DESIGN OF A THIRD HARMONIC SUPERCONDUCTING RF SYSTEM AT PLS

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Abstract

The preliminary results on feasibility study to introduce a third harmonic superconducting rf system in the 2.5 GeV PLS storage ring are presented. The study has being performed in parallel with the tasks of low emittance ring and rf power upgrade for high-brilliance of the ring. The beam lifetime was estimated to be around 10 hours in the ring operation with emittance of 10 nm and beam current of 250 mA after the completion of the tasks. It is shown that a superconducting third harmonic rf system with 1.5 GHz in the ring can increase the beam lifetime at least by a factor of two. We present the effects of the third harmonic rf systems on beam dynamics in the ring. In this paper we also present the preliminary results on designs of the third harmonic rf cavity and cryogenic system.

INTRODUCTION

In December 1994 PLS storage ring started to operate with 2 GeV beam. Since Sep. 2002 the storage ring has being operated by a 2.5 GeV full energy injection from a linac[1]. At this moment, PLS storage ring is being operated with the beam current of 180 mA and the emittance of 18.9 nm at 2.5 GeV. There has been a continuous user's demand for more bright X-ray sources. To satisfy this requirement, we have performed the tasks for low-emittance of ring and upgrade of total rf power. In the next year, one more rf cavity will be inserted into the storage ring and so fifth rf cavity is to be installed to the ring after placing four 60 kW klystrons with five 75 kW klystrons[2]. Then, total rf voltage will be increased from 1.6 MV to 2.0 MV. Design on low emittance lattice for a high-brilliance in the ring showed that the emittance could be reduced to around 10 nm[3]. These tasks can lead to a higher brilliance of the synchrotron radiation in the ring. However, reduction in beam lifetime due to a higher beam current and low emittance beam may cause a trouble to users of the beam lines. Estimated beam lifetimes in the PLS ring are shown in Table 1. Accrodingly, we have investigated introduction of a superconducting third harmonic rf system to the ring in order to increase the beam lifetime that has also widely implemented and operated in light sources[4,5]. This paper presents the considerations for optimizing the beam lifetime using passive third harmonic rf cavities. Preliminary results on design of the harmonic rf system that provides the increase of beam lifetime in a factor of about two are also presented.

LONGITUDINAL BEAM DYNAMICS

Bunch lengthening and lifetime increasing

We investigated longitudinal density distribution of the beam when main voltage of 500 MHz rf system is combined with the harmonic voltage of 1.5 GHz superconducting rf system. Fig. 1 shows the potentail well and longitudinal beam distribution for a harmonic voltage of 0.56 MV and main rf voltage of 2.0 MV. It is shown that the bunch length is elongated by a factor of 2.2 ($\sigma_z = 15mm$, $\sigma_{zo} = 6.7mm$) with the beam induced voltage of 0.56 MV at 1.5 GHz. On the other hand, the energy acceptance in the harmonic rf system plus main rf system showed almost the same as one of main rf system. It means that the Touschek lifetime can be improved by a factor of two. We can also control the voltage of the harmonic rf cavity by using of its frequency tuning system. Fig. 2 shows the beam lifetimes and bunch lengths as a function of the induced voltage in the harmonic cavity at 250 mA when the main rf voltage is 2 MV and the emittance is 10 nm. The longitudinal beam distribution has two peaks in the harmonic voltages higher than 0.65 MV and the expected elongation in bunch length shows a factor of 2.2 around a harmonic voltage of 0.6 MV, resulting the improvement in lifetime by a factor of 2.3.

Effects of beam induced voltage

In normal operation we usually use a gap of 68 rf buckets in the harmonic number of 468 in order to clean out ion traping. Then the induced modulation in the rf voltage may generate a phase modulation through the bunch train. The maximum amplitude of this phase modulation is estimated to be about 3.1^o at 1.5 GHz rf cavities for a gap 68 bunches, $R/Q = 90\Omega$ and V=0.56 MV. Such a phase spread in the bunch train does not become a problem, on the contrary it may act as Landau damping. On the other hand, we have also in detail investigated the transient beam effects in the presence of the harmonic rf system by using a multiparticle and multibunch simulation method.

Stabilization of coupled-bunch instabilities

Bunch lengthening results in decreasing in peak current of the beam and raises threshold current for single bunch instability. We also expect a considerable amount of Landau damping which helps in stabilizing longtitudinal coupled-bunch instabilities due to 758 MHz and 1300 MHz HOMs that may be generated in beam currents higher than 200 mA in the PLS ring.

HARMONIC RF CAVITY DESIGN

We adopted a two cavities assembly with a R/Q value of 90 Ω and a beam current of 250 mA at 2.5 GeV. We founded out that a harmonic voltage of 0.56 MV is induced at 1.5 GHz rf cavities when the cavities are detuned by 60 kHz. The amount of the beam induced voltage can be kept even at lower beam currents by controlling the detuned frequency. The beam power lost into the fundamental mode was very small when it was compared to the synchrotron radiation losses per turn. Our third harmonic cavity was designed to satisfy the following requirements: 1) The total impedance of the cavities is sufficient to achieve the optimal elongation condition. 2) The higher order modes in the cavities are also sufficiently tunable. A cross-sectional view of the preliminary designed cavity is shown in Fig. 1. The parameters of the cavity are also listed in Table 1.

PRELIMINARY DESIGN OF CRYOSTAT

A Cryomodule consists of resonant cell, HOM removal system, cryogenic cooling system, vacuum system and safety system. Fig. 4 shows the conceptual drawing of cavity cryomodule, which is for estimation of thermal budget to decide the heat capacity of helium refrigerator. The approximate estimation of thermal load is described in Table 3. As shown in it the power dissipation in cavity surface and conduction heat via warm flange are major heat sources in cryomodule itself. The thermal load from HOM removal system is not inspected due to that its type has not been determined yet, but it will be several Watt at most from review of ELETTRAs work[5]. While, the cryogenic losses in cryogenic cooling supply system, of which consists piping system for liquid helium and valve box for coolant distribution, is another big heat load outside the cryomodule. The heat loads in Table 3 are assumed to be optimal design, so the total thermal budget will be slightly higher in real system. Anyway the required heat capacity of helium refrigerator is 120 to 150 W at 4.5 K in condition for sufficient operation margin. Resonant cavity is sealed from beam pass in helium tank and cooled by direct contact with liquid helium (LHe). The vaporized helium circulates beam tube, 1st thermal shield and other thermal transient regions between LHe temperature and ambient temperature. The 2nd thermal shield is cooled by liquid nitrogen (LN2) supplied from outer LN2 vessel, which is to reduce the volume of cryomodule. To monitor the operation status for reliable operation of cryomodule a number of instruments and sensors must be installed at cavity and its related systems. RF gap voltage, RF phase and RF frequency are for operation status of storage ring, and LHe level, temperatures in cavity surface and thermal shields, pressure in helium tank, vacuum in cryostat are for safe operation of SC cavity. To protect SC cavity integrity from quench, voltage (resistance) at cavity surface has to be monitored continuously. All the wires of instruments and sensors and cryogenic piping systems communicate between low temperature parts and ambient temperature regions, so the feed-through flanges such as number of feed-through, size, position, and etc, are planed to minimize the heat inflows. The mechanical properties of titanium for LHe tank is superior to that of stainless steel (SUS) in cryogenic temperature, more over its thermal expansion coefficient is similar to that of niobium, which is very important property to weld between different materials. Though the superior properties of titanium, LHe tank is to be fabricated with stainless steel (316L) in order to save manufacturing cost. As shown Fig. 4(top), niobium beam tube is connected to stainless steel flange via titanium bellow and LHe tank is connected with SUS flange by Tig welding. This design scheme is capable of absorbing thermal shrinkage effectively during the cooling and design tolerance impact in fabrication. It also avoids welding between niobium and stainless steel. The 1st and 2nd thermal radiation shields are copper cylinders with winding copper tubes for flow of vaporized helium and liquid nitrogen, respectively. Auxiliary devices such as HOM removal system are installed with SUS ConflatTM flange at niobium beam tube. Because welding between Nb and SUS is impossible, they are brazed with special material, Nioro (82% cold, 18% nickel).

CONCLUSION AND FUTURE PLAN

We expect at least increase of a factor of 2 in the beam lifetime at 250 mA by a third harmonic rf system in the 2.5 GeV PLS. Thermal capacity of cryogenic cooling system, 120 W at 4.5 K is thought to be enough to cover the operation margin and emergency LHe storage for the third harmonic rf system. Though titanium is best material for LHe tank, SUS316L is our choice to reduce manufacturing cost. After conceptual design on HOM removal system and on optimal tuning of the cavity, detailed engineering design will be performed. Commissioning of prototype harmonic cavity to confirm the cavity design and HOM structures is expected to perform in the beginning of next year. The test cryostat is designed for multi-uses for various superconducting devices, as shown in Fig. 4 (bottom), and is in the last stage of engineering design.

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Table 1: Estimated beam lifetimes in the PLS storage ring.

Current	Emittance	RF cavity	3rd HC	Lifetime
180 mA	18.9 nm	4 EA	No	19.4 h
250 mA	18.9 nm	5 EA	No	22.2 h
250 mA	10 nm	5 EA	No	10.2 h
180 mA	18.9 nm	4 EA	Yes	35.8 h
250 mA	18.9 nm	5 EA	Yes	50 h
250mA	10 nm	5 EA	Yes	23 h

Table 2: Main parameters in the PLS storage ring.

	Units	Values
Emittance (low emittance lattice)	nm	18.9 (10)
Beam energy	GeV	2.5
Circumference	m	280.56
Rms energy spread		8.6×10^{-4}
Rms bunch length at 1.6 MV(2MV)	mm	7.6 (6.7)
Main rf frequency	MHz	500.08
Number of rf cavity		4 (5)
Main rf voltage	MV	1.6 (2.0)
Synchrotron tune		0.01
3rd harmonic rf frequency	GHz	1.5
3rd harmonic rf voltage	MV	0.56
R/Q of 3rd harmonic cavities		90
Rms bunch length with 3rd cavities at 1.6 MV (2.0 MV)	mm	14 (15)

Table 3: Heat loads of cryogenic system.

Heat sources	W
Dissipation in cavity surfaces	32
Conduction via warm flange of cryomodule	11
Conduction via feed-through for instruments	8
HOM removal systems	< 10
Cryogenic losses in cryogenic supply system	30
Total	< 91

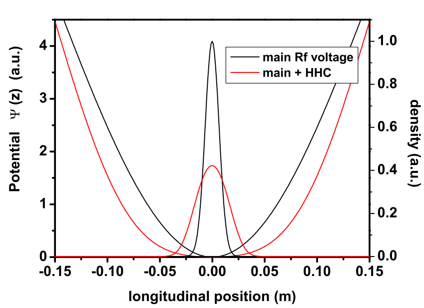

Figure 1: Potential well and longiudinal bunch distribution. Voltages of the main rf and the third harmonic rf are 2 MV and 0.56 MV, respectively.

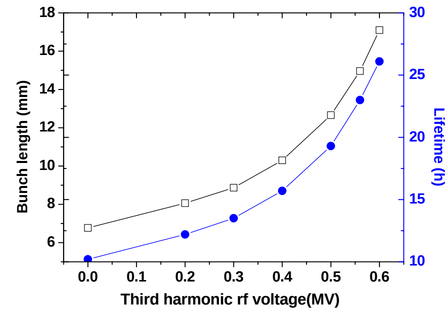

Figure 2: Lifetimes (points) and bunch lengths (squares) for the different third harmonic rf voltages.

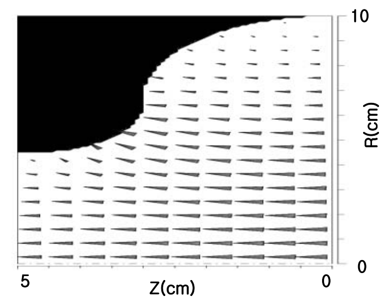

Figure 3: The cell geometry for the third harmonic rf cavity and fundamental mode electric field.

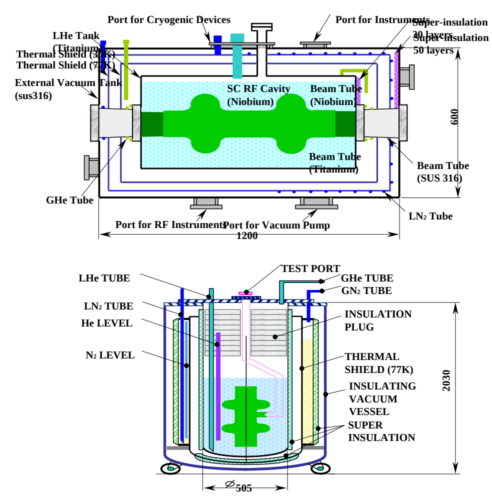

Figure 4: Conceptual drawing of cryomodule for the harmonic cavities(top). Test cryostat for test of the prototype harmonic cavity.