CONCEPTUAL DESIGN OF A SUPERFLUID SUPERCONDUCTING THIRD HARMONIC RF SYSTEM FOR THE SSRF STORAGE RING

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Abstract

Harmonic cavity can improve the beam quality through bunch size lengthening which includes providing Landau damping, suppressing coupled bunch instability and microwave instability, enhancing the beam current per bunch besides the beam lifetime improvement. A passive third harmonic superconducting cavity operating at super fluid liquid helium has been proposed for the SSRF storage ring with compromise on the required harmonic voltage, limited installation space and dissipated cryogenic power. This paper will mainly present the conceptual design of the harmonic rf system including the requirement of SSRF, a brief review on beam dynamics of harmonic rf system and the harmonic cavity choice.

INTRODUCTION

Shanghai Synchrotron Radiation Facility (SSRF) has been opened to users since 2009. Up to now, the machine is operated in top-up mode with beam current 220mA. The total rf voltage is around 4.5 MV with amplitude stability better than ±1% and phase stability better than ±1 degree. With more and more insertion devices and beam lines installed in the SSRF beam line phase-II project, it needs to improve the beam quality and to increase the beam life time. Higher harmonic cavity will be a good choice for beam quality improvement because of its capability not only to increase life time by lengthening bunch size without reducing the photon beam brightness or increasing the average beam energy spread, but provide landau damping to suppress the multibunch instabilities [1-4]. The harmonic system can raise the threshold for single bunch instabilities through decreasing peak current and synchrotron tune spread, too. Furthermore, the passive system will use the beam to induce the required voltage in the harmonic cavities and thereby an external rf source is not required. The superconducting cavity has sufficient impedance to generate enough voltage to achieve similar lifetime improvement even at relatively low beam currents, which is useful for a filling mode with high current/bunch with low total beam current. And it also has a relatively low R/Q value to suppress the transient effect.

Higher harmonic cavities have been used to improve beam quality in many accelerator machines, however, there are only several third generation synchrotron light sources [5] adopting superconducting cavities. The beam lifetime has been increased 2.2 times in SLS while 3.5 times in ELETTRA light source. It is planed to install two passive higher harmonic superconducting cavities operating at 4.2K to provide about 1.6MV voltage in total to lengthen the beam size at NSLS-II in USA [6,7]. A higher harmonic system will be established in SSRF Phase-II project aiming to control the bunch length and to suppress coupled-bunch and microwave instabilities and raise the threshold for single bunch instabilities.

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REVIEW OF DOUBLE RF SYSTEM

The harmonic rf system will generate a harmonic voltage by beam itself when using a passive cavity, thus the combined voltage from main and harmonic rf system is given by [1-2]

$$V(z) = V_{rf}[\sin(\frac{\omega_{rf}}{c} z + \phi_s) + k \sin(n\frac{\omega_{rf}}{c} z + n\phi_h)]$$
(1)

where k is the relative harmonic voltage to the main rf voltage, ϕ_s is the synchrotron phase, ϕ_h is the harmonic phase and n is the harmonic number. Here n equals to 3 for SSRF phase-II. The longitudinal density distribution of the bunch has a Gaussian distribution in energy is given by

$$\rho(z) = \rho_0 \exp[-\frac{\Phi(z)}{\alpha^2 \sigma_l^2}] \qquad (2)$$

where ρ_0 is a normalization constant and $\Phi(z)$ is the potential. The longitudinal bunch distribution can be shaped by varying the relative amplitude and phase of the harmonic voltage. The bunch will be lengthened while the harmonic voltage is adjusted to cancel the slope of the main rf voltage. It can be obtained that the optimal bunch lengthening condition which can be seen in equation (3), where U0 is the radiation loss per turn and Vrf is the main accelerating voltage.

$$k = \sqrt{\frac{1}{n^2} - \frac{(U_0/V_{rf})^2}{n^2-1}}$$

$$\tan n\phi_h = \frac{nU_0/V_{rf}}{\sqrt{(n^2-1)^2 - (n^2U_0/V_{rf})^2}} \qquad (3)$$

$$\sin\phi_s = \frac{n^2}{n^2-1}\frac{U_0}{V_{rf}}$$

Table 1 shows the nominal parameters of SSRF and the required harmonic values, and what should be notified is that the Touschek lifetime improvement factor is a

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calculated value under the optimal bunch lengthening conditions. In fact, it is impossible to reach the optimal conditions with a superconducting cavity because of its narrow bandwidth. Thus a factor of ~2 is preferred concerning the real operation conditions. Figure 1 shows the potential well and bunch distribution with main rf voltage and with the harmonic cavity voltage.

Table 1: Nominal SSRF Parameters

Parameter	Value
Beam energy	3.5 GeV
Circumference	432 m
DC beam current	0.2-0.3 A
RF voltage	≥4.5 MV
RF frequency	499.654 MHz
Harmonic number	720
Momentum compaction	4.2e-4
Energy spread	0.001
Radiation loss per turn	1.44 MeV
Nominal synchrotron tune	0.0075
Nominal rms bunch length	3.8 mm
Harmonic rf voltage	1.4 MV
Rms bunch length with HHC	4~8 mm
Optimum lifetime improvement factor	3.9

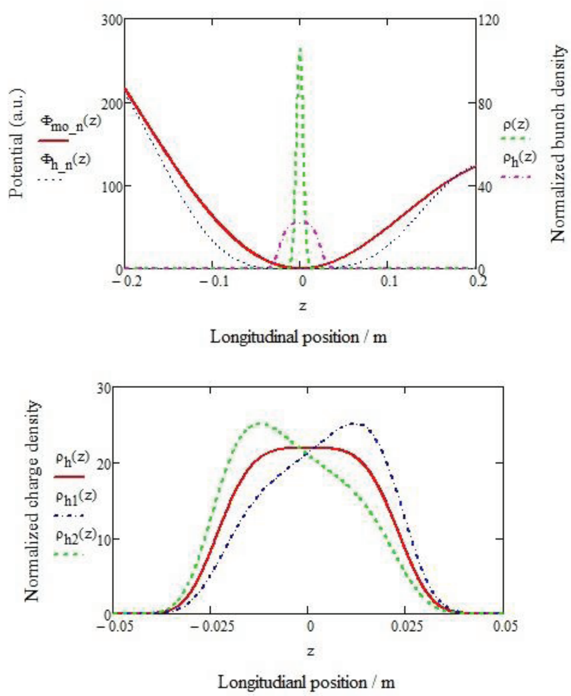

Figure 1: (up) Flattened potential well and normalized bunch profile with the harmonic cavity under optimal conditions. (down) The normalized bunch profile with harmonic cavity phase adjusted to be ±0.5 degree from the optimal condition.

HARMONIC CAVITY CHOICE

The harmonic cavity for the bunch length control system for SSRF has been decided to be a superconducting cavity. The design of the superconducting cavity will be the key issue in the harmonic rf system. Some principles should be stressed during the harmonic cavity design.

- The cavity dynamic loss should be lower which will decrease the cost of cryogenic plant.
- The total cryomodule length should be as short as possible not to occupy long straight section in the storage ring.
- The higher order modes should be damped efficiently.

For SSRF, the harmonic cavity is planed to be installed in a short straight section around 2 meters generated by a super-bend lattice thus the harmonic module length is confined. The required harmonic voltage is near 1.5 MV with 4.5 MV main rf voltage to lengthen the bunch. The quality factor of the worldwide installed 1500MHz harmonic cavity is only around 1E8 when operating at 4.2K with a gradient at 5MV/m. This means totally three modules will be needed which is impossible for SSRF. If increasing the gradient to obtain high induced voltage, it will decrease the quality factor resulting in high cryogenic power consumption.

There are two types of 1500MHz passive harmonic cavity for the third generation light sources: the super-3HC and the NSLS-II type. The former has an uncoupled two-cell niobium cavity installed in one cryostat, while the latter has a coupled two-cell niobium cavity. Different cavity geometry design and different means of higher order modes suppression and different tuner type have been developed. It is better to have a coupled two-cell cavity module because of its external mechanical tuner frame and control motor, and its beam line higher order modes damper which can be cooled by water saving extra cryogenic power. This kind of cavity has to be careful designed not to excite the unwanted zero mode and to have a wide PI mode tuning band for harmonic cavity operating in parking mode, bunch lengthening mode and bunch shortening mode.

Table 2: Parameters of SSRF Harmonic Cavity

Parameter	Value
R/Q (PI mode)	~90 Ohm
Harmonic voltage	1.4~1.8 MV
Quality factor	>1E10
Harmonic frequency	1498.96 MHz
Operating temperature	2 K
Static loss	20 W

Because of the limited installation space and the required high harmonic voltage, a passive coupled two-cell superconducting module operating at super-fluid liquid helium temperature will be a better choice for the SSRF phase-II project. Assuming R/Q value is 90 Ohm and the quality factor is 1E10 at 1.5 MV induced voltage, the dynamic loss will be only several watts. The total cryogenic loss will be mainly dominated by the static loss. Figure 2 shows a conceptual scheme of this cryomodule, which will have a 2 K liquid helium vessel, a 5 K helium gas thermal shielding, a 77 K liquid nitrogen thermal shielding and a vacuum vessel. Two magnetic shielding will be located at the inner layers of liquid nitrogen vessel and the vacuum vessel, respectively. Two higher order modes dampers will be equipped at both ends of the beam pipes. Table 2 shows the conceptual design parameters of the SSRF harmonic cavity. The development of this kind of cryomodule can share the fabrication experience of the L-band superconducting cavities for ILC and TESLA. The detail design of the cavity, cryostat, tuner, HOM damper and low level rf controller needs to be carried out.

The harmonic system will include one harmonic cryomodule, one low level rf controller, one set of cryogenic equipment and one control unit for cryomodule supervision and valve-box control and interlocks. The low level rf controller will adopt the digital IQ based technique and will be operated to make the harmonic module keep constant voltage with different beam current.

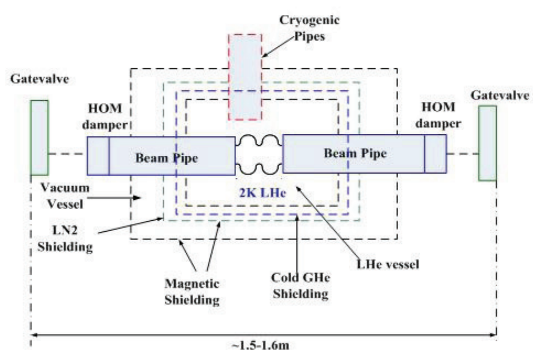

Figure 2: Conceptual design scheme of a coupled two-cell passive 1500MHz harmonic cavity for the SSRF phase-II project.

DEVELOPING ACTIVITIES ON SC CAVITIES AT SINAP

SINAP has started the research on superconducting cavity at 1500MHz and 500MHz. A single cell 1500MHz harmonic cavity has been designed and fabricated for studying the double rf system theory and exploring the fabrication techniques [8,9]. Simulation on uncoupled two-cell niobium cavity has been carried out, too.[8] A 500MHz KEKB type single cell niobium cavity has been fabricated, surface treated and vertical tested successfully in 2010 which shows a gradient high to 10MV/m with quality factor around 4E8 [10]. A 500MHz 5cell low lossy niobium cavity with large beam aperture has also been in-house designed, fabricated, surface treated and vertical tested successfully in 2012. The result shows a cavity voltage high to 7.5MV and quality factor better than 1E9 [11]. These achievements prove that a set of superconducting cavity developing facility has been constructed at SINAP which will benefit the development and establishment of the harmonic rf system.

SUMMARY AND OUTLOOK

The bunch length control system will be developed and established for the SSRF phase-II project. The installation space limitation and cryogenics power consumption decide that a passive superconducting module with a coupled two-cell niobium cavity operating at super fluid liquid helium turns out to be a better scheme. A conceptual design of the bunch length control system and the relative parameters have been proposed.

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[11] Paper in prepared.

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