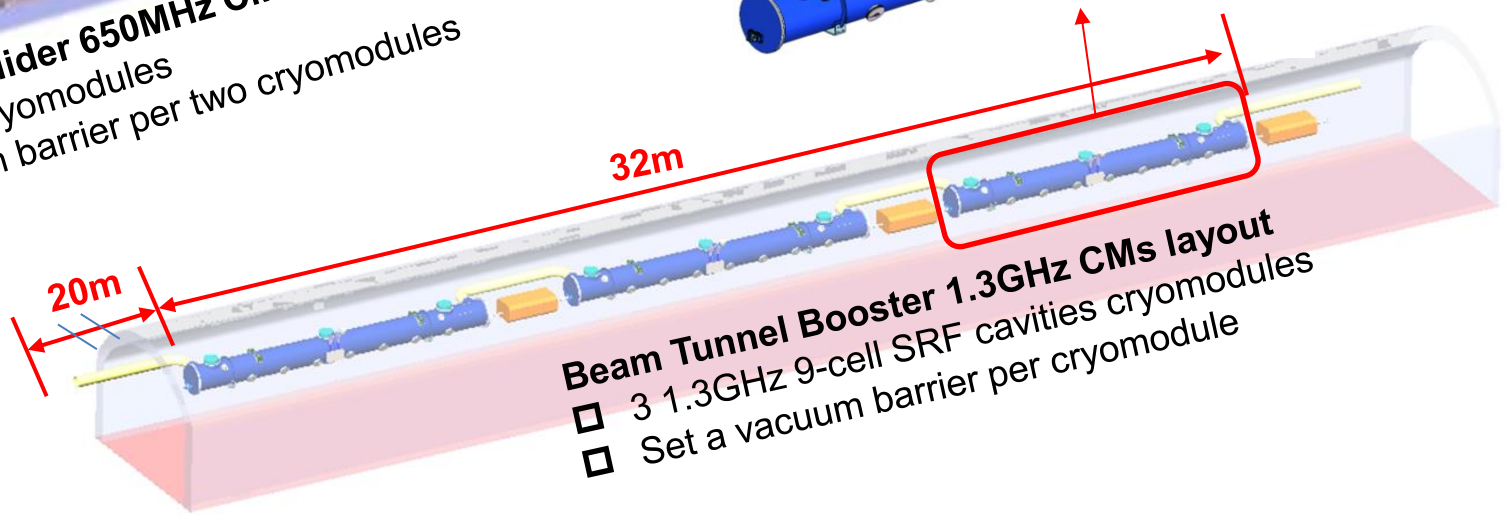




- Ground: tanks zone to shaft: 150m
- Shaft length: 300m~400m
- Auxiliary gallery: shaft to cryo-section: 660m
- Beam tunnel:
  Cryo-section in Auxiliary gallery →Collider 14th CM: 304m;
  Cryo-section in Auxiliary gallery → Booster 3th CM: 52m;
- Total 3.0km transfer is challenging for achieving an efficient design.

Beam Tunnel Collider 650MHz CMs layout
- 14 650MHz cryomodules
- Set a vacuum barrier per two cryomodules





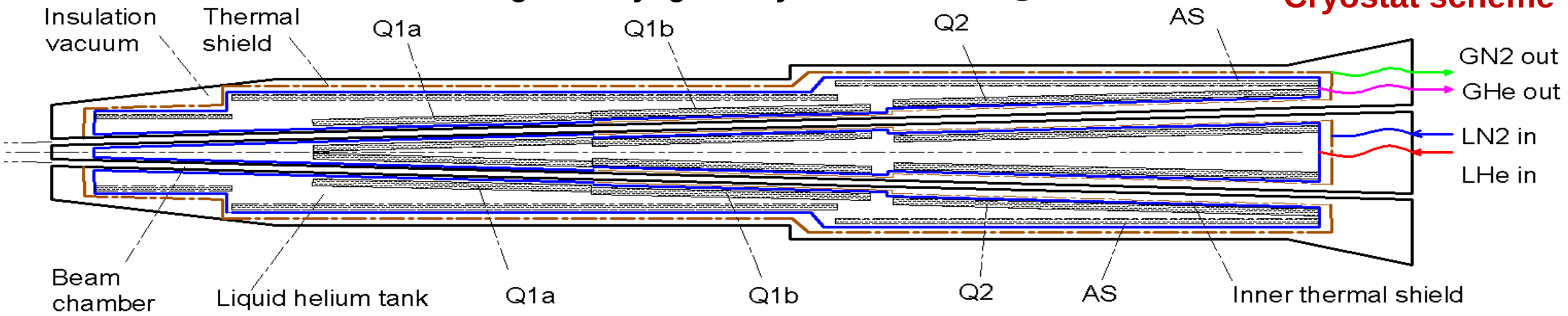
Beam Tunnel Booster 1.3GHz CMs layout
- 3 1.3GHz 9-cell SRF cavities cryomodules
- Set a vacuum barrier per cryomodule

MDI IR Magnets Cryogenic System Brief Introduction

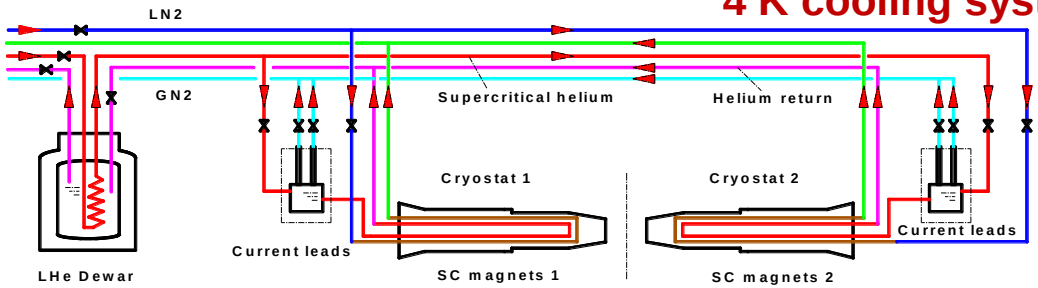
Yang Xiaochen's talk

IR MDI magnets Cryogenic System : 2×1 kW@4.5K

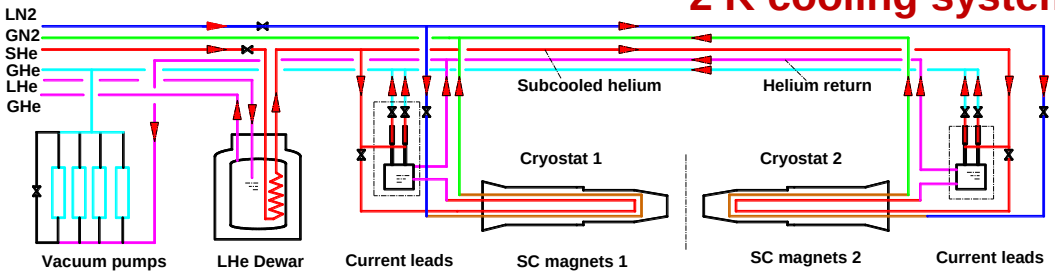
Cryostat scheme

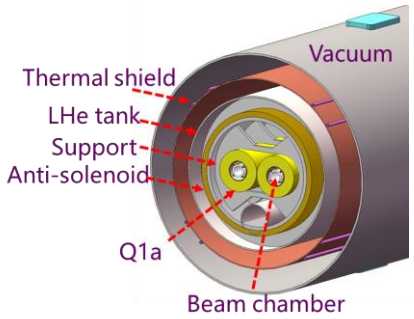


4 K cooling system

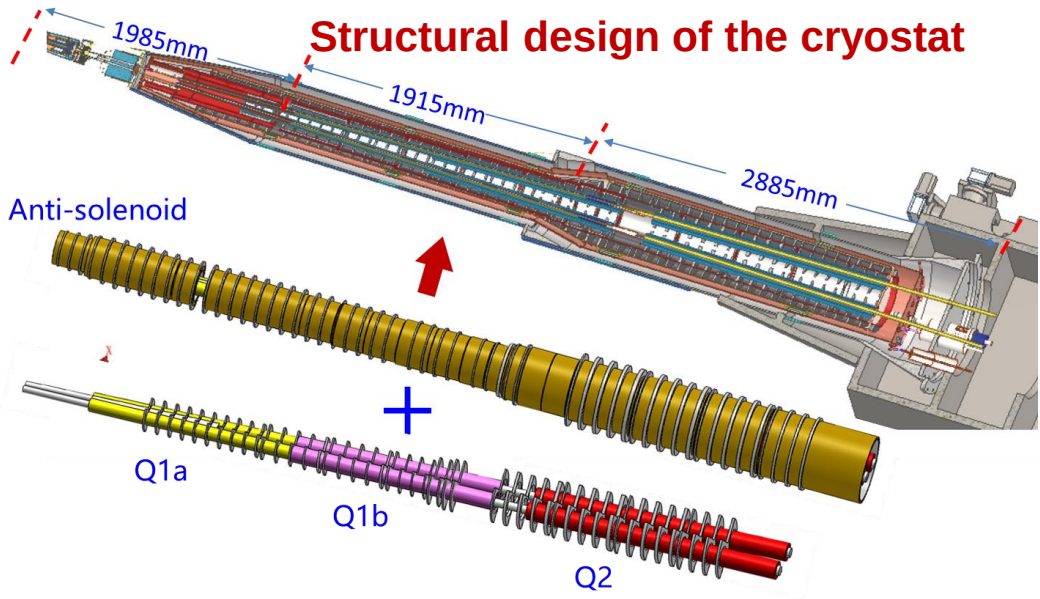


2 K cooling system



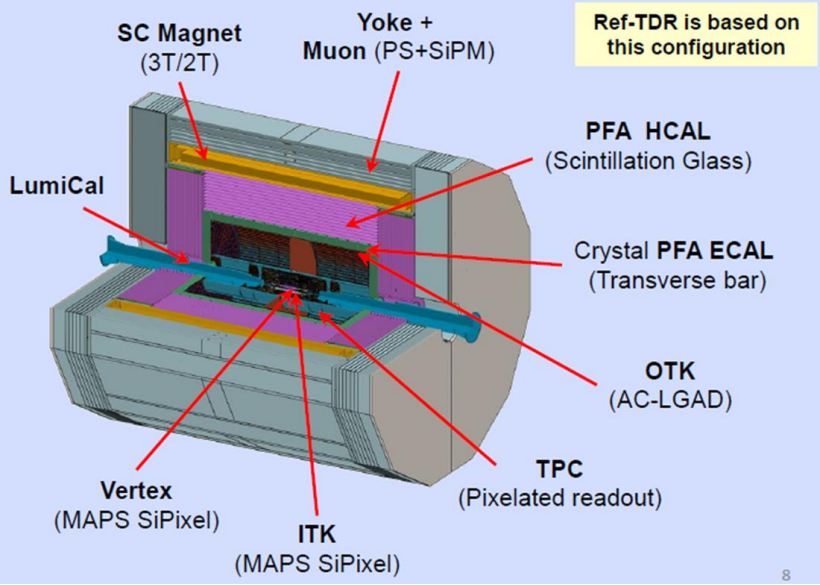


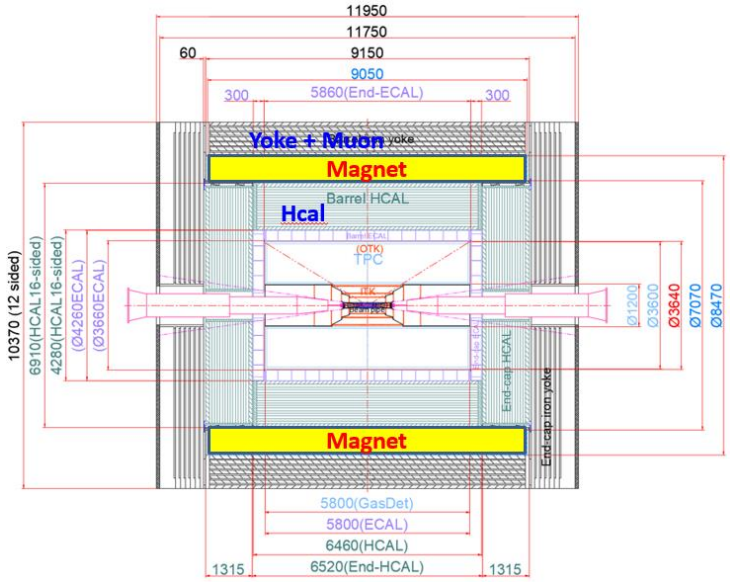
Structural design of the cryostat

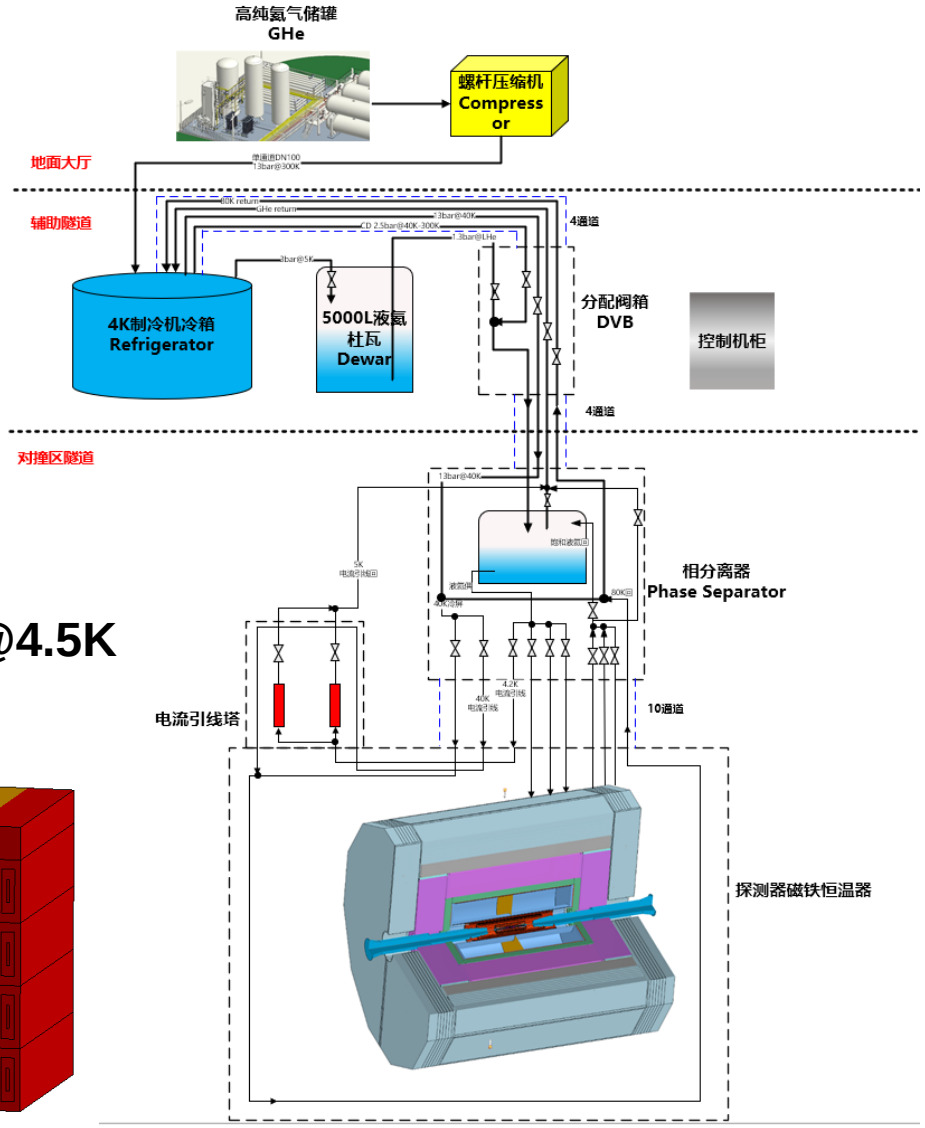


Detectors Cryogenic System Brief Introduction

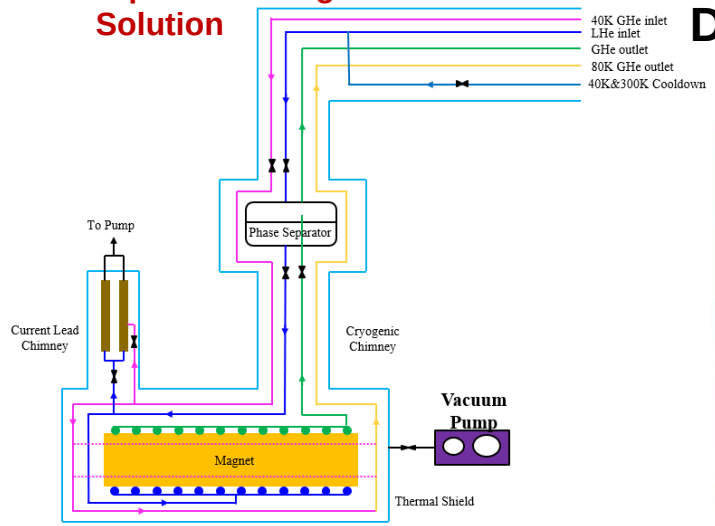
Chang Zhengze, Zhu Keyu



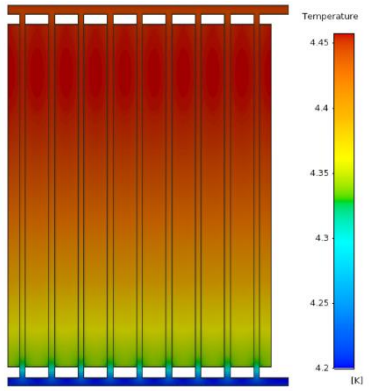


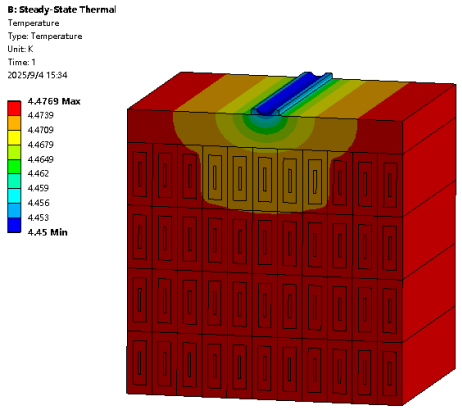


Thermosiphon Cooling Solution



Detectors Cryogenic System: 2×1kW@4.5K





Cryogenic-TDR and EDR Works Summarized table

	Cryogenic system Composition		TDR	EDR
1	Process flow scheme design and simulation	SRF side	According to TDR tunnel layout, have completed: ✓ Process flow scheme design and calculation; ✓ 5~8K circuit, 40~70K TS calculation; ✓ unsteady cooldown simulation; released article	Because of tunnel layout optimized and modified, need to complete: • Process flow scheme design and calculation again; • Cooling scheme peer review (Nov. of 2024)
		SC magnet side	✓ Completed MDI cryostat preliminary cooling scheme design & calculation ✓ Completed Detector preliminary cooling scheme design & calculation	Need to complete: • MDI/detector more detailed scheme PFD, design & calculation, verification in EDR
2	Cryomodule/Cryostat design	SRF cavity cryomodule	✓ Completed 1.3GHz high performance cryomodule design, manufacyturing and test	• **Need to complete full-seze 650MHz cryomodule cryogenic test in EDR**
		SC maget cryostat	✓ Completed MDI cryostat preliminary structrucral design; ✓ Completed MDI cryostat preliminary mechanical and heat tranfer design;	• **MDI/detector PI&D scheme determination, Assembly process design and alignment considerations, machine key component verification in EDR**
3	Large helium refrigerator		✓ The CAS pilot project for 18 kW @4.5K manufacturing has completed in 2024: jointly with FULLCRYO Corporation.	• **The mega-watts large helium refrigerator is expected to finalize the commissioning test in EDR (TIPC, CAS providing).**
4	Mechanical design		✓ Completed preliminary Cryogenic hall, tanks zone and tunnel layout	• Need to Complete detailed Cryogenic hall, tanks zone and tunnel layout diagram
5	JT heat exchanger		✓ Completed HX Basic Design and Optimization ✓ Completed cryogenic test plaform design and Manufacturing	• **CEPC killowatts-scale 2K HX Cryogenic experiment will be finished in EDR**
6	Cryogenic fluid transfer and distribution design	High-performance cryogenic TL	✓ Completed the scheme diesign ✓ Completed the equipment manufacturing	• Need to complete the experimental verification test in EDR
		Distribution valve box	✓ Completed similar valve box design, manufacture and test in PAPS/HEPS project, accumulated experience prepared for CEPC	• Continue to design and optimize, collaborate well with the supplier fully prepared for CEPC
7	Helium recycling and purification system		✓ Completed similar helium recovery system design, manufacture and test in PAPS/HEPS project, accumulated experience prepared for CEPC	• Continue to design and optimize, collaborate well with the supplier fully prepared for CEPC
8	Liquid nitrogen system		✓ Completed similar liquid nitrogen system design, manufacture and test in PAPS/HEPS project, accumulated experience prepared for CEPC	• Continue to design and optimize, collaborate well with the supplier fully prepared for CEPC
9	Cryogenic Control system		✓ Completed similar Cryogenic Control system design, manufacture and test in PAPS/HEPS project, accumulated experience prepared for CEPC	• Continue to design and optimize, collaborate well with the supplier fully prepared for CEPC
10	Cryogenic safety design		✓ Completed similar Cryogenic safety design, test in PAPS/HEPS project, accumulated experience prepared for CEPC	• Continue to design 100km tunnel helium quench protection scheme, fully prepared for CEPC

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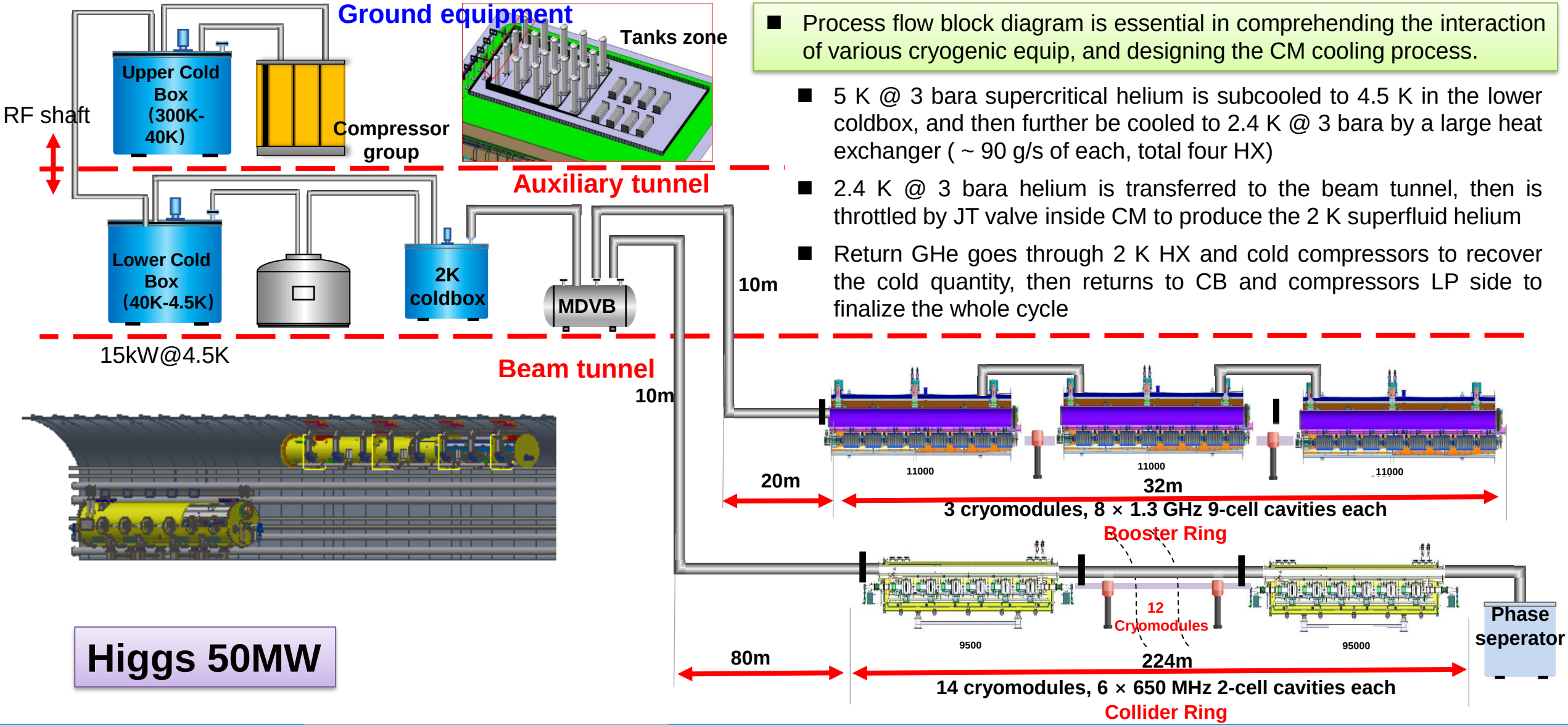
- 2.1 Process Design & Calculation
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◆ **3. Issues and Plans for Next Steps**

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◆ **4. Summary and Outlook**

Process Flow Block Diagram of SRF Cryogenic System

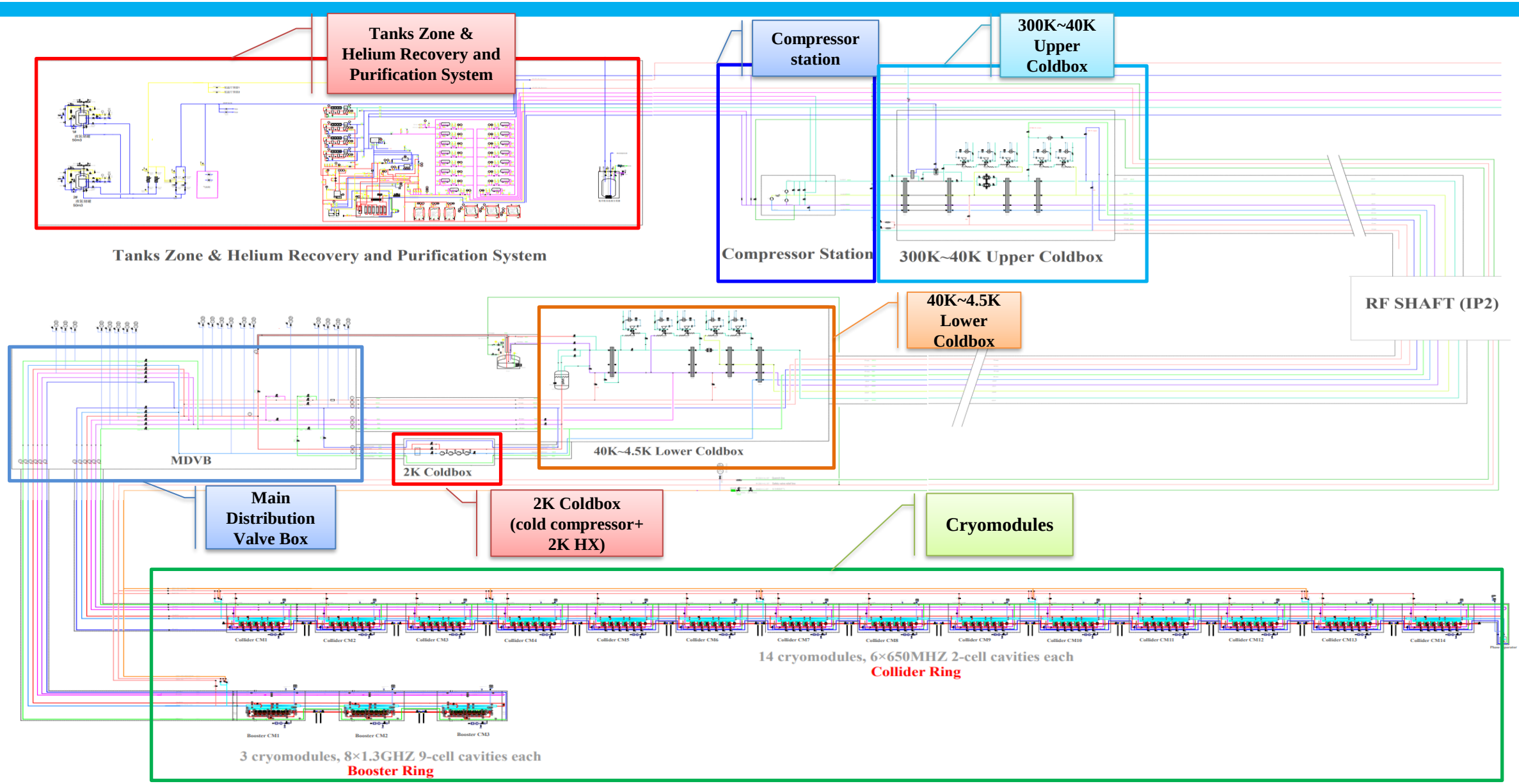


- Process flow block diagram is essential in comprehending the interaction of various cryogenic equip, and designing the CM cooling process.

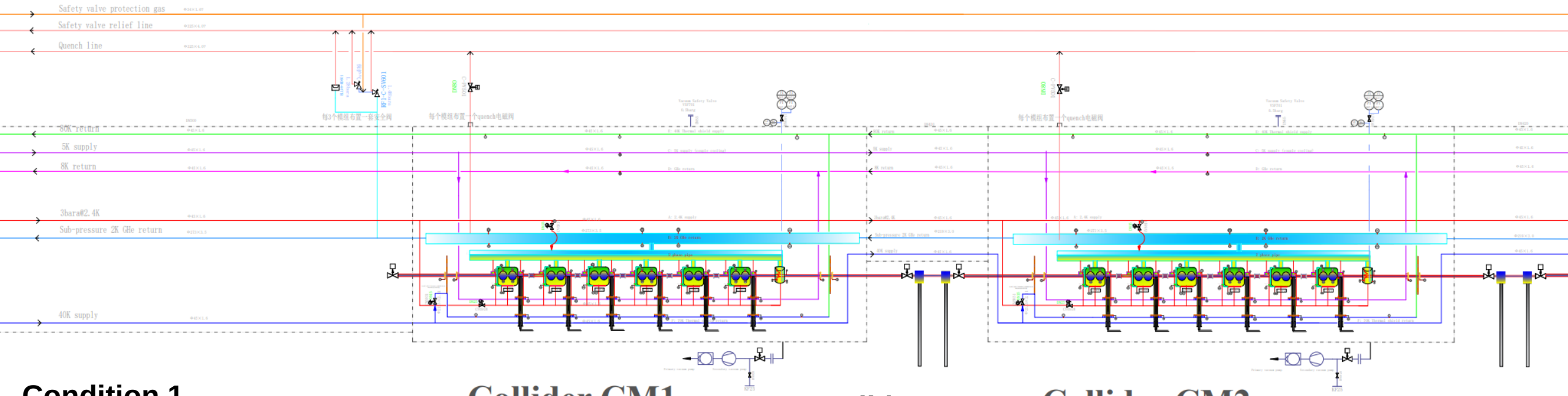
- 5 K @ 3 bara supercritical helium is subcooled to 4.5 K in the lower coldbox, and then further be cooled to 2.4 K @ 3 bara by a large heat exchanger (~ 90 g/s of each, total four HX)
- 2.4 K @ 3 bara helium is transferred to the beam tunnel, then is throttled by JT valve inside CM to produce the 2 K superfluid helium
- Return GHe goes through 2 K HX and cold compressors to recover the cold quantity, then returns to CB and compressors LP side to finalize the whole cycle

Higgs 50MW

SRF Cryogenic system process flow diagram / IP2 RF1 Section



Individual CM Warmup Consideration When Abnormal Conditions



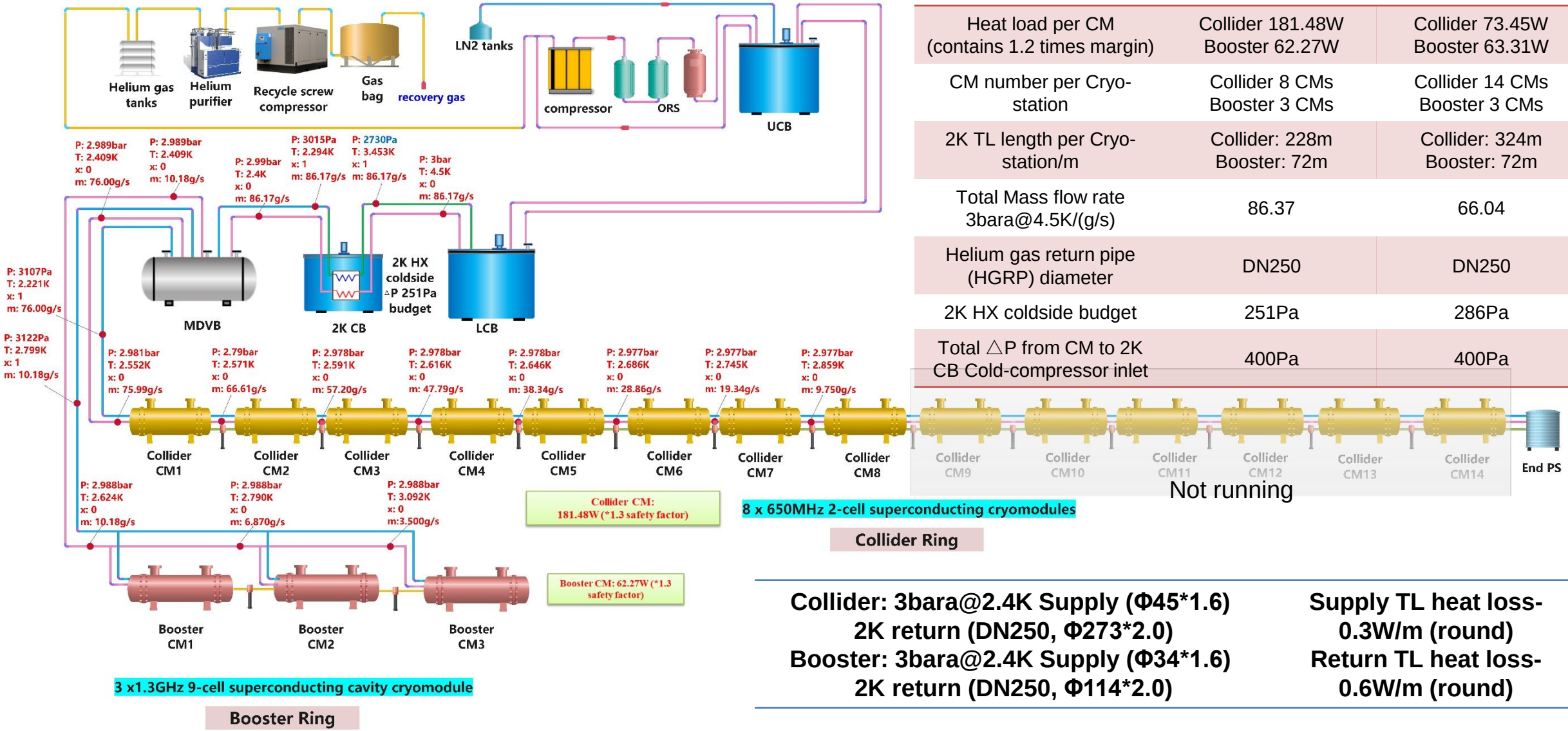
Condition 1

- Cavities or one CM performance is not well, we can **warm up this CM to 40K** using the thin-filmed electrical heater which is attached in the bottom of the helium vessel, then fast cooldown to cross the transition temperature 9.2K → 4.5K directly, following that accumulated the required LHe level, and pump 2K

Condition 2

- When one CM has problem, it can be bypassed(closed CD valve, GHe goes through quench valve) without influence other CMs operation;
- It occurs the accident (leakage, vacuum becoming bad, cavities damage, etc.),we have set the **vacuum barrier**, to prevent vacuum deterioration spreading to all CMs;
- Because of the series connection, all CMs need be warmed up together.

Higgs30MW--2K process calculation and optimization

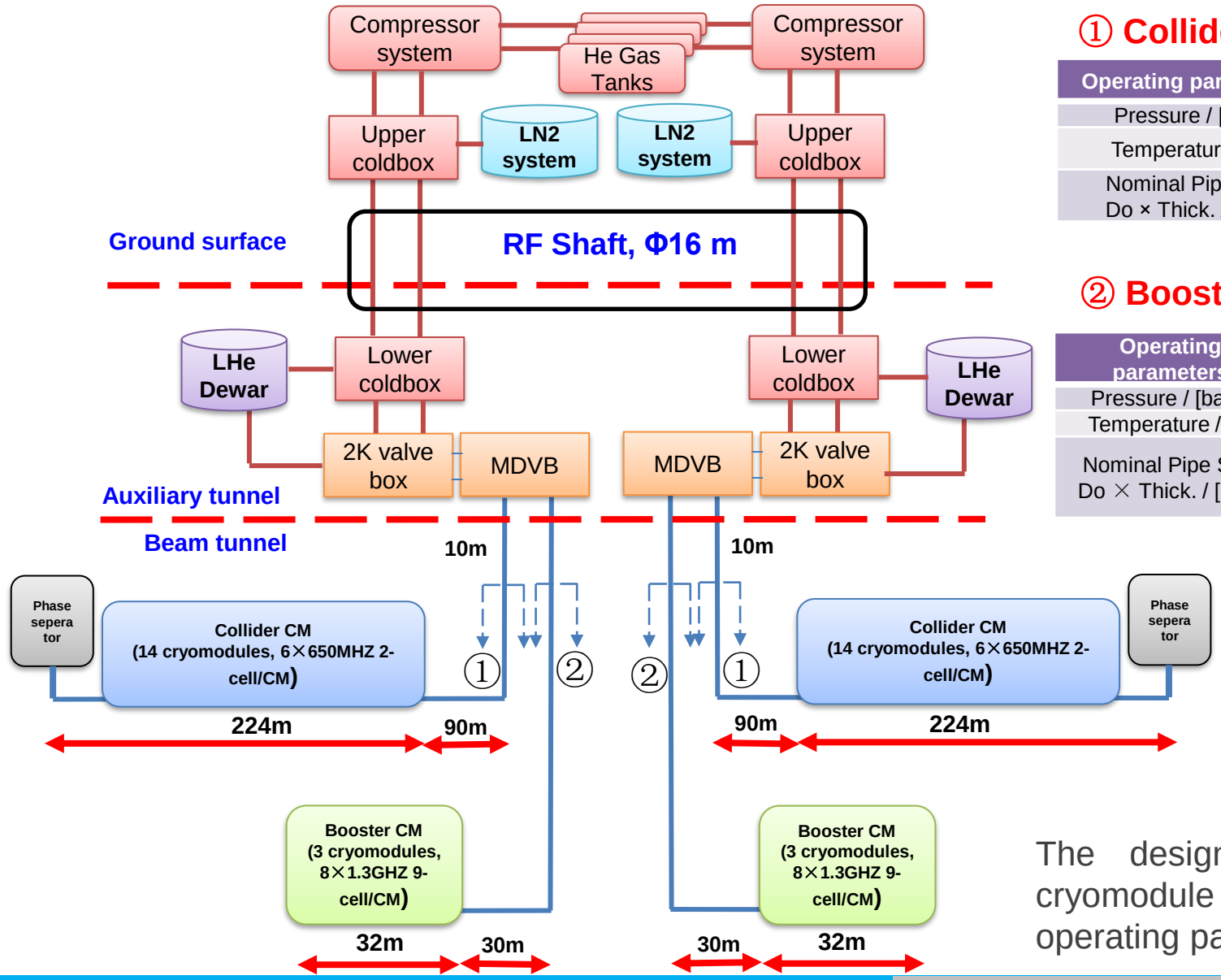


Item	Higgs 30MW	Higgs 50MW
Heat load per CM (contains 1.2 times margin)	Collider 181.48W Booster 62.27W	Collider 73.45W Booster 63.31W
CM number per Cryo-station	Collider 8 CMs Booster 3 CMs	Collider 14 CMs Booster 3 CMs
2K TL length per Cryo-station/m	Collider: 228m Booster: 72m	Collider: 324m Booster: 72m
Total Mass flow rate 3bara@4.5K/(g/s)	86.37	66.04
Helium gas return pipe (HGRP) diameter	DN250	DN250
2K HX coldside budget	251Pa	286Pa
Total △P from CM to 2K CB Cold-compressor inlet	400Pa	400Pa

Collider: 3bara@2.4K Supply (Φ45*1.6)
2K return (DN250, Φ273*2.0)
Booster: 3bara@2.4K Supply (Φ34*1.6)
2K return (DN250, Φ114*2.0)

Supply TL heat loss-0.3W/m (round)
Return TL heat loss-0.6W/m (round)

EDR- CEPC Cryo-layout at RF section- Higgs 30/50MW

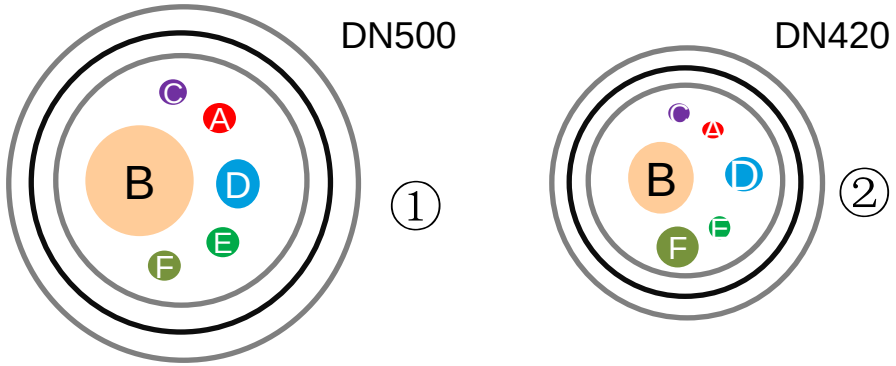


① Collider Multiple TL to CMs

Operating parameters	A	B	C	D	E	F
Pressure / [bara]	3	0.031	3	2.5	13	10
Temperature / [K]	2.4	2	5	8	40	70
Nominal Pipe Size Do × Thick. / [mm]	Φ45×1.6	Φ273×3.5	Φ45×1.6	Φ45×1.6	Φ45×1.6	Φ45×1.6

② Booster Multiple TL to CMs

Operating parameters	A	B	C	D	E	F
Pressure / [bara]	3	0.031	3	2.5	13	10
Temperature / [K]	2.2	2	5	8	40	70
Nominal Pipe Size Do × Thick. / [mm]	Φ34×1.6	Φ114×2	Φ34×1.6	Φ42×1.6	Φ34×1.6	Φ42×1.6



The design results can well illustrate the tunnel-based cryomodule distribution with their associated transfer line operating parameters (pressure, temperature, pipe dimensions).

EDR-Higgs 30MW Heat Loads

$$Q_0 = \frac{(E_{acc_Pt} \cdot L_{eff})^2}{R/Q * Q_{dynamic}} = \frac{Q_t \cdot P_t}{Q_{dynamic}}$$

Cavity RF voltage 11.5MV

Higgs Mode 30MW	Unit	Collider			Booster		
		40-80K	5-8K	2K	40-80K	5-8K	2K
Predicted module static heat load	(W/module)	300	60	25	140	20	20
Predicted module HOM static heat load	(W/module)	2.4	1.2	0.1	0	0	0
Predicted module Input coupler static heat load	(W/module)	6	3	0.3	16	8	0.8
Predicted module dynamic heat load (RF)	(W/module)	0	0	123.2	0	0	40.9
Predicted module HOM dynamic heat load	(W/module)	2.9	1.4	0.2	7.1	3.6	0.6
Predicted module Input coupler dynamic heat load	(W/module)	90.1	22.5	3.8	208	20.8	2.6
Cryomodule number	-	32	32	32	12	12	12
Total module static heat	**(kW)**	**9.87**	**2.05**	**0.81**	**1.87**	**0.34**	**0.25**
Total module dynamic heat	**(kW)**	**2.98**	**0.76**	**4.07**	**2.58**	**0.29**	**0.53**
Each Module total heat load	W	401.4	88.1	152.6	371.1	52.4	64.9
MDVB heat loss	W	50	30	10	50	30	10
MDVB number	-	4	4	4	4	4	4
Total cryogenic transfer line length	m	2232	2232	912	1608	1608	288
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	4464	1116	273.6	3216	804	86.4
Non-module heat load	(kW)	4.664	1.236	0.314	3.416	0.924	0.126
Total predicted heat	**(kW)**	**17.509**	**4.055**	**5.197**	**7.869**	**1.553**	**0.905**
Total predicted mass flow	(g/s)	83.903	126.527	245.259	37.709	48.449	42.720
Ideal power based on total estimated heat	(kW)	80.628	192.644	800.480	36.238	73.766	139.431
Heat uncertainty factor on static heat (Fus)		1.000	1.000	1.000	1.000	1.000	1.000
Heat uncertainty factor on dynamic heat (Fud)		1.000	1.000	1.000	1.000	1.000	1.000
Heat load per cryogenic unit including uncertainty	(kW)	17.509	4.055	5.197	7.869	1.553	0.905
Mass flow per cryogenic unit including uncertainty	(g/s)	83.903	126.527	245.259	37.709	48.449	42.720
Weighted ideal power	(kW)	80.628	192.644	800.480	36.238	73.766	139.431
4.5 K equiv weighted power	(kW)	1.228	2.934	12.191	0.552	1.123	2.124
Efficiency (fraction Carnot)		0.280	0.240	0.220	0.280	0.240	0.220
Operating power based on predicted heat	(kW)	287.956	802.684	3638.546	129.420	307.360	633.777
Operating power including uncertainty	(kW)	287.956	802.684	3638.546	129.420	307.360	633.777
Overall net cryogenic capacity multiplier		1.540	1.540	1.540	1.540	1.540	1.540
Heat load per cryogenic unit (Fus, Fud, and Fo)	**(kW)**	**26.964**	**6.245**	**8.003**	**12.119**	**2.391**	**1.394**
Installed 4.5 K equivalent heat loads (1.54 margin)	**(kW)**	**2.026**	**5.648**	**25.602**	**0.911**	**2.163**	**4.459**
Total installed 4.5 K equivalent power (kW)			**33.276**			**7.533**	
Total 4.5K equiv. heat load with multiplier	kW			40.808			
Installed power (COP(219W/1W))	MW		7.287			1.650	

EDR-Higgs 50MW Heat Loads

$$Q_0 = \frac{(E_{acc_Pt} \cdot L_{eff})^2}{R/Q * Q_{dynamic}} = \frac{Q_t \cdot P_t}{Q_{dynamic}}$$

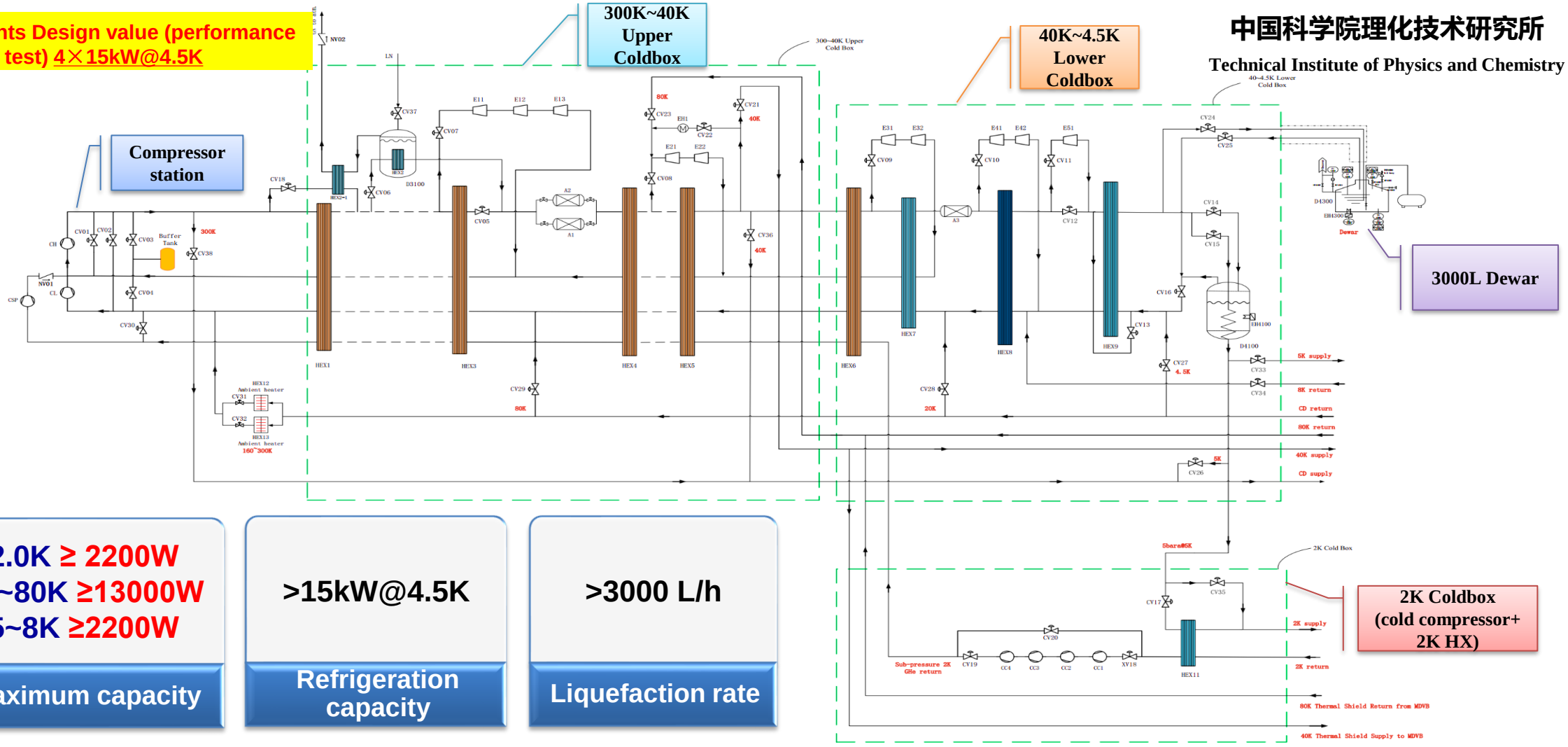
Cavity RF voltage 6.5MV

Higgs Mode 50MW	Unit	Collider			Booster		
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Predicted module static heat load	(W/module)	300	60	25	140	20	20
Predicted module HOM static heat load	(W/module)	2.4	1.2	0.1	0	0	0
Predicted module Input coupler static heat load	(W/module)	6	3	0.3	16	8	0.8
Predicted module dynamic heat load (RF)	(W/module)	0	0	40.1	0	0	40.9
Predicted module HOM dynamic heat load	(W/module)	4.8	2.4	0.4	9.6	4.8	0.8
Predicted module Input coupler dynamic heat load	(W/module)	85.8	21.5	3.6	256	25.6	3.2
Cryomodule number	-	56	56	56	12	12	12
Total module static heat	**(kW)**	**17.27**	**3.60**	**1.42**	**1.87**	**0.34**	**0.25**
Total module dynamic heat	**(kW)**	**5.07**	**1.34**	**2.47**	**3.19**	**0.36**	**0.54**
Each Module total heat load	W	399	88.1	69.5	421.6	58.4	65.7
MDVB heat loss	W	50	30	10	50	30	10
MDVB number	-	4	4	4	4	4	4
Total cryogenic transfer line length	m	2616	2616	1296	1608	1608	288
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	5232	1308	388.8	3216	804	86.4
Non-module heat load	(kW)	5.432	1.428	0.429	3.416	0.924	0.126
Total predicted heat	**(kW)**	**27.776**	**6.362**	**4.321**	**8.475**	**1.625**	**0.915**
Total predicted mass flow	(g/s)	133.103	198.490	203.917	40.613	50.696	43.173
Ideal power based on total estimated heat	(kW)	127.908	302.211	665.547	39.028	77.187	140.910
Heat uncertainty factor on static heat (Fus)		1.000	1.000	1.000	1.000	1.000	1.000
Heat uncertainty factor on dynamic heat (Fud)		1.000	1.000	1.000	1.000	1.000	1.000
Heat load per cryogenic unit including uncertainty	(kW)	27.776	6.362	4.321	8.475	1.625	0.915
Mass flow per cryogenic unit including uncertainty	(g/s)	133.103	198.490	203.917	40.613	50.696	43.173
Weighted ideal power	(kW)	127.908	302.211	665.547	39.028	77.187	140.910
4.5 K equiv weighted power	(kW)	1.948	4.603	10.136	0.594	1.176	2.146
Efficiency (fraction Carnot)		0.280	0.240	0.220	0.280	0.240	0.220
Operating power based on predicted heat	(kW)	456.815	1259.211	3025.213	139.386	321.612	640.498
Operating power including uncertainty	(kW)	456.815	1259.211	3025.213	139.386	321.612	640.498
Overall net cryogenic capacity multiplier		1.540	1.540	1.540	1.540	1.540	1.540
Heat load per cryogenic unit (Fus, Fud, and Fo)	**(kW)**	**42.775**	**9.797**	**6.654**	**13.052**	**2.502**	**1.409**
Installed 4.5 K equivalent heat loads (1.54 margin)	**(kW)**	**3.214**	**8.860**	**21.286**	**0.981**	**2.263**	**4.507**
Total installed 4.5 K equivalent power (kW)			**33.361**			**7.750**	
Total 4.5K equiv. heat load with multiplier	kW			41.111			
Installed power (COP(219W/1W))	MW		7.306			1.697	

Large Refrigerator PFD diagram

This PFD diagram provides a comprehensive overview of the refrigeration cycle and the interactions between various components, serving as a blueprint for the system's operation and performance.

Cryo-plants Design value (performance test) 4×15kW@4.5K



2.0K ≥ 2200W 40~80K ≥13000W 5~8K ≥2200W	>15kW@4.5K	>3000 L/h
Maximum capacity	Refrigeration capacity	Liquefaction rate

Mega-watts Large refrigerator R&D status

From Zhengyu Li (TIPC)





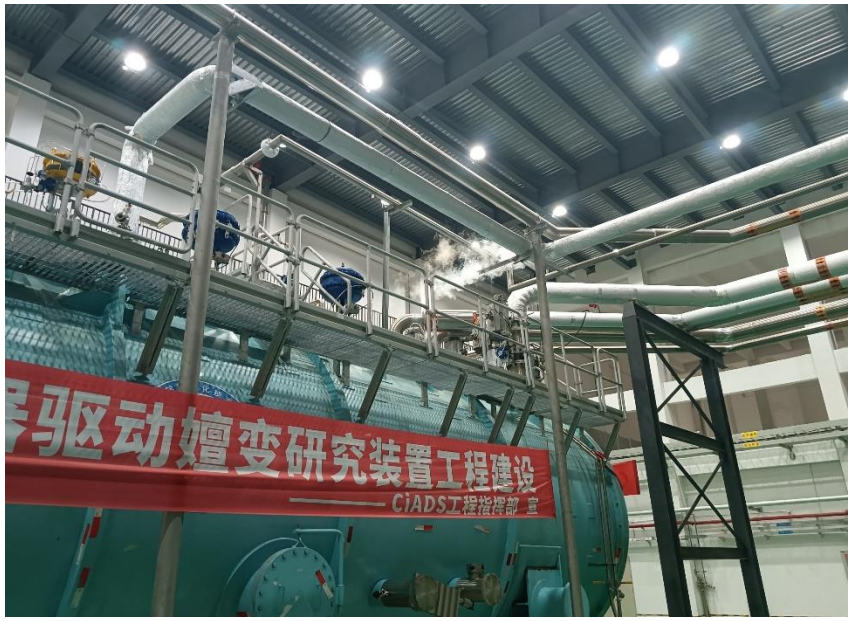
Factory testing result （liquefaction mode）		
	Design Value	Test value
Turbine efficiency	80%	80.6%
Helium liquefaction rate	3567 L/h	3377.7 L/h

This image depicted China’s first domestically developed 10 kW@4.5K refrigerator, which was being shipped to Huizhou, Guangdong, to be deployed in CiADS.

Mega-watts Large refrigerator R&D status

From Zhengyu Li (TIPC)







Temperature (K)	P（bar）	Design Heat Load（W）	Test Load （W）
2.0K	0.03	≥4400	Due to helium supply issues, only the cooling test was completed.
4.36K	1.17	-	3570
50~75K	10~20	≥13500	13562
4.5~75K	3~1.15	≥4300	4389

Content

◆ **1. CEPC Cryogenic System Overview**

- 1.1 CEPC Project Brief Introduction
- 1.2 General Layout of Cryogenic System
- 1.3 EDR scope

◆ **2. CEPC SRF Cryogenic System Scheme Design**

- 2.1 Process Design & Calculation
- 2.2 Large Helium Refrigerator

◆ **3. Issues and Plans for Next Steps**

- 3.1 Helium Recovery and Purification System
- 3.2 Safety System

◆ **4. Summary and Outlook**

2025 IARC Comments

- **Pursue highly reliable and sustainable CEPC cryogenics system, enabling to realize full helium resource recovery and conservation in superconducting magnet and RF system operation associated by fundamental infrastructure;**

Answer: Detailed calculations and analyses are currently underway to ensure full helium recovery and conservation. During the IARC meeting, we also had in-depth discussions with Prof. Akira Yamamoto from KEK, which provided valuable insights for enhancing system sustainability.

Core Committee Observations

• Preparations for **complete helium resource recovery** under all emergency conditions must be exhaustive.
• Helium conservation is a critical global resource issue; emergency losses must be minimized.
• The committee acknowledged significant progress in cryogenic design and positive responses to prior review feedback.

Key Strategic Recommendations

• Deploy dedicated infrastructure to ensure full helium recovery and conservation during magnet/SRF operation.
• Establish comprehensive safety designs to safeguard superconducting systems during quenches or failures.
• Integrate redundant monitoring systems to enable rapid response to anomalies and prevent helium loss.

- He Recovery & Protection under Emergency Situations
- Parameters & Calculation
- Equipment Selection
- Annual Helium Consumption

Helium Inventory

SRF(H50MW)

Pipeline gas volume 1 cryo-station

		工作温度k	管道压力bara	管径mm	长度m	容积m3	容积气量m3
Tanks zone — Cryogenic hall	中压放气	300	20	50	210	1.65	32.99
	高纯充气	300	5	20	210	0.26	1.32
	高纯储存	300	1.05	20	210	0.26	0.28
	不纯储存	300	1.5	20	210	0.26	0.40
	不纯气囊	300	1.1	300	210	59.38	65.31
	中压缓冲	300	20	125	210	10.31	206.17
	中压稳压	300	1.05	250	210	41.23	43.30
Cryogenic hall —— LCB	IP-RF-R	300	1.05	300	950	268.61	282.04
	CD supply	40	16	150	950	67.15	8058.19
	CD RETURN	80	14	200	950	119.38	6267.48
	40k supply	40	16	65	950	12.61	1513.15
	80k RETURN	80	14	80	950	19.10	1002.80
	UCP-SP	2	0.5	200	950	119.38	8953.54
	UCB-LP	10	1.2	250	950	186.53	6715.15
	UCB-MP	20	4.2	200	950	119.38	7520.97
	UCB-HP	40	16	150	950	67.15	8058.19
	QUENCH	300	1.1	300	950	268.61	295.47
	SV-RELIEF	300	1.8	300	950	268.61	483.49
	sv-PROTECTION	300	2.5	50	950	7.46	18.65
LCB to eq	CD supply	40	20	150	500	35.34	5301.44
	CD RETURN	80	6	200	500	62.83	1413.72
	40k supply	40	20	65	500	6.64	995.49
	80k RETURN	80	6	80	500	10.05	226.19
	5k supply	5	3	65	500	6.64	1194.59
	8k RETURN	8	2	80	500	10.05	753.98
	40K Thermal Shield supply	40	20	25	500	0.98	147.26
	3bar@4.5K/5K	5	3	40	500	2.51	452.39
	Sub-pressure 2K GHe return	2	0.1	200	500	62.83	942.48
	80K Thermal Shield Return	80	6	32	500	1.61	36.19

Pipeline volume~~~ 61000 normal cubic meters/cryo-station

Equipment gas volume 1 cryo-station

	工作温度	容积m3	个数	工作压力	容积气量m3
high pressure tank	300	300	1	5	1500
buffer tank	300	150	1	1.05	157.5
Medium-pressure tank	300	150	5	2.5	1875
UP-ColdBox	40	45	1	5	1687.5
L-ColdBox	5	35	1	3	6300
1.3G模组	4	0.39	3	1.2	1404
650模组	4	0.4	14	1.2	6720
DW	4	3	1	1.2	3600
MDVB	5	33	1	5	9900
2K-CB	2	33	1	1.4	6930
High-pressure compressor	300	3	4	19	228
Low-pressure compressor	300	4	6	4	96
Vacuum-pressure Sub-atmosphere compressor	300	2	6	4	48
Recycling high pressure compressor	300	3	3	1.5	13.5
Recycling booster compressor	300	3	8	10	240
Purifier	300	2	1	200	400
Others	300	10	1	19	190

Equipment volume~~~42000 normal cubic meters

SRF Cyogenic: pipeline and equipment = 61000+42000=103000NM3 / each cryo-station

MDI

MDI cryogenic: pipeline and equipment = 9000 NM3

Sixturpole magnet

Sixturpole magnets are dry-cooled and do not require liquid helium

Detector

Detector cryogenic : pipeline and equipment = 500 NM3

Total Helium Inventory in Cryogenic System: 103000*4+9000+500≈430,000NM3

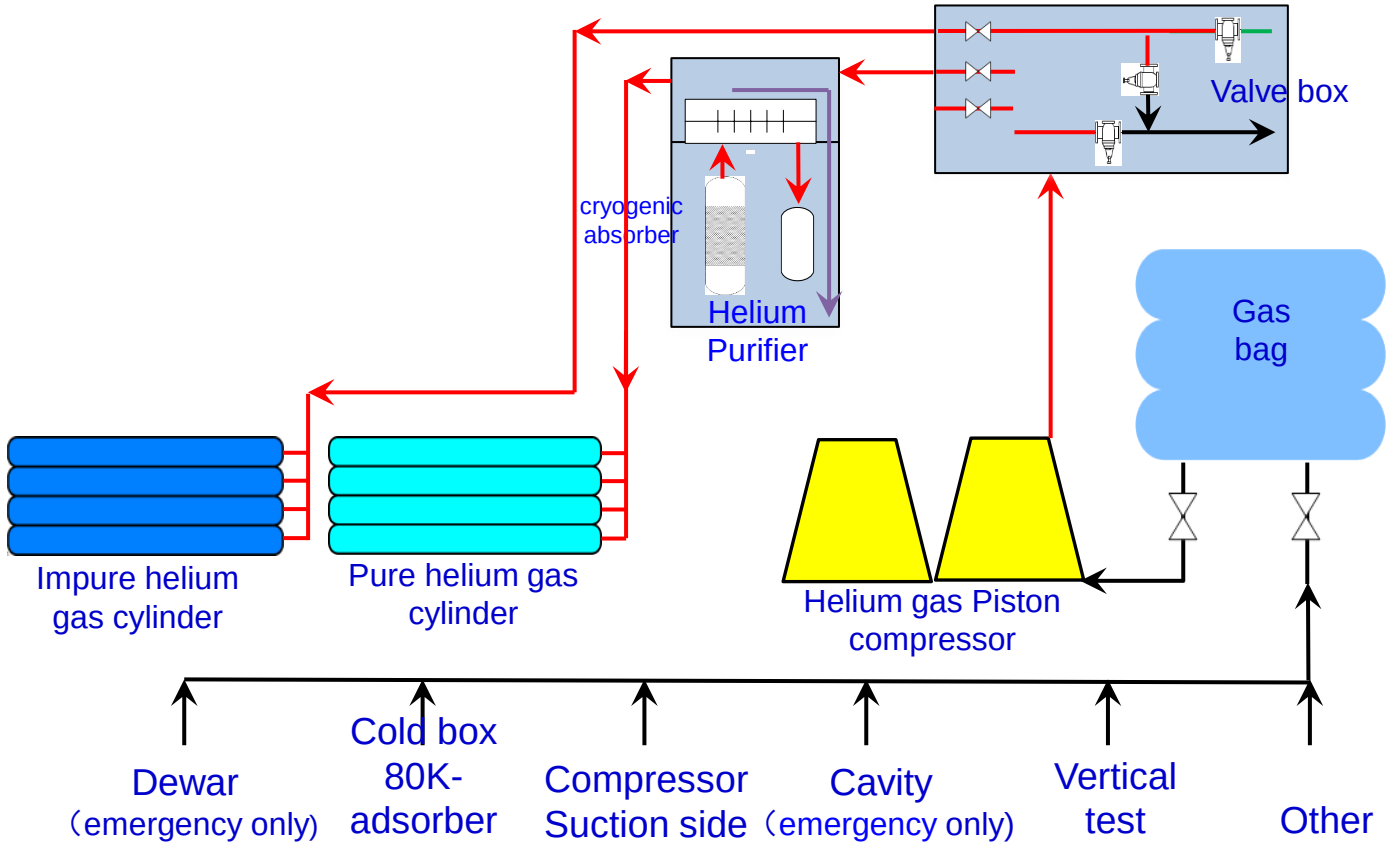
Complete Recovery & Protection of Helium Resources in Emergency Situations

Total Gas Emission & Recovery Process under Emergency Conditions

In extreme conditions where compressors and refrigerators fail due to malfunctions, all helium gas will be fully recovered to prevent resource loss and ensure safety.

Strategic Objectives

- **100% Recovery:** Guarantee complete helium gas recovery under all emergency venting scenarios.
- **Resource Reutilization:** Transform emergency discharge from a consumptive loss into a reusable resource.
- **Safety Assurance:** Ensure compliance with stringent safety standards for superconducting magnets and SRF cavities.



Emergency Venting & Helium Recovery Process

From Zhang Zhuo

Complete Recovery & Protection of Helium Resources in Emergency Situations

Total Gas Emission Volume Analysis

Calculation Conditions

• **Early Stage:** Constant volume process with rigid sealed volume, continuous static heat leakage, and rising temperature/pressure.

• **Later Stage:** After helium pressure reaches the safety venting pressure, part of the helium undergoes isothermal pressure rise (inside the container), and part is discharged (enthalpy change from heat leakage).

Basic Parameters

• Closed Volume: 1 m³
• Initial Temperature: 5 K
• Initial Pressure: 5 bar
• Heat Leakage: 1.25 kW

Calculation Assumptions

• Static heat leakage is affected by temperature difference and vacuum degree. The value is estimated from the calculation document and remains constant.

• Initial parameters (volume, temperature, pressure) are based on the calculation document and drawings.

• Venting pressure affects the end value of the early stage and the initial conditions of the later stage.

Venting Pressure	Venting Temp	Venting Time	Molar Flow	Std. Flow
5.0 bar	5.0 K	0 s (Immediate)	12.3 mol/s	≈ 1000 Nm³/h
5.1 bar	5.1 K	≈ 12 s	11.8 mol/s	≈ 950 Nm³/h
8.0 bar	8.0 K	≈ 362 s	7.5 mol/s	≈ 600 Nm³/h
20.0 bar	20.0 K	≈ 816 s	3.0 mol/s	≈ 240 Nm³/h

Short-term & Emergency Total Gas Emission Volume

CEPC Cryogenic Heat Load
(20250212)

- 40K-80K: 7.01 KW
- 5K-8K: 1.58 KW
- 2K: 0.34 KW
- 300K-80K: Estimated

Case 1:
Working Pressure = discharging Pressure
Heat Leakage Remains Constant

→

687 m³/h
1242 m³/h
317 m³/h
25 m³/h

Total: 2271 m³/h

- 40K-80K: discharging pressure 19 bar
- 5K-8K: discharging pressure 8 bar
- 2K: discharging pressure 1.1 bar
- 300K-80K: Estimated
- Cryomodule & Dewar: discharging pressre 1.2 bar

Case 2:
discharging pressure > working pressure

→

165 m³/h
761 m³/h
295 m³/h
25 m³/h
500 m³/h

Total: 1746 m³/h

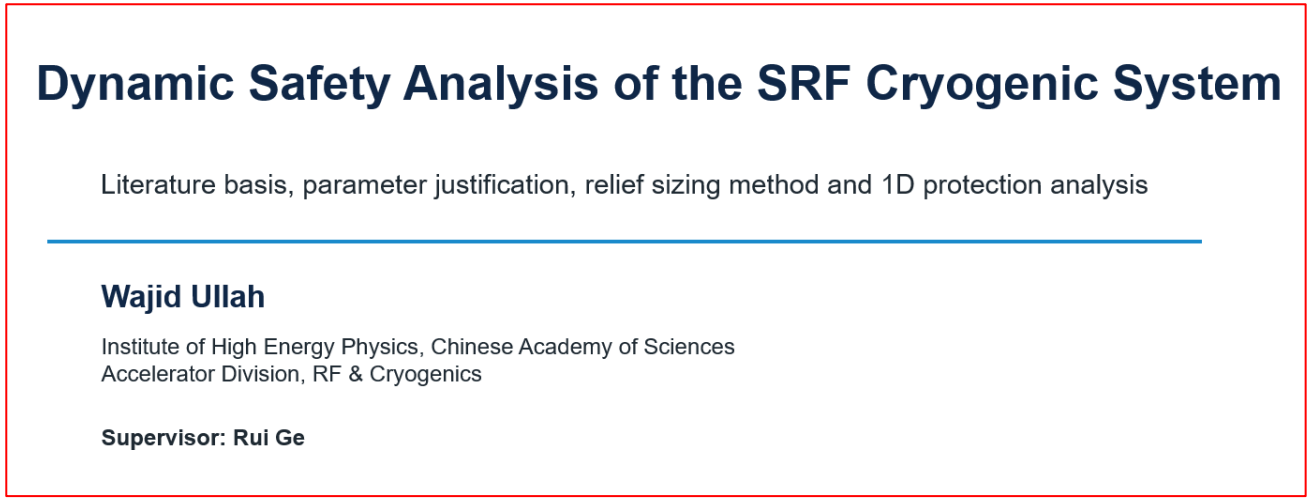
Note: 2,271 m³/h was calculated based on the operating pressure, while 1,746 m³/h was calculated using a discharge pressure higher than the operating pressure, which is why the value is lower.

Conclusion: **The calculated total emergency gas emission volume is 1746 m³/h , which is the key design parameter for our helium recovery system. This value ensures that the system is sized to handle the maximum expected gas release, providing a robust safety margin for all operational scenarios.**

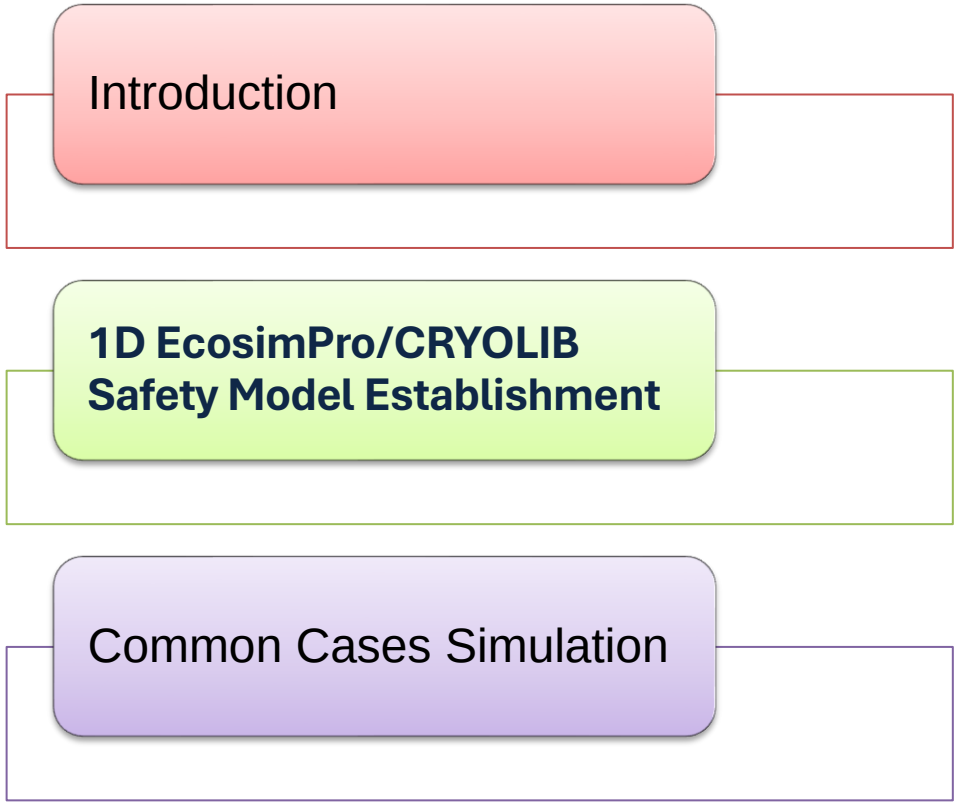
2025 IARC Comments

- **Establish the safety design for protecting the superconducting magnet and SRF systems, in case of quench and other failures.**

Answer: We are currently performing detailed simulations and analyses to develop a robust safety design that ensures protection of the superconducting magnet and SRF systems during quench and other failure scenarios.







4th COMMENT & PROGRESS

1 Identify scenario

Loss of vacuum, quench, trapped liquid, valve error, fire or loss of cooling

→

2 Define allowable pressure

Use component MAWP and temperature-dependent rating

→

3 Calculate heat and mass generation

Convert heat input into transient boil-off / mass-flow demand

→

4 Size relief capacity

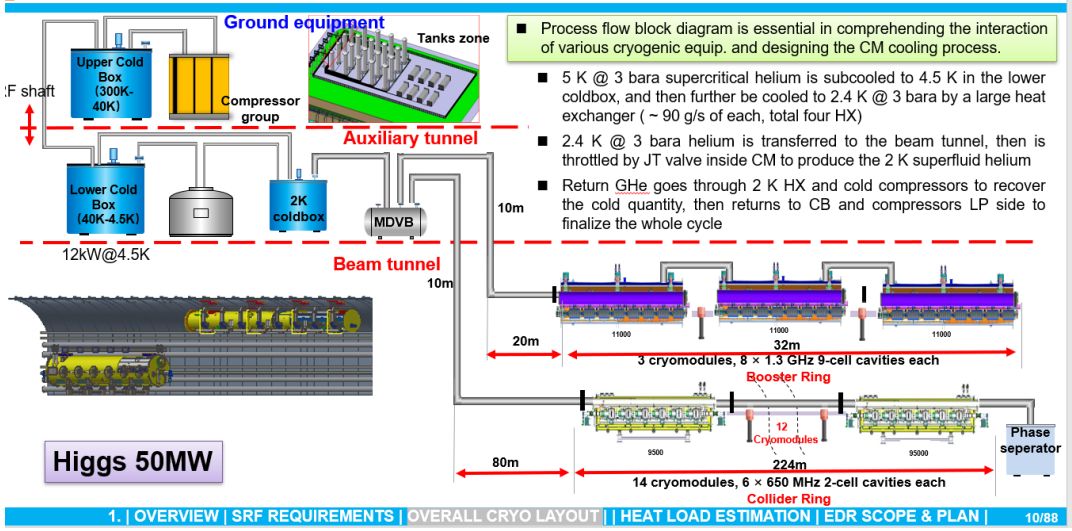
PSV for reusable relief; rupture disc as independent backup where justified

→

5 Route discharge safely

Limit back-pressure and avoid personnel exposure or ODH

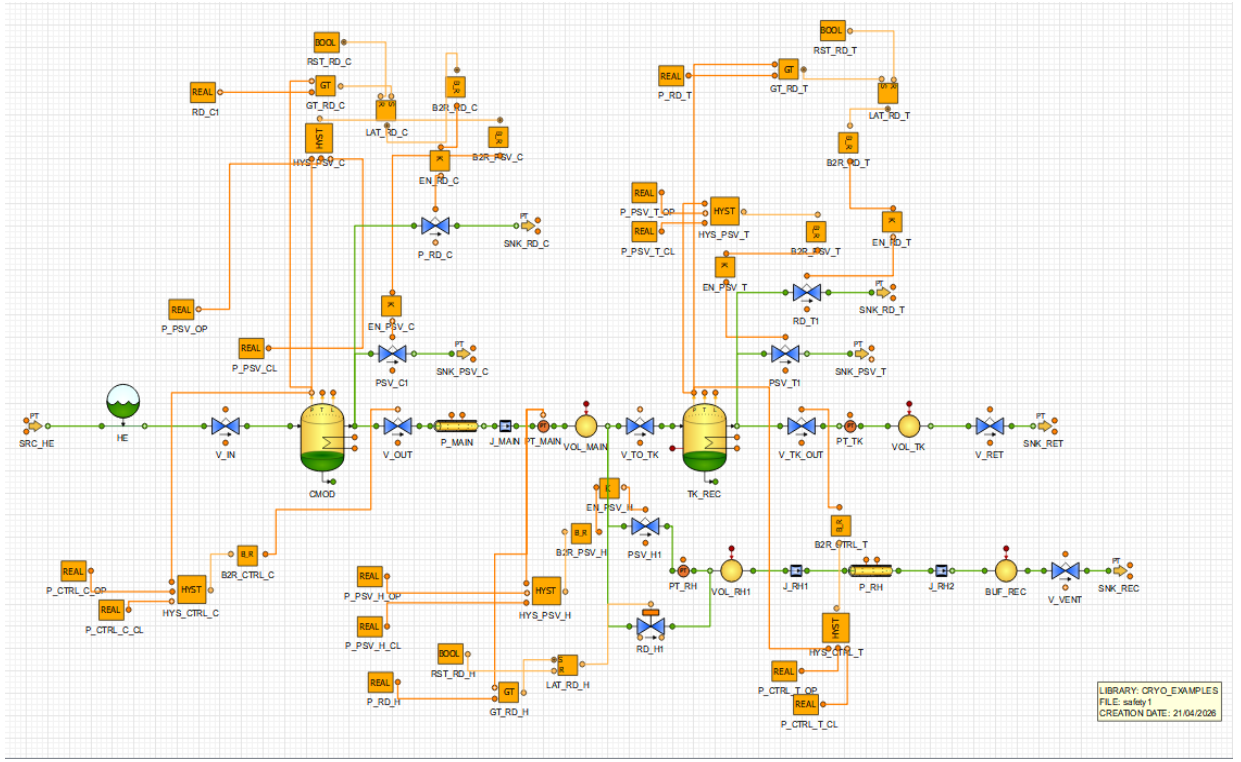
Process Flow Block Diagram of SRF Cryogenic System



Normal control prevents the event → PSV limits foreseeable overpressure → rupture disc provides independent emergency backup → vent/recovery system manages released helium

1D EcosimPro/CRYOLIB Safety Model Establishment

Component group	Model elements	Physical role
Supply and inlet	SRC_HE, HE, V_IN	Supply boundary, conditioning and inlet-flow control
Cryomodule	CMOD	Protected helium inventory representing the cavity vessel
Main transfer line	V_OUT, P_MAIN, VOL_MAIN, V_TO_TK	Flow restriction, pressure loss, transport and line storage
Recovery tank	TK_REC	Second protected helium volume
Tank outlet	V_TK_OUT, PT_TK, VOL_TK, V_RET	Outlet control, measurement and downstream storage
Normal return	SNK_RET	Normal downstream pressure and temperature boundary
Recovery system	P_RH, VOL_RH1, BUF_REC, V_VENT, SNK_REC	Recovery transport, accumulation, buffer storage and final discharge



Complete 1D safety-model architecture

The model represents helium transport through the cryomodule, transfer line and recovery tank to the return and recovery boundaries.

Combined CMOD–Tank LOIV Fault: Heat-Load Sensitivity Without Active Protection

$$Q_{component} = q''A, \qquad A = 1.10\ m^2$$

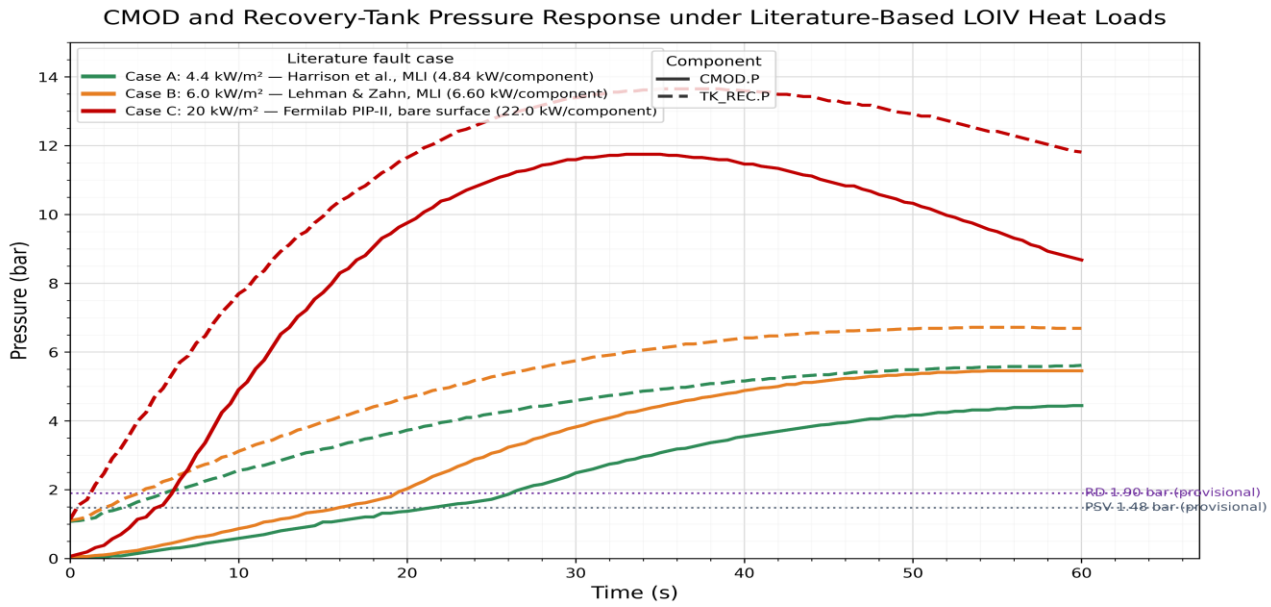
$$Q_{combined} = Q_{CMOD} + Q_{tank}$$

Case	Literature heat flux	CMOD load	Tank load	Combined load
A	4.4 kW/m²	4.84 kW	4.84 kW	9.68 kW
B	6.0 kW/m²	6.60 kW	6.60 kW	13.20 kW
C	20 kW/m²	22.0 kW	22.0 kW	44.0 kW

Calculation of the 22-kW heat load

$$Q_{CMOD} = 20 \times 1.10 = 22\ kW$$

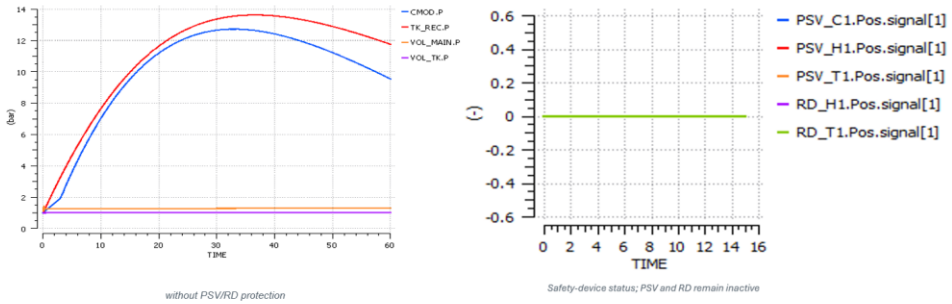
$$Q_{combined} = 22 + 22 = 44\ kW$$



- **The three fault loads were selected to represent the range of LOIV (Loss of Insulating Vacuum) conditions reported in the literature:** A--an experimentally measured MLI-covered case, B--a conservative MLI-covered case, C--the PIP-II bare-cavity design case.
- Using (Q=q"A) and an assumed exposed area of 1.10 m², the corresponding loads applied to each component were 4.84, 6.60 and 22.0 kW. The same load was imposed simultaneously on the CMOD and recovery tank without active pressure protection to compare their unmitigated responses.
- **Case C was selected for the subsequent PSV and rupture-disc study because it represents the most severe literature-based condition and produces the highest pressure and required relief capacity.** It is therefore used as a conservative bounding case, subject to later confirmation of the actual CEPC exposed area and credible LOIV conditions.

Total 4 Cases Simulation

Case 1 — Combined fault without safety response



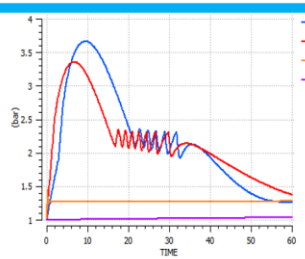
without PSV/RD protection

Safety-device status; PSV and RD remain inactive

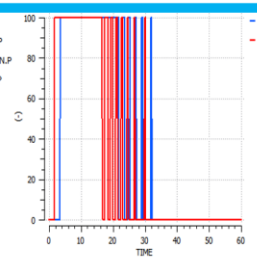
- With no PSV or rupture-disc protection, the 22-kW heat load applied to each component causes rapid pressurization.
- CMOD reaches approximately 12.8 bar and the recovery tank reaches approximately 13.7 bar, greatly exceeding the 2.31-bar PSV and 2.61-bar rupture-disc thresholds.
- Pressure later decreases because helium continues to leave through the available normal process paths. This decrease does not indicate adequate protection because the unsafe peak has already occurred.

Case 2: Pressure and relief response with PSV-only protection

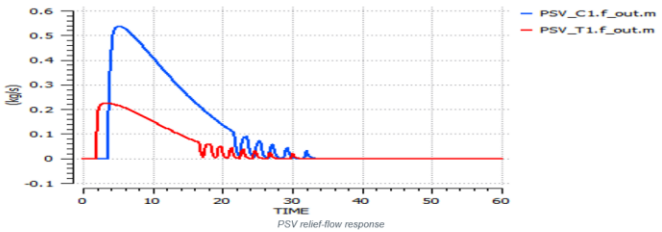
- This case evaluates PSV-only protection.
- When pressure reaches 2.31 bar, the CMOD and tank PSVs open and discharge helium. They reseat at 2.10 bar, causing valve cycling and pressure oscillations.
- Peak pressures are reduced to approximately 3.67 bar in CMOD and 3.35 bar in TK_REC. However, both exceed the 2.61-bar rupture-disc threshold, showing that PSV-only protection is insufficient for the combined fault.



Pressure response with PSV-only protection



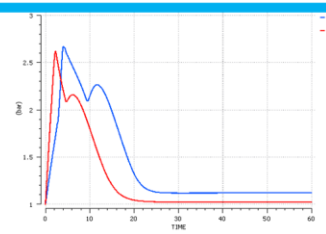
PSV position signals



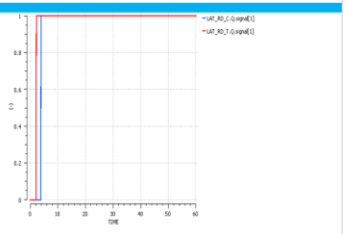
PSV relief-flow response

Case 3: Two-stage PSV and rupture-disc response

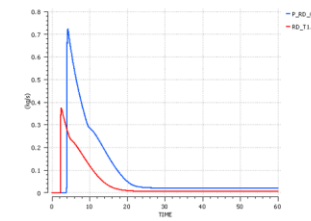
- Under the combined 44 kW fault, the tank reaches the 2.61-bar rupture-disc threshold first, followed by the CMOD.
- Both RD latch signals change from 0 to 1 and remain latched, confirming irreversible activation. The PSV and RD branches discharge helium during the transient.
- The RD flows peak at approximately 0.72 kg/s for CMOD and 0.37 kg/s for TK_REC, providing the additional capacity required to reduce both pressures rapidly.



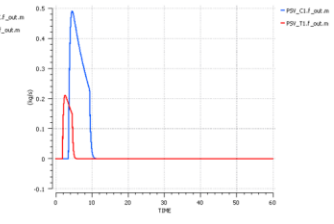
Pressure response of protected components



Rupture-disc activation and permanent latch



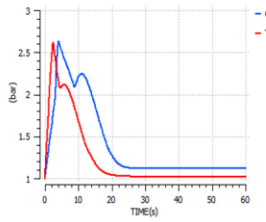
Rupture-disc branch mass-flow response



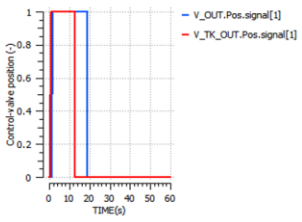
PSV relief mass-flow response

Case 4: Assessment of control-assisted protection

- The control valves open before the mechanical protection devices, but their limited flow capacity produces only a small reduction in peak pressure.
- Compared with Case 3, the CMOD peak decreases from 2.67 to 2.62 bar, while the recovery-tank peak remains at approximately 2.62 bar.
- Both PSVs and rupture discs still activate, showing that the existing outlet paths cannot provide independent preventive control. A dedicated higher-capacity recovery path is therefore required.



Pressure response with active control and PSV/RD backup



Activation of CMOD and recovery-tank control valves

Comparison of Case 3 and Case 4 protection performance

Result	Case 3	Case 4
CMOD peak pressure	2.67 bar	2.62 bar
TK_REC peak pressure	2.62 bar	2.62 bar
PSV activated	Yes	Yes
CMOD RD activated	Yes	Yes
Tank RD activated	Yes	Yes

Findings and next experimental plan

Main findings

• The same combined fault enables direct comparison of all protection cases.

• PSV-only protection reduces pressure but remains insufficient.

• PSV and rupture-disc protection limits both peaks to approximately 2.6 bar.

• Active control lowers the CMOD peak from 2.67 to 2.62 bar but does not prevent PSV or RD activation.

• The existing control paths require greater flow capacity.

• The model still requires validation against CEPC engineering data.

Next experimental / validation plan

1. Verify helium inventory, protected volumes, pipe dimensions and temperature-dependent pressure ratings from CEPC design data.

2. Recalculate PSV and rupture-disc capacity for individual credible scenarios: quench, loss of vacuum, blocked outlet and control failure.

3. Validate transient pressure and relief-flow predictions against a controlled test platform or qualified reference case.

4. Add the phase separator, grouped cryomodules and return header only after the present safety subsystem is validated.

Conclusion: The present model is a research-level safety comparison, not yet a final CEPC engineering design. The next priority is validation of inputs, relief sizing and transient response.

Summary & Outlook

I. **Comprehensive Design addresses nearly all critical aspects of the CEPC SRF cryogenic system.**

II. **Key R&D Milestones**:

a) Completed 650 MHz cryomodule 2K Horizontal test in next phase.

b) Completed CEPC Cryogenic System EDR Documentation in 2027.

III. **Collaboration & Scalability:**

a) Collaboration with other projects (e.g., SHINE, Ci-ADS, S3FEL, HALF, etc.) and institutions will be maintained to leverage existing experience and expertise.

b) Develop AI-driven monitoring for real-time tracking of safety parameters (pressure, temperature).

IV. **Long-Term Goals:**

a) The cryogenic system design aims to support the long-term operation of the CEPC SRF project, with considerations for potential upgrades and future expansion. The system is designed to be flexible and adaptable to evolving requirements.

b) Safety and reliability of the cryogenic system will remain a top priority. Continuous monitoring, testing, and validation of safety systems will be conducted to ensure the protection of personnel and equipment.

Thanks for your attention!