DESIGN OF SUPERCONDUCTING RF SYSTEM FOR PLS-II UPGRADE

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Abstract

The RF system for PLS-II upgrade, of which beam current and emittance are 400 mA and 5.6 nmrad at 3 GeV, becomes much more important compared to PLS. To reduce the HOM intensity in RF cavities for stable beam, a superconducting RF cavity is selected for the PLS-II. The SRF system has to compensate beam loss power of 547 kW from 24 bending magnets, 20 insertion devices and other losses by RF HOMs and broadband losses along vacuum chambers. For sufficient energy acceptance and lifetime the design RF voltage is 4.5 MV. Two 500 MHz superconducting cavities will be operated first from October 2012, following commissioning with PLS NC cavities from July 2011. Then the third module will be prepared for redundancy for a backup system. For the 3 SRF cryomodules, a 700 W class helium cryogenic system will be prepared in 2011. The design of PLS-II SRF system including cryogenic system is reported in the paper.

INTRODUCTION

The PLS-II is the upgrade machine from the original PLS, which is a 3rd generation synchrotron light source with 2.5 GeV energy and 190 mA beam current and has provided users beam since 1996. The energy and beam current of PLS-II are 3 GeV and 400 mA, respectively. The number of insertion devices at PLS-II will be 20, compared to 10 of PLS by modifying TBA to DBA magnetic lattice. It can be possible by shortening bending radius of dipole magnet with same ring circumference of PLS. The expected power loss from 24 BMs and 20 IDs including broad band losses in RF cavities, vacuum chambers, BPMs, gate valves and etc will be estimated as high as 547 kW. The RF related parameters of PLS-II are shown Table 1.

Table 1: Parameters of PLS-II Storage Ring

Parameters	Unit	Values
Energy	GeV	3
Current	mA	400
Circumference	m	281.82
Emittance	nm-rad	5.6
RF acceptance (W/O IDs)	%	2.8
Accelerating Voltage	MV	4.5
Energy Loss per turn (24BM+20ID)	keV	1242
Harmonic number	-	470
Momentum compaction	-	1.38×10^{-3}
RF frequency	MHz	499.973

The 24 straight sections with small circumference give tough conditions in points of beam instability and beam power. The prior design requirements for PLS-II upgrade are low higher- order modes (HOM), high reliability and high power capability. Even though top-up mode operation at PLS-II, long beam lifetime - as long as 10 hours is also important requirement. For required lifetime and sufficient RF bucket height at injection system the energy acceptance ($\Delta E/E$) must be higher than 2.7%, which can be assured by 4.5 MV RF voltage with the over voltage factor of 2.71. The frequency of PLS-II RF system is 499.972 MHz which is a slight modification from 500.082 MHz at PLS due to minor changing ring circumference.

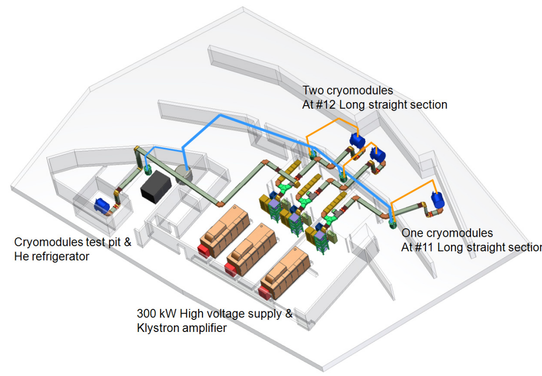

Figure 1: Installation layout SRF system.

After deliberate design and investigations for an usual (NC) and advanced (SC) RF technology based on the requirements above, the internal and external severe disputes were done, resulted in an superconducting cavity, a 300 kW klystron type power system and a digital LLRF system. By selecting superconducting RF cavities, PAL gave the highest impact factor on the beam stability among the other factors, such as PAL self-supported RF technologies, costs, system reliability. The less number of cavities, low impedances from cavity HOMs are expected to make possible stable beam at high beam current with low beam emittance. The relative short MTBF (Mean Time Between Failure) compared to NC RF system should be accepted at the initial phase of SRF operation, but with deliberate efforts such as sufficient aging SRF cavities with beam operation and more experiences with training the MTBF at PLS-II is expected to be approached to reasonable standard.

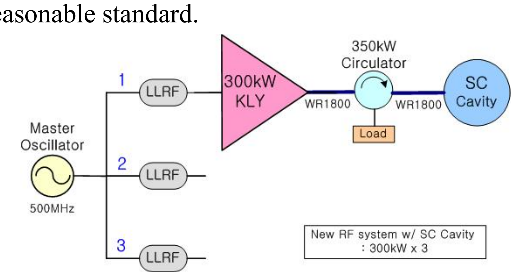

Figure 2: Scheme of SRF system.

PLS-II RF system consists of three 500 MHz-class SRF cryomodules, three 300 kW-class power amplifiers and a

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700 W-class cryogenic cooling system, which construct 3 independent RF systems shown in Figure 1. The scheme of RF power transmission is as simple that each RF system integrates a digital LLRF, 300 kW klystron amplifier, 350 kW class circulator, ferrite load and a SRF cryomodule including valve box, shown in Figure 2.

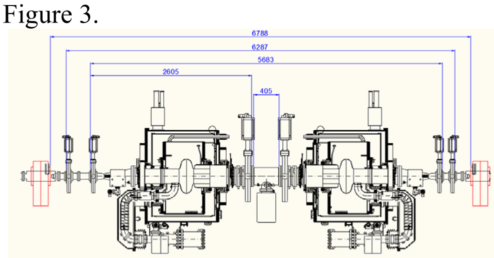
Three (3) cryomodules can provide the required RF power, 547 kW and voltage, 4.5 MV, the detail design parameters of RF system are shown in Table 2

Table 2: Parameters of PLS-II RF System: ( ) is for case of two cavities.

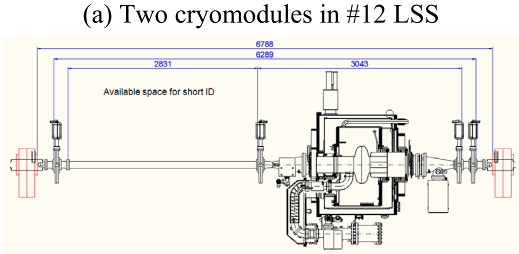
Parameters	Unit	Values
Conductor type	-	Superconducting
Number of SRF cavity	-	3 (2)
RF voltage per cavity	MV	1.5 (1.65)
RF power per cavity	kW	183 (220)
Number of power amplifier, 300 kW	-	3 (2)
Cryogenic thermal loads @4.5 K	W	700
SR Tunnel space (# of straight section)	-	2-long

Due to the long delivery time of cryomodules and helium refrigerator, the installation schedule of SRF system is mismatched to the other systems so that the upgraded PLS-II is forced to be operated with 5 PLS NC cavities during first year including commissioning and user service, August 2011 – July 2012. Meanwhile, two SRF cavities will be placed at the tunnel with substitution of 3 NC cavities during the scheduled maintenance August-September 2012. The RF capacity such as voltage and power of so-called hybrid cavity system with 2 NC and 2 SC cavities are 4.3 MV and 540 kW respectively. The third SRF cavity is the redundancy in case which two SC cavities can't provide target performance even with long-term aging and improvement of operation condition. Also it is spare for a failure of one SC cavity.

Three SRF cryomodules occupy 2 long straight sections (LSS), 6800 mm long, two modules of CESR-III type are in one LSS and third one in another LSS. But the third one occupies only half of a LSS, so the remained half section can be available for a short insertion device as shown Figure 3.



(a) Two cryomodules in #12 LSS



(b) One cryomodule in #11 LSS

Figure 3: Required space for 3 cryomodules.

SUPERCONDUCTING CAVITY AND CRYOMODULE

A SC cavity is the key component in a SRF system so that the RF characteristics related to the beam is decided by the design of cavity. A cryomodule which contains a SC cavity also provides impact on system reliability. The time required to develop a new SRF cryomodule is quite long as several years. Moreover, to assure the reliable performance within the given tight schedule as an user machine gives some risks. With such circumstance the available designs for a 500 MHz SRF cryomodule were investigated and then the CESR-III type cryomodule was determined by the PLS-II critical factors as available length of straight section at PLS-II, procurement easiness, reputation in the light sources and costs between KEK-B and CESR-III types. Figure 4, which provides the distributions of longitudinal HOM impedances for NC and SC cavities, shows why a SC cavity was selected for PLS-II. The solid line is the calculated threshold impedance for multi-bunched instabilities. As shown in plot all HOM impedances from SC cavities are below the solid line.

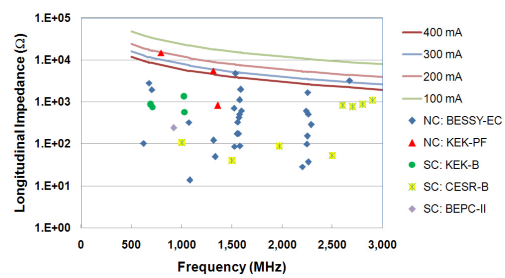


Figure 4: Distribution of longitudinal HOM impedance.

The CESR-III SRF cavity has a large beam pipe with diameter of 240 mm at both sides, in which one is rounded shape and the other is fluted pipe to extract dipole mode HOM at the downstream of electron beam.

Table 3: Characteristics of CESR-III SRF Cavity

Parameters	Unit	Values
Resonant frequency	MHz	499.765
R/Q	Ω	89
Q0	-	> 1.0 E9
Operating temperature	K	4.5
Accelerating voltage / cavity	MV	>2.5
Max. RF power / cavity	kW	300
HOM removal	-	ferrite absorber
Input power coupler	-	waveguide

The power coupler is little bit complicated with waveguide type. It has a rectangular shape ceramic window, two heat exchangers at LHe and LN2 temperatures for thermal transition between cold cavity temperature, 4.5 K and room temperature and pressure barrier between vacuum and environment. The window can be powered up 500 kW in travelling wave mode and 150 kW in standing wave mode, with Ti coating at vacuum side. Most part of HOMs' power are extracted to ferrite HOM absorbers attached to the beam pipes outside of cryostat, they are able to absorb the heat, up to 7 kW with water cooling. With these design the R/Q can be reduced low as 100. The important specification of CESR-III cavity is given in Table 3.

HELIUM REFRIGERATOR SYSTEM

The cryogenic system to maintain a Nb cavity in stable superconducting state also gives an impact on the stable operation of SC cavity. The condition for frequency stability at the upstream of valve box is that the pressure fluctuation (ΔP) of LHe and LN2 are 1220□3 mbar and 3000□50 mbar, respectively. Meanwhile valve box regulates their pressures to 1220□1.5 mbar and 3000□15 mbar in the cryomodule to keep LLRF requirement.

The total heat load from 3 SRF cryomodules and cryogenic components is estimated 425 W. Meanwhile, the cooling capacity of He refrigerator is designed with 700 W including the operation margin of 50%. The requirement of the refrigerator is 450 W at 4.5K without LN2 pre-cooling and 715 W with LN2 pre-cooling. It has a liquefying capacity of 18 L/h at 4.5K. It can provide the mixed mode operation with 700W refrigeration and 27 L/h liquefaction with LN2 pre-cooling. The cryogenic thermal loads are summarized in Table 4. The arrangement of cryogenic system is shown in Figure 1

Table 4: Cryogenic Heat Loads for SRF System

Sources and parameters	Value	Unit
Number of SRF cryomodule	-	3
Static heat load from cavity	W	30 × 3
Dynamic heat loads from cavity @ 1.7 MV	W	65 × 3
From input power coupler (flow of cold gas He)	Liter/hour	6 × 3
Distribution valve box	W	30
LHe transfer line (length: 35 m +15 m x 3)	W	80
LHe dewar (2000 liter)	W	30
Estimated heat load from main SRF modules	W	425
Total heat loads	W Liter/hour	425 18
Machine capacity margin	%	50
Required capacity of He refrigerator	W	>700

HIGH POWER RF SYSTEM

With deliberate study on different types of high power RF sources such as a klystron, IOT(Inductive Output Tube) and solid state amplifiers, a 500 MHz, 300 kW klystron amplifier type was selected for SRF system of PLS-II. The decided model of klystron is Thales TH2161B and high voltage power supply of 55kV/12A is the switching type with pulse step modulation of Thomson. The wall losses of three SC cavities are negligibly small, about 150 W with 4.5 MV compared to 547 kW required RF power, so that all RF power from klystrons can be supplied to the cavities. Three 300 kW klystrons can provide the required beam power with more than 10 % margin and will be installed three RF stations independently shown in Figure 1. Therefore, to have redundant power, each klystron can be operated with 183 kW maximum RF power level.

Figure 3 shows simple block diagram of the high power RF system for three SC cavities with 300kW klystron which is base design. But, the existing two 75kW klystron amplifiers with two normal conducting cavities of PLS would be operated for several years until the third cryomodule is to be prepared.

The components of RF station such as waveguides, circulator, load, directional couplers, splitter, elbows, flexible sections and so on have designed with 350 kW power capacity. The 350kW RF loads are also required to absorb the reflected RF power for independent tests of klystron amplifier without beam in order to isolate and protect the klystron from the reflected RF power from the SRF cavity.

LOW-LEVEL RF SYSTEM

The control errors of RF gap voltage, phase and frequency from the low-level RF system (LLRF) could develop a beam instability in a storage ring. The phase fluctuations or jitters of the accelerating RF voltage bring jitters on the arrival time of the synchrotron radiation pulses through longitudinal oscillation of the bunched beam. These kinds of instabilities by a LLRF should be controllable by LLRF itself. Not only for control of accelerating field, frequency and phase, but also the LLRF must provide diagnostics for the calibration of field gradient. A cavity detuning, and controlling frequency tuner, interlock, expert system for automatic initialization or restarting are realized by LLRF also. To realize all these functions more reliably a digital feedback control technique will be adopted for flexibility of the feedback and feed forward algorithm at PLS-II

The phase and amplitude requirements for PLS-II and PLS are summarized in Table 5. The performance target of the PLS-II RF system is that the long-term stability for the amplitude and phase of the accelerating RF voltage are within ±0.35 % and ±0.35o, respectively.

Table 5: RF Phase and Amplitude Requirements for PLS and PLS-II

	PLS-II		PLS	
	Vertical	Horizontal	Vertical	Horizontal
beam size at the straight section	11 μm	248 μm	35 μm	455 μm
10 % beam size	1.1 μm	25 μm	3.5 μm	45.5 μm
Dispersion	5 mm	250 mm	5 mm	20 mm
Δp/p limit	1.1 μm /5 mm = 2.2×10^{-4}	1.0×10^{-4}	7.0×10^{-4}	2.2×10^{-3}
Δφ limit	0.78°	0.35°	5.9°	19°
ΔV/V limit	0.029	0.0075		

To control RF field, phase and frequency, the PLS-II LLRF consists of a direct digital synthesis (DDS) to produce the 50MHz IF output, feedback control incorporating to RF down conversion, ADCs / DACs interfaced to the digital signal processing and a Field Programmable Gate Array (FPGA) and ethernet network to communicate to control room or other systems.

Embedded IOC such as single board computer (SBC) and compact PCI architectures will be employed for local control to communicate to upper EPICS IOC. END.