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CONCEPTIONAL DESIGN OF CEPC CRYOGENIC SYSTEM

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Abstract

The Circular Electron and Positron Collider（CEPC）has two rings, the booster ring and the collider ring. There are 336 superconducting cavities in total, which group into 68 cryomodules. In the booster ring, there are 96 1.3 GHz 9-cell superconducting cavities. In the collider ring, there are 240 650 MHz 2-cell cavities. There are 4 cryo-stations along the 100 km circular collider. Each cryo-station is supplied from a common cryogenic plant, with one refrigerator and one distribution box. The cooling capacity of each refrigerator is 18 kW @ 4.5 K.

INTRODUCTION

The Circumference of CEPC is 100 km with the booster ring and the collider ring. The collider ring is located in the tunnel, with the booster ring on the surface. There are 336 superconducting cavities in total. In the booster ring, there are 96 ILC type 1.3 GHz 9-cell superconducting cavities, eight of them will be packaged in one 12-m-long module. There are 12 such modules. In the collider ring, there are 240 650 MHz 2-cell cavities, six of them will be packaged in one 11-m long module. There are 56 of them.

All the cavities will be cooled in a liquid-helium bath at a temperature of 2 K to achieve a good cavity quality factor. The cooling benefits from helium II thermo-physical properties of large effective thermal conductivity and heat capacity as well as low viscosity and is a technically safe and economically reasonable choice. There are 4 cryo-stations along the 100km circular collider, as shown in Fig. 1.

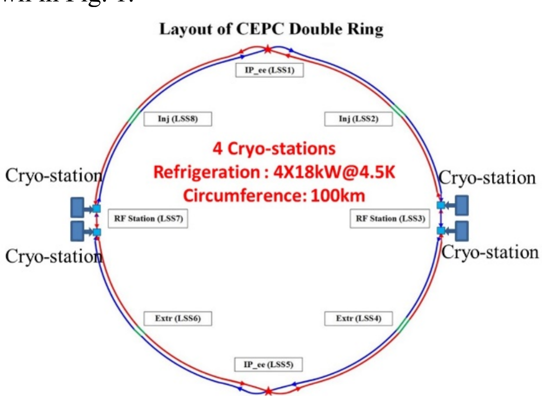

Figure 1: Layout of the CEPC cryogenic system.

CRYOGENIC DISTRIBUTION

General Layout

There are 4 cryo-stations. Each cryo-station includes two strings; one string groups 3 modules from the Booster and the other groups 10 modules from the Collider. The temperature of the RF cavities is 2 K. In order to decrease the high thermodynamic cost of refrigeration at 2 K, the design of the cryogenic components aims at intercepting heat loads at higher temperatures. There are two shields intercept both radiation and conduction at two temperatures: 40 ~80 K and 5~8 K.

During operation, one-phase helium of 2.2 K and 1.2 bar is provided by the refrigerator to all cryomodules. Each cryomodule has one valve box with two valves. The JT-valve is used to expand helium to a liquid helium separator. A two-phase line connects each helium vessel and connects to the major gas return header once per-module. A small diameter warm-up/cool-down line connects the bottom of the helium vessels at both ends. The cavities are immersed in baths of saturated superfluid helium, gravity filled from a 2 K two-phase header. Saturated superfluid helium flows along the two-phase header which is connected to the pumping return line and then to the refrigerator. Details of Booster and Collider cryogenic strings are in Figs. 2 and 3.

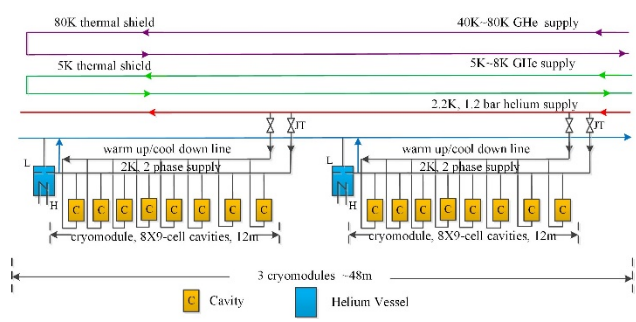

Figure 2: Booster cryogenic string.

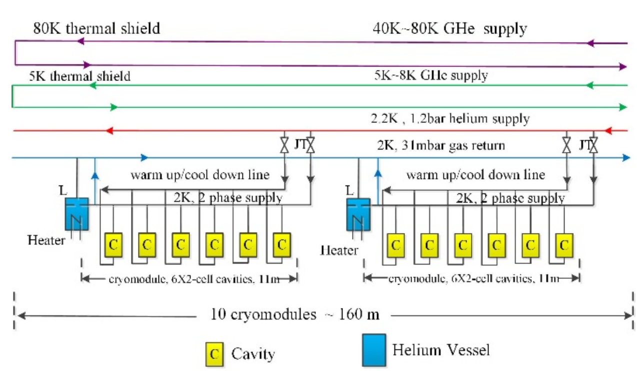

Figure 3: Collider cryogenic string.

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Cryomodules

In the booster ring, each eight 1.3 GHz 9-cell superconducting cavities are packaged in one 12-m-long cryomodule. Since many projects have used this type of cryomodule, it is a matured design. In the collider ring, one cryomodule includes six 650 MHz 2-cell cavities, six high power couplers, six mechanical tuners and two HOM abosorbers. In order to have a good performance, fast cool-down is introduced, which means 2-3 K/minute below the 9.2 K critical temperature. In the collider cryomodule, the structure design of the collider cryomodule is shown in Fig. 4. The diameter of the vacuum vessel is 1.4 m, and overall length is 9.5 m. The cavity is supported by the post with the material of fiber reinforced plastic (G-10).

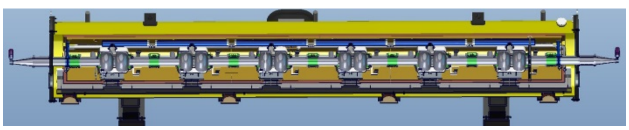

Figure 4: Structural design of the Collider Cryomodule.

Heat Load

The heat load is mainly from the superconducting cavities. The 1.3 GHz 9-cell cavities with quality factor 1×10^{10} @ 19.8 MV/m are for the Booster and the 650 MHz 2-cell cavities with quality factor 1.5×10^{10} @19.7 MV/m are for the Collider. The cavity dynamic heat load of each cryomodule for collider and booster is 153.59 W and 13.98 W.

Table 1 summarizes the static and dynamic heat during Higgs mode at different temperature levels. This amounts to a total equivalent entropic capacity of 47.53 kW at 4.5 K. The corresponding installed power is 10.4 MW. The figures in Table 1 include an “overall net cryogenic capacity multiplier,” a multiplier of the estimated heat loads, and in general use in the cryogenic community. This factor includes a margin for plant regulation, a buffer for transient operating conditions, a buffer for performance decreases during operation and a buffer for general design risks. This multiplier parameter is from the ILC Design report [1]. In the ILC design, the real COP at 40~80 K, 5~8 K and 2 K are 16.4, 197.9 and 700.2 respectively.

Table 1: Heat Load

Higgs Mode	**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
Connection boxes	W	50	10	10	50	10	10
Cryomodule number			40			12	
Total heat load	kW	17.20	4.88	7.34	2.78	0.41	0.34
Total predicted mass flow	g/s	82.42	152.26	346.58	13.34	12.73	16.07
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	1.99	6.80	36.18	0.32	0.57	1.68
Total 4.5K equiv. heat load with multiplier	kW		44.96			2.57	
Total 4.5K equiv. heat load of booster and collider	kW			47.53			
Installed Power	MW		9.84			0.56	
				10.4			

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REFRIGERATION

The heat loads shown in Table 1 require the helium refrigerator plants to have a total capacity over 47.53 kW at 4.5 K. Four individual refrigerators will be employed. Including an operating margin, the cryogenic plant capacities are 18 kW at 4.5 K for each cryogenic station. The total cryogenic capacities are equivalent to 72 kW at 4.5 K.

Many aspects must be taken into account during refrigerator design, including cost, reliability, efficiency, maintenance, appearance, flexibility and convenience of use. The initial capital cost of the cryogenic system as well as the high energy costs of its operation over the life of the facility represent a significant fraction of the total project budget, so reducing these costs has been the primary focus of our design. Reliability is also a major concern, as the experimental schedule is intolerant of unscheduled down time.

The refrigerator main components include a compressor station with oil removal system, vacuum pumps and the cold box which is vacuum insulated and houses the aluminum plate-fin heat exchangers and several stages of turbo-expanders.

The fundamental cooling process expanding compressed helium gas to do work against low-temperature expansion engines, then recycling the lower pressure exhaust gas through a series of heat exchangers and subsequent compression is a variant of the Carnot process that has been in use for many decades.

There are five pressure levels in the cryoplant: 20 bara, 4 bara, 1.05 bara, 0.4 bara and 3 kPa. These are obtained with the high pressure screw compressor group, middle pressure screw compressor group, warm compressors and cold compressors. At the 40 K and 5 K temperature levels helium flows are directed to the thermal shields of the cryomodules. The corresponding return flows are fed back to the refrigerator at suitable temperature levels. Inside the refrigerator cold-box the helium is purified of residual air, neon and hydrogen by switchable absorbers at the 80 K and 20 K temperature levels. Figure 5 is the refrigerator flow diagram.

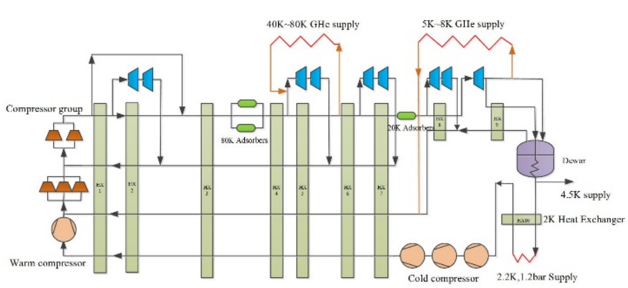

Figure 5: Refrigerator flow diagram.

The cryoplant will supply 4.5 K and 2.2 K helium to the cryomodules. At each cryomodule, the helium goes through a phase separator and a 2K counter flow heat exchanger to recover the cooling power, then expanded to 31 mbar via a JT-valve, resulting in liquid He II at 2K. The low pressure helium vapor from the 2K saturated baths surrounding the cavities returns to the refrigerator through the gas return pipe. The vapor is pumped away and returned to the cryoplant.

There are two options for such a pumping system. One relies solely on cold compressors; the other employs a set of cold compressors followed by a final stage of warm compression. After superheating in the counter flow heat exchanger, the gas is compressed in the multiple-stage cold compressors to a pressure in the 0.5 to 0.9 bar range. This stream is separately warmed up to ambient in exchangers and goes back to the warm compressors. The choice of a warm vacuum compressor makes it easier to adjust for the heat load variations. This approach, which CERN uses in the LHC [3], also allows for an easier restart of the 2 K system after a system stoppage.

INFRASTRUCTURE

The 2 K cryogenic system consists of oil lubricated screw compressors, a liquefied-helium storage vessel, a 2 K refrigerator cold box, cryomodules, a helium-gas pumping system and high-performance transfer lines. The cryogenic station is located near the RF station. The cooling power required at each RF station will be produced by a refrigerator with a capacity of 18 kW at 4.5 K, installed at four cryogenic stations, and distributed to the adjacent superconducting cavities [2, 3].

For reasons of simplicity, reliability and maintenance, the number of active cryogenic components distributed around the ring is minimized and the equipment locations chosen following these principles:

1) Equipment is installed as much as possible above ground to avoid excavation. Normal temperature equipment will be installed at ground level.
2) To decrease heat loss, low-temperature equipment will be installed nearby the cryomodules [4].

Equipment at ground level includes the electric substation, the warm compressor station, helium storage tanks, cooling towers and helium purification. Underground are the cold-boxes, cold compressor, 2 K cryomodules, cryogenic transfer lines and distribution valve boxes. Figure 6 shows the overall schematic.

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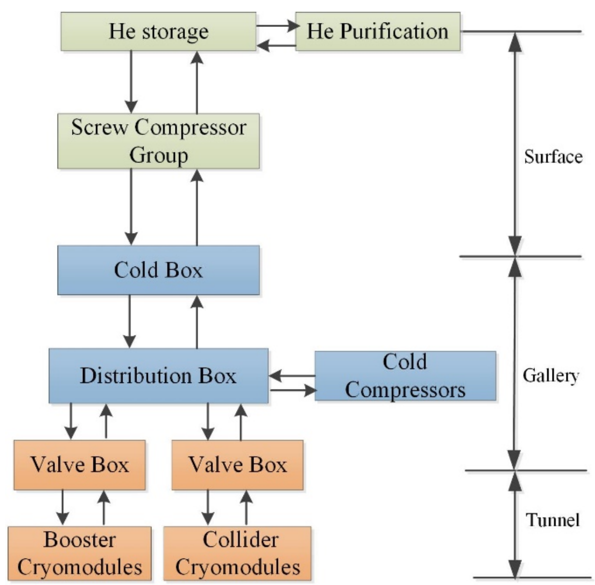

Figure 6: General architecture of the cryogenic system.

Each cryo-station has an underground plant in the gallery, the size is 37 meters long and 8 meters wide, including Cold box, distribution box and cold compressor. The height of the gallery is 5 meters. There are normal temperature magnets between cryomodules. So each cryomodule is equipped with a valve box in the power source tunnel and connected by a transfer line. The cryogenic distribution in the tunnel for booster and collider is shown in Figs. 7 and 8.

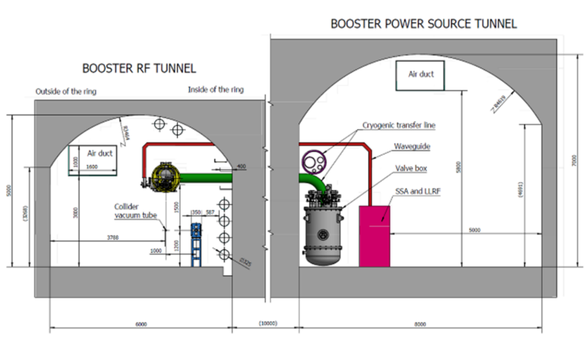

Figure 7: Tunnel for booster.

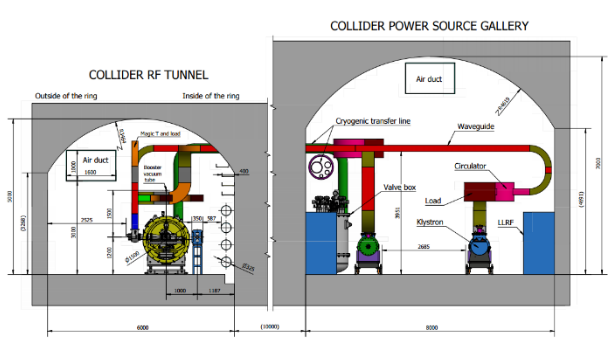

Figure 8: Tunnel for Collider.

HELIUM INVENTORY

Most of the helium inventory is liquid which bathes the RF cavities and is roughly 70% of the whole system. The volumes of one 1.3 GHz module and one 650 MHz module is about 320 liters and 346 liters, respectively. The total liquid helium volume in the system is 17,680 liters.

Accounting for the liquid in the Dewar and in the transfer lines, and using the 70% factor mentioned above, the liquid volume in the system is about 25,257 liters, or about 3,679 kg [5].

Assuming that all the helium is returned to the helium tanks after machine shutdown, the inventory will be 2.3×10^4 m^3. To safely operate the cryogenic system, a factor of 60% is added, so 3.8×10^4 m^3 is required helium inventory system. The total helium inventory of the whole machine is about 6,131 kg.

CONCLUSION

The CEPC cryogenic system were designed with cooling scheme, cryomodules, heat load, refrigeration and architecture. The required total 4.5 K equiv. heat load is 47.53 kW and total installed power is 10.4 MW. There are four cryo-stations and each station has an individual 18 kW@4.5 K refrigerator. Research and discovery about cold compressor and 2 K JT heat exchanger have been carried out. More detailed work will be proceeded later.

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