

400 mA BEAM STORE WITH SUPERCONDUCTING RF CAVITIES AT PLS-II*

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Abstract

Three superconducting RF cavities were commissioned with electron beam in way of one by one during the last 3 years, and now PLS-II is in user service on the way of beam current to 400mA, the target of PLS-II. The cavities and cryomodels were prepared with SRF standard technology and procedures, then vertical test, windows conditioning, cryogenic test in each cryomodel, horizontal power test, conditioning, and commissioning without and with beam at PLS-II tunnel by collaboration with industries. All the cavities showed stable performances as good as not-observing any RF instability from cavities, couplers and windows up to 400 mA beam store, but observing several cavity quenches and minor vacuum bursts by abrupt power with control and human errors. The initial beam current for user run were recorded as 150 mA with one cavity, 280 mA with two cavities and 320 mA with three cavities. The 400 mA beam was also achieved with two cavities by decay mode and also with three cavities by top-up mode. The stabilities of RF amplitude and phase are good enough not to induce beam instabilities.

INTRODUCTION

The PLS-II of which is the upgraded light source from former PLS is mainly to increase the number of ID beamlines by changing magnet arrangement from double bend achromat lattice (DBA) to triple bend achromat lattice (TBA) [1], so that 20 ID beamlines are afforded at PLS-II. Also the upgrade machine is to provide higher brightness of photon beam, order of two through increasing electron beam energy and stored beam current, as 3 GeV and 400 mA, respectively.

The RF system of PLS-II should be high capacity of RF power and free from cavity higher mode (HOM) instabilities. The RF system must compensate the energy loss as much as 1024 keV and 200 keV from 24 bending magnets and 20 insertion devices, respectively. So the RF system must afford to provide 550 kW RF power properly for additional broad band loss from the SR structures and no coupled bunch instabilities (CBI) should be shown to 400 mA beam current by installing HOM free cavities. A superconducting RF (SRF) system is chosen to meet such a requirement, described above.

The baseline design [2] is a three-independent RF station, of which each RF cavity has its own power amplifier, transmission system, and a LLRF. With 3 SRF

cavities, the design Vacc and forward RF power per each cavity are lower than their specification, which has been contributed to reduce cavity abnormality and to increase the lifetime of ceramic window and also of high power amplifier.

The 3 SRF stations were installed one by one during last 4 years as first 3 normal conducting cavities in 2011 and they were replaced with one SC cavity, then two more SC cavities during following two years. It is strategy to make time for operator to be familiar to SRF system, meanwhile for machine to be conditioned gradually by low synchrotron energy. Even though these consideration, we suffered from a lot of troubles such as vacuum bursts at RF window, cavity quenches from bad RF power control resulted to violent He evaporation and He refrigerator trip by poor protection and many human error by LLRF in the first 3 months. The trial and errors during beginning 3 months contributed to the performance normalization. First of all, we improved the listed trouble makers such as LLRF, interlock system between RF source and cavities, electric power control of He refrigerator. Also, we setup maintenance procedures as cavity partial warmup and pulse conditioning cavity and window before start of every user-run.

Then, the beam current with two SC cavities by top-up mode in 2013 was 120 mA at beginning of user run to 280 mA at last run. During the machine study, 400 mA beam current was touched during several ten minute, but it couldn't go on due to vacuum burst. Also we tried to increase beam current with one more SC cavity installation in 2014. Even with frequent partial warmup and pulse conditioning, the window vacuum burst still one of trouble for high beam current. It was overcome with deep study of relationship between RF forward power, reflected power and window dissipation heat [3]. With these result, stable 400 mA beam current with top-up mode was achieved during 2 hours in machine study.

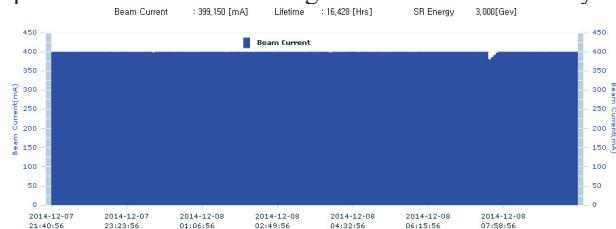


Figure 1 : Achievement of 400 mA top-up mode.

In 2nd half year of user run, beam current increased in run by run, 300 mA, 320 mA and 350 mA. At 350 mA operation, we couldn't provide stable user beam due to the vacuum interlock from the in-vacuum undulators.

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There were melt down of Al foil to make smooth beam conductance from magnetic poles [4]. As a result, user beam current has been restricted to 320 mA top-up up to April 17th, 2015. Now the beam current is 340 mA with careful monitoring. Even though these situations, the SRF system was investigated successfully for stable operation, with 400 mA user-beam service during 48 hours without any trouble.

SC CAVITY PREPARATION

PLS-II RF system consists of three independent SRF stations which have CESR-B type 500 MHz SC cavities. The SC cavities were prepared with usual recipe as careful quality controlled cavity fabrication, degreasing with light chemical etching, then barrel chemical polishing (BCP) as much as 100 μm , high pressure water rinsing (HPR) with conductivity, 12.5 M Ω -m, annealing 10 hours at 600 $^{\circ}\text{C}$ with vacuum environment, final BCP-20 μm and HPR, finally leak tight of cavity assembly. All the cavities showed V_{acc} as high as 2.8 MV (Eacc, 9.3 MV/m) at Q0 of 8.5×10^8 . Figure 2 shows cavities characteristics of CESR-B family, in which PAL 1, 2, and 3 are for PLS-II.

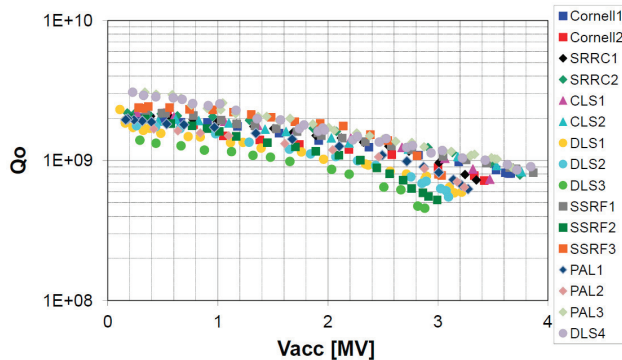


Figure 2: Cavity characteristics of CESR-B family.

The RF window and cavity were conditioned with several different pulses of which width, repetition rate and intensity by on-resonance travelling wave power and off-resonance standing wave power before beam commissioning. Figure 3 shows the history of cavity and window conditioning during 4 days.

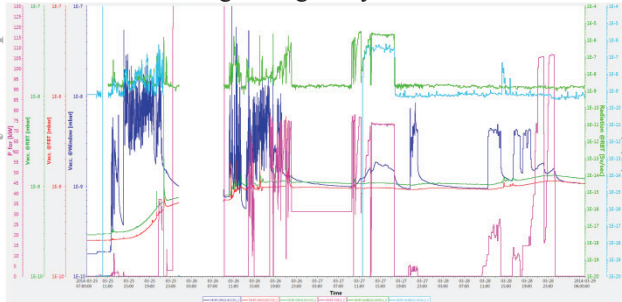


Figure 3: Conditioning history of cryomodule 1 with pulse & continuous RF power; blue and red colors are vacuum pressures, green color is radiation intensity.

After conditioning cavities and window, Q0s are measured with measurement of liquid Helium evaporation rate. As comparison of Q0 between vertical test and horizontal test about 10 % of Q0 were degraded by combination of components like coupler, beam tube, He vessel, filed pickups, and so on.

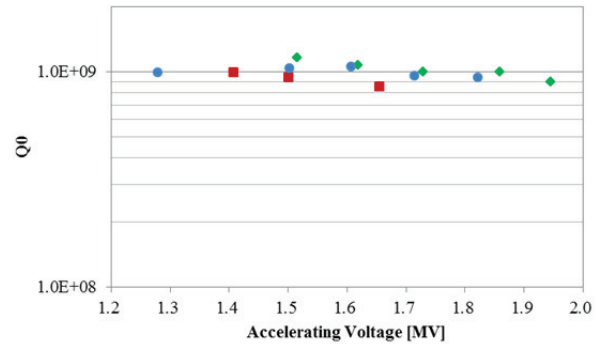


Figure 4: Measured Q0 with Cryomodule 1; Green for after installation in SR tunnel, red for 4 months beam operation, and blue for one year operation.

BEAM COMMISSIONING

PLS-II RF was beam commissioned with 3 normal conducting cavities during 3 months in 2011 and was on service to synchrotron users during 4 months in 2012. Then they were replaced with one SC cavity, operated for 80-120 mA decay mode beam. During those time, the stabilities of amplitude ($\Delta V/V$) and phase ($\Delta\Phi$) were 0.5% and 0.6 degree, respectively which was acceptable for the beginning. But we fronted a lot of machine trips, most parts from vacuum bursts at window and cavity. The severe case was cavity quenches from improper interlock system of high power at cavity trip signals. At a vacuum burst, the control system of cryomodule produces the direct signal to switch off high power. The signal of relay type switch took several hundred m-second, then during those time a lot of RF power fed into cavity, resulted to cavity quench. Another severe one was the very sensitive characteristics of He compressor against the electric power stability like voltage fluctuation from electric network. Those events gave a disaster to all He cooling system.

In February 2013, the second SC cavity was installed. Two SC cavities provided proper operation stability so that beam current went to 200 mA easily, compared to one cavity operation. But the storage ring, beamlines, and also SC cavities were still on a new road after PLS-II upgrade, which PLS-II never had gone to higher than 200 mA, although the cavities trip rate was still on the reasonable level. The cavity partial warmup and pulse conditioning before starting every two user runs broke through 200 mA barrier. The stable beam current, 280 mA top-up was achieved with performance, mean time between failure s (MTBF) of 186 hours by two SC cavities. Also 400 mA beam current by decay mode was touched during machine study.

The final cavity was commissioned in April 2014, then PLS-II upgrade was finalized with 3 SC cavities in point of hardware. The most stable beam current for user service was 320 mA up to end of 2014. Also higher currents like 350 mA, 380 mA, and 400 mA were tried during machine study.

BEAM CURRENT INCREASE

For vacuum conditioning of storage ring by synchrotron radiation, the beam current increased gradually from reasonable low current for the normal user service during every commissioning of SC cavities. The vacuum pressures from every cavity and windows looks decreasing gradually run by run, even though beam current increases or stays shown in Figure 5, which is to be beam cleaning effect. To reduce cavity trips by vacuum burst the cavity partial warmup and pulse conditioning are conducted in very frequently as every 2 user-run and every user-run, respectively from 2013. That would have contributed the reduction of cavity trips.

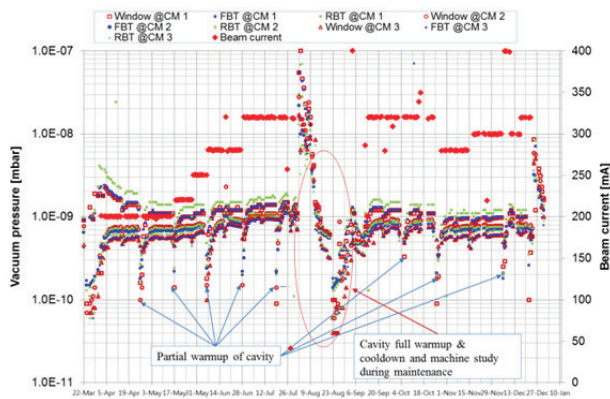


Figure 5: History of beam current increase with 3 SC cavities in 2014.

Even though its annoying conditioning procedure, its effect was limited to 320 mA. For high than 320 mA, no more forward power could be supplied for beam requirement at given Vacc, 1.6 MV due to the deviation from the optimal reflection power in relationship between forward & reflection powers and Vacc. Then the vacuum pressure in window increases as higher beam current, resulted vacuum burst to cavity trip. We studied that what makes rapid heat increase in the window during reflection power increasing again from the optimal (lowest) value as beam current increase, with theoretical and experimental method. The conclusion was; The phase of electric field distribution at the window is changed to invert as the beam current increases, and, therefore, the RF window is located at maximum peak of the electric field distribution. Moreover, the LLRF system puts more klystron forward power into the cavity to maintain the accelerating field as the beam current increases, then the electric field amplitude at the RF window is exponentially increased. This high electric field amplitude raises the

probability of RF breakdown of the RF window, which comes with a rapid increase of the window vacuum pressure. Based on these studies, we can find out the optimal reflection power at the given RF voltage and beam current by avoiding window breakdown. This would be the key contribution to store 400 mA top-up mode beam current. We demonstrated the design performance of SRF system with 400 mA user beam operation as shown in Figure 1.

CONSLUTION

During the last 3 years, we have been devoted to commission and optimize SRF system for better beam quality. Although we have got a lot of troubles from intrinsic problems to minor ones, the design performance of SRF system are achieved successfully. By the storage ring characteristics, when the beam current is higher than 200 mA, we need the transverse feedback system for stable orbit of e-beam. Now the stability of amplitude and phase are less than 0.15% and 0.3 degree at 320 mA beam. They are still slight higher than PLS-II target, 0.1 % and 0.1 degree. We will have tried to improve SRF system to meet the goal.

Operation statistics of SRF system are reasonable compared to that of other light sources, for example MTBF in 2013 and 2014 were 186 hours and 197 hours as shown in Figure 6.

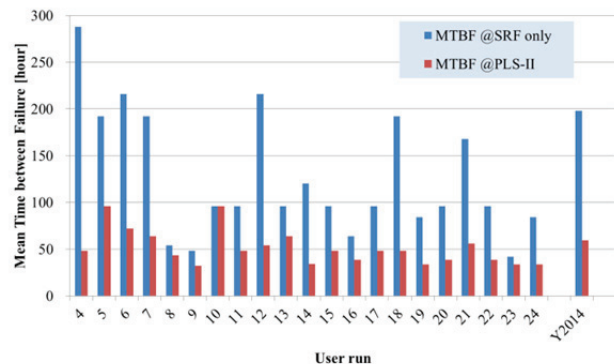


Figure 6: MTBF with 3 SRF systems in 2014.

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