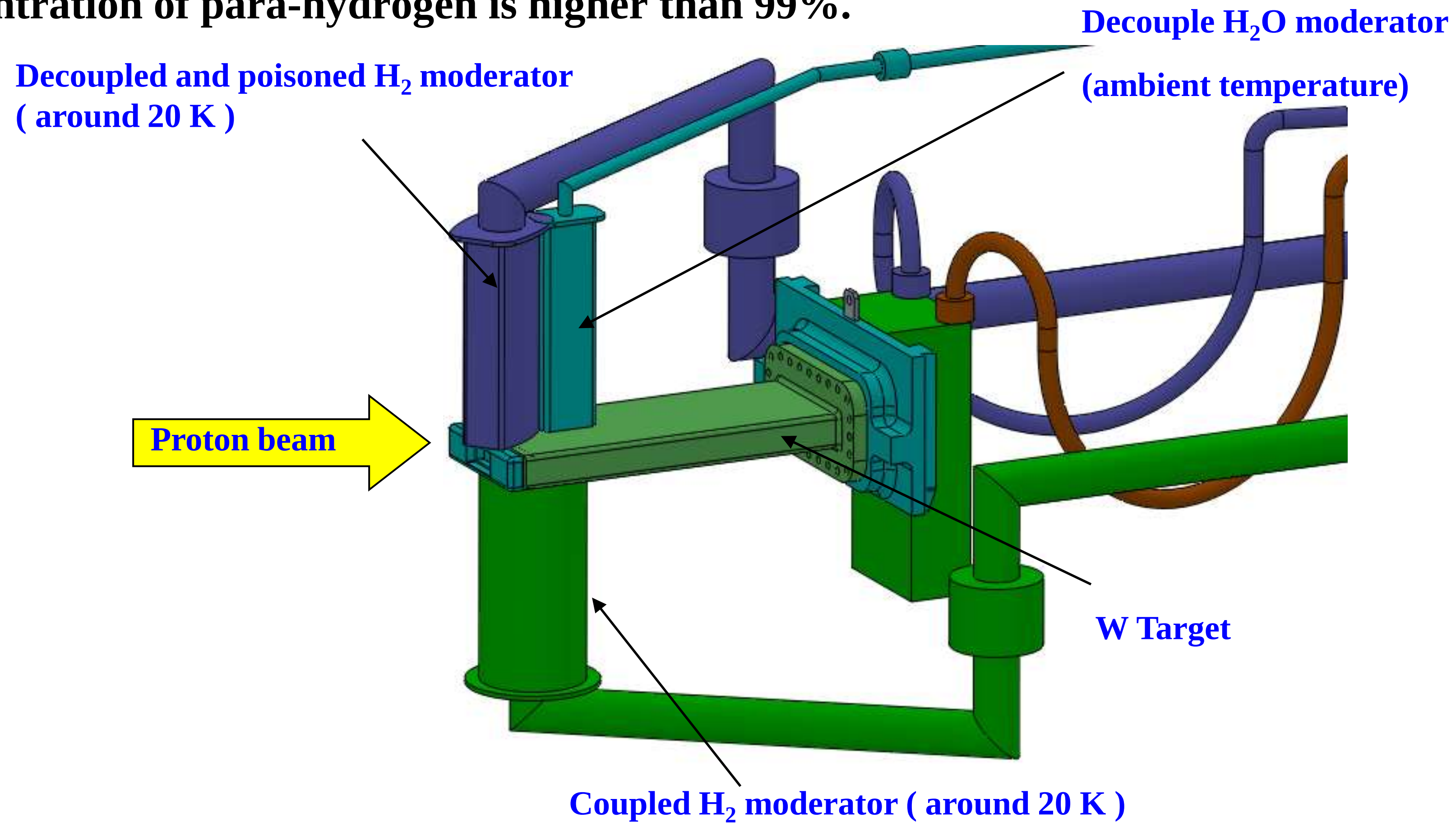
The Operation of
CSNS Cryogenic System

CSNS
CHINESE ACADEMY OF SCIENCES

Background

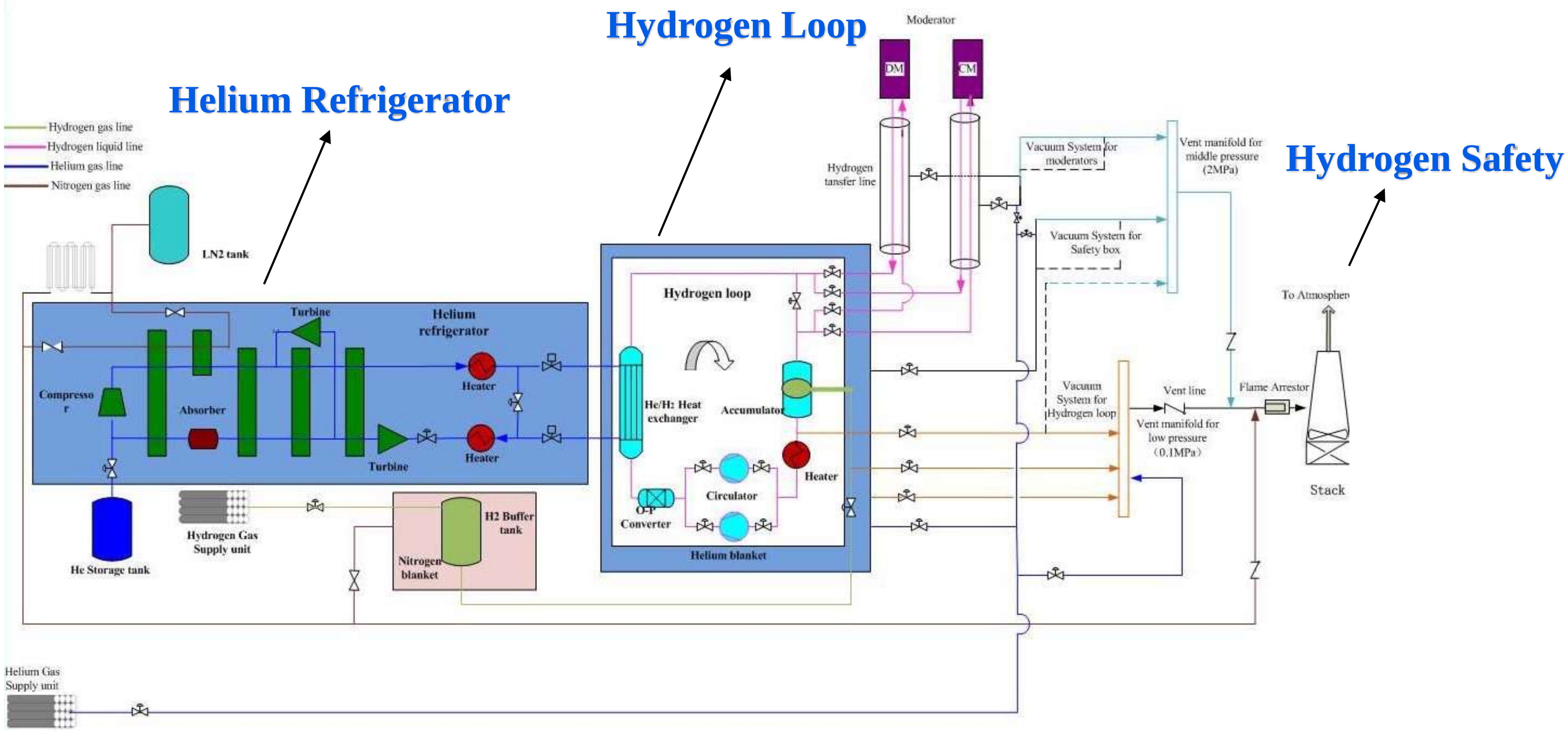
Requirements

- CSNS cryogenic system provides hydrogen at 19~21K@15bar to keep the average temperature of two moderators below 20K.
- Temperature difference is lower than 3 K between the entrance and exit of hydrogen moderator.
- Concentration of para-hydrogen is higher than 99%.



Background

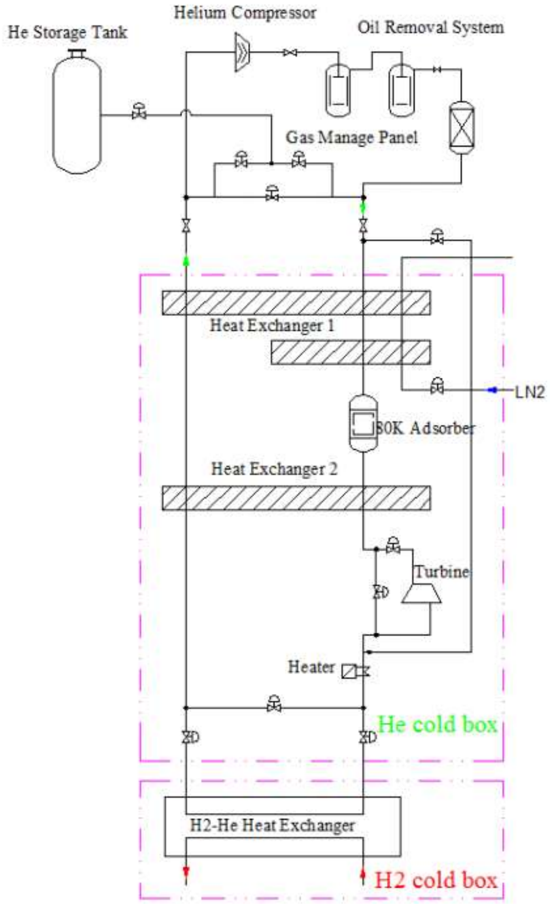
Flow diagram



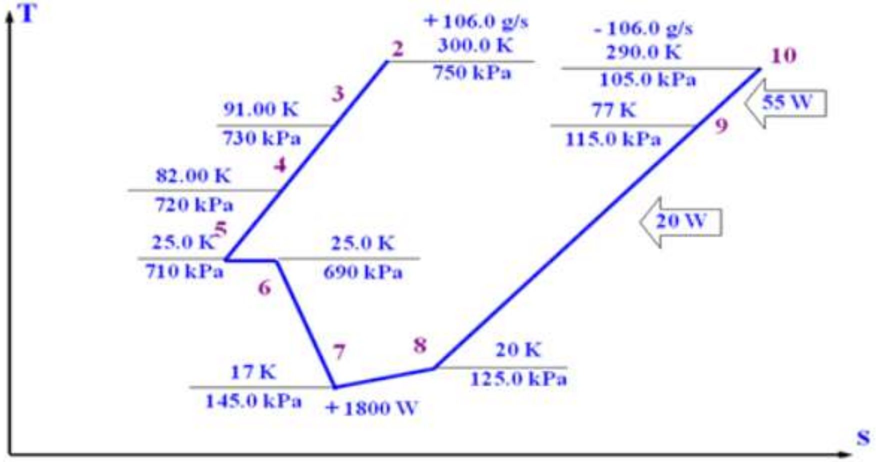
The cryogenic system's flow diagram comprises three core components: the helium refrigerator, the hydrogen loop, and hydrogen safety system.

Background

Helium Refrigerator



Parameter	Value
Cooling capacity	2.2 kW@20K
Compressor Power	200 kW
Discharge Pressure	8.0 bar
Suction Pressure	1.5 bar
Inlet temperature of H2/He HEX	16.5 K
Turbo expander efficiency	70%
Mass flowrate	80g/s

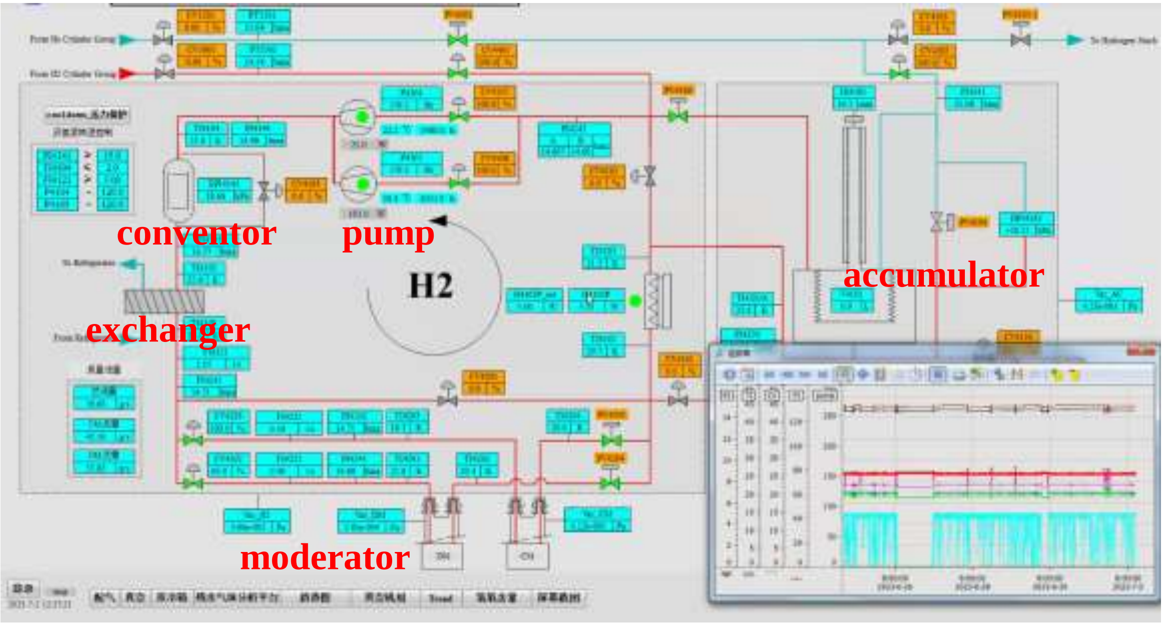



Helium compressor and oil remove system

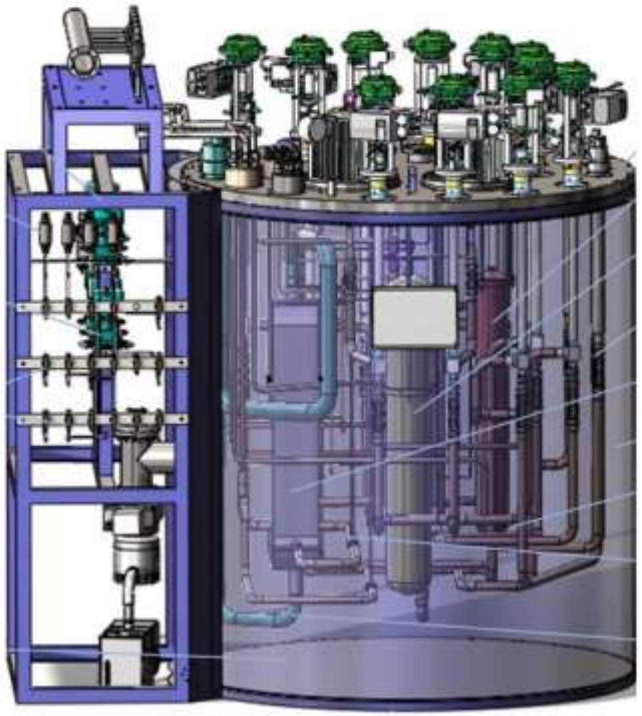

Helium cold box

This is the flowchart and photo of the refrigerator, primarily consisting of a compressor, oil separator, and cold box. It employs a modified Claude cycle with a minimum turbine outlet temperature of 16K, achieving cooling down and warming up processes of the hydrogen loop through a hydrogen-helium heat exchanger.

Hydrogen Loop



control Interface of hydrogen loop

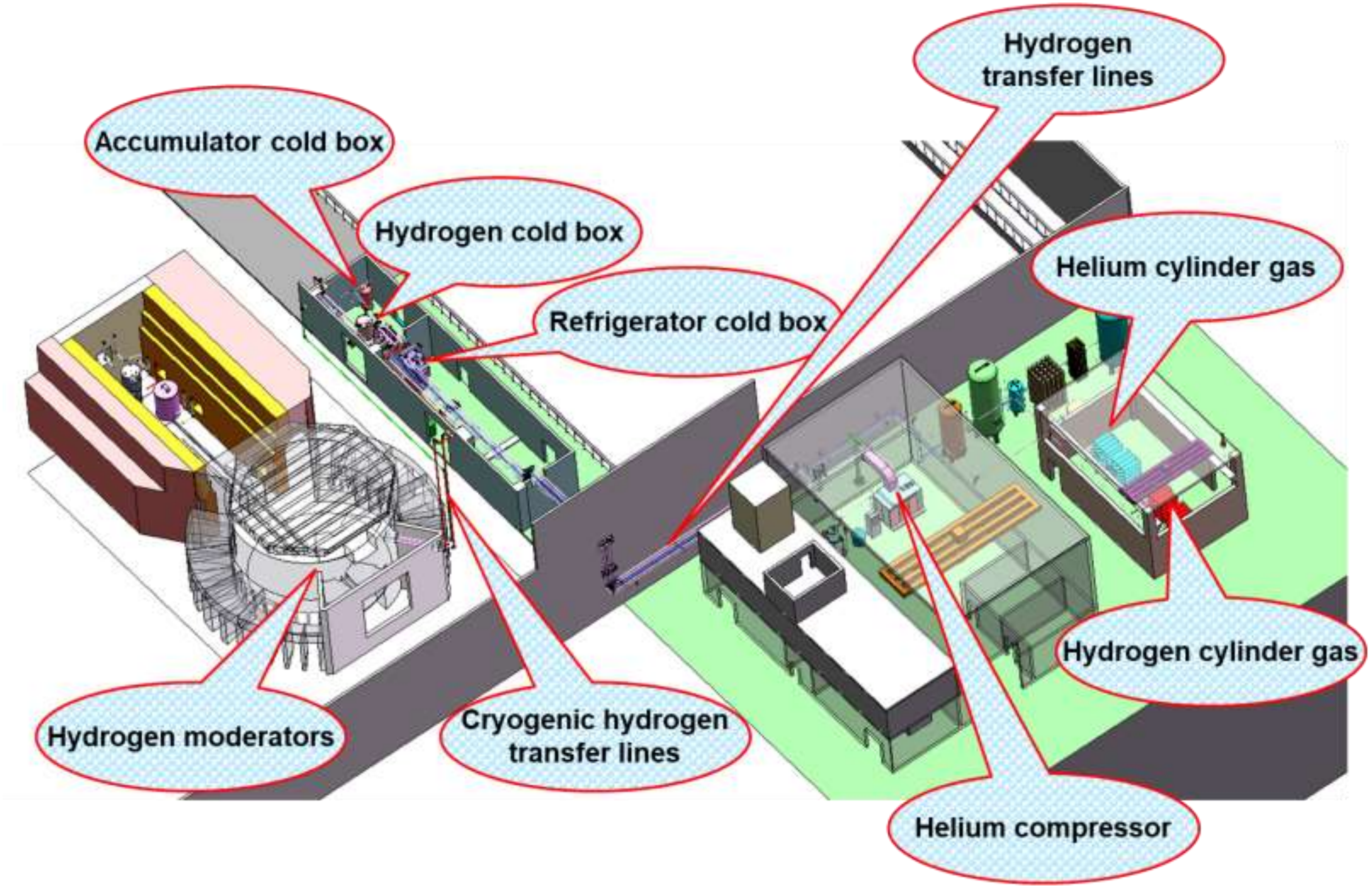


hydrogen cold box

accumulator box

The hydrogen loop consists of a hydrogen cold box and accumulator box. The core principle is : Liquid hydrogen is directed into the ortho-para hydrogen converter via hydrogen pumps. The heat generated during the conversion of ortho-hydrogen to para-hydrogen is rapidly dissipated by the hydrogen-helium heat exchanger, which effectively lowers the overall cycle's average temperature. Moderators are located downstream of the heat exchanger, which is the coldest point within the system. The accumulator, which located upstream of the pump, is used to maintain a stable inlet pressure.

Layout of CSNS cryogenic system



The helium compressor is located in the cryogenic hall, which is the lowest place of the entire cryogenic system.

The refrigerator cold box is placed near the hydrogen cold box, which could reduce the length of the cryogenic pipelines. It is helpful to reduce the thermal resistance.

The main equipment of the cryogenic hydrogen loop , including accumulator box and hydrogen cold box, are installed on the third floor of the target hall, which is highest position of target hall for hydrogen safety reason.

Background

Milestone

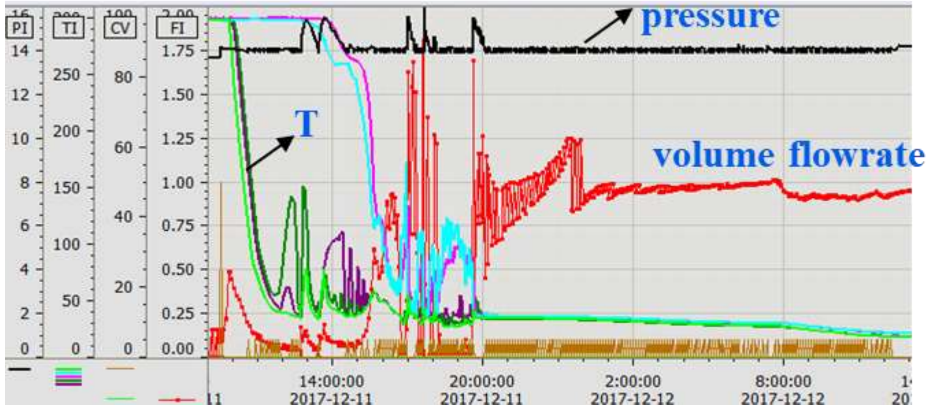
- 2016.8 Refrigerator commissioning
- 2017.6 Hydrogen loop commissioning
- 2017.8~9 First-round operation
- 2017.10~11 Second-round with proton beam targeting at 10 kW, 20 kW
- 2018.7 After 258 days trial operation, it entered official operation
- 2018.9~2022 More than 6000 hours per year at 100kW
- 2022~Today Increase the beam power to 140kW

The cryogenic system successfully completed its acceptance in 2017 and was officially operational from July 2018, guaranteeing more than 6,000 hours of annual operation. Even in the past year, with a power increase from 100kW to 140kW, it remained stable and reliable.

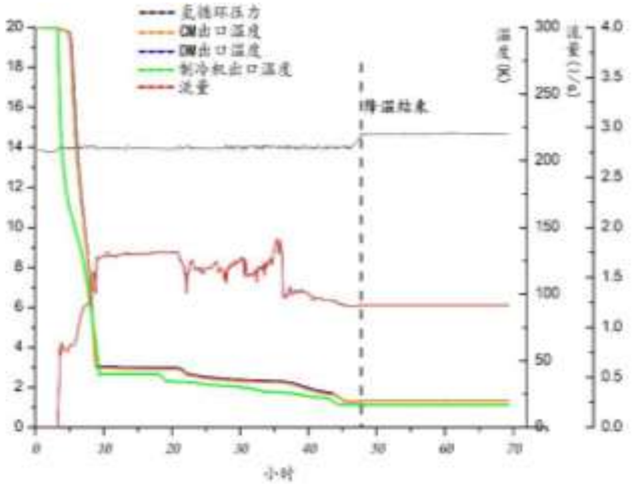
Normal Operation

Cool-down

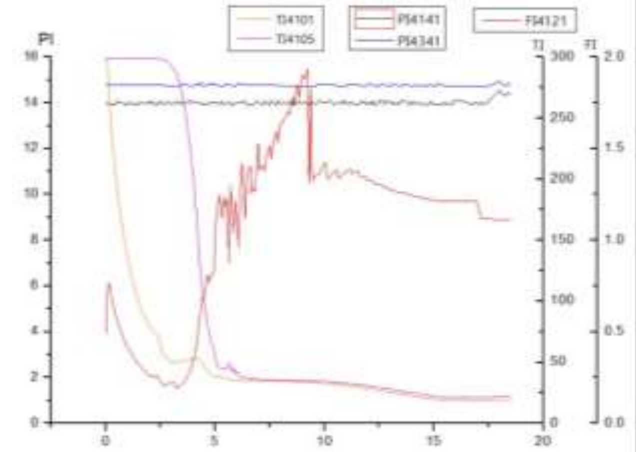
Typically, we perform cooling operations twice a year, following the Spring Festival and summer maintenance. The following chart depicts the annual cooling trends from 2017 to 2022.



2017



2019

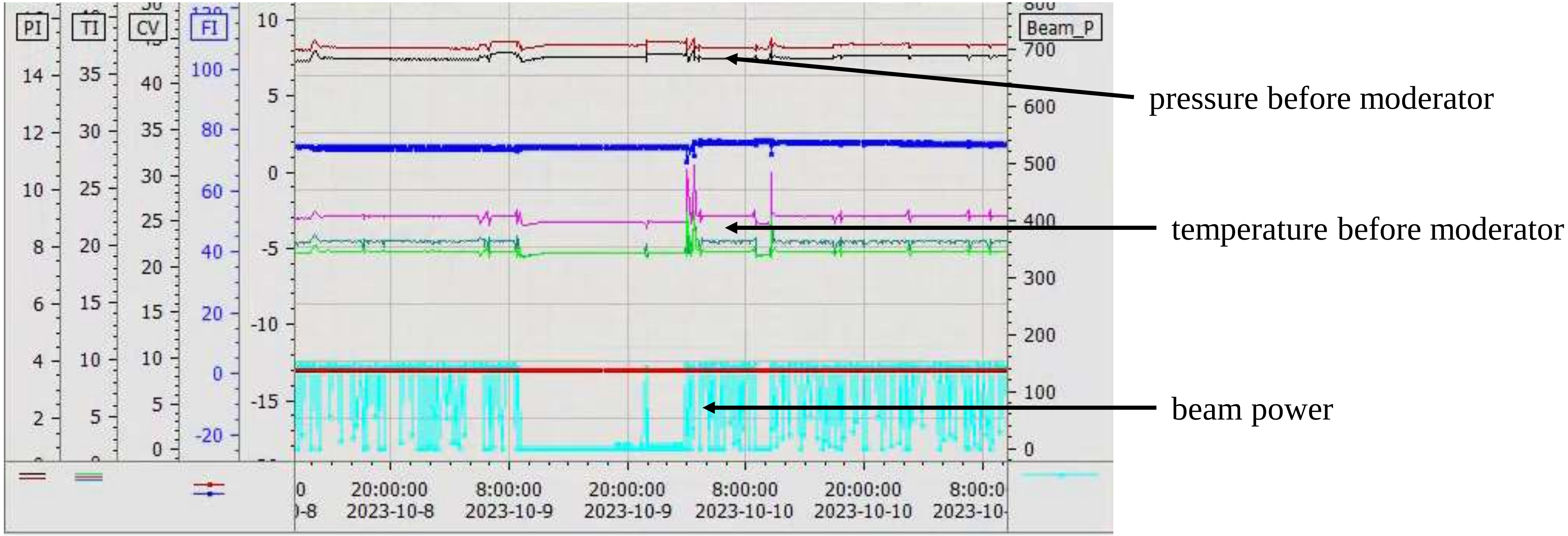


2021

- In 2017 and 2018, the cooling down process experienced substantial temperature and pressure fluctuations. However, through adjustments to the cooling down logic, we achieved a consistent temperature drop without further fluctuations during the cooling process in 2019.
- Over the past three years, we have managed to reduce the cooling time gradually from 48 hours to 24 hours, maintaining a high level of stability and repeatability.
- As the cryogenic system's control logic continues to improve, manual interventions have significantly decreased, and we have effectively transitioned to automated cooling procedures.

Normal Operation

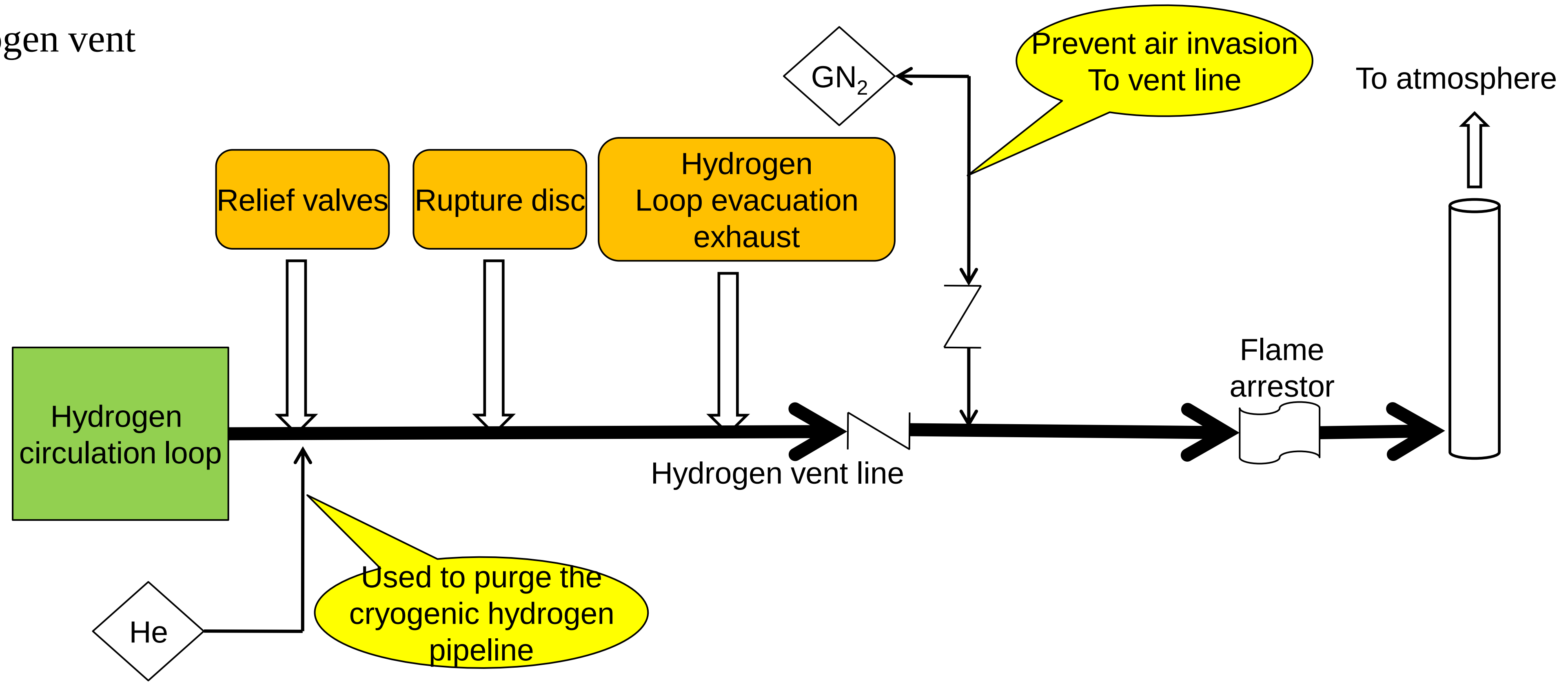
ready



When the beam power is supplied and withdrawn frequently, the cryogenic system experiences significant pressure and temperature fluctuations. To maintain system pressure stability, we employ an accumulator and electric heater. When pressure changes occur, accumulator can additionally supply up to 4 liters of liquid hydrogen to the system. During beam power withdrawal, the electric heater provides a thermal load that equivalent to the beam power, to keep the load stable.

Through these measures, we have maintained the moderator pressure within the range of 14.4-14.8 bara, with a maximum temperature fluctuation of less than 3 K, and the system can return to stability within half an hour.

1、Hydrogen vent



Hydrogen is primarily concentrated in the hydrogen cold box, accumulator box, moderator, and cryogenic transfer pipelines. All safety valves and bursting discs are connected to the hydrogen vent pipeline, which releases hydrogen into the atmosphere on the roof.

① The hydrogen vent system is required to be capable of rapidly discharging all hydrogen within the system.

② Nitrogen is continuously passed through the hydrogen vent system at a low flow rate to prevent external air from entering the system and maintain a positive pressure within it.

③ To provide fire prevention and prevent flames from entering the system, a flame arrester, a check valve, and a spark detector are installed at the end of the hydrogen vent system.

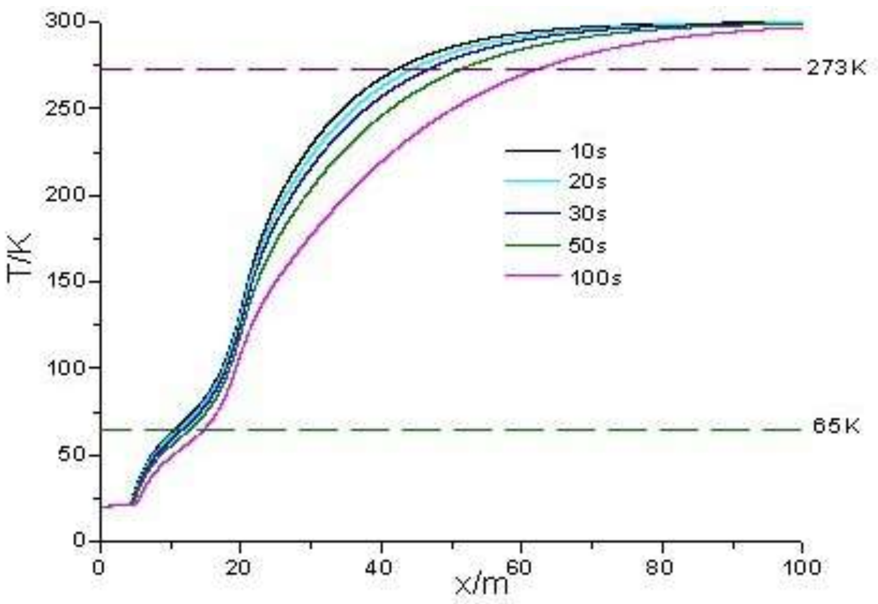
Hydrogen Safety

1、Hydrogen vent

In emergency vent mode, the 20K cryogenic hydrogen is directly discharged into the hydrogen vent pipe.

- At the outlet of the vent pipe, the temperature of the hydrogen must be maintained above the temperature of liquid air (about 81K) to prevent the backflow of liquid air.
- The temperature of the hydrogen should be kept above the freezing point of nitrogen at the point where the vent pipe connects to the nitrogen pipe.

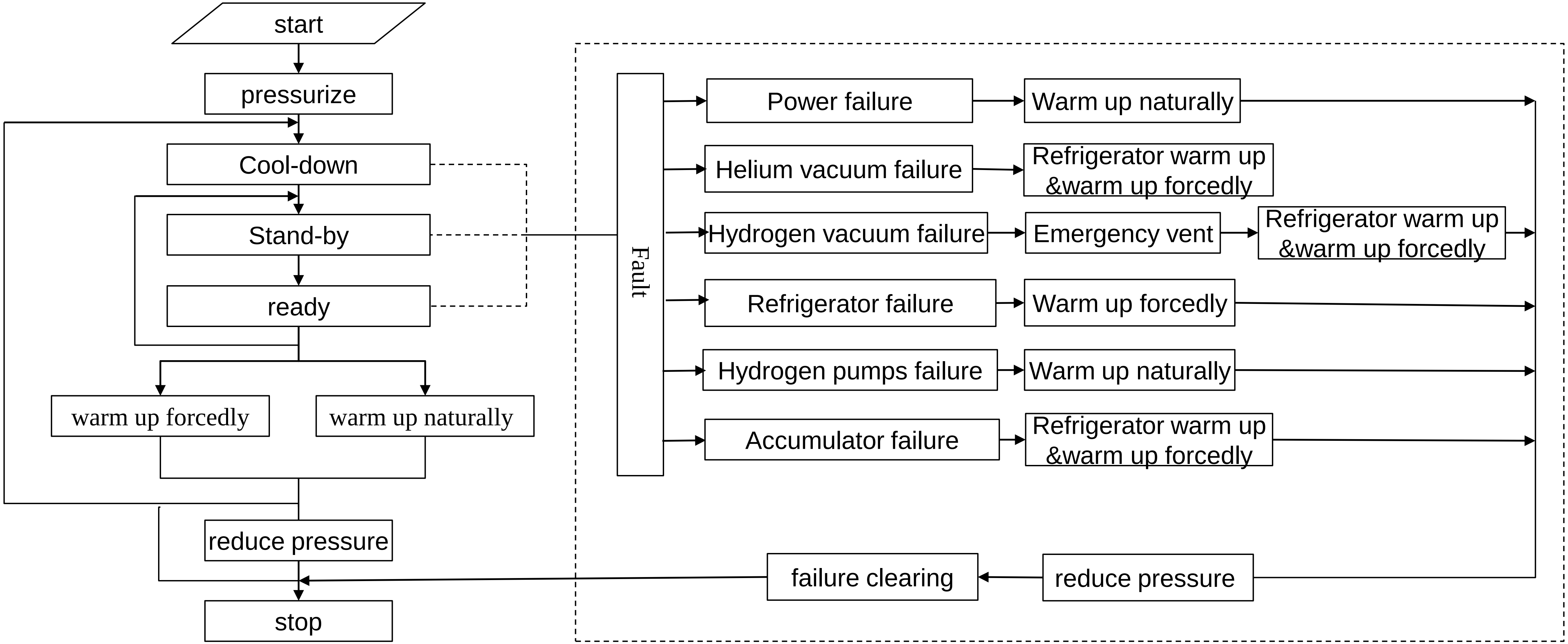
Part of hydrogen vent line



Hydrogen temperature distribution in the tube

Based on the calculation, it has been determined that the junction point of the hydrogen and nitrogen must be positioned 14.8m downstream, and the total length of the hydrogen vent pipe must exceed 19 m.

Hydrogen Safety

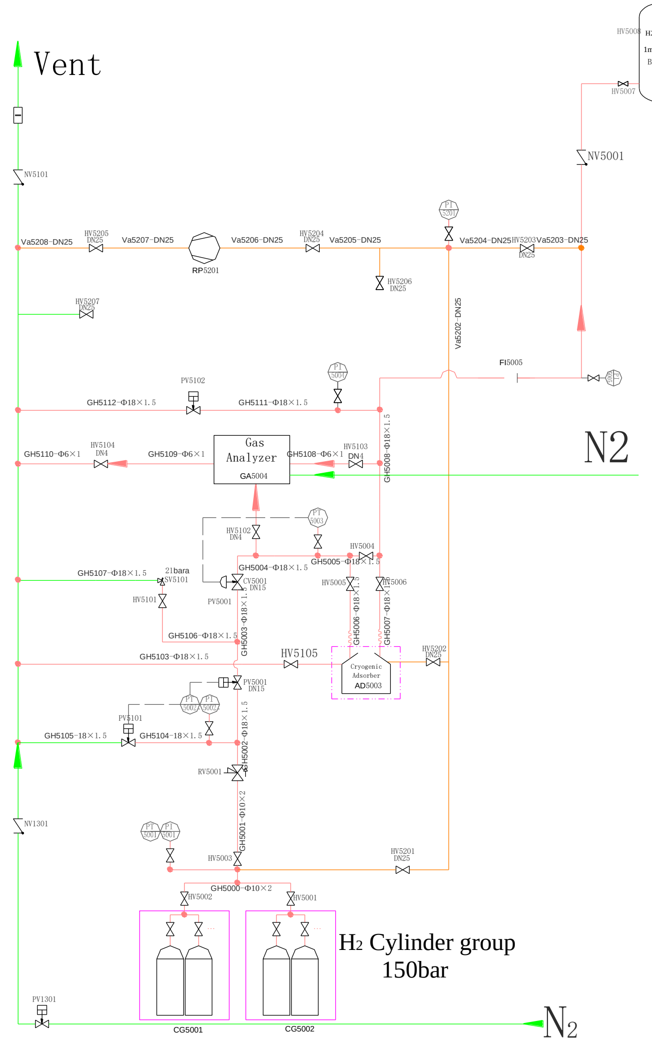


Interlock is the core of the entire system's stability and safe operation. After the system pressurizes and cools down, it goes into a stand-by mode once it's in position. The central control at the target station can supply the beam power upon receiving our 'ready' signal. In case of a malfunction, the system will initiate interlocks based on the type of fault. Beyond forcedly warm up and naturally warm up modes, there is also an emergency vent mode, which rapidly expels hydrogen from the system to ensure safety.

Hydrogen Safety

2、hydrogen supply

	Monitoring object	Value	Action
Hydrogen supply	Pressure after regulator (PT5001)	＜19bara	Check the cylinder pressure
	Pressure before H2 buffer (PT5002)	>20bara	alarm, open the relief valve
		>21bara	Safety valve



When the pressure at the outlet of the regulator falls below 19 bara, the person on duty should conduct an inspection in the gas room. This inspection should involve checking the pressure of the hydrogen cylinder and assessing if there are any leaks in the gas distribution hose. If it is determined that the pressure is inadequate, the hydrogen cylinder should be replaced

When the pressure upstream of the hydrogen buffer tank exceeds 20 bara, an alarm signal is triggered, and the relief valve is activated to safeguard the downstream equipment from potential damage. If the pressure surpasses 21 bara, the safety valve will open automatically to release excess pressure

Hydrogen Safety

3、vacuum

	Monitoring object	Value	Action
Vacuum	hydrogen cold box, accumulator box, refrigerator box, cryogenic transfer lines	≥1Pa	alarm，stop the molecular pump

We utilize five sets of molecular pumps in conjunction with mechanical pumps to evacuate the hydrogen cold box, accumulator, refrigerator box, and two cryogenic pipelines. This evacuation process ensures that the pressure within the vacuum interlayer remains below 10e-3.

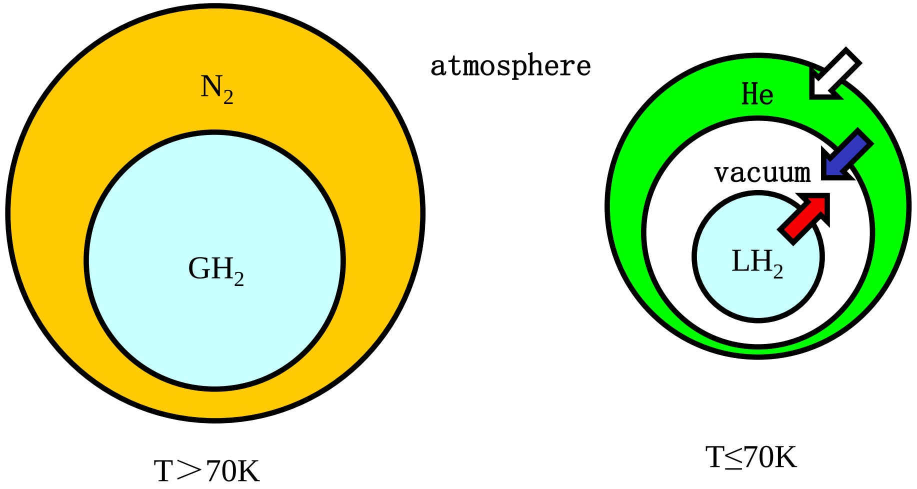
In the event that the pressure exceeds 1Pa, an alarm signal is triggered, and the molecular pump is halted. The duty personnel then conduct an inspection to identify any potential air, helium, or hydrogen leakage. Based on their assessment, they make a determination on whether to initiate a warming-up procedure as necessary.

3、protective layer

Monitoring object	Value	Action
Pressure of N_2 layer	≤1.2bara or ≥1.5bara	open the supple or relief valve
	≤1bara or ≥2bara	alarm, warm up forcedly
Pressure of He layer	≤1.2bara or ≥1.5bara	open the supple or relief valve
	≤1bara or ≥2bara	alarm, check the vacuum

The hydrogen pipeline in the target station hall is designed with a gas protective layer. The room-temperature hydrogen pipeline is safeguarded by N2, while the cryogenic hydrogen pipeline is protected by He in addition to the vacuum layer.

The pressure of the N2 and He layers is automatically regulated within the range of 1.2 to 1.5 bara. If the N2 pressure exceeds this adjustment range, an alarm will be triggered, and the system will undergo a forced warm-up process. However, when the He pressure exceeds the adjustment range, and the vacuum layer pressure remains stable, normal operation can be sustained until a scheduled periodic shutdown.



Hydrogen Safety

3、hydrogen loop

Monitoring object	Value	Action
Pressure before moderator	≤13.9bara	open the supple valve
	≥15.5bara	alarm，open the relief valve
	≥17bara	safety valve
	≥18bara	bursting disc
Temperature after moderator	≥22K	alarm
Hydrogen pumps	Failure	alarm，warm up naturally
accumulator DPI4142	≥120kPa or ≤-80kPa	alarm
Refrigerator	Failure	alarm，warm up naturally

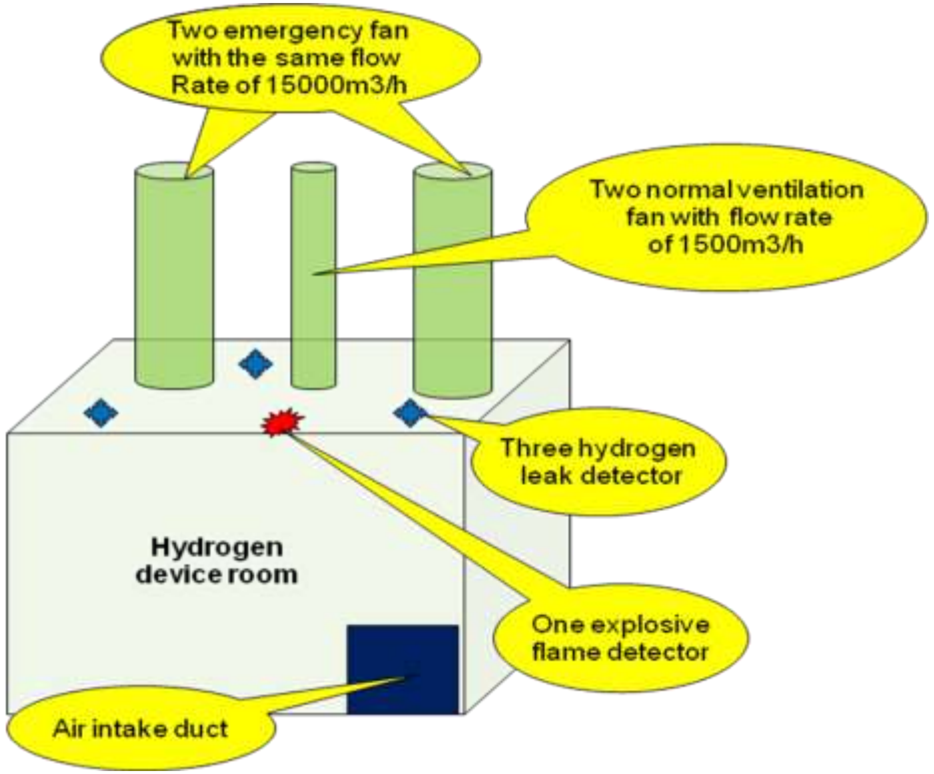
The hydrogen loop is designed to maintain the pressure within the range of 14 to 15 bara. If the pressure cannot be adjusted and continues to rise, safety valves and bursting discs are employed as safety measures.

In addition, when the temperature exceeds 22K, an alarm signal will be activated. The duty personnel will then conduct an inspection to determine if there is any leakage or a failure in the refrigerator.

Hydrogen Safety

4、hydrogen leakage

	Monitoring object	Value	Action
Hydrogen content	hydrogen leakage detector	>1%	start emergency fans
		>4%	alarm, emergency vent
		>25%	fire alarm



In the hydrogen equipment room, three hydrogen leakage detectors are installed. These detectors are set to trigger an alarm when the hydrogen concentration in the air reaches 25% of the lower explosive limit.

- When two detectors simultaneously detect hydrogen concentrations exceeding 1%, two emergency fans with a combined flow rate of 30,000m³/h are activated to ventilate the area.
- If the hydrogen concentration exceeds 4%, the emergency vent mode is initiated.
- In the event that the hydrogen concentration exceeds 25%, a fire alarm is activated, and a PPS (Personnel Protection System) signal is sent to the target station. Additionally, all power supplies above 220V are disconnected, with the exception of fans and lighting.

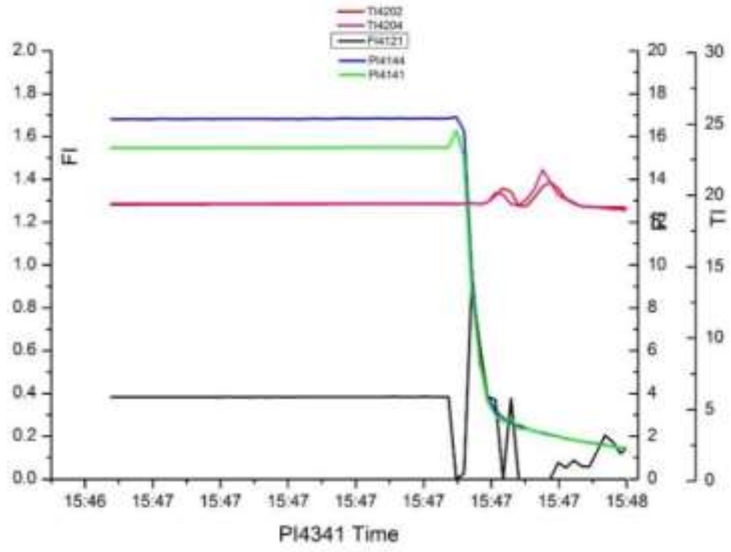
Troubles and Failures

Hydrogen supply regulating valve CV5001 failure(2019.11.08)

At 14:47, there was a sudden and significant increase in hydrogen loop pressure, exceeding the bursting disc's set value, which led to an emergency discharge of liquid hydrogen.

Cause: The incident was triggered by the need for critical tasks, such as replacing the bursting disc and conducting helium purging. The cryogenic system was re-cooled down at 21:00. Early on the morning of the 11th, during the cooling process, pressure began to rise uncontrollably, necessitating a prolonged deflation. Upon inspection, internal leakage in the hydrogen supply valve CV5001 was discovered.

Solution: To address the issue, the pneumatic ball valve at the front end of CV5001 was synchronized for opening and closing, and the faulty valve was replaced during the summer maintenance period. The fault resolution took a total of 73 hours.



Pressure and temperature changes during the failure

Replace bursting disc

Troubles and Failures

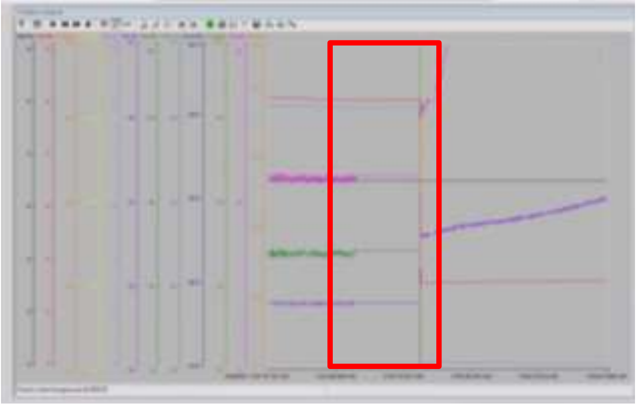
UPS failure(2023.03.26)

At 05:54, an alarm indicating the compressor shutdown was triggered and the system was in a warming-up state.

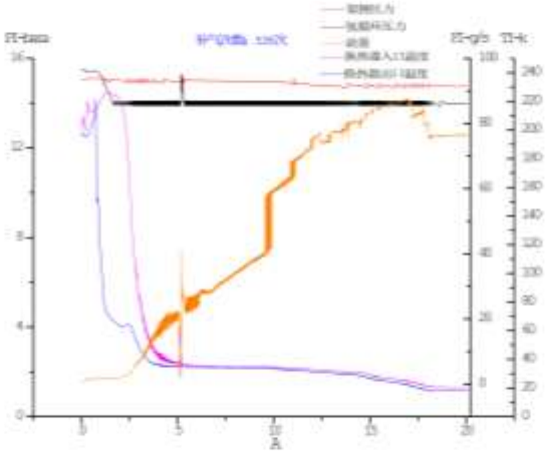
Cause: Upon inspecting the refrigerator room, our attention was drawn to an issue with the Uninterruptible Power Supply (UPS) that had switched to bypass, and the panel indicated that the inverter was OFF. To uncover the root cause of the incident, we reviewed the historical data of the refrigerator and confirmed that the control system lost power for one minute. This confirmed that the UPS was the source of the failure.

Compressor voltage restored

UPS switched to bypass



Control system lost power



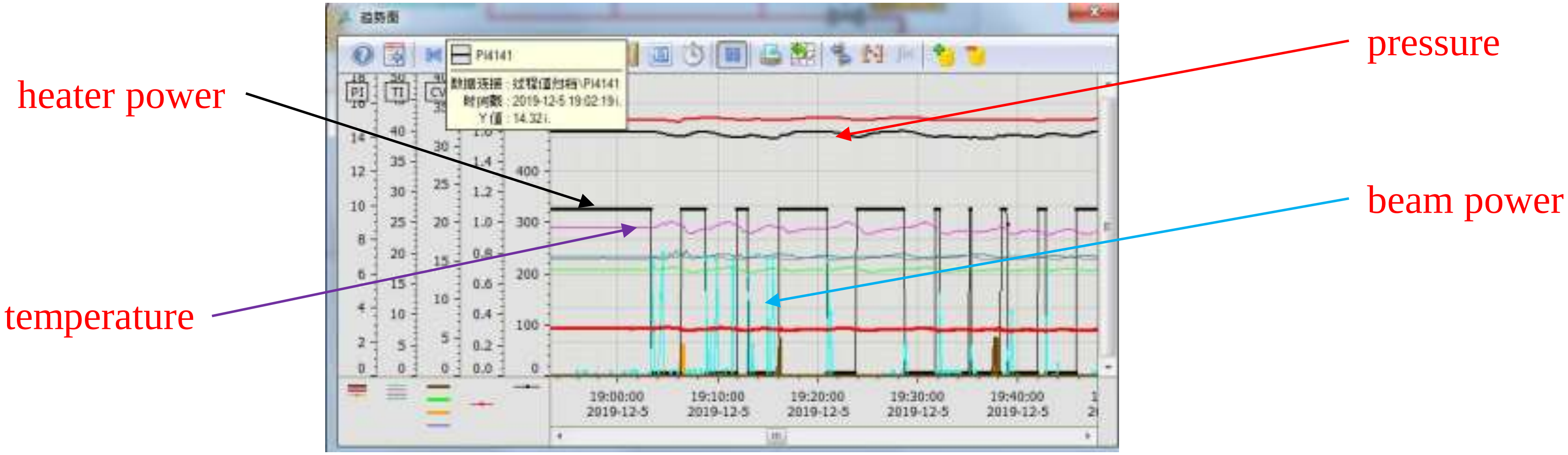
Cooling down again

Solution: We replaced the UPS and initiated the system's cooling process in the 230K temperature zone at 18:30 and successfully completed the cooling by 14:30 on the 27th, which took about 20 hours.

Troubles and Failures

Beam fluctuation troubles

Due to the frequent cycling of the beam power and heater power, the actual heat load generated by the heater couldn't compensate for the dynamic heat load from the beam. This led to fluctuations in flow, temperature, and pressure. The issue was resolved by optimizing the logic of the heater and refrigerator, eliminating these significant temperature fluctuations.



Hydrogen pumps troubles

The hydrogen pumps have encountered multiple failures. However, thanks to the parallel operation of two hydrogen pumps, the backup unit has been able to sustain the system's operation until the scheduled summer maintenance. During both the summer maintenance and New Year period, one of the hydrogen pumps will be replaced.

Summary

Since 2018, we have consistently ensured over 6,000 hours of annual operation, with decreasing response times for troubleshooting. Moreover, thanks to the comprehensive design for hydrogen safety, no safety incidents have ever occurred.

	Operation time	Failures	
2018	6192h	0h	/
2019	6185h	73h	Hydrogen supply valve failure
		70h	Hydrogen pump failure
		70h	Hydrogen pump failure
2020	6900h	0h	/
2021	6840h	50h	Hydrogen pump failure
2022	6480h	30h	Ups failure

Thanks！