Design and Operation of the Dual Return Valves to Stabilize Helium Vessel Pressure of the SRF Module

Mei-Hsia Chang, Chaoen Wang, Ming-Chyuan Lin*, Meng-Shu Yeh, Chih-Lung Lo, Ming-Hsun Tsai, Po-Yuan Chen,
Fu-Tsai Chung, Ling-Jhen Chen, Lung-Hai Chang, Tsung-Chi Yu, Zong-Kai Liu and Chi-Lin Tsai
National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan, R. O. C
*Corresponding author

Abstract—**The Taiwan Photon Source at National Synchrotron Radiation Research Center selects the KEK-B type superconducting radio-frequency (SRF) module to deliver RF energy to the 3-GeV electrons circulated in the storage ring. Each SRF module has its own control valve box to adjust the flow rate of transferring cryogens to SRF module and back to the cryogenic plant. The major dynamic cryogenic load comes from the various quantity of vaporized liquid helium along the transferring path from the liquid helium Dewar to SRF module, whereas the dynamic surface heating by various RF gap voltages is successfully eliminated by a heater compensation unit. To regulate pressure of the liquid helium vessel at high stability, two cryogenic valves of different sizes for the cold return gas are equipped on each control valve box. Both the design and measured performance of the dual return valves are presented herein. Currently the pressure fluctuation can be suppressed to +/- 2 mbar at the nominal operation condition. A venturi-type flow meter on the return line for gaseous helium is used to monitor the static heat load on the liquid helium under various operation conditions. It is aimed to further reduce the pressure fluctuation by optimizing the operating parameters of the controllers for the dual return valves.**

Keywords-SRF module; cryogenics; dual valves

I. INTRODUCTION

Taiwan Photon Source (TPS) started the Phase-I commissioning in 2014 and reached the goal of 100-mA stored beam current with electron energy of 3 GeV on March 26, 2015, with two conventional 5-cell PETRA cavities operated as the accelerating cavities for its storage ring [1]. Two superconducting radio-frequency (SRF) modules of KEKB type [2] then replaced the PETRA cavities to serve as the accelerating cavities for Phase-II commissioning and initial routing operation of TPS. These two SRF modules are expected to support operation of current up to 500-mA with a total accelerating gap voltage of 2.8 to 3.2 MV and delivered beam power up to 480 kW [3]. One 700-W helium cryogenic system [4] and a cryogenic transfer system [5] were built to support the SRF operation at liquid helium temperature. Together with its home-made electronic control system [6], shown in Fig. 1 is the control valve box (CVB) that provides the functions of delivering and controlling liquid helium (LHe) and liquid nitrogen (LN) to the SRF module, gaseous helium (GHe) back to the cryogenic helium system, and gaseous nitrogen (GN) to the venting device, as well as to maintain the cryogenic service to its downstream SRF modules through multi-channel transfer lines (MCL) [5, 7]. Each CVB consists of twelve pneumatic cryogenic valves and two manual cryogenic valves for cryogens control [3, 6] as shown in Fig. 2.

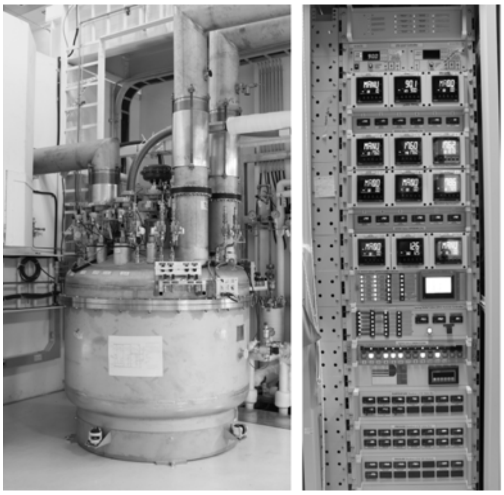

FIGURE I. THE CONTROL VALVE BOX FOR SRF MODULE IS INSTALLED OUTSIDE THE RADIATION-SHIELDING TUNNEL OF TPS, WHEREAS ITS ELECTRONICS CONTROL SYSTEM IS LOCATED TOGETHER WITH THE LOW-LEVEL RF CONTROL SYSTEM

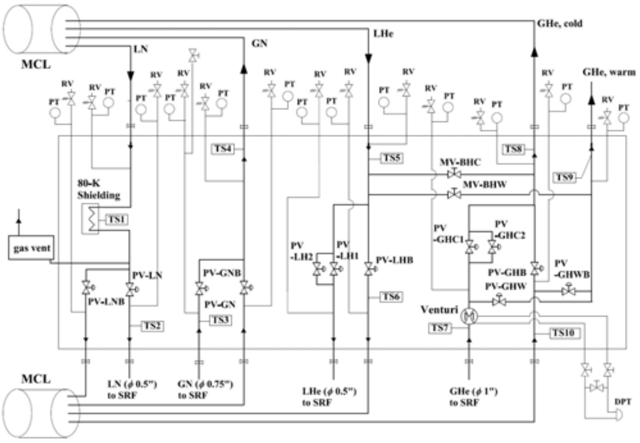

FIGURE II. SCHEMATIC FLOW DIAGRAM OF THE CONTROL VALVE BOX FOR SRF MODULE. MCL: MULTI-CHANNEL TRANSFER LINE; PV: PNEUMATIC VALVE; MV: MANUAL VALVE; RV: RELIEF VALVE; TS: TEMPERATURE SENSOR; PT: PRESSURE TRANSDUCER; DPT: DIFFERENTIAL PRESSURE TRANSDUCER.

The niobium cavity in the helium vessel of SRF module is a shell-type hollow structure with high vacuum inside it, and nominally its thickness distributes from 1.8 to 2.7 mm. Pressure of the helium vessel squeezes the cavity and thus is guaranteed to be below 0.3 barg by a mechanical relief valve to protect the cavity structure from elastoplastic buckling [8]. Meanwhile a pneumatic safety valve with a setting of 1.45 bar abs. (21.0 psi abs.) and a bust disk of 1.0 barg are also installed to prevent the helium vessel from high pressure conditions in case the mechanical relief valve is malfunctioned or can not vent out all the boiled helium immediately. The operation pressure of the liquid helium vessel is limited to be below 1.26 bar abs. (18.3 psi abs.) [7], only with a small margin of 40 mbar to the mechanical relief valve. On the other hand, the lower bound of the operation pressure is limited to the suction line pressure (1.05 bar abs.) plus pressure drops along the return path of cold gaseous helium to the cryogenic helium system at various operation conditions of the SRF modules, such as a high cryogenic load of 250 W at high-voltage processing and an ordinary cryogenic load of 140 W at routing operation. Moreover, pressure fluctuation of the liquid helium vessel changes the resonance frequency of the SRF cavity, thus the cavity tuner has to compensate the corresponding frequency shift by longitudinally pushing or pulling the cavity structure. It is highly expected to stabilize the pressure of the liquid helium vessel as possible. For the 500-MHz SRF cavity with an operation temperature around 4.4 K, it is ordinarily requested to have a pressure fluctuation of less than +/- 3 mbar. To keep the helium vessel pressure stay at a limited range under various operation conditions, a scheme of dual return valves is applied. A larger cryogenic valve, PV-GHC1 in Fig. 2, with valve coefficient of KV, max of 7.8 and a smaller one, PV-GHC2 in Fig. 2, with KV, max of 0.6 are operated together to regulate the helium vessel pressure of the SRF module [7].

As shown in Fig. 2, there are also two cryogenic valves to deliver liquid helium (LHe) to the SRF module. The smaller one, PV-LH2, provides a small flow rate to meet the requirement of slow cooldown rate of 3 K/hr from 300 K to 60 K, to minimize the induced thermal stresses during the cooldown process. The larger one, PV-LH1, works for ordinary operation to keep the liquid helium level at 90%. Another key component inside the CVB is the ventrui-type flow meter at the return line of gaseous helium. The venturi features of small overall pressure drop as generating a pressure difference at the inlet flat section and the central narrowest section. The mass flow rate through the venturi is proportional to the square root of the generated pressure difference [9, 10]. With an external differential pressure transducer (DPT), the pressure difference on the venturi at various operation conditions can be measured to calculate the mass flow rate and thus to obtain the total heat load [11, 12].

The measured results on pressure fluctuation of an SRF module are illustrated herein to present performance of the dual return valves in the CVB. With various power applied to the heater inside the liquid helium vessel of the SRF module, it is shown that the proportional-integral-derivative (PID) controllers for the two return valves with proper parameters can regulate the pressure of the helium vessel within an acceptable range, meanwhile the total static load of the transfer lines and the SRF module is obtained by the measured differential pressure at venturi. The pressure fluctuations under normal operation at a certain period with various beam operation conditions are also examined.

II. Design and Operation of Dual-Valve

Liquid helium and liquid nitrogen cool the SRF cavity and the 80-K thermal shielding layer of the SRF module, respectively. The SRF cavity locates inside the liquid helium vessel, thus only the helium-related issues are focused on herein. Figure 3 is a simplified sketch to show the dual-valve design on both supply of the liquid helium and return of the cold gaseous helium of the SRF module. For liquid helium supply, the valve PV-LH2 aims for low flow rate to achieve a cool-down rate of below 3 K/hr as the SRF cavity is cooled down from room temperature to 60 K, thus it has a much smaller size than PV-LH1. The process of slow cooldown reduces the temperature gradient and the thermal stresses to protect the SRF module from leak problems, but it takes 4 to 5 days to complete the slow cooldown process during which the opening of the PV-LH2 valve is adjusted from time to time. Once the cavity temperature is below 60 K, the larger valve PV-LH1 is gradually opened to speed up the cooldown rate and to accumulate liquid helium. Then the level sensor is activated and the PV-LH1 valve is switched to auto mode so that the PID controller can handle the opening of the PV-LH1 valve to keep the liquid helium level at 90%.

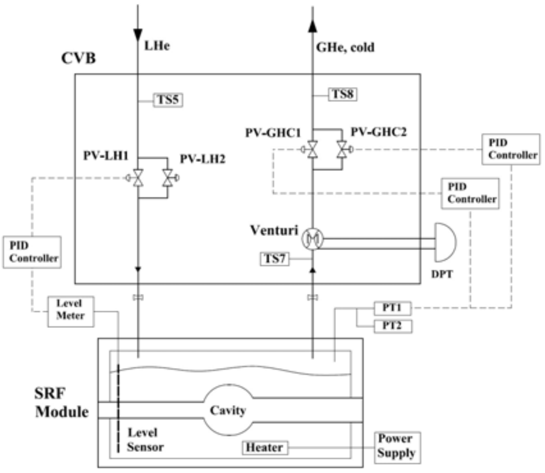

FIGURE III. CONTROL SCHEME ON LIQUID SUPPLY AND PRESSURE REGULATION OF THE LIQUID HELIUM VESSEL OF THE SRF MODULE BY DUAL-VALVE OPERATION

The SRF cavity is a shell-like hollow structure with high vacuum inside it, thus its RF resonance frequency is sensitive to the fluctuation of the external pressure. A mechanical tuner on the SRF module adjusts its resonance frequency by applying a longitudinal displacement on the cavity structure. Because the SRF cavity is inside the liquid helium vessel, the mechanical tuner always responds to pressure fluctuation of the liquid helium vessel. The pressure fluctuation is expected to be below +/- 3 mbar so that the mechanical tuner can act in a limited range. Meanwhile a fast release of the gaseous helium is required once a sudden increasing pressure occurs, such as in a quench event. This means not only high resolution but also a large flow capacity are required on the valve of gaseous return line. The dual-valve design is thus applied to handle the gaseous helium return of the SRF module. As shown in Fig. 3, the pressure transducer PT1 monitors the pressure of the helium vessel and provides signals to independent PID controllers of the pneumatic control vales PV-GHC1 and PV-GHC2. The PID parameters for the larger valve PV-GH1 are set to a slower responding rate to work for general conditions, and the parameters of the smaller valve PV-GHC2 for rapid action to suppress pressure fluctuations. To avoid both warming up of the transfer line as no cold gas flowing through and full-opening operation for a long period, opening of the smaller valve PV-GHC2 is constrained to between 20% to 80%. The pressure transmitter PT1 is of typically industrial type, with a range of 0 to 2.07 bar abs. (30 psi abs.) and accuracy of 0.25% full scale, i.e. 5.2 mbar (0.075 psi). Another pressure transducer, PT2, of manometer-type with a range of 0 to 1000 torr abs. (1.33 bar / 19.285 psi abs.), accuracy of 2.7 mbar (0.039 psi) and high resolution of 0.04 mbar (0.00058 psi), is also equipped on the SRF module for verification. Though the pressure transducer PT2 has better accuracy and resolution, its upper range is close to the operation pressure of the helium vessel; a quench event may cause a high pressure above its upper limit and thus this high-resolution pressure transmitter is not used as input source of PID controllers.

A. *Pressure Fluctuation at Various Heat Loads*

The pressure stability of the helium vessel and operation conditions of the valves are firstly examined at various heater powers with no external RF power transmitted to the SRF module, i.e., no surface heating on the cavity. As shown in Fig. 4, the reading of the PT1 stays at 17.46 +/- 0.04 psi (1204 mbar +/- 2.7 mbar) when the heater power is consequently adjusted from 40.1 W to 100.7 W and back to 45W, while the reading of the PT2 within 17.75 to 17.80 psi abs. (1224.1 to 1227.6 mbar). Note the analog-to-digital (AD) converter for the data acquisition system generates a white noise of +/- 0.02 psi (+/- 1.38 mbar) and +/- 0.01 psi (+/- 0.69 mbar) to the readings of PT1 and PT2, respectively, thus the real pressure fluctuation is about half of the values listed above. As a comparison on behaviors of the dual return valves, it is shown in Fig. 4 that the smaller valve PV-GHC2 has a much faster and larger change on opening as the heater power is changed, whereas the larger valve PV-GHC1 gradually changes its opening within a very limited range from 14% to 16%. It is also observed that once the opening of PV-GHC2 reaches either the upper limit 80% or the lower limit 20%, the larger valve PV-GHC1 itself can still keep the vessel pressure within the same pressure fluctuation range. The measurement results prove that the PID parameters meet the operation requirements at various heat loads.

B. *Measurement of Static Heat Load*

Also shown in Fig. 4 is that the measured pressure difference *ΔP* by venturi varies corresponding to the applied heater power, and it takes about 15 minutes to stabilize the reading of the measured pressure difference to a certain range every time the heater power is changed. Note the reading of the venturi has an offset of 0.058 mbar, which is not eliminated in Fig. 4. The square root of the measured pressure difference *ΔP* by venturi is proportional to the mass flow rate and the mass flow rate is proportional to the total heat load, a linear formula can thus be deduced [11, 12]

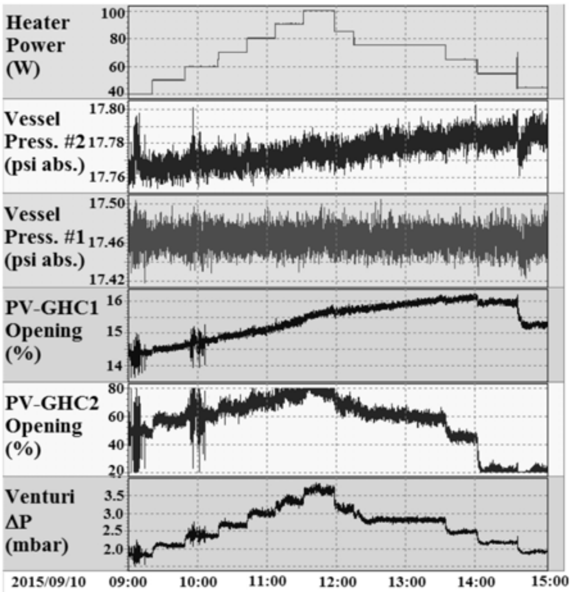

FIGURE IV. PRESSURE OF THE LIQUID HELIUM VESSEL IS WELL CONTROLLED WITHIN A FLUCTUATION OF +/- 0.04 PSI (2.7 MBAR) BY THE DUAL RETURN VALVES FOR GASEOUS HELIUM UNDER VARIOUS APPLIED HEATER POWERS

$$\dot{q}_H = C \times \sqrt{\Delta P} - \left(\dot{q}_{TL} + \dot{q}_{SRF}\right) \tag{1}$$

where: $\dot{q}_H$ is the applied heater power, *C* a constant dependent on characteristics of the venturi and state of the saturated liquid helium [12], $\dot{q}_{TL}$ and $\dot{q}_{SRF}$ the static heat loads of the liquid helium transfer lines and the SRF module, respectively. Pairs of the square root of the measured ΔP at stable region and the corresponding applied heater power in Fig. 4 behavior a linear relationship, as shown in Fig. 5, as a result a linear fit of least mean square is obtained as

$$\dot{q}_H = 104.11 \times \sqrt{\Delta P} - 97.43 \tag{2}$$

Note values of the pressure difference ΔP in Fig. 5 have eliminated the offset 0.058 mbar. By comparing (1) and (2), it is concluded that the total static heat load on liquid helium, as sum of $\dot{q}_{TL}$ and $\dot{q}_{SRF}$, is about 97.4 W. According to an independent measurement on decreasing rate of the liquid helium level under various heater powers, the static heat load of this SRF module is approximately 30.3 W. Hence the accumulated heat load of the transfer lines for liquid helium is about 67.1 W, all along the transfer path from the 7000-liter Dewar, one distribution valve box (DVB) [5], one control valve box (CVB), three sections of multi-channel transfer lines of total length around 43 meters, and one vacuum jacketed flexible line of length 2 meters. However, the total static heat load of 97.4 W is above the expected value but still in an acceptable range of the design value. The opening of PV-LH1 is below 16% at an applied heater power of 100.7 W, which means a total heat load of 198.1 W to vaporize the liquid helium, and thus primarily proves the dual-valve operation meets the one of the design goals as handling a high flow rate. The venturi is expected to generate a differential pressure of 10 mbar at a flow rate equivalent to a heat load of 300W. With (2), a total heat load of 329 W, as summation of the heater power and the static heat load, at ΔP = 10 mbar is obtained, this confirms that the venturi has an acceptable engineering error of 9.7% to the design specification.

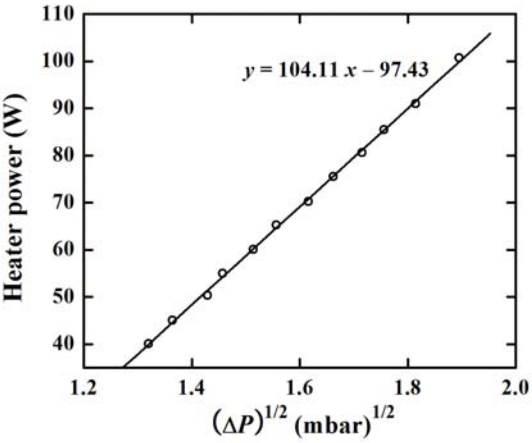

FIGURE V. THE APPLIED HEATER POWER IS LINEARLY CORRESPONDING TO THE SQUARE ROOT OF THE MEASURED PRESSURE DIFFERENCE BY VENTURI

C. *Pressure Fluctuation under Various RF Loads*

Storage ring of the TPS is currently in Phase-II commissioning, not only the stored beam current is gradually increased but also ten insertion devices and corresponding beam lines are tested and integrated one by one. Due to the complex commissioning procedures, each SRF module is operated at various conditions to provide an accelerating gap voltage ranging from 0 to 1.6 MV as depending on testing requirements. The heat generated on the cavity surface is proportional to the square of the gap voltage, as long as the unloaded quality factor Q0 does not drop at high accelerating electric field [13]. Varying gap voltages means changing heat load to the liquid helium, a heater compensation unit is thus applied to the heater power supply to calculate the related heat generated on the cavity surface and correspondingly adjust the heater power so that a constant heat load at the liquid helium vessel is remained. Illustrated in Fig. 6 is a typical commissioning period with various beam currents and accelerating gap voltages on the SRF module. It shows that the pressure of helium vessel stays at a stable condition at the first eleven hours even the stored beam current varied from 0 to a peak value of 170 mA. Reading of the pressure transmitter PT1 mostly stays at 17.44 to 17.50 psi abs. (1202.8 to 1206.9 mbar abs.) in this stable period, whereas 17.835 to 17.87 psi abs. (1229.3 to 1232.4 mbar abs.) for PT2. The pressure fluctuation is within +/- 2 mbar of the setting value, whereas opening of the larger return valve PV-GHC1 fluctuates slightly around 14.6%, and much greater variation for the smaller valve PV-GHC2 from 20% to 42%. As expected, the vessel pressure is mainly regulated by the smaller return valve under an operation condition of stable heat load as confirmed by the measured pressure difference on ventrui.

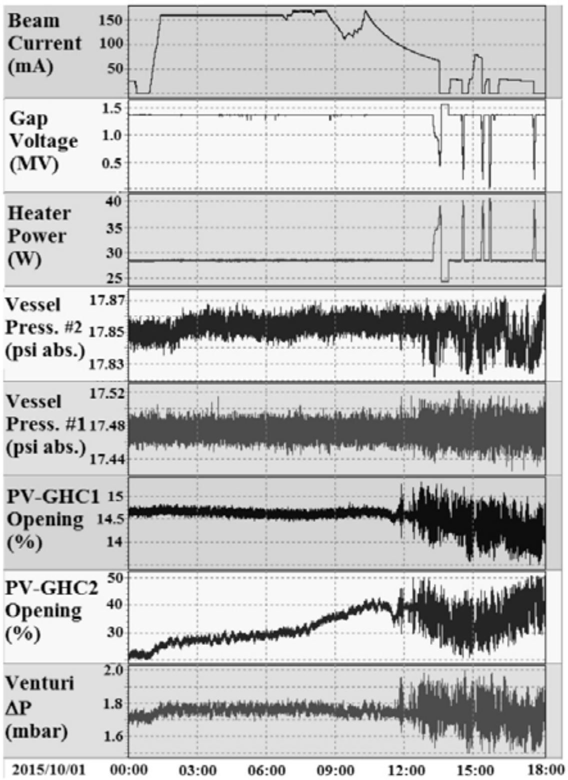

FIGURE VI. PRESSURE OF THE LIQUID HELIUM VESSEL IS WELL CONTROLLED WITHIN A FLUCTUATION OF +/- 0.03 PSI (2.1 MBAR) BY THE DUAL RETURN VALVES FOR GASEOUS HELIUM UNDER VARIOUS RF OPERATING CONDITIONS

It is also shown in Fig. 6 the pressure of the helium vessel fluctuates much greater near 12:00 when the stored beam current is below 100 mA and some machine parameters are varied. Though the heater compensation successfully keeps a constant heat load on the liquid helium when the gap voltage varies, a rapid pressure fluctuation is observed and the dual return valves can not handle the pressure very well. It is firstly suspected that either these two return valves beat to each other or synchrotron light heat the cavity surface under specified operation conditions of the storage ring. Thus it is further examined for a 48-hour routine operation with not only the RF gap voltage fixed at 1.4 MV and ring lattice not changed but also the smaller return valve PV-GHC2 completely closed. As the results shown in Fig. 7, the rapid pressure fluctuation still occasionally happens and the larger return valve PV-GHC1 opens at 15 +/- 0.7 %. It is thus concluded that the rapid pressure fluctuation is caused by another unknown source. One possibility is the vaporized helium gas along the transfer path of liquid helium, which is longer than 50 meters and with various heights, may arrive at the helium vessel with severely fluctuated quantities to excite rapid pressure fluctuation. Thermal acoustic at somewhere is another possibility. This shall be further studied to find a way to suppress the pressure fluctuation. The operation parameters of the PID controllers of the dual return valves can be optimized as the first attempt.

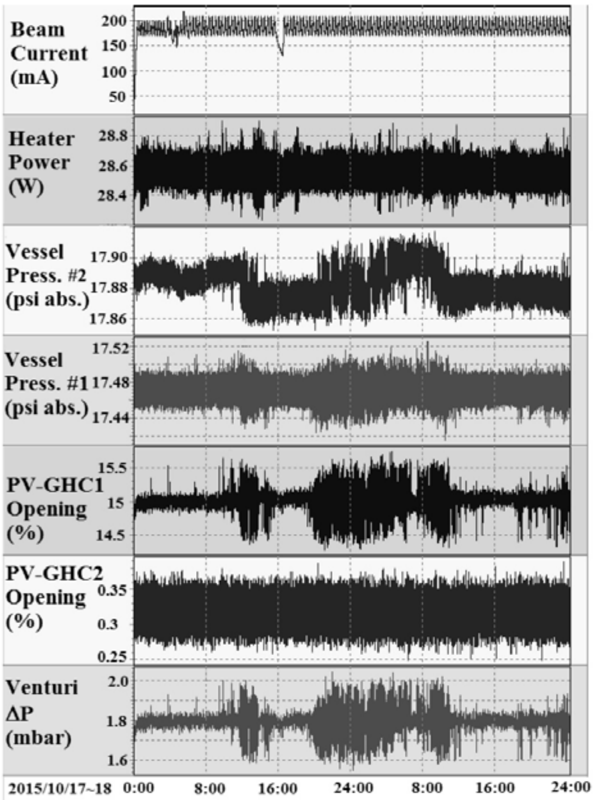

FIGURE VII. PRESSURE OF THE LIQUID HELIUM VESSEL WAS CONTROLLED WITHIN A FLUCTUATION OF +/- 0.05 PSI (3.5 MBAR) BY ONLY THE LARGER RETURN VALVE PV-GHC1 DURING ROUTINE BEAM OPERATION

Also observed in Fig. 7 is that reading of the pressure transmitter PT1 stays at 17.44 to 17.50 psi abs. (1202.8 to 1206.9 mbar abs.) under stable condition but increases to 17.42 to 17.52 psi abs. (1201.4 to 1208.3 mbar abs.) when rapid pressure fluctuation happens. This means the single valve operation can still keep a small pressure fluctuation within +/- 3.5 mbar when the storage ring is operated at a routine condition. The small fluctuations at both the heater power of 28.6 +/- 0.4 W and the closed small valve PV-GHC2 of 0.25% to 0.4 % as shown in Fig. 7 again indicate the AD converter of data acquisition system generates white noises, which shall be improved to record real signal readings.

III. CONCLUSION AND REMARK

The heater compensation unit reads the applied RF gap voltage on the SRF cavity and correspondingly adjusts the heater power to keep a constant heat load on the liquid helium bath of the SRF module, this greatly helps on stabling pressure of the liquid helium vessel. The venturi-type flow meter in the control valve box measures the flow rate of the cold gaseous helium with a good accuracy and thus is currently used to monitor the heat load on the liquid helium. The dual return valves on the control valve box are capable of handling the helium vessel pressure of the SRF module within a fluctuation below +/- 3 mbar, which even reduces to +/- 2 mbar at stable conditions. Because the AD converter of data acquisition system generates noises on the recorded signals, it is believed that the pressure stability is actually better than the demonstrated value. Rapid pressure fluctuations are observed occasionally and disturb the stable operation of the dual valves for cold gaseous helium. Its mechanism will be studied and suppressed as the next scope to further reduce the pressure fluctuation. A practical difficulty on operating the dual return valves is each PID controller actually reads a slightly different pressure value, though the same current signal of 4-20 mA is fed from the single pressure transmitter PT01. For example, both the PID controllers may present the same value of 17.46 psi since the reading of each PID controller is carefully calibrated to last digit, but the real inputs to them may be scaled to 17.458 and 17.462 psi, respectively. The smaller valve could thus gradually reaches either its upper or lower opening limits and fails to respond to the pressure fluctuation at the limited direction. It takes a lot of effort to calibrate reading of each PID controller to eliminate the invisible slight difference, but this inconsistent reading problem would happen again once the working pressure is changed and obviously becomes the major operation challenge for the dual-return-valve scheme.

REFERENCES

[1] Kuo C. C. et al., "Commissioning of the Taiwan Photon Source," Proceedings of IPAC2015, Richmond, VA, USA, A05: pp. 1314-1318, 2015.

[2] Furuya T. et al., "A prototype module of a superconducting damped cavity for KEKB," Proceedings of EPAC96, pp. 2121-2123, 1996.

[3] Wang Ch. et al., "Design features and construction progress of 500-MHz RF systems for the Taiwan Photon Source," Proceedings of PAC'11, New York, NY, U.S.A., THP211: pp. 2513-2515, 2011.

[4] Tsai H. H. et al., "The Installation and Commissioning of the Helium Cryogenic System for the TPS Project," Proceedings of IPAC2013, Shanghai, China, THPME040: pp. 3600-3602, 2013.

[5] Tsai H. H. et al., "Design of a liquid-helium transfer system for the TPS project," Proceedings of PAC'11, New York, NY, U.S.A., TUP218: pp. 1220-1222, 2011.

[6] Chung F. T. et al., "The Electronic System Design and Realization for 1st Set 500MHZ KEKB SRF Module High Power Test," Proceedings of IPAC2013, Shanghai, China, THPME035: pp. 3588-3590, 2013.

[7] Chang M. H. et al., "Design of a Cryogenic Regulation Valve Box for SRF Operation at TPS," Proceedings of IPAC2011, San Sebastian, Spain, WEPO036: pp. 2475-2477, 2011.

[8] Lin M. C. et al., "Effects of Material Properties on the Elastoplastic Buckling of an SRF Cavity Under External Pressure," IEEE Trans. Applied Superconductivity, vol. 21, pp. 2605-2608, 2011.

[9] Forster M. and Graber J., "Cryogenic Ventur-type Flow Meters," CESR SRF Internal Note, 1996.

[10] Belomestnykh S. et al., "Operating Experience with Superconducting RF at CESR and Overview of Other SRF Related Activities at Cornell University," CESR SRF Note, SRF-000202-03, 2000.

[11] Lin M. C. et al., "Cryogenic Related Performance of an SRF Cavity Module in NSRRC," Advances in Cryogenic Engineering, vol. 5, pp. 1156-1163, 2006.

[12] Lin M. C. et al., "Operational Characteristics of the 200-m Flexible Cryogenic Transfer System," Journal of Superconductivity and Novel Magnetism, vol. 26, pp.1479-1483, 2013.

[13] Padamsee H., Jnobloch J., Hays T., "RF Superconductivity for Accelerators," John Willey and Sons, Inc., New York, 1998.