

PLS-II SUPERCONDUCTING RF SYSTEM*

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Abstract

Pohang Accelerator Laboratory has obtained a full funding to upgrade Pohang Light Source. In the PLS-II storage ring, three elliptical superconducting RF cavities of 500 MHz will be used for accelerating an electron beam with energy of 3.0 GeV, and working at temperature of 4.4 K. Each cavity is powered by one set of high power source, and controlled by one set of digital LLRF and control system. The cryomodules are cooled by a cryogenic plant of 700 W.

INTRODUCTION

Pohang Light Source (PLS) of Pohang Accelerator Laboratory (PAL) has been making the significant contribution to the scientific research from all over Korea and foreign countries since 1995 first at 2.0 GeV and later at 2.5 GeV [1]. In recent years, the PLS customers need PLS offering the lower emittance beam, higher energy photons and more insertion devices eagerly. Unfortunately, the existing PLS can not offer high energy photons and does not allow more ID (inert device) sections. In order to meet PLS customers' requirements, PLS needs to be upgraded immediately. In March of 2009, PAL has obtained a full funding for upgrading the PLS. After upgrading, the PLS-II's electron beam energy will be increased from 2.5 GeV to 3.0 GeV; beam current will be increased from 200 mA to 400 mA, and beam emittance will reduce from 18.9 nm rad to 5.9 nm rad in the storage ring. Table 1 lists the primary parameters relative to RF systems of PLS and PLS-II storage rings.

Table 1 shows that the PLS-II electron beam energy, current, and emittance have the significant change compared with those of PLS, these induce the beam loss power and RF voltage of PLS-II to be sharply different from PLS. It indicates that the PLS RF system can not meet the PLS-II's requirements, and need to be upgraded.

After comparing the operation reliability, beam stability, available ID numbers, cost, project schedule for both choices to superconducting RF (SRF) system and normal conducting RF (NRF) system for PLS-II, and considering the future project and technology development at PAL and in Korea, a SRF system has been chosen finally for PLS-II storage ring. Two single-cell cavity cryomodules are going to be used and installed in one long-straight section of the PLS-II storage ring tunnel. One cryomodule will be developed for a short straight section in future. Every cryomodule is powered by one high power station, and controlled by one set of digital LLRF (low-level RF) and control system. The cryomodules are working at 4.4 K and cooled by a

cryogenic plant of 700 W.

Table 1: Primary parameters relative to RF systems of PLS and PLS-II storage rings.

Parameters	PLS	PLS-II
Energy [GeV]	2.5	3.0
Current [mA]	200	400
Emittance [nm rad]	18.9	5.9
Circumference [m]	280.56	281.82
Revolution frequency [MHz]	1.068	1.064
Harmonic number	468	470
Beam power loss due to dipoles [KW]	110	417.3
Electron energy loss due to IDs [KW]	32	246
RF frequency [MHz]	500.082	499.973
Beam loss power due to radiation [kW]	142	663.3
RF Voltage [MV]	1.6	3.3*

*the RF voltage of 3.3 MV is the minimum requirements based on the beam lifetime, energy acceptance etc. Normally, higher RF voltage can give more benefits for the beam lifetime, energy acceptance etc.

RF CAVITY CHOICE

Both the SRF system and normal conducting RF system can meet the PLS-II requirements, but only one type RF system will be used for PLS-II. For PLS-II RF cavity selection, following issues need to be considered:

- Operation reliability:** PLS-II RF system should have a small number of trips and can provide a stable and long-lifetime beam to customers.
- Beam stability:** RF system should not decrease the beam lifetime and quality, and affect the beam stability.
- ID numbers:** PLS-II will have 12 long straight sections (LSS) and 12 short straight sections (SSS). LSS is more valuable for the IDs than the SSS. RF system should save more long straight section and give more sections for the IDs as able as possible.
- Cost:** the RF system has to be completed with the lowest capital cost. Also the future operation cost needs to be considered.
- Schedule:** project period of the PLS upgrade is three years. We have to start the commissioning in July 2011, and offer the beam to user in October 2011. This schedule forces us to do not let RF system delay whole project.
- Future project and technology development:** for the RF system choice, we should consider what kind of

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technology will be used in the future project at PAL and in Korea.

In order to make a right choice for this important system, we have surveyed the choice reasons and operation status and experiences of the RF systems for the light sources over the world; and two international review meetings for the PLS-II RF system had been held. The first international review meeting for PLS-II RF system was held from April 27 to 28, 2009, at PAL, Pohang, Korea; the second international review meeting for PLS-II RF system was held during PAC2009 conference on May 6, 2009 in Vancouver, Canada.

After two international review meetings and discussing with the light source and SRF experts, we obtained following conclusions:

Operation Reliability

Trip rates and downtime for the NRF and SRF systems are similar once steady state operation has been attained. Trip rate depends on the team experience and the size of the institution. Mean time between failures is probably similar or lower for the SRF systems but the mean time to repair might be higher.

In addition, the survey of the design and operation powers for the RF cavities used in light sources shows that the PLS-II coupler power and gradient assumed for the NRF option are conservative, but that for SRF option are reasonable.

Beam Stability

Both HOM (higher order mode) damped NRF cavity and SRF cavity are probably stable against coupled bunch instability due to HOMs. The SRF solution with the lower number of cavities has greater headroom. Either transverse or longitudinal feedback systems are not necessary in SRF case. Transverse feedback systems might be needed in the NRF case to stabilize some dipole modes at full current. If so, they will take some straight section space. The NRF cavities have higher R/Q and there are twice as many as SRF cavities so that the beam induced transient due to the ion clearing gap will be significantly larger for the NRF case.

ID Numbers

The NRF option needs one LSS and one or two SSSs. The SRF option needs one LSS for two commercial SRF cavities. The third SRF cavity will be developed for a SSS. Here one long straight section is only for RF cavities and can not be used for any IDs. Therefore, both NRF and SRF options can offer the same room for IDs.

Cost

SRF option needs 3 subsystems, and NRF option needs 6 subsystems at least. An individual SRF cavity could be more expensive than that of a NRF cavity, but the SRF option needs a smaller number of the subsystems. An SRF system needs a cryogenic system, which is expensive, while a NRF system does not need a cryogenic plant. The

cost survey and estimation show the capital cost for both options is the almost same.

For the long-term operation cost, even including cryogenic operation cost, the energy cost for SRF system will be lower than that for NRF system.

Schedule

RF system project delay would induce PLS-II whole upgrade project to be delayed. The vendors of the NRF and SRF cavities said the both options have the almost same delivery period. For NRF cavities, the vendor probably can ship the cavities to PAL on schedule, but no guarantee. For SRF cavities, indications from Mitsubishi Electric Corporation in Japan suggest that they would have to rely on support from KEK for cavity processing and therefore may not be able to guarantee a delivery schedule. However, ACCEL (now Research Industries) is also notorious for late delivery. Therefore, PLS-II should allow at least 2 years for SRF cavity module delivery in either case. Based on above facts, we are going to use the existing NRF cavities during the commissioning in order to insure the PLS-II commissioning on schedule and extend the RF project period until all the RF cavities are all ready. This indicates that either NRF or SRF option can meet the PLS-II commissioning requirements.

Future Project and Technology Development

In Korea, PAL is going to develop new generation free electron laser (XFEL), the SRF accelerator would be the best choice for it; Proton Engineering Frontier Project (PEFP) is going to use SRF cavities in its extended project [2,3,4]. Based on the Korean future projects and the national interest, PLS-II needs to use and develop SRF experience and technology including cryogenics and 'dust-free culture' at PAL and in Korea.

Above discussions show the SRF option has the same operation reliability and capital cost as the NRF option, and can meet the PLS-II requirements of the ID numbers, schedule, but better beam stability, lower long-term operation cost than the NRF option. With these advantages and the consideration of the Korean future projects, SRF option is the best choice for PLS-II. Finally, the SRF system was chosen for PLS-II.

SRF CRYOMODULE

The currently available commercial cryomodule is the CESR- and KEKB-type cryomodules. The CESR-type cryomodule is fabricated by ACCEL (now RI), and the KEKB-type cryomodule is built by Mitsubishi Electric Corporation. So far, we have not decided which cryomodule will be used for PLS-II RF system. Either CESR- or KEKB-type cryomodule has the almost structure [5,6,7], but the type of fundamental power coupler (FPC) is different.

SRF Cavity

The main difference between CESR and KEKB SRF cavities is coming from the different FPC types. A CESR

cavity uses a waveguide FPC. A KEKB cavity adopts an antenna-type coaxial FPC. This difference induces the cavity shapes a little change. For accelerating TM₀₁₀ π mode, both cavities have the almost same RF parameters.

HOM Induced Power

According the CESR and KEKB HOM dampers' testing results [8, 9], a reasonable estimation for all the HOMs' Q_{ext} could be 100. Based on this estimation and HOM calculation results, the HOM reduced power in the PLS-II cryomodules are 4.17kW for a CESR-type cavity, and 0.717 kW for a KEKB-type cavity.

Q_{ext} of the Fundamental Power Coupler

An external quality factor Q_{ext} of a FPC is decided by the beam current, cavity operation frequency, cavity accelerating voltage, cavity shunt impedance, cavity intrinsic quality factor, synchronous phase angle, Lorentz force detuning frequency, and microphonics. Because the PLS-II SRF cavities are operating at a CW mode, we needn't to consider the Lorentz force detuning frequency effect on the Q_{ext} . The amplitude of the microphonics is assumed about 100 Hz normally. Based on above discussions and PLS-II SRF cavity operation parameters, an optimal Q_{ext} for PLS-II RF cavities is 1.33×10^5 .

Cryomodule Arrangement

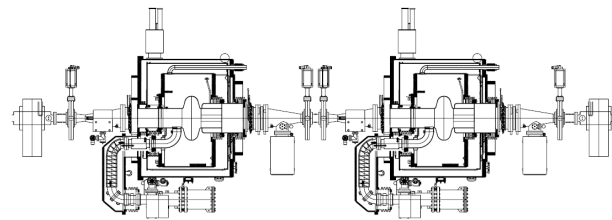
The available length for cryomodule of a LSS is 6.3m (from the elliptical-transverse vacuum chamber flange to flange), and it of a SSS is 2.8 m. Actual length of a CESR-type cryomodule is 3.043m for SSRF case [10], and it of a KEKB-type cryomodule is 3.48m for BEPC-II case [11]. Two CESR-type cryomodules can be installed into a LSS (see Fig. 1). In order to install two cryomodules into one LSS, we need to take off the tapers of two KEKB cryomodules and connect them together by a beam-pipe. An ion pump with 300 l/s and a photon absorber will be installed on the beam-pipe. Two big RF shorted gate valves will be installed on the both sides of the beam-pipe (see Fig. 1).

The third cryomodule will be developed and installed into a SSS in future.

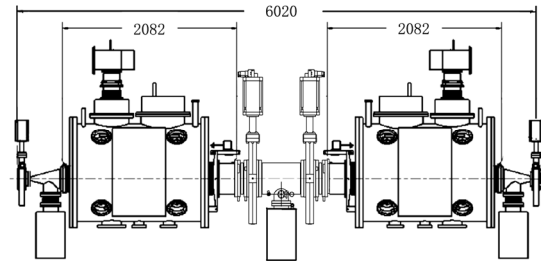
HIGH POWER SYSTEM

In the PLS-II storage ring, the beam-loss power is 663.3 kW. The maximum HOM reduced power is 15 kW. The total beam lost power is 678.3 kW, which is supplied by three SRF cavities equally. The RF power transfers to a cavity through a FPC. For the FPC Q_{ext} with tolerance of 20%, in order to keep the same beam power for PLS-II cavity, the extra RF power need is 2.83 kW. The RF power loss is 2.62 kW in the transfer line. The RF power loss in a circulator is 5.85 kW. So total RF power need for a SRF cavity is: 237.4 kW. Normally, considering the operation reliability, a 25% extra power is need at least. The RF output capacity of the amplifier should thus exceed 300 kW. Therefore, the maximum RF

load for a circulator and RF load of the PLS-II transmission line should not be less than 350 kW.



A. Two CESR-type cryomodules for one LSS.



B. Two KEKB-type cryomodules for one LSS.

Figure 1: Two-cryomodule installation in a long-straight section.

Amplifier Choice

There are three main kinds of CW high power amplifiers: klystron, IOT (Inductive Output Tube) and solid-state amplifier. Because the output power of the solid-state amplifier can not be up to 300 kW at 500 MHz and CW mode at present, this amplifier could not be used for PLS-II RF system. The IOT CW output power at 500 MHz can be up to 320 kW by combining 4 IOTs, each of which can output a maximum power of 80 kW. The available commercial klystron can output 310 kW or 800 kW CW RF power at 500 MHz. A comparison between the klystron and IOT for PLS-II RF system shows that the reliability and room need of the klystron is better than that of IOT system, other properties of the both power sources are the almost same. The final choice will be decided by the bidding price.

High Voltage Modulator

There are two kinds of the high voltage modulators for high power source: traditional crowbar circuit and pulse step modulation (PSM). The crowbar circuit modulator has been used in many accelerators. In past years, the crowbar circuit modulator is the main fault parts of the high power system. At present, many accelerator institutes don't want to use this modulator, instead of the PSM. PSM consists of element modules, for example, a 300kW and 55 kV PSM modulator is composed of 86 modules. Because the individual module contributes a low voltage to whole modulator, the faults of the individual modules can not effect the klystron operation. The modules are easy to be replaced. In order to improve the PLS-II RF system reliability, the PSM modulator will be used in the PLS-II RF system.

Transmission Line

During first commissioning stage, the cryomodules could not be available, 4 PLS NRF cavities will be used (two are in LSS 12, another two in SSS 12). One 300 kW klystron will supply the RF power to two NC cavities in the LSS 12. Two NRF cavities of the SSS 11 will be powered by two PLS power sources. After obtained the cryomodules, two NC cavities will replace by one cryomodule in the LSS 12. Therefore the waveguide transmission lines should be assembled for the NRF cavities as well as the SRF cavities.

To operate a SRF cavity, a 300kW RF source supplies the power to one cavity directly. The transmission lines are consisted of the WR1800 straight lines, flexible lines, directional couplers, elbows and a 350kW circulator and a 350 kW ferrite RF load. For operating two NC cavities by one 300 kW power source, a splitter and a phase shifter will be added to divide the 300kW RF power into two ways. A three-way transfer switch is used to test the klystron, circulator, RF load. A stub-tuner could be use to match the impedance of a SRF cavity. Figure 2 and 3 show the layouts of the PLS-II RF transmission line for a SRF and two NRF cavities.

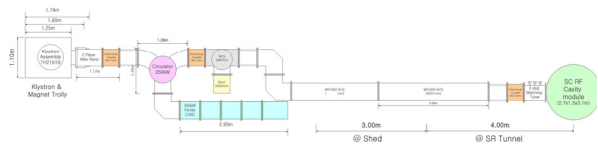


Figure 2: A layout of the PLS-II RF transmission line for a SRF cavity.

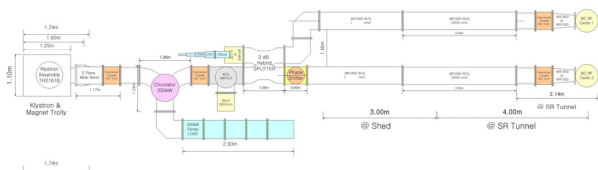


Figure 3: A layout of the transmission line for two NC cavities.

LOW-LEVEL RF AND CONTROL SYSTEM

The main function of a LLRF and control system is to control a RF cavity's accelerating field amplitude, frequency and phase, protect the cryomodule, high power system, cooling system, initialize and restart the RF system, communicate with central control system, and to compress beam longitudinal instability.

Phase fluctuations or jitters of the accelerating RF voltage bring time jitters on the arrival time of the synchrotron radiation pulses through longitudinal oscillation of the bunched beam. The general expectation is that the amplitude of beam jitters should less than 10%, based on the beam parameters of the PLS-II storage ring, the requirement for the synchronous phase stability of a PLS-II RF cavity is less than 0.3° , and that for voltage stability is less than 0.5%.

LLRF System-type Choice

Main LLRF and control systems of the charged-particle accelerators are analogous and digital at present. Analogous LLRF and control system has the merits: easy to implement hardware, single input/output systems and quick response speed. But it is complicated, and with low stability and control precision. In contrary, digital LLRF and control system is reliable and flexible, and has high control precision and simple circuit. After its cost survey for current-operating and recent-building light source accelerators, we found the cost of a digital LLRF and control system is 50% lower than that of an analogous LLRF and control system. Considering following factors:

1. PLS-II needs reliable and high control precision LLRF system;
2. Digital LLRF and control system can meet PLS-II requirements;
3. Digital LLRF and control system can save an amount of budget;

finally, a digital LLRF and control system was chosen for PLS-II.

Overview of the LLRF and Control System

The LLRF and control system includes: feedback loops for cavity frequency, phase and voltage amplitude, control system of the cooling system, interlock systems, communication system for transferring RF system's information to central control system, expert system for automatic initialization or restarting, and the alarm-call system. The feedback loops for the cavity frequency, phase and voltage amplitude control are performed by a digital LLRF control system. The control system of the cooling system, interlock systems and the alarm-call system are conducted by the PLC (programmable logical controller) and fast analogue section, which also communicate with digital LLRF system. The expert system for automatic initialization or restarting is achieved by a reset section.

PLS-II RF system has three sets of the individual subsystems or three stations. Every subsystem includes one set of LLRF control system, one set of high power system and one cryomodule. Three stations are controlled by one signal distributor, which is control by control center. The control center can communicate with three stations individually

Digital LLRF Control System

The digital LLRF (DLLRF) control system of PLS-II is based on digital IQ modulation and demodulation technique carried out by a commercial cPCI FPGA board. The function block includes the local oscillator (LO) signal, RF IN, RF OUT, clock signal distributor, digital processor, and communication between the controller and local host PC [12]. The FPGA board implements the control algorithm of the DLLRF. The RF IN processes three signals: the reference signal, the forward power signal from waveguide directional coupler, and the cavity signal from the field probe. They are down-converted to

IF signal in this part. The RF OUT translates the base-band control signals of the digital processor from digital to analog signals and then up-converts them to the RF frequency. The clock generator distributes various clocks for sampling, synchronizing, triggering, and so on. The FPGA board interfaces with the Carrier board by the PCI bus.

RF COOLING SYSTEM

The RF cooling system consists of two parts, one is a water cooling system for removal of working heat from klystron & HVPS, power transmission systems, photon absorbers, HOM absorbers and tapers of SRF cavities; another is a cryogenic cooling system to keep the SRF cavity at the operating temperature and cool the fundamental power coupler.

The central utility distributes low conductivity water (LCW) to each cooling station. For the reliable operation, the temperature rise of the cooling media in the power amplifier and its transmission system must not be higher than 10 degree. The 20°C cooling water with low conductivity (>1 MΩ.cm) from the central utility is supplied via main piping system and branched to each component.

The cryogenic cooling system is consisted of mainly helium refrigerator and nitrogen liquid supplier. The estimation cryogenic heat load per cryomodule is 103 W including static, dynamic heat loads and FPC heat load. The cryogenic heat produced from valve boxes, transfer line and Dewar (2000 liters) is 140 W. The capacity of He refrigeration is 673.6 W at 4.4K, which has about 50 % capacity margin. The installation capacity of cryogenic cooling system is more than 700 W at least.

RF SYSTEM-COMMISSIONING SCENARIO

The SRF cryomodules have long lead time for being fabricated and conditioned, and we have to start the PLS-II commissioning in July 2011. So the special milestone for the construction of SRF system is indispensable compared to other systems of storage ring.

Fortunately, the NRF system of PLS, of which power capacity and RF voltage is about 200 KW and 2 MV respectively, is available before the preparation of the cryomodules. The basic idea of PLS-II operation scenario in the point of RF system that the PLS NRF system will be re-used from commissioning phase to some extended period until SRF system to come in operation. The NRF cavities will be replaced by SRF cryomodule with 3 phases in step by step. The construction target is that all SRF system will be equipped in September 2012, then the full performances is to be achieved in April 2013.

SUMMARY

A SRF system has been decided to use in the PLS-II storage ring, based on consideration of the machine operation reliability, beam stability, available ID numbers,

project cost, project schedule, and future project and technology development at PAL.

Based on the SRF system choice, a PLS-II RF system has been designed. The PLS-II RF system of the storage ring is composed of three cryomodules, high power systems, LLRF & control systems, one cryogenic system and associate facilities. All the subsystems have been designed and studied, and are under bidding or developing.

ACKNOWLEDGEMENTS

The authors would to thank S. Park and H. Wiedemann from SLAC, M. Isawa and H. Hayano from KEK, E. Wehreter from BESSY, J. Tückmantel from CERN, W. Namkung from PAL, S. H. Park from KAERI, M. Kwon and H. S. Chang from NFRI, D. H. Han from Dong-Eui University, R. Rimmer, H. Wang and F. Marhauser from JLab, J. Liu from SSRF, Q. Qin from IHEP, K. Baptiste from LBNL, J. Rose from BNL, L. Dallin from CLS, D. Einfeld and M. Langlois from ALBA for their review and discussion for choosing PLS-II RF system.

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