DESIGN OF A PASSIVE SUPERCONDUCTING HARMONIC CAVITY FOR HALF STORAGE RING

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Abstract

Higher harmonic cavities, also known as Landau cavities, have been proposed to improve beam lifetime and provide Landau damping by lengthening the bunch without energy spread for stable operations of present and future low-emittance storage rings. This contribution presents design of a passive superconducting 3rd-harmonic cavity (super-3HC) for the planned Hefei Advanced Light Facility (HALF) at University of Science and Technology of China. It is designed to provide 0.43 MV at 1499.4 MHz for the nominal 2.2 GeV, 350 mA electron beam, and 1.44 MV main RF voltage in storage ring. Through optimizations it has a low R/Q < 45 Ω, which has potential to achieve a good bunch lengthening. Higher-order-modes are strongly damped using a pair of room-temperature silicon carbide (SiC) rings to meet the requirement of beam instabilities. In addition, preliminary engineering design for the super-3HC cryomodule is also described in this contribution.

INTRODUCTION

Hefei Advanced Light Facility (HALF) [1] is a soft X-ray and Vacuum Ultra-Violet (VUV) fourth-generation diffraction-limited light source which is planned to be constructed by National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China (USTC). The HALF storage ring employs modified hybrid 6BA lattice as the baseline lattice to generate a beam with 85 pm·rad emittance, 350 mA current and 2.2 GeV energy [2]. The storage ring parameters are listed in Table 1.

Table 1: HALF Storage Ring Parameters

Parameters	Symbol	Value
Energy reference particle	E_0 [GeV]	2.2
Average current	I_0 [mA]	350
Harmonic number	h	800
Circumference	C [m]	~480
Energy spread	σ_p	0.00062
Nature emittance	ε_e	85 pm·rad
Momentum compaction	α	0.00009
Energy loss per turn (1st Term)	U_{s1} [MeV]	~0.4
Energy loss per turn (2nd Term)	U_{s2} [MeV]	~0.6

PHYSICAL REQUIREMENTS

In order to suppress the emittance diluting caused by the intrabeam scattering effect and increase the beam Touschek lifetime in storage ring, a passive superconducting 3rd-harmonic cavity (super-3HC) is employed to lengthen the beam bunches. Then the HALF storage ring has double RF systems: the main one and harmonic one. In such a storage ring, the voltage V(τ) seen by an electron in the beam with arrival time τ is

$$V(\tau) = V_1 \cos(2\pi f_{\mathrm{rf}}\tau + \phi_1) + V_{\mathrm{m}} \cos(3 \times 2\pi f_{\mathrm{rf}}\tau + \phi_{\mathrm{m}}), \qquad (1)$$

where V_1 and V_{m} are the voltage amplitude of the main and harmonic RF cavities, respectively, f_{rf} is the frequency of the main RF cavity, ϕ_1 and ϕ_{m} are the phases of the synchronous particle in the main and harmonic RF cavities, respectively.

To compensate for the energy loss per turn $U_{\mathrm{s}} = eV_{\mathrm{s}}$, it is required that $V(0) = V_{\mathrm{s}}$ for the synchronous particle. The longitudinal dynamics in the double RF systems described by Eq. (1) has been comprehensively discussed, together with optimal conditions for bunch lengthening [3]. Thus we obtain the optimum parameters for HALF double RF systems consisting of a single main superconducting cavity and a single super-3HC, as shown in Table 2.

Table 2: HALF Storage Ring Double RF Systems

RF System Parameters	Symbol	1st Term	2nd Term
Energy loss per turn	U_{s} [MeV]	~0.4	~0.6
Main frequency	f_{rf} [MHz]	499.8	499.8
Harmonic frequency	$3f_{\mathrm{rf}}$ [MHz]	1499.4	1499.4
Main voltage	V_1 [MV]	1.20	1.44
Harmonic voltage	V_{m} [MV]	0.374	0.43
Main phase	ϕ_1 [°]	70.53	65.37
Harmonic phase	ϕ_{m} [°]	90.0038	90.0044
Main quality factor	Q_1	1E9	1E9
Harmonic quality factor	Q_{m}	2E8	2E8
Harmonic detuning angle	ψ_m[°]	89.9962	89.9956
Bunch lengthening factor	$\sigma_{\mathrm{tm}}/\sigma_{\mathrm{t0}}$	5.7	5.9
Tousheck life time ratio	R_{Touschek}	6.1	6.2

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RF DESIGN OF THE SUPER-3HC

A single-cell superconducting cavity, which is capable of providing an accelerating voltage of ≥ 0.43 MV, is chosen for the super-3HC.

Geometry Optimizations

Given that the electron speed of $\beta = 1$, the cavity gap is determined to be 100 mm. A cavity based on TESLA-shape is chosen for the super-3HC. CST Microwave Studio [4] is used for the modelling which can be seen in Fig. 1. Through the tracking simulations [5], it was found that a super-3HC with a R/Q < 45 Ω is necessary to ensure a good bunch lengthening for the HALF storage ring. Through optimizations, the RF parameters are obtained for the super-3HC, as shown in Table 3.

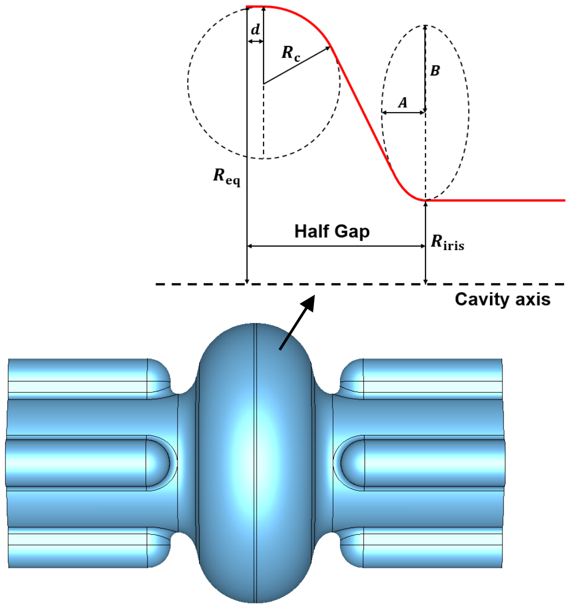

Figure 1: Geometrical modelling for the super-3HC.

Table 3: Optimized RF Parameters for the Super-3HC

RF parameters	
π mode frequency f [MHz]	1499.4
R/Q [Ω]	39
E_p/E_{acc}	2.14
B_p/E_{acc} [mT/(MV/m)]	5.46
Unloaded quality factor Q_0 [4.5 K]	2×10^8

Higher-order-modes Analysis

Higher-order-modes (HOMs) are components of the wakefield and can be excited by electron beam traversing an accelerating cavity. These modes may affect the beam stability and cause an additional refrigeration load to the superconducting cavities if left unchecked. This is critical for high-current storage ring where the impedance growth has to be well managed. HOMs in the super-3HC are calculated by using CST Microwave Studio [4]. Figure 2 gives R/Q for monopole and dipole modes at super-3HC.

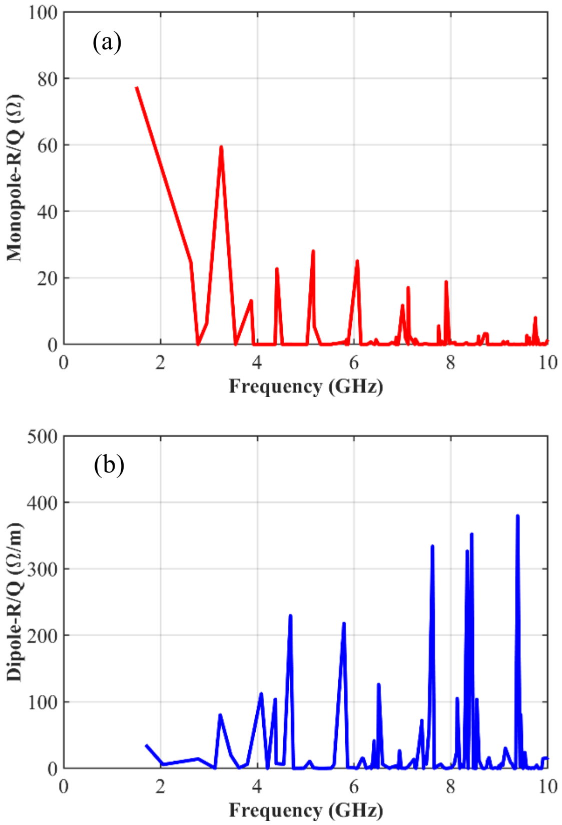

Figure 2: The R/Q of monopole (a) and dipole (b) modes for the super-3HC.

SiC HOM Damper

A pair of silicon carbide (SiC) rings is chosen for HOMs damping because of its promising property, such as broadband, low loss and sufficiently high conductivity at room temperature. The super-3HC connected with thermal transitions, SiC dampers, a sliding tuner, and taper transitions is modelled as a whole, which can be seen in Fig. 3. The total HOMs load is expected to be less than 5 kW.

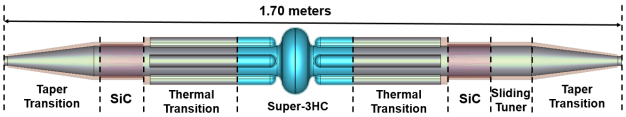

Figure 3: The whole system of the super-3HC.

The impedance threshold are calculated as

$$R_L^{\text{thresh}} = \frac{2(E_0/e)Q_s}{f_L I_b \alpha \tau_z} \tag{2}$$

$$R_T^{\text{thresh}} = \frac{2(E_0/e)}{f_{\text{rev}} I_b \beta_{x,y} \tau_{x,y}} \tag{3}$$

where R_L^{thresh} and R_T^{thresh} are longitudinal and transverse impedance threshold, f_L is the longitudinal HOMs frequency, E_0 is the beam energy, Q_s is the synchrotron tune, I_b is the average beam current, α is the momentum compaction, $\tau_{x,y,z}$ is the damping time, f_{rev} is the revolution frequency, and $\beta_{x,y}$ is the β function at the location of super-3HC. The calculated impedance of monopole and dipole modes for the whole system (see Fig. 3) is shown in

Fig. 4. It can be clearly seen that these impedances are lower than those of thresholds. This means that using a pair of SiC rings is sufficient for damping HOMs to meet the requirement.

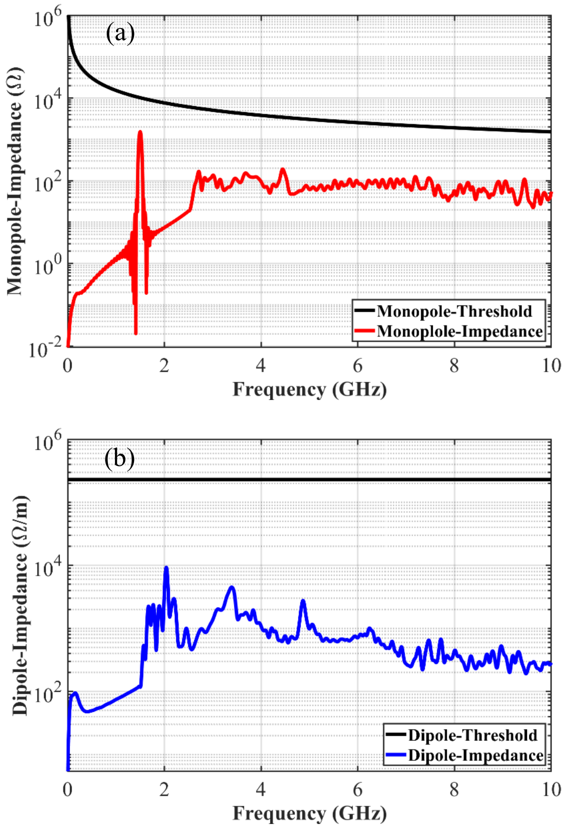

Figure 4: Impedance of monopole (a) and dipole (b) modes as compared to the thresholds for the super-3HC.

PRELIMINARY ENGINEERING DESIGN FOR CRYOMODULE

The super-3HC system requires that the cavity have an intrinsic quality factor, $Q_0 = 2 \times 10^8$, in order that cavity wall losses and heat to the helium bath are manageable. High Q_0 of ~10^{10} is not needed and, therefore, the operating temperature is relaxed to be 4.5 K. At 4.5 K, the static power loss is required to be smaller than 15 W while dynamic power loss is calculated to be about 12 W for an accelerating voltage of 0.43 MV.

In order to ensure that the super-3HC works normally at 4.5 K [6], a cryomodule consisting of a vacuum vessel, a thermal shield (cooled by liquid nitrogen to 77 K), two magnetic shields (reducing earth-magnetic field by a factor of 5), and a liquid helium vessel (with pressure fluctuation of 1200 mbar ±1 mbar) is required. The preliminary mechanical design of cryomodule has been completed, as shown in Fig. 5. The whole assembly including this cryomodule and other sections (sliding tuner, taper transitions, valves, and bellows) is expected to be fitted in a straight section of 2 meters. The cryomodule length is determined to be 800 mm in order to allow a reasonable length for the taper transitions. The total loss factor for such an assembly is calculated to be 1.9 V/pC.

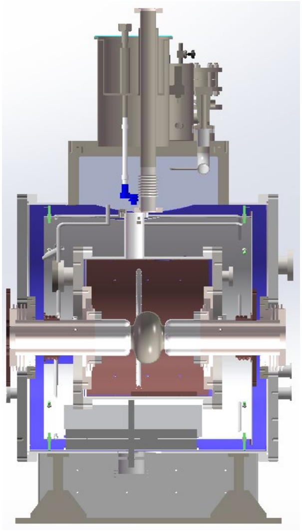

Figure 5: Conceptual cryomodule design for the super-3HC.

CONCLUSION

A passive superconducting 3rd-harmonic cavity consisting of a single cell with TESLA-shape has been designed for the HALF storage ring. HOMs damping by using a pair of SiC rings has been analysed, which meets the requirement of beam instabilities. In addition, a preliminary design for the super-3HC cryomodule has been completed. Further studies are undergoing including the frequency tuner and low level RF control system development.

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