

# Operational Experiences of J-PARC cryogenic hydrogen system for a spallation neutron source

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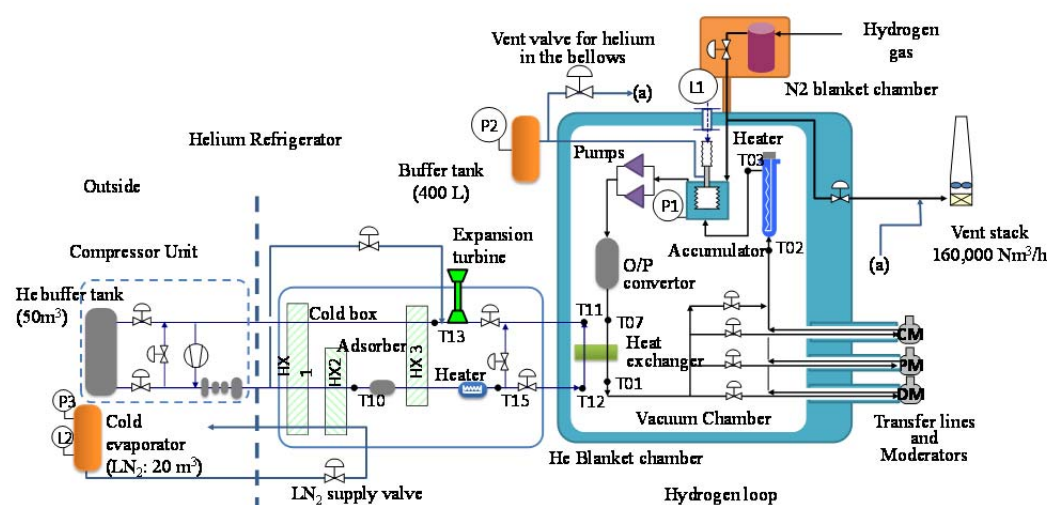
**Abstract.** The Japan Proton Accelerator Research Complex (J-PARC) cryogenic hydrogen system was completed in April 2008. The proton beam power was gradually increased to 500 kW. A trial 600-kW proton beam operation was successfully completed in April 2015. We achieved long-lasting operation for more than three months. However, thus far, we encountered several problems such as unstable operation of the helium refrigerator because of some impurities, failure of a welded bellows of an accumulator, and hydrogen pump issues. Furthermore, the Great East Japan Earthquake was experienced during the cryogenic hydrogen system operation in March 2011. In this study, we describe the operation characteristics and our experiences with the J-PARC cryogenic hydrogen system.

## 1. Introduction

At Japan Proton Accelerator Research Complex (J-PARC), high-energy MeV-order neutrons, which are produced via a spallation reaction between 3-GeV protons and the mercury nucleus, are moderated to cold neutrons of MeV-order energy, which are suitable for neutron scattering experiments, by passing them through three types of cryogenic hydrogen moderators (coupled, decoupled, and poisoned). We developed the cryogenic hydrogen system for the J-PARC spallation neutron source, as shown in Figure 1. Cryogenic hydrogen with a para-hydrogen concentration of more than 99 % at a pressure of 1.5 MPa, which is supercritical pressure, and temperature of 18 K is supplied to the three moderators, and it removes 3.8 kW of nuclear heating during 1-MW proton beam operation [1]. Two hydrogen pumps with dynamic gas bearings are simultaneously operated in parallel for redundancy and circulate the cryogenic hydrogen at the supercritical pressure at a flow rate of 0.19 kg/s. The temperature rise because of nuclear heating during operation of the 1-MW proton beam is estimated to be 2.4 K. There was a concern that the slight temperature rise could lead to a large pressure rise in the hydrogen loop because the hydrogen behaves as incompressible fluid. We prepared a heater for thermal compensation and an accumulator, which can spontaneously change the volume of the hydrogen loop via the expansion and contraction of bellows, so as to maintain the pressure fluctuation below an allowable value of 0.1 MPa [2].

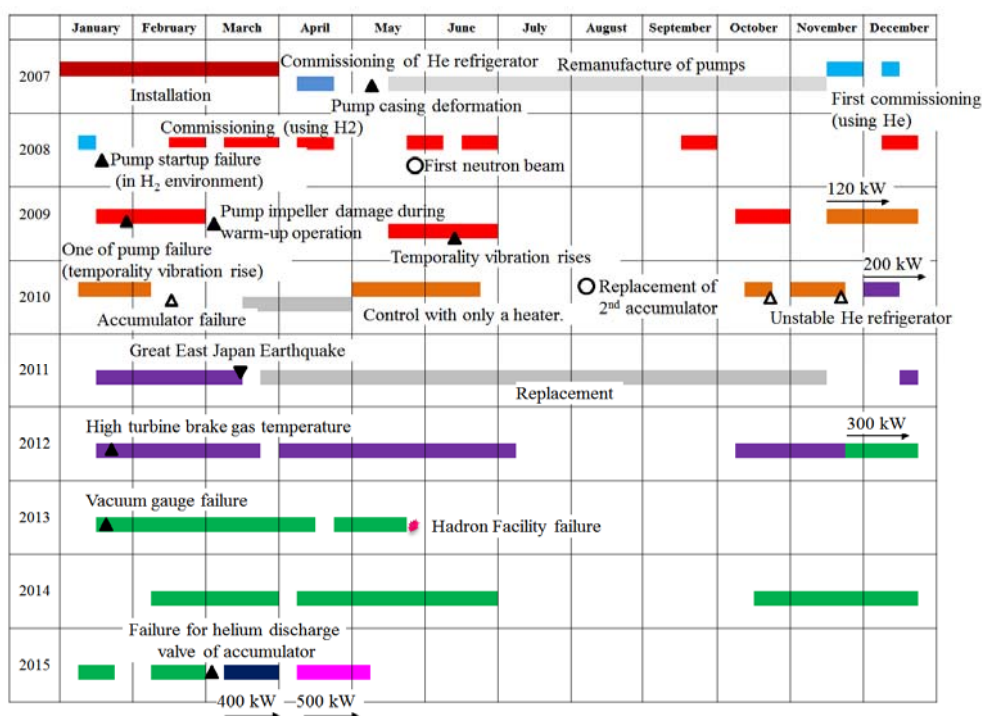
Figure 2 shows the operation status of the cryogenic hydrogen system thus far. The cryogenic hydrogen system was installed from August 2006 to March 2007. The commissioning of only the helium refrigerator was conducted without the hydrogen loop [3]. We confirmed that the helium refrigerator had a refrigerator power of 6.45 kW at 15.6 K with a flow rate of 260 g/s and liquid





**Figure 1.** Schematic of the J-PARC cryogenic hydrogen system

nitrogen consumption of 18.6 g/s as expected. The commissioning of the entire cryogenic hydrogen system has been conducted since November 2007. We performed the first cryogenic tests using helium instead of hydrogen. The operational control approaches were established and the operation parameters were optimized. The first cryogenic test with circulation of supercritical hydrogen was adjourned because of an unexpected issue with the hydrogen pump. However, the cryogenic hydrogen system was successfully cooled down to the rated condition within 19 h for the first time in March 2008 [4]. Toward the end of May 2008, we succeeded in generating the first cold neutron beam at JSNS. The proton power smoothly increased, although the J-PARC facilities were stopped for nine months because of the Great East Japan Earthquake in March 2011. Stable 500-kW proton beam operation has been conducted since April 2015. The plan is to increase the proton beam power toward



**Figure 2.** Operation status of the cryogenic hydrogen system.

our goal of 1-MW in 2016. In this study, the operational characteristics of the J-PARC cryogenic hydrogen system and our experience in dealing with the associated issues are introduced.

## 2. Normal operation

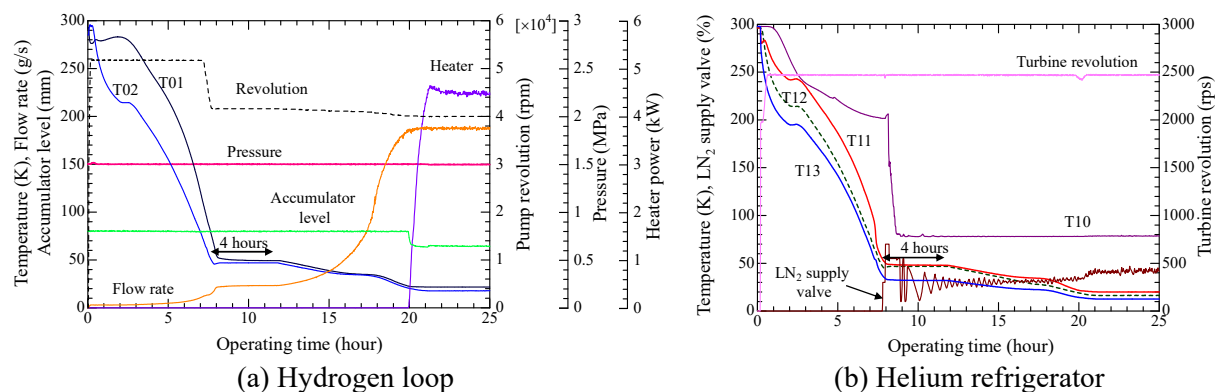
According to the J-PARC accelerator operation plan, we normally conduct cool-down operations thrice annually. The cryogenic hydrogen system can be operated almost automatically using an operational control approach, which comprises cool-down, beam injection, stand-by, warm-up, and quick hydrogen discharge modes.

Before supplying hydrogen, helium and nitrogen are enclosed in inert gas blankets where the pressure is maintained at 0.155 MPa, which is slightly higher than the atmospheric pressure. Figure 3 shows an example of a recent cool-down operation profile. The hydrogen loop, where the pressure is always maintained at 1.5 MPa, is cooled from ambient temperature to approximately 20 K by the helium refrigerator. The initial pump speed is 52,000 rpm, and a hydrogen flow of a few g/s circulates approximately at room temperature. At 45 K, which is slightly higher than the pseudo-critical temperature, the cool-down operation is temporarily held for 4 h to supply liquid nitrogen for precooling and to directly adjust the cooling rate using the heater. The cool-down operation is completed within 22 h, and the operation mode automatically transitions to the steady-state mode.

In the rated condition, we can choose two operation modes: standby and beam injection. During short maintenance periods of less than a week, we conduct the operation in the standby mode, whereby the helium refrigerator is operated without liquid nitrogen precooling so as to reduce liquid nitrogen consumption. During normal operation, we supply 7 m<sup>3</sup> of liquid nitrogen to the cold evaporator thrice a week.

We prepared a cryogenic accumulator with bellows [2] and a heater to compensate for nuclear heating when the proton beam is switched off to maintain the pressure fluctuation because of switching on and off of the proton beam within the allowable limit of 0.1 MPa. The heater exit temperature is always maintained at 20.95 K using a PI control. At this temperature, the heater power is 4.8 kW. After the proton beam is switched on, a certain temperature rise appears at the heater inlet (T02), and the heater power corresponding to nuclear heating is quickly reduced. Accordingly, the thermal balance at the heat exchanger remains virtually unchanged, and there is no fluctuation in the temperature of the hydrogen supplied to the moderators. The sequence of the heater control approach is called the “beam injection mode.” Dynamic behaviors in the hydrogen loop for 400-kW proton beam operation are shown in figure 4. As soon as the proton beam is switched on, the pressure rises. However, the pressure rise is controlled within the allowable limit via spontaneous contraction of the bellows. The temperature at the heater inlet rises at approximately 20 s after proton beam injection. The feed-forward heater control approach is able to mitigate the pressure and temperature fluctuations and maintain a constant supply temperature.

As shown in figure 5, for proton beam injection with a fairly short time, execution of the feed-forward control when the proton beam is off fails because of lack of temperature reduction at T02,



**Figure 3.** Cool-down operation

although it is successfully executed when the proton beam is on. The temperature fluctuation propagates over the hydrogen loop and the pressure temporarily decreases to 20 kPa. The pressure fluctuation is continued until the temperature at T03 is adjusted to the setvalue of 20.95 K by feedback heater control. Thus far, in such a case, resumption of the proton beam operation had to wait until the fluctuations disappeared. In 2005, we improved the operational program to automatically avoid the stagnating problem.

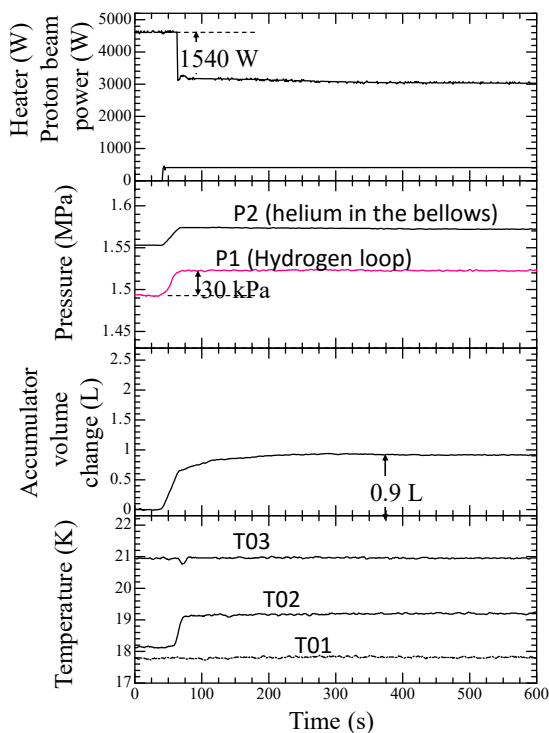
After beam operation for user programs, all hydrogen is discharged through a ventline, whereas nitrogen and helium gas are always purged. The hydrogen is diluted below the lower explosion limit at the stack with a huge flow rate of 160,000 Nm<sup>3</sup>/h. If an off-normal event occurs, we quickly discharge hydrogen for safety reasons. Furthermore, we prepare “quick hydrogen discharge mode” for emergency use, whereby most of the hydrogen can be discharged by supplying helium to the vacuum chamber at pressures of up to 6 kPa. Although we already confirmed this during commissioning, we have never executed said mode since May 2008.

### 3. Troubles and failures

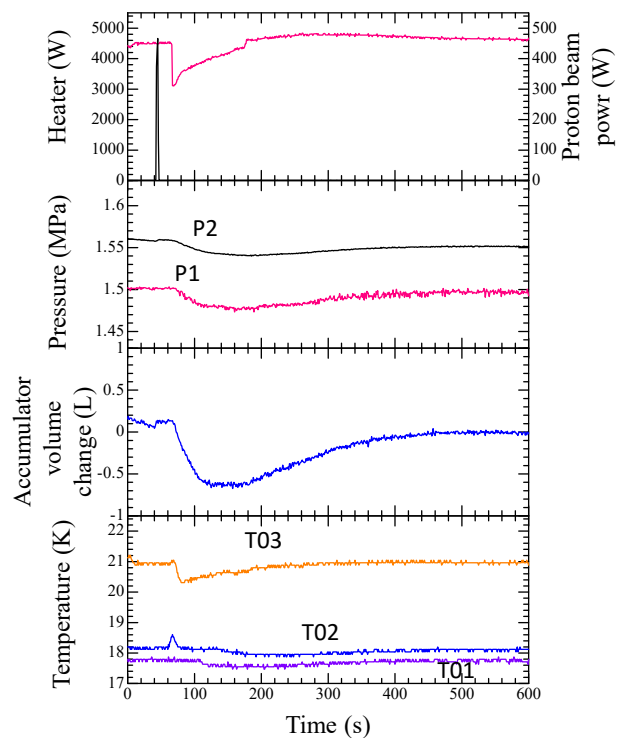
#### 3.1. Set-up failure of hydrogen pump

Figure 6 shows a centrifugal pump with a dynamic gas bearing. A foil-type self-acting gas dynamic bearing is adopted as the journal bearing. The clearance between the casing and the G10 block is set to 0.2 mm to reduce heat inleak. The allowable revolution speed ranges from 30,000 rpm to 63,000 rpm, and the allowable pump head is 120 kPa. The space where the motor is placed is filled with ceramic balls to reduce the amount of hydrogen gas passing through the gas bearings because of the pressure fluctuations in the hydrogen loop.

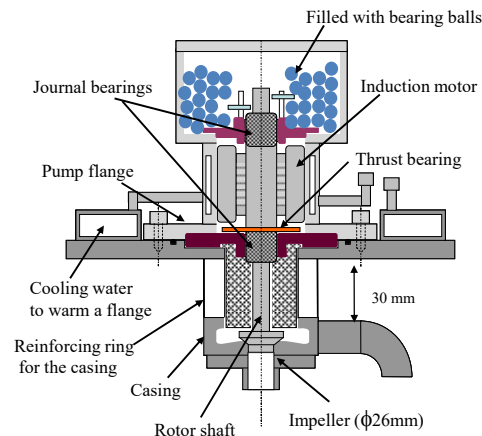
In December 2007, the pumps could not be started in hydrogen environment because of motor overload, even after we had completed the cryogenic test in helium environment in November. We thought that this was because of increased static friction at the journal bearing and unstable gas membrane stiffness because of lower density and viscosity. We found through infrared-ray



**Figure 4.** Behaviors under 400-kW beam injection.



**Figure 5.** Behavior under short beam injection.



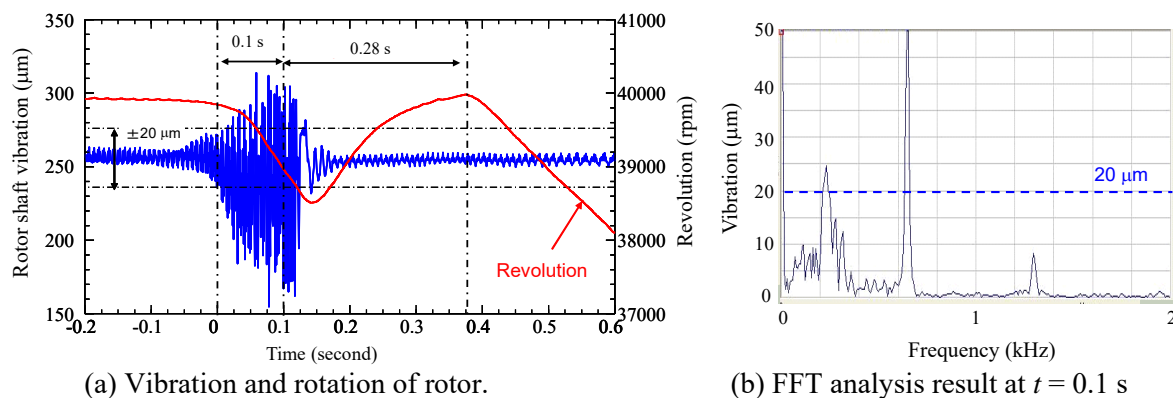
**Figure 6.** Dynamic gas bearing hydrogen pump.

spectroscopic analysis that persisting water-soluble cutting oil was detected in trace amounts rotor shaft. We tried to remove this oil completely using ultrasonic cleaning. Furthermore, the stiffness of the journal bearing was increased. In February 2008, the pump was able to circulate cryogenic hydrogen at supercritical pressure for the first time and was cooled down to the rated condition.

However, we had an unexpected temperature reduction in the pump flange region, where the temperature was maintained around room temperature, by design during cool-down below 33 K. The temperature in the flange region, which houses the journal bearings, a thrust bearing and an O-ring seal, was decreased to 250 K. We were concerned about instability of the gas membrane because of decrease in viscosity and density, and hydrogen leakage because of degradation of the sealing performance. To avoid the problem of excessive cooling, we installed a water channel on the casing flange to warm it using the cooling water for the pump induction motor. Accordingly, the temperature around the flange could be maintained at approximately 291 K at the maximum adiabatic efficiency, although the heat loads increased by a few hundred watts. This excessive cooling problem must be solved to achieve long-term stable operation of the hydrogen pump for 1-MW proton beam operation. We have developed an experimental liquid hydrogen recirculation system to this end and we are studying the thermal-hydraulic phenomena in the pump experimentally and numerically.

### 3.2. Transient elevation of pump rotor shaft vibration

Normally, the rotor shaft rotates with a vibration of approximately 4  $\mu\text{m}$ , which is always monitored by a fast Fourier transform (FFT) system. In 2009, we often encountered tentative elevation in vibration for more than two weeks after the cool-down operation, as shown in figure 7. It was found from the FFT analysis that only at the frequency of 666 Hz, which corresponds to a pump speed of 40,000 rpm, did the vibration rapidly increase to 100  $\mu\text{m}$ , exceeding the allowable value of 20  $\mu\text{m}$ ; it



**Figure 7.** Transient elevation of rotor shaft vibration

became normal again after 0.2 s. Moreover, the revolution speed recovered spontaneously within 0.4 s. However, the pump operation was shut down by its protective interlock 0.28 s after it exceeded the set value because of transmission lag. We tentatively extended the duration of the abnormal vibration to get the interlock at 0.5 s and achieved complete proton beam operation for user programs. It was considered that the tentative shaft oscillation was caused by imbalance in the rotor shaft because of the frequency content corresponding to the rotation speed. It was assumed that some impurities from the ceramic balls could be attached to the shaft and could be removed by physical contact of the shaft and the frictional heat. Based on the assumption, we definitely clean the shaft several times using pressure swing of purified hydrogen gas before cool-down. Accordingly, the phenomenon has never occurred since then, although the real cause remains unclear.

### 3.3. Accumulator

In February 2010, a leakage through the welded bellows was found before cool-down. Details have already been described in previous papers [6-8]. The investigation revealed that the leak was caused by the lack of weld penetration between the bellows plates. During remanufacturing of the second accumulator, we tentatively altered the hydrogen loop and the leakage was caused by lack of weld penetration between the bellow plates. The 120-kW proton beam operation was resumed without the accumulator in May 2010 [7].

The diameter of the welded bellows in the second accumulator was decreased from 500 mm to 330 mm to ensure weld penetration. However, the allowable pressure difference of the welded bellows was reduced to 0.94 MPa, which is lower than the design pressure of 2.0 MPa. A pneumatic control valve with a Cv value of 5 was installed into the helium region to avoid exceeding the allowable value. The second accumulator was in use from September 2010 to May 2013, when the proton beam power was increased to up to 300 kW. However, it had a large hysteresis, which would reduce the number of cycles before failure. We developed a third accumulator with higher pressure tolerance and long failure life cycle to achieve long-term, stable operation of the 1-MW proton beam, which will be achieved in 2016. A new partitionable structure was also adopted to replace the accumulator more easily and to shorten the replacement process. The installation was completed in December 2013 [8].

### 3.4. Helium refrigerator

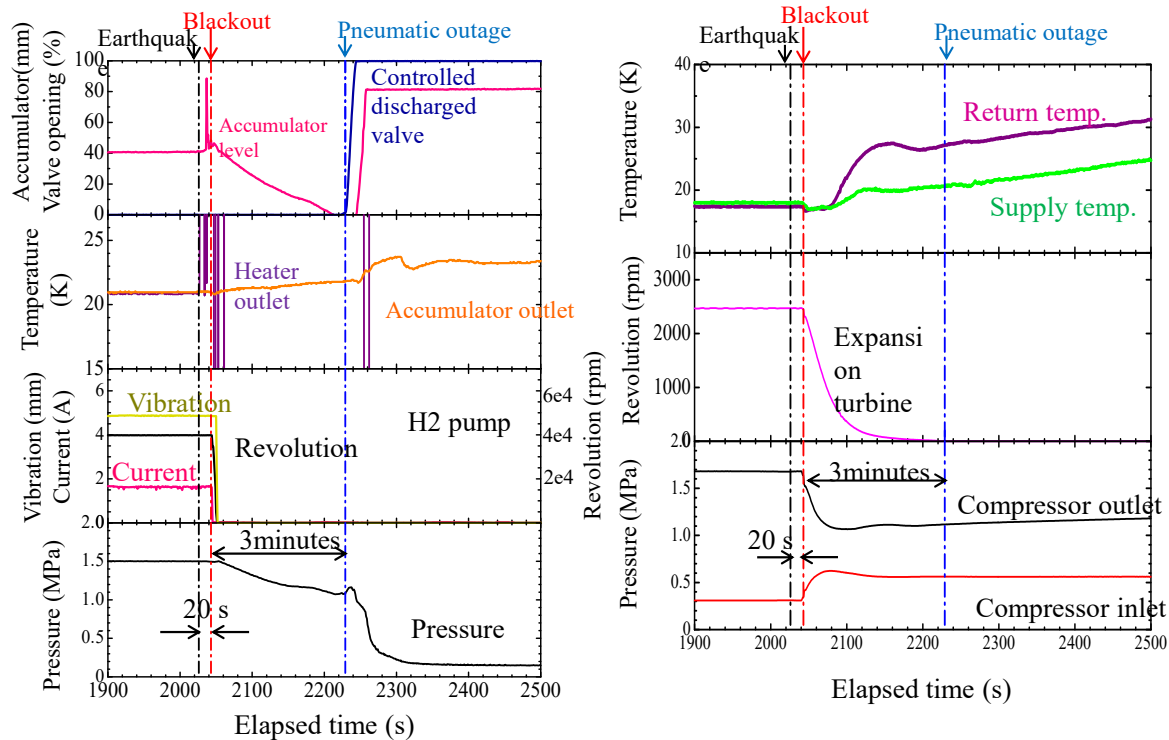
We encountered the problem of unstable helium refrigerator operation. Details have already been presented in a previous study [9]. The pressure difference through the heat exchangers and the adsorber gradually increased because of some impurities originating from the activated charcoal for the screw compressor. This led to performance degradation of the heat exchanger. In 2011, a purification system was established to effectively remove impurities from the helium refrigerator. We have since achieved stable operation of the helium refrigerator for periods longer than three months without any problems.

### 3.5. Great East Japan Earthquake

When the Great East Japan Earthquake with a magnitude of 9.0 struck on March 11th, 2011, the cryogenic hydrogen system was operating at the rated condition. Blackout occurred after 20 s and, furthermore, instrument air failed after 3 min because the air supply piping buried in the ground was broken because the ground around the facility building sank 1.5 m. The liquid nitrogen tank with a volume of 20 m<sup>3</sup> and the helium buffer tank with a volume of 50 m<sup>3</sup> were inclined by 0.84% and 2.14%, respectively. Part of the external supply piping such as hydrogen, nitrogen, helium and vacuum were also bent because of sinking of the ground. However, there was no hydrogen leakage from the bent part.

Figure 8 shows the behaviors of the cryogenic hydrogen system during the occurrence of the earthquake. The compressor, turbine and pumps were normally operated during the huge earthquake. There were no obvious abnormalities in term of the vibration, current and pump speed, although it had a dynamic gas bearing and a narrow gap. The compressor was shut down because of the blackout. The





(a) Hydrogen loop

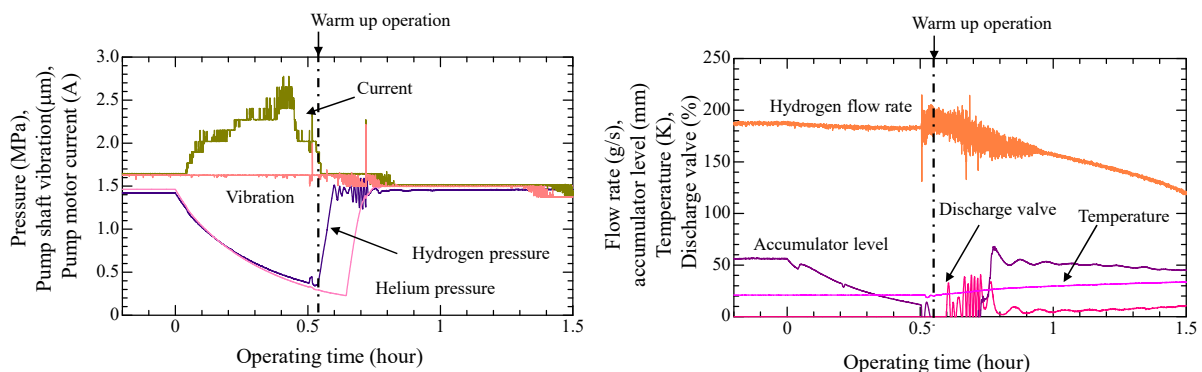
(b) Helium refrigerator

**Figure 8.** Behaviors of cryogenic hydrogen system during earthquake.

turbine and pumps were normally terminated by the interlock signals because of our uninterruptible power supply system. The helium in the bellows returned to the buffer tank and the bellows contracted. As the result, the hydrogen pressure decreased, although hydrogen was not discharged. The pneumatic failure resulted in opening of the hydrogen vent valve, and the hydrogen pressure decreased to atmospheric pressure. We confirmed through the huge earthquake that the established interlock system met our performance requirements, although the earthquake caused extreme damage to the external instruments.

### 3.6. Control valve malfunction

In February 2015, the hydrogen pressure abruptly decreased from 1.5 MPa to 0.4 MPa for 30 min during cryogenic operation as shown in figure 9. No hydrogen discharged through the vent valve, because the inert gas pressure in the blanket chamber, where the vales and part of the vent line were

**Figure 9.** Phenomenon of sudden hydrogen pressure reduction during cryogenic operation.

housed, decreased slightly during the cryogenic hydrogen discharge. No hydrogen was leaked because there was no pressure rises in the inert gas blanket chambers and the vacuum chamber, and there were no alarm signals from the hydrogen gas leak detectors. The vibration and the current of the pump increased suddenly at the hydrogen pressure of 0.4 MPa because of two-phase flow. We shut down the cryogenic system operation at this point to avoid pump damage.

We ascribe this pressure drop to the bellows contraction because of the discharge of helium gas in them through the helium vent valve, which was installed in 2010 for protecting the bellows of the second accumulator as well as for protection against earthquakes, as mentioned above. However, it is still unknown why the valve opened abruptly although the opening was less than 0.1% of the total valve opening. The discharge valve has been unnecessary since December 2014 because it was exchanged for the third accumulator with a higher pressure tolerance of 2.0 MPa. The instrument air supply was cut off temporarily until the summer outage of 2015, when the electro-pneumatic positioner and the regulator will be exchanged. We were able to resume cryogenic operation 4 days after the failure in 2015.

#### 4. Conclusions

Until now, we have considerable experiences and gained a lot of knowledge by facing several problems such as unstable operation of helium refrigerator because of impurities, leakage through the welded bellows of an accumulator, hydrogen pump impeller damage, and blackout and instrument air failure due to the Great East Japan Earthquake. We have confirmed through the problems that the cryogenic hydrogen system and its interlock system meet our design requirements.

#### Acknowledgements

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