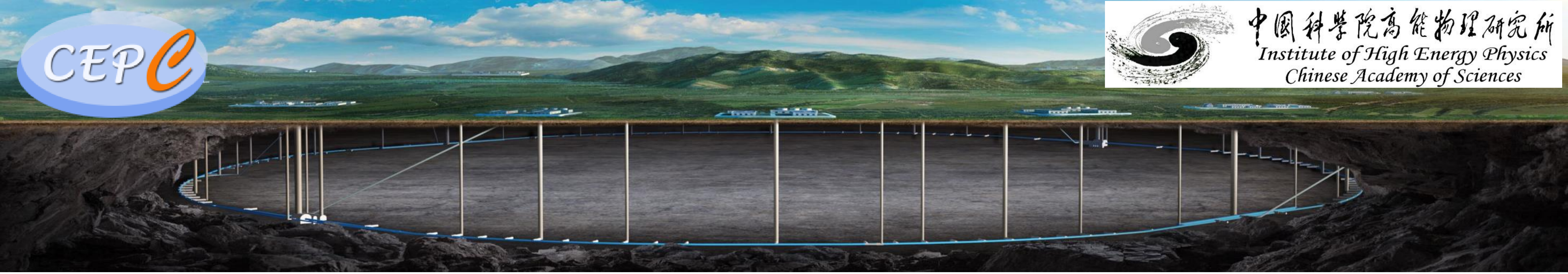

CEPC Green Accelerator Technology Development

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On behalf of CEPC accelerator team

International Workshop on Future Linear Colliders, LCWS2024, July. 8~11th, Tokyo, Japan

Content

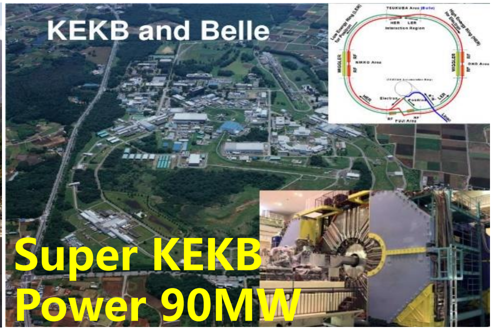
- **Brief introduction of Green Particle Accelerator**
- **Approaches to a green accelerator**
- **Summary**

Green Particle Accelerator：issues and challenges

- China is reducing energy pollution, promoting green accelerator and boosting unit energy GDP (China dual carbon strategy: achieve peak CO_2 emissions before 2030 and carbon neutrality before 2060)
- Huge energy is needed for modern large colliders such as LHC, ILC, CEPC…Huge energy means huge cost and huge pollution.

Saving power=lower pollution=lower operation cost

- Most of electricity has been converted into the waste heat, which is emitted directly to the environment through the cooling water;
- If this part of waste heat is utilized effectively, it is of great significance to the energy gradient utilization and saving power.



Key factors of green accelerators

ICFA: International Panel on "Sustainable colliders and accelerators"

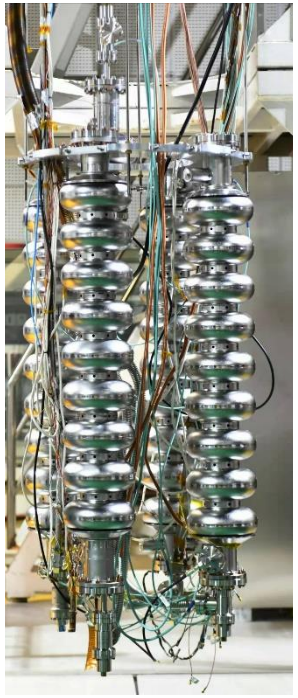
- energy efficient and sustainable accelerator technology
  - ✓ efficient RF sources (klystron, magnetron, solid state, IOT)
  - ✓ s.c. cavity advancements relevant for efficiency (low cryo losses: high Q, HTC materials)
  - ✓ efficient beam transport (permanent magnets, optimized electromagnets and pulsed magnets, s.c. magnets)
  - ✓ optimization of large cryogenic systems
  - ✓ technology for energy recovery: heat recovery in accelerator facilities, high T cooling circuits, recovery of RF power, recovery of pulsed magnet field energy, recovery of spent beam energy (ILC)
  - ✓ efficient targets for neutron, neutrino, muon production
  - ✓ minimizing the consumption of cooling water
  - ✓ long term equipment and infrastructure sustainability, e.g. suitable selection of materials and re-usable modular components
- energy management for large research facilities
  - ✓ using excess energy in an era of fluctuating sustainable sources; best mix of conventional and renewable sources
  - ✓ dynamic operation avoiding periods of low supply, efficient standby modes and fast recovery
  - ✓ integration of energy recovery and storage techniques in the overall energy management concept

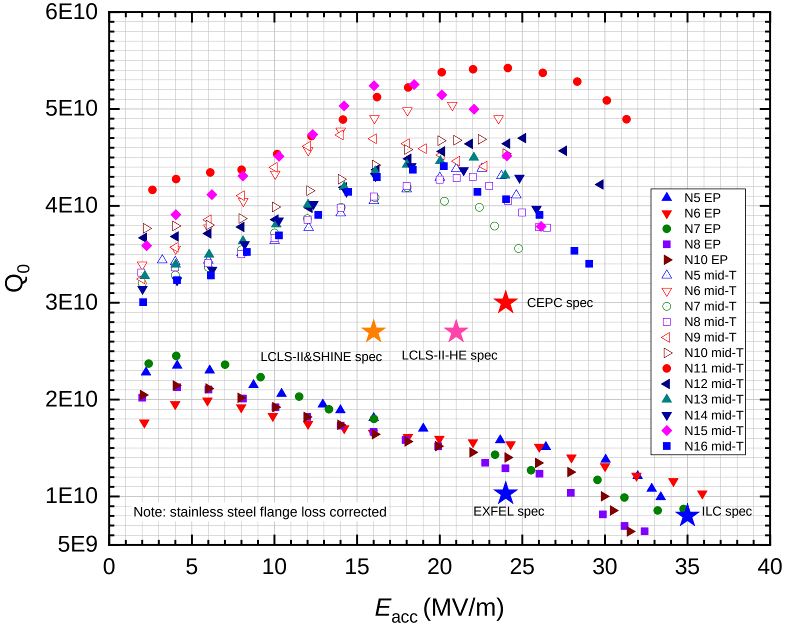
Approaches to a green CEPC accelerator

- **Improving the key technology energy efficiency**
  - Superconducting technology: High Q SRF cavity and cooling system; HTS magnets
  - High performance & efficiency RF source
  - Novel magnets: dual aperture magnet, permanent magnet
  - ……
- **Clean energy implement and utility**
  - Solar panel
  - ……
- **Energy/non-renewable resource recovery**
  - Helium recovery
  - Waste energy recovery from cooling water and utility in civilization
  - ……

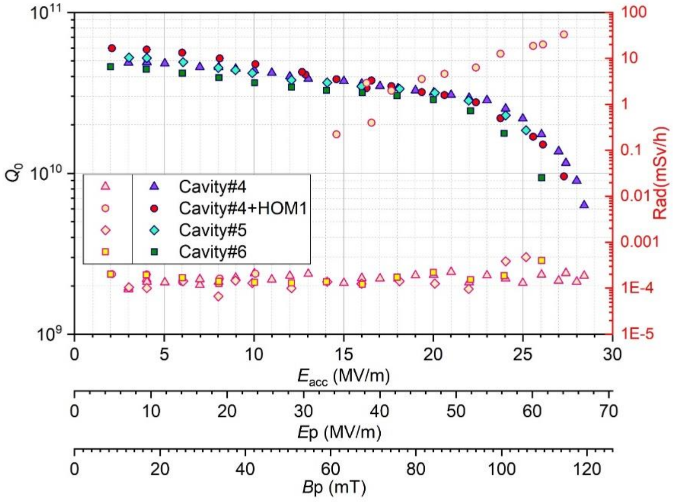
IHEP High Q 650 MHz and 1.3 GHz Cavity

High Q 1.3 GHz 9-cell

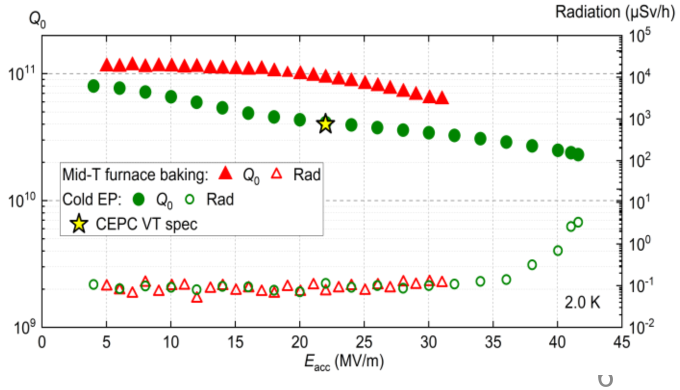




650 MHz 2-cell BCP



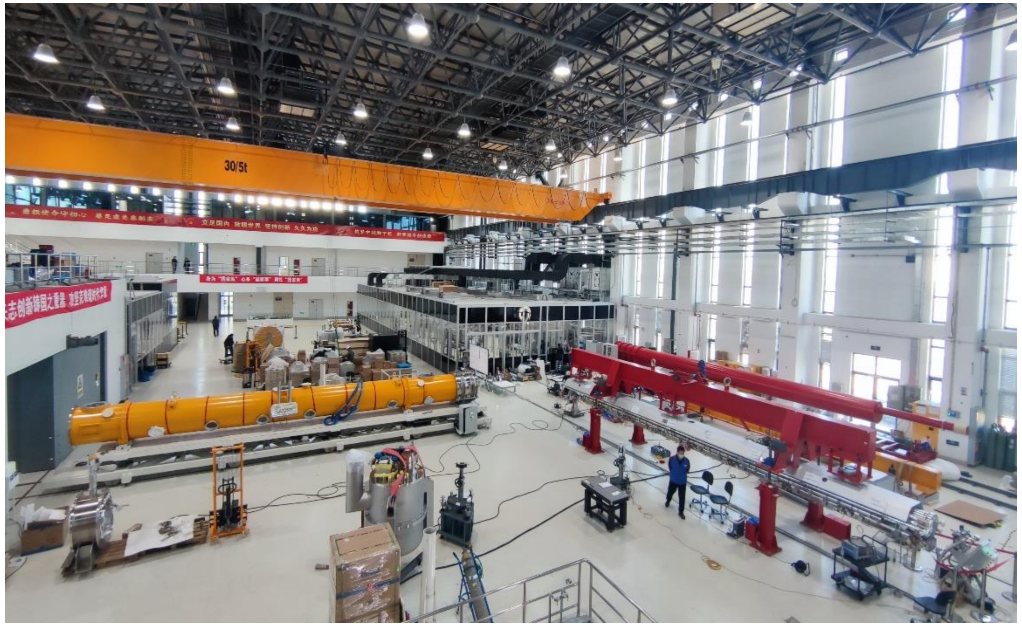
High Q 650 MHz 1-cell



IHEP Mid-T High Q 1.3 GHz Cryomodule

From Jiyuan Zhai

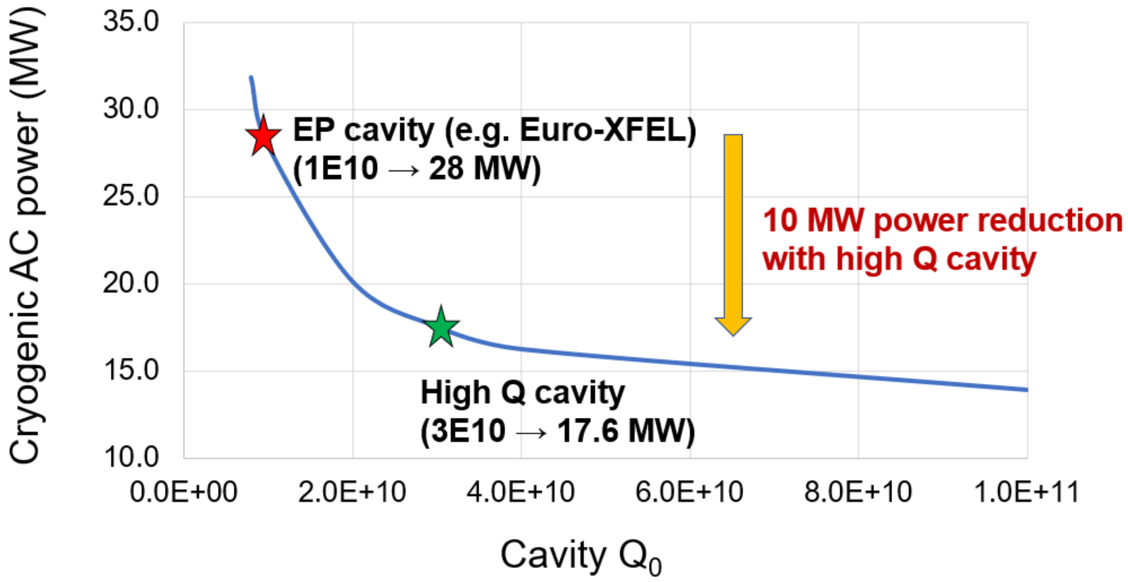
- World's first 1.3 GHz cryomodule with 8 mid-T (medium-temperature furnace bake) 9-cell cavities.
- World's record Q cavity in the cryomodule. Exceeds CEPC specification.



Parameters	IHEP Mid-T CM Horizontal Test	LCLS-II & HE Spec	CEPC Booster Higgs mode Spec
Avg. usable CW E_{acc}	> 23 MV/m	2.7×10^{10} @ 16 & 20.8 MV/m	3.0×10^{10} @ 21.8 MV/m
Avg. Q_0 @ 21 MV/m	3.6×10^{10}		

High Q SRF significance for a green machine

- The SRF system, along with its cryogenic auxiliaries, is one of the major electricity consumers. High Q-factor SRF cryo-modules effectively reduce the heat load, resulting in lower energy.
- The CEPC 1.3GHz SRF cavities adopt the mid-temp baking technology, which enhances the Q factor by 5 times compared to the EP technique.
- Using the high-Q SRF in CEPC 30MW mode may reduce the operational power by 10MW, For CEPC ttbar collider ring:2 K dynamic heat load will decrease from 60 kW to 20 kW by increasing Q0 from 1E10 to 3E10, saving 30 MW electric power.



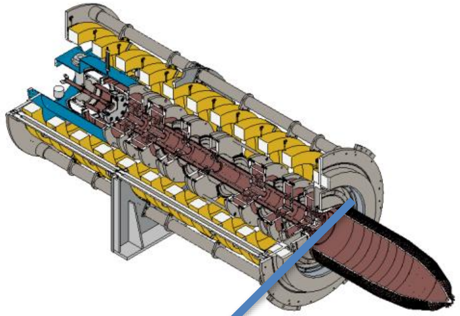
Power consumption with respect to the cavity Q-factor
CEPC 50MW Higgs operation

Develop high-efficiency klystron



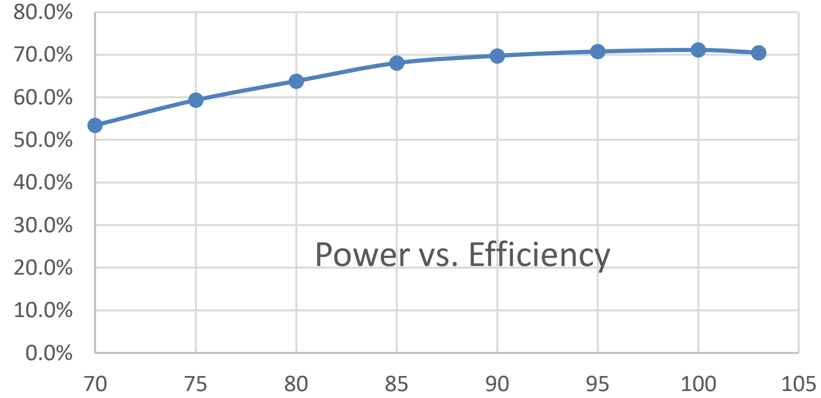


Efficiency target of 80.5% for the third klystron (multiple injection high efficiency)



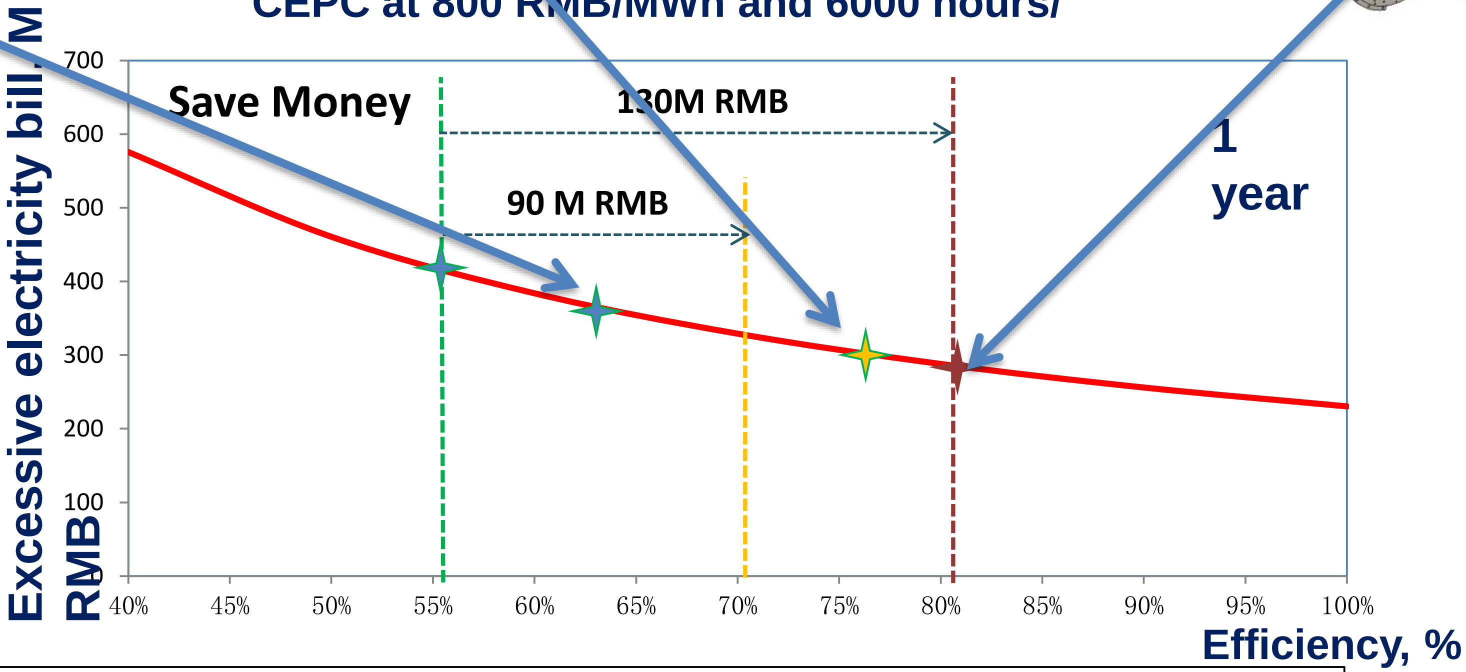
Efficiency target of 75% for the second klystron (single injection high efficiency)

First klystron, 62% efficiency, already met the standard



High-efficiency prototype klystron efficiency has reached 70.5% @ 630kW, now has been further modified

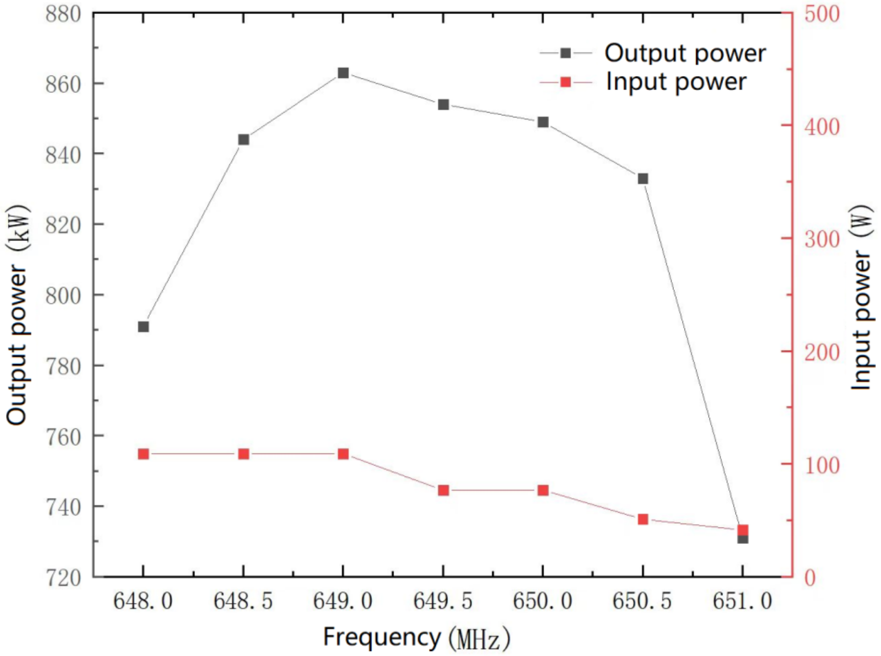
CEPC at 800 RMB/MWh and 6000 hours/1 year



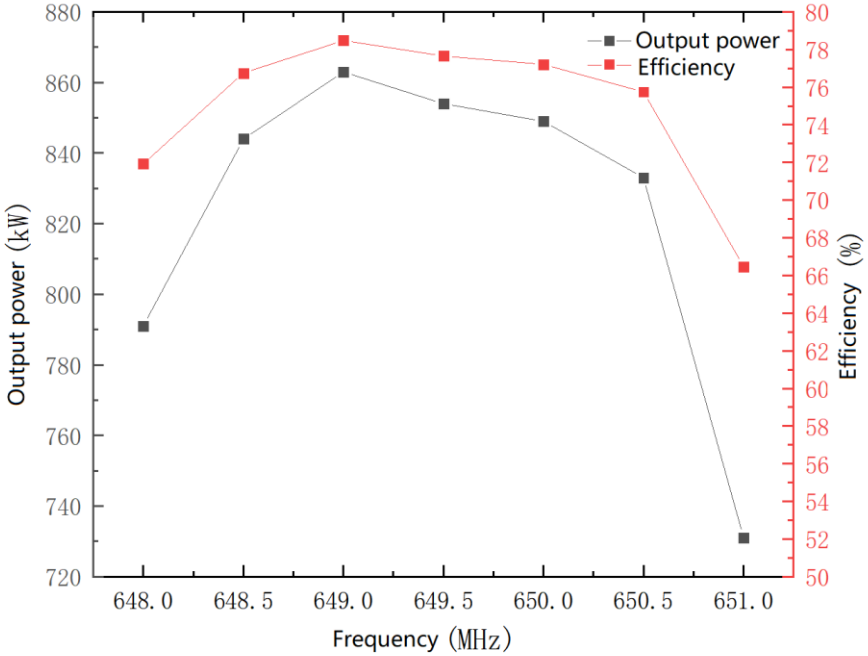
The CEPC can save 160M kWh of electricity per year by increasing the conventional efficiency (55%) of the klystron to a high efficiency of 80%.

Develop high-efficiency klystron

2nd round test is on-going



Output power vs. input power



Output power vs. Efficiency

- 2nd round test since January of 2023, 77.2% @849 kW was achieved in pulse mode
- Further test is on going for wider pulse and CW mode

A Multi-Beam Klystron will be completed soon, with the high power test scheduled in 2024

Environmental protection and optimization of Magnet design

- Magnets provide one of the largest sources of power consumption in modern accelerators. By reducing the power requirements of magnets, more sustainable accelerators can be designed and built.
- In CEPC magnet system, large amount magnets are needed. The following aspects are considered to optimize the magnet construction and operation cost.
  - Low current density with less power consumption in the power cables.
  - Compact magnets with narrow yokes and simple structure
  - Dual aperture dipole and quadrupole magnets can save about 50% power consumptions.
  - Low field strength dipole magnets, so combined magnets can be used.
  - Recycling related to magnet heating is considered.
  - Permanent and superconducting magnets are also an option under consideration.

HEPS employs a permanent dipole magnet

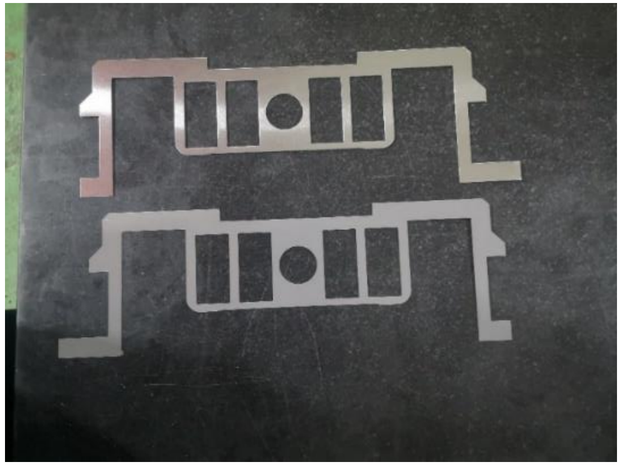
- Developing new technologies, the dipole magnets are made from pure permanent magnetic materials without consuming electricity during operation, all without affecting the device's performance.

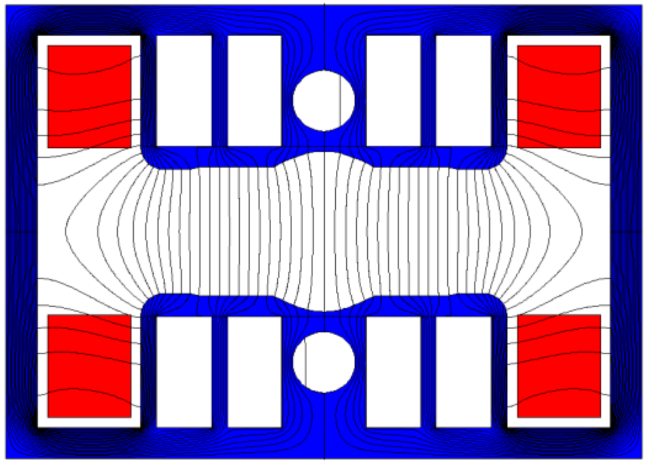
- Equivalent single excitation energy consumption of about 1.62kW.
- Equivalent cooling, power efficiency additional energy consumption of about 1.3kW
- 240 magnets in the whole ring
- Annual running time of 8000 hours

Annual saving electricity about **5.6 million kWh**

CEPC Booster magnets design

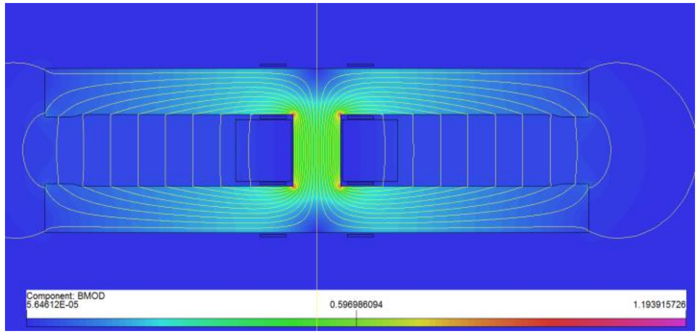
- CEPC Booster magnets (**19624 sets of magnets cover about 74 km)**
  - Field ramping with the beam energy (from 30 GeV to180 GeV) in 10 seconds
  - Low field and long dipole magnets: 95 Gs @30 GeV to 564 Gs @180 GeV with a length of 4.7 m.
  - Resistant laminated magnets are the first choice.
  - Low field dipole magnets with interleaved non-steel/steel laminations, narrow yoke and holes in the pole to reduce the magnet weight
  - Aluminum busbar coils for cheap price and low weight (Vs Copper)
  - Combined dipole and sextupole magnets are used to reduce the power consumption of individual sextupole magnets.

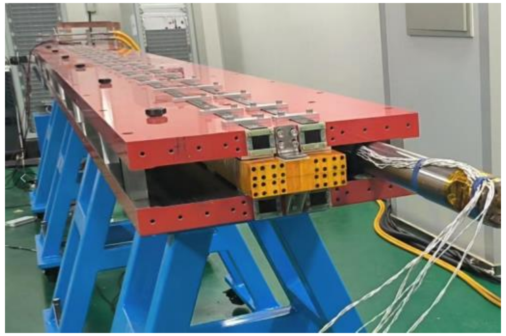


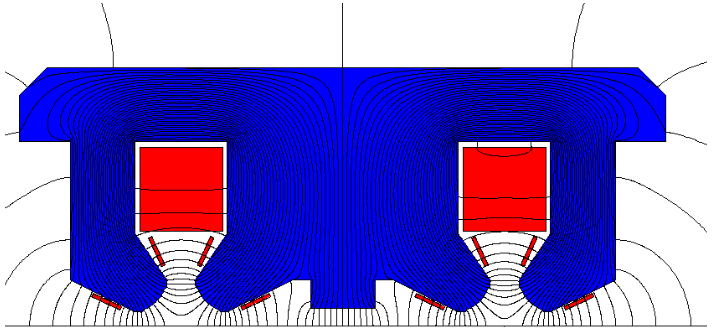


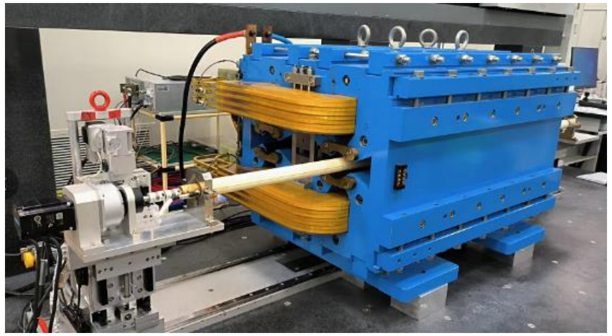
CEPC Collider magnets design

- CEPC Collider magnets (**17574 sets of magnets cover about 84.67 km**)
  - DC magnets work at four energies of 45.5, 80, 120 and 180 GeV
  - Dual aperture magnets can decrease the number of units to manufacture, test, transport, install, maintain, and save about 50% power consumption.
  - Compact magnets with narrow yokes and simple pole shape
  - Pure solid iron is used for dual aperture dipole magnet with aluminum excitation bars
  - Simple racetrack coil is used for dual aperture quadrupoles.



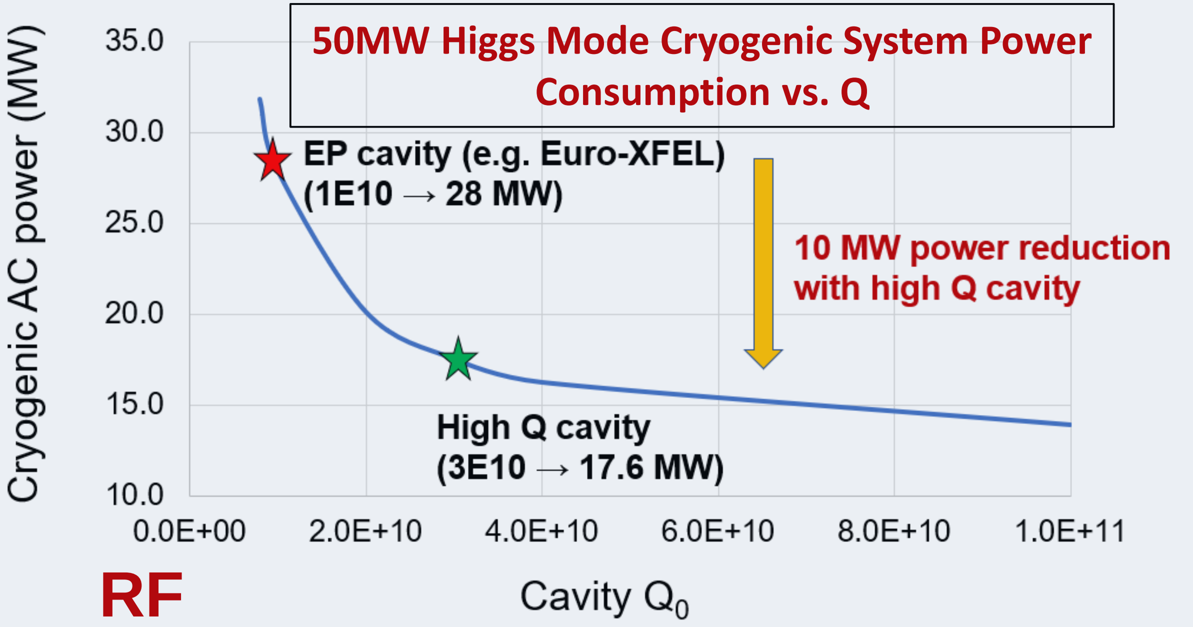






Develop the superconducting technology

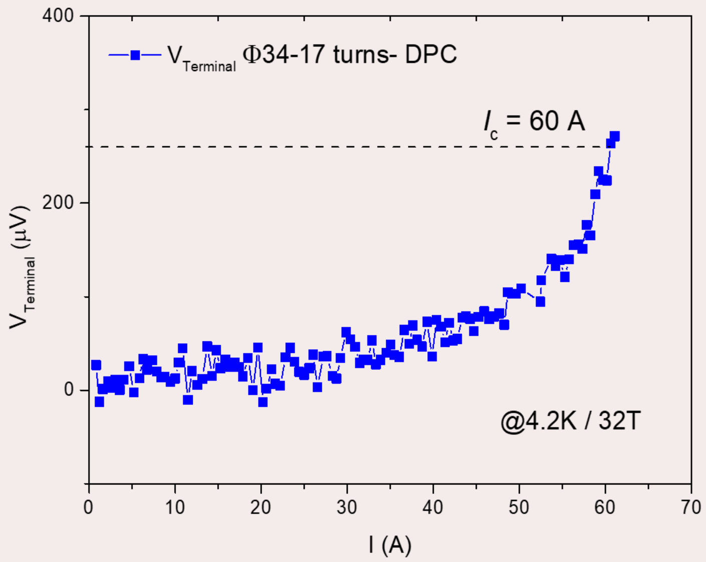
- CEPC's superconducting high-frequency system (with attached cryogenic system) is the main source of energy consumption. The high Q superconducting cavity can effectively reduce the heat load of the cryogenic system, effectively saving power
- High-Q superconducting cavities at IHEP, with a quality factor of ~5e10. Average Q of superconducting cavities at EuXFEL is ~1e10
- High Q cavity for CEPC, comprehensive accounting can reduce the operating power of **10MW**, annual power savings of about **60M kWh**



RF

- High-temperature superconducting (HTS) technology, can dramatically change the technical solutions of accelerator magnets and reduce energy consumption
- High-performance superconducting cable is the key technology for superconducting magnets;
- Chinese scientists pioneered iron-based high-temperature superconductivity technology IBS

◈ **low cost** ◈ **good stability** ◈ **flexible winding**



Performance of IBS solenoids under a 32 T

I_c reach **60 A at 4.2 K and 32 T**

SC magnet

Clean energy implement and utility

High Energy Photon Source (HEPS) Photovoltaic facilities

- HEPS buildings in Huairou are designed and **installed with photovoltaic (PV) power generation systems on the roofs** to realize the win-win effect of architectural functions and grid-connected power generation, and to create a clean, environmentally friendly, intelligent, convenient, and aesthetically pleasing high-tech park.
- Adopting 465Wp/550Wp monocrystalline silicon photovoltaic modules, the first phase has a total installed capacity of **9,950.92 kWp**. It is expected that the average annual power generation will be **10.30766 million kWh**, and the equivalent average annual utilization hours will be 10,035.85h.
- **The electricity generated by the project is consumed locally**.
- The second phase is planned to lay PV modules on the ground inside the storage ring with an installed capacity of **7314.45kWp**.

储存环屋顶施工现场

HEPS onsite picture

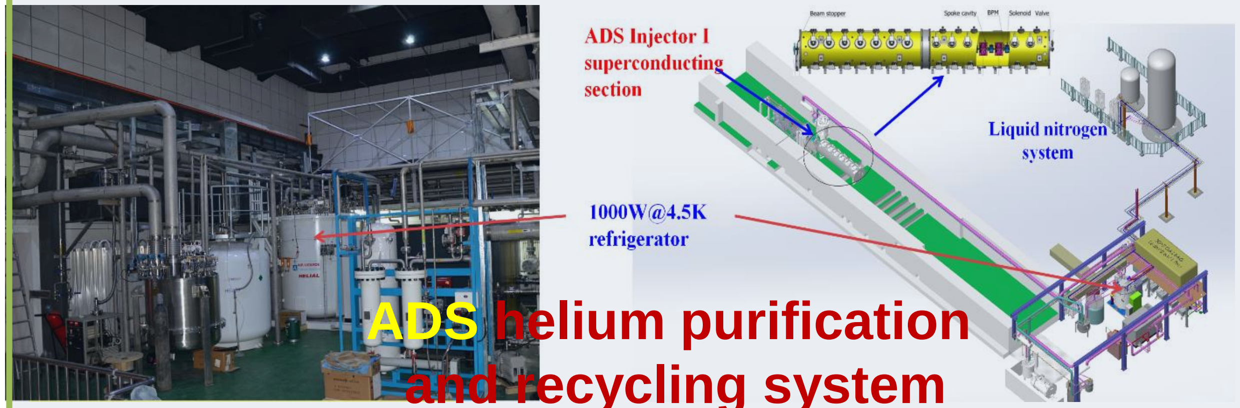
Clean energy implement and utility

- The CEPC site selection is currently in progress， the utilization of clean energy should fully consider the geographical and climatic conditions of candidate locations.
- Hydroelectric power, wind power, solar energy, bioenergy (biogas), these forms of energy represent renewable energy and are of great significance in reducing dependence on fossil fuels and mitigating climate change.
- Even the energy storage, load shifting and peak shaving……

Full recovery/recycling of the liquid helium/helium gas

- Helium gas is an associated resource of natural gas, which is non-renewable and mainly relies on imports in China. In recent years, due to the international situation, the price fluctuates greatly;
- All the devices in IHEP realize all helium gas recovery: the liquid helium recovery and purification system of BEPCII(ADS)/PAPS、HEPS has been running stably for many years.
- Promote the localization of large-scale liquid helium recycling system.

PAPS helium purification and recycling system

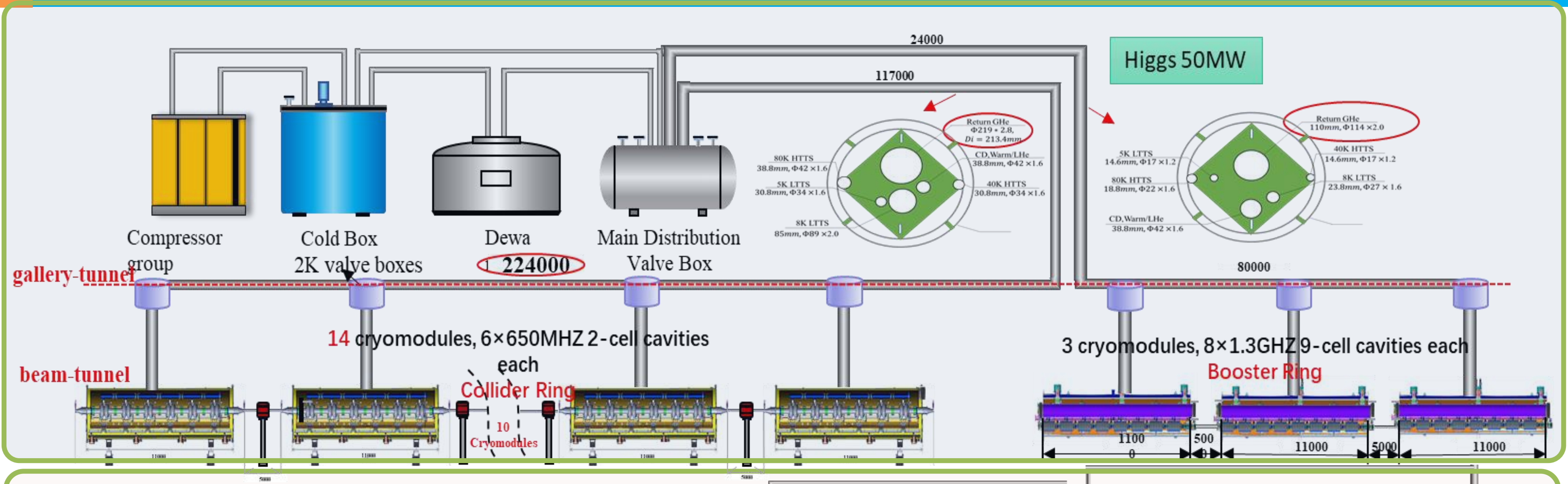


ADS helium purification and recycling system

BEPCII cryogenic system

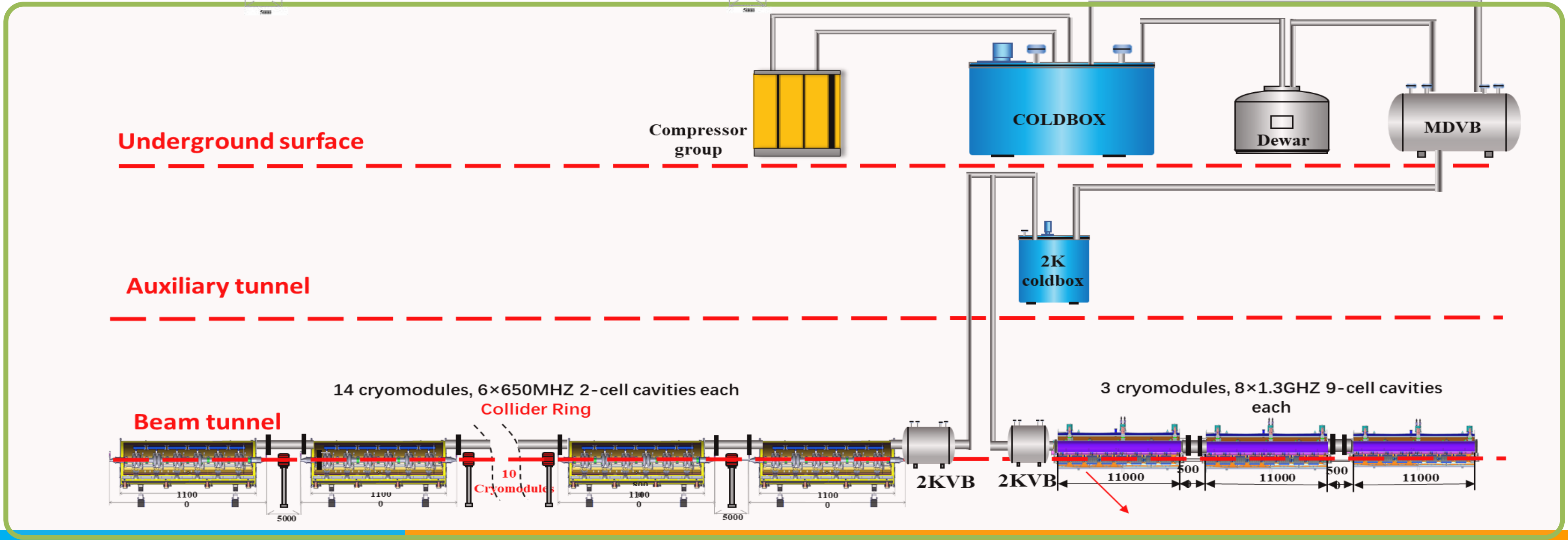
HEPS cryogenic system

Optimization of the large cryogenic system



CDR

TDR



- Eliminate many small valve boxes;
- Process flow looks more easier;
- Reduce the cryogenic cost;

CEPC waste heat recovery/reuse requirements

- The CEPC collision ring has 16 cooling water circuit sites with a cooling water circuit heat load of 221MW.
- The cooling water system comprises a low-conductivity water (LCW) closed-loop circuit, a cooling tower water (CTW) circuit, and a deionized water make-up system.
- LCW system absorbs heat from the various accelerator equipment, which is transferred through a heat exchanger to CTW, and finally taken away by the cooling water system;

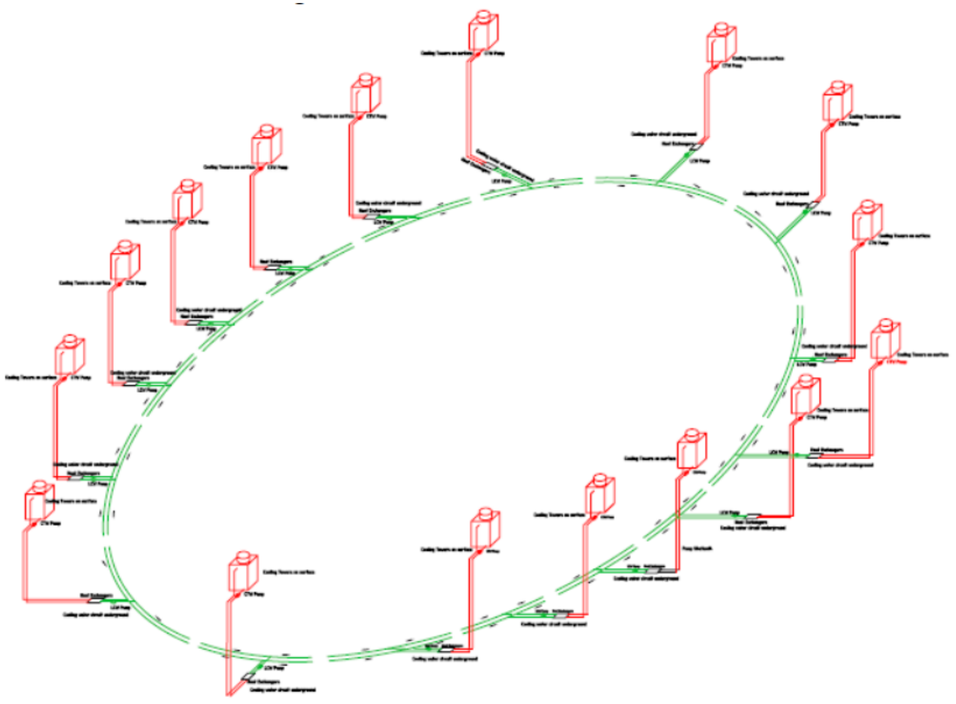


Figure 9.8.2: Layout of cooling water circuits around the ring.

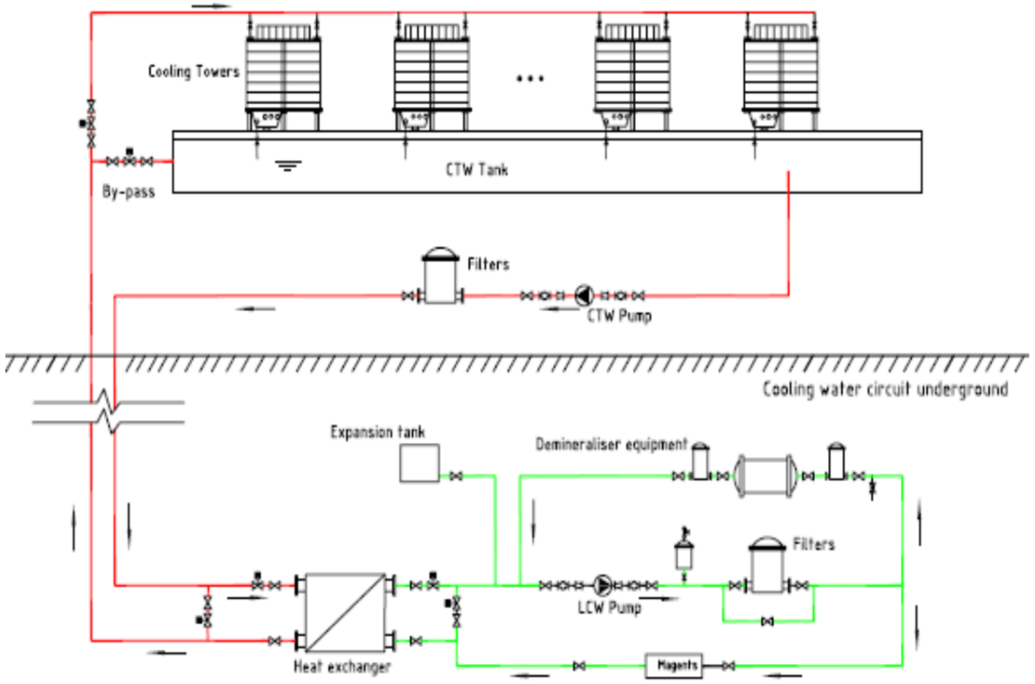


Figure 9.8.1: Flow diagram of a typical cooling water system.

CEPC waste heat recovery/reuse requirements

- **CTW temperature： 5° C inlet and 11° C outlet; Total cooling load of 197 MW.(TDR report P854)**
- **LCW temperature: 29° C inlet and 34° C outlet (TDR report P852); Total cooling load of 221MW (16 sites).**
- **Low-grade energy can be converted into high-grade energy and utilized effectively through heat pump technology, photo-thermal technology and thermal energy storage technology.**

Table A3.11: Total facility power consumption in Higgs mode (30 MW/beam)

	System for Higgs (30 MW /beam)	Location and power Requirement (MW)						Total (MW)
		Collider	Booster	Linac	BTL	IR	Surface building	
1	RF Power Source	96.90	0.15	12.26				109.31
2	Cryogenic System	9.72	1.71			0.16		11.59
3	Vacuum System	5.40	4.20	0.60				10.20
4	Magnet System	42.16	8.46	2.15	4.89	0.30		57.96
5	Instrumentation	1.30	0.70	0.20				2.20
6	Radiation Protection	0.30		0.10				0.40
7	Control System	1.00	0.60	0.20				1.80
8	Experimental Devices					4.00		4.00
9	Utilities	37.80	3.20	1.80	0.60	1.20		44.60
10	General Services	7.20		0.30	0.20	0.20	12.00	19.90
	Total	201.78	19.02	17.61	5.69	5.86	12.00	261.96

TDR report *P973

Table 9.8.1: Estimated cooling water heat loads (at Higgs /30MW)

System	Location and heat loads (MW)					
	Collider	Booster	Linac	BTL	IR	Total
Accelerating tube / Waveguide			1.36			1.36
Power source	36.90	0.15	9.18			46.23
Cryogenics	9.50	1.60			0.16	11.26
Experimental devices					3.60	3.60
Magnets	31.22	5.18	1.76	4.31		42.47
Vacuum chamber of ring	64.00	6.20	0.50			70.70
Power convert for magnets	4.05	0.81	0.18	0.47	0.03	5.54
Condenser in stub tunnel	13.20					13.20
Pump	21.65	1.46	1.65	1.32	1.05	27.13
Total	180.52	15.40	14.63	6.10	4.84	221.49

TDR report **P851

Table 9.8.2: Parameters of the cooling tower water system (at Higgs /30 MW)

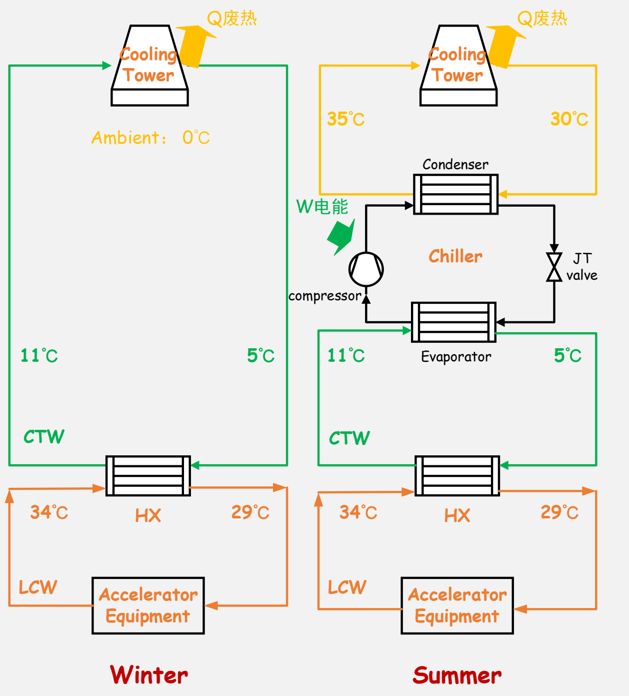
Parameters	Collider	Booster	Linac	BTL	IR	Total
Heat load (MW)	180.52	15.40	14.63	6.10	4.84	221.49
Supply water temperature	29°C					
Temperature rise	5°C					
Flow rate (m^3/h)	31044	2648	2516	1049	832	38089

TDR report P853

Possible solutions for CEPC waste heat reuse

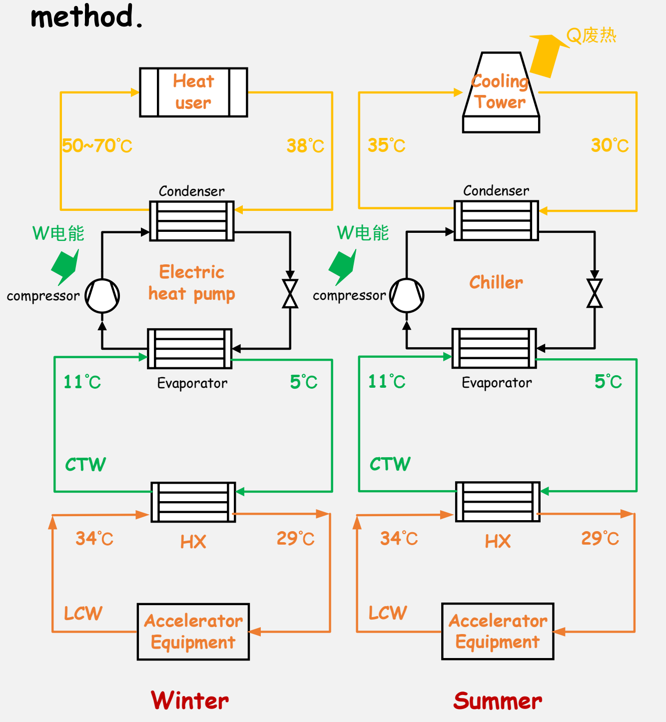
1、Conventional method

- LCW is cooled by CTW through heat exchanger.
- **Winter:** Cooling tower cools the CTW and discharges waste heat to the outside environment.
- **Summer:** Chiller consumes electricity and provides cold energy to cool the CTW.



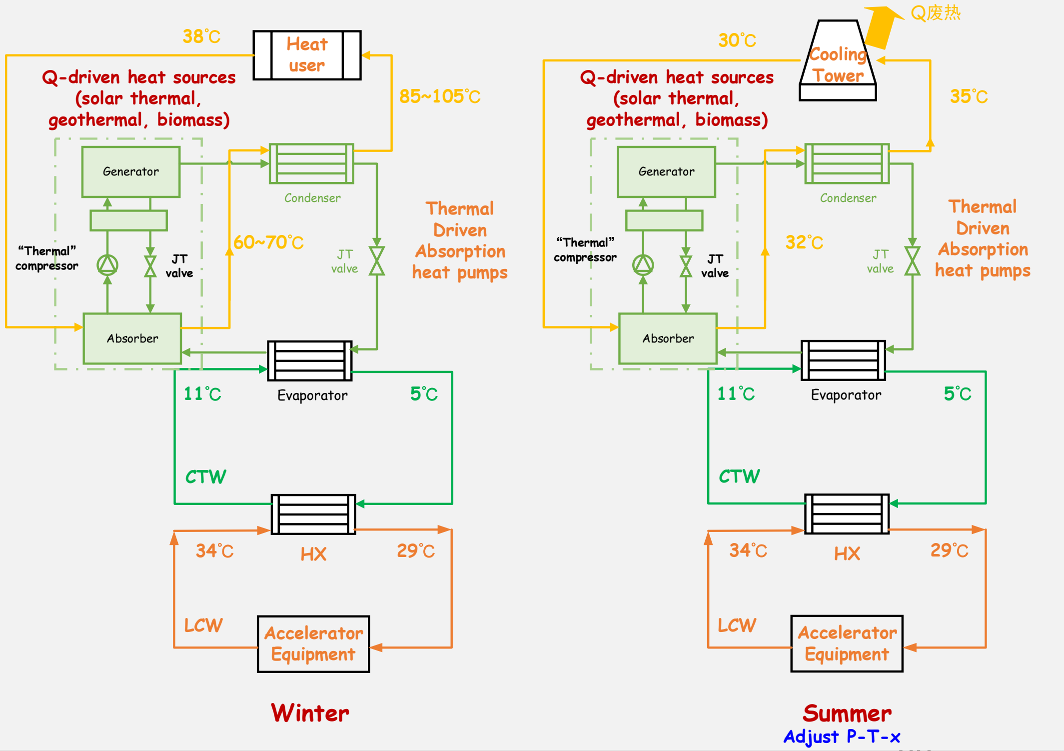
2、Existing improvement methods

- LCW is cooled by CTW through heat exchanger.
- **Winter:** electric heat pump consumes electric energy and recovers CTW waste heat to heat users.
- **Summer:** chiller consumes electricity to provide cold energy to cool the CTW.
- **Issue:** Although it can recover the waste heat for heating in winter, it consumes more electricity than the conventional method.



3、Further improvement method

- LCW is cooled by CTW through heat exchanger
- **Winter:** Absorption heat pump driven by renewable energy sources such as solar thermal, recovering CTW waste heat to supply heating to heat users
- **Summer:** Using existing absorption heat pump unit (Utilizing PV Heat) to cool the CTW, not consuming the electricity, saving power.
- **Advantage:** Utilizing renewable energy sources such as solar thermal to recover waste heat for heating in winter and provide cooling energy to cool the CTW in summer, with less power consumption than conventional methods.



Advantages of AHP

- Solar energy has advantages of renewability and cleanliness. Comparing ① the required solar energy and ② heating supply capacity between the two different schemes, with the condition that utilize the solar energy and recover the same quantity of waste heat, can reveal the environmental and economic implications of each technology.
- **Two different schemes:**
  - Photovoltaic (PV) to power → electric driven heat pumps (EDHP)
  - Photovoltaic (PV) to heat → absorption heat pumps (AHP)
  - Recovering **14MW waste heat from 1 site** (221MW/16 sites);

Conclusion:

✓ For the same recovery of 14MW of waste heat:

- PV to heat → AHP solution requires **25% less** solar energy than the PV to power →EDHP solution;
- PV to heat → AHP solution provides **50% more** heating energy than the PV to power →EDHP solution;

✓ ***A smaller initial investment for a larger gain.***

(1) PV to power → EDHP:

Required PV energy to power: $W_E = \frac{Q_W}{COP_{EDHP}-1} = \frac{14MW}{3-1} = 7MW$; COP_{CHP} is the coefficient of performance of EDHP

Required solar energy: $W_S = \frac{W_E}{\eta_{PV}} = \frac{7MW}{15\%} = 46.67MW$, η_{PV} is the coefficient of solar photovoltaic efficiency

heating supply capacity: $Q_S = Q_W + W_E = 14MW + 7MW = 21MW$

(2) PV to heat → AHP:

Required PV energy to heat: $Q_H = \frac{Q_W}{COP_{AHP}-1} = \frac{14MW}{1.8-1} = 17.5MW$, COP_{AHP} is the coefficient of performance of AHP

Required solar energy: $W_S = \frac{Q_H}{\eta_{PT}} = \frac{17.5MW}{50\%} = 35MW$; η_{PT} is the PV to heat efficiency

heating supply capacity: $Q_S = Q_W + Q_H = 14MW + 17.5MW = 31.5MW$

What is the efficiencies difference between PV to power and PV to heat?

EDHP

PV→power→heat

15% * 3 = 45%

(1) (2)

AHP

PV→PV heat→heat

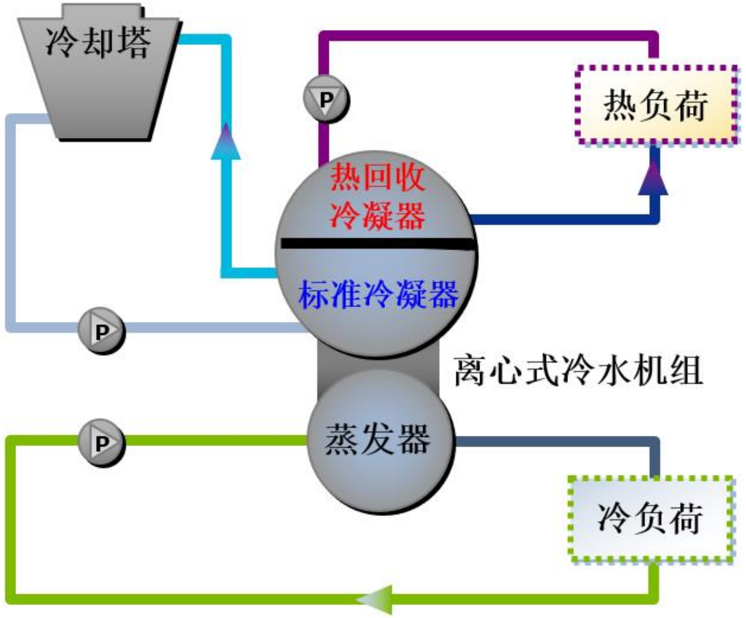
50% * 1.8 = 90%

(3) (4)

1. GB/T 39857-201
2. GB/T 18430
3. GB/T 17581-2021
4. GBT 34620-2017

HEPS Waste Heat Sources Utilization

- A heat recovery chiller unit is used to recover waste heat typically discharged into the atmosphere through cooling towers. While meeting the cooling load, this system utilizes the byproduct of refrigeration operation, which is waste heat, to produce inexpensive hot water. Simultaneously, it reduces the heat emissions and noise from the cooling tower, thereby mitigating the "heat island effect" in the city.
- HEPS (presumably a facility or system) has installed four heat recovery chiller units: 2 * 5500 kW and 2 * 2800 kW. During operation, it can provide a maximum of approximately 13 MW of recovered heat energy at 42° C.
- The maximum heat load for HEPS is 10,413 kW in winter and 4,117 kW in summer. When the system is running, the recovered heat source can fully replace municipal heat sources.
- The equipment was installed and commissioned by the end of 2022.



Summary

- **The development of environmentally friendly, green and sustainable accelerator is one of the current hot topics;**
- **The comprehensive development of green accelerator requires a cross-section of management, municipal planning, energy recycling, specialized technology, theoretical innovation and other areas, and it is complex and difficult to coordinate all aspects of integrated consideration;**
- **Further green accelerator development & research works are still going on**
- **……**