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SYNCHROTRON LIGHT SHIELDING FOR THE 166 MHz SUPERCONDUCTING RF SECTION AT HIGH ENERGY PHOTON SOURCE

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Abstract

The High Energy Photo Source (HEPS) project has been under construction since 2019, and will be first diffraction-limited synchrotron light source in China. A 6 GeV electron beam with 200 mA current will be stored in the main ring. If synchrotron light produced from this energetic electron beam hits the superconducting cavity's surface, it would cause thermal breakdown of the superconductivity. In the current lattice design, these lights cannot be fully blocked by the collimator in the upstream lattice cell, therefore a shielding scheme inside the rf section is required. This however brings great challenges to the already limited space. The design of the collimator has been focused on fulfilling shielding requirements while optimizing beam impedance, synchrotron light power density, thermal and mechanical stabilities. Shielding materials are subsequently chosen with dedicated cooling to ensure long-term stable operations. In this paper, a shielding scheme inside the rf section of the HEPS storage ring is presented. The synchrotron light mainly from the upstream bending magnet is successfully blocked. The sensitivity to beam position movement and installation error is also analyzed.

INTRODUCTION

High Energy Photo Source (HEPS) is a 6 GeV, high-energy diffraction-limited storage ring light source [1]. The HEPS storage ring consists of 48 modified hybrid seven-bend achromats (7BAs) with a circumference of 1360.4 m [2], and the specifications are summarized in Table 1.

Eleven bending magnets in each hybrid-7BA arc section of HEPS storage ring are shown in Fig. 1. Each bending magnets in the storage ring produces an intense beam of synchrotron radiation (SR), and shall be shielded properly. However, in current lattice design, after the beam comes out of bending magnets with longitudinal gradient (BLG), it transverses a drift distance and then enters the cavity. It would cause thermal breakdown of the superconductivity and increase additional power consumption.

There are two ways to reduce synchrotron radiation [3], one is to weaken the strength of the bending magnet; the other is to shield the radiation using collimators. In order to achieve extremely low emittance, a compact magnetic focusing structure design was selected for the HEPS storage ring. Limited by the compact space of the lattice cell, it is impossible to increase the bending radius to reduce synchrotron radiation. Therefore, the collimator is an indispensable method to block SR.

The nearest upstream collimator has a diameter of 18.3 mm, located downstream of the BLG5, 1.1 m away from the rf section. Synchrotron lights cannot be fully blocked by the upstream collimator, so a shielding scheme inside the rf section is required, which brings great challenges to the already tight space in rf section.

The total length of rf section is strictly and undisputedly limited to six meters. In addition to the rf system, this length also includes two BPMs. Because the cavity frequency is very low, only 166.6 MHz, although the compact quarter-wave cavity is adopted, the longitudinal length of the cavity main body is still 523 mm [4]. The proof-of-principle (PoP) cavity has been successfully developed [5–7]. The beam diameter of the cavity is increased from 170 mm to 505 mm to realize heavy high order mode (HOM) damping. Then the HOM impedances can be reduced below the threshold by a ferrite absorber mounted on the left beam pipe. Since the beam pipe radius outside the rf section is only 22 mm, tapers are necessary to match the large aperture difference between the inside (505 mm) and outside (22 mm) of the rf section. These also increase the difficulty of suppressing the broadband impedance and take up more axial space. Figure 2 shows one set of the compact 166.6 MHz cavity equipment in the rf section, including the cavity, transition beam pipe, damper, taper, bellow, vacuum pump and so on. Therefore, it is a challenge to put down two set of the components in a 6 m straight section, and the space will be very tight.

In this paper, the layout optimization of cavity string in rf section, the structure of the collimators, the cooling, and tolerance analysis are described in detail.

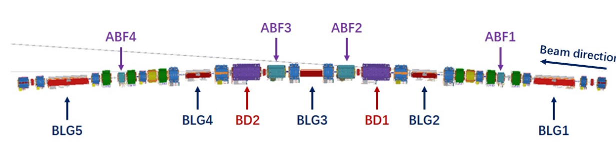

Figure 1: Distribution of bending magnets in a hybrid-7BA arc section. "BD" stands for bending magnets with defocusing gradient. "ABF" stands for anti-bends combined with focusing gradient.

LAYOUT OPTIMIZATION OF CAVITY STRING IN RF SECTION

The layout of the cavity string will directly affect the irradiation position of the sync light, the beam impedance,

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Table 1: Specifications of the HEPS Storage Ring Parameters

Parameter	Value	Unit
Beam energy	6	GeV
Beam current	200	mA
Frequency	166.6	MHz
Circumference	1360.4	m
Max. magnetic field (BLG5-5)	0.48	T
Min. bending radius (BLG5-5)	41.4	m
Max. bending angle (BLG5-5)	0.42	deg
Vacuum degree	$\leq 1\times10^{9}$	Torr
Length of rf straight section	6	m
Beamline aperture	22	mm
SBP diameter	80	mm
LBP diameter	505	mm

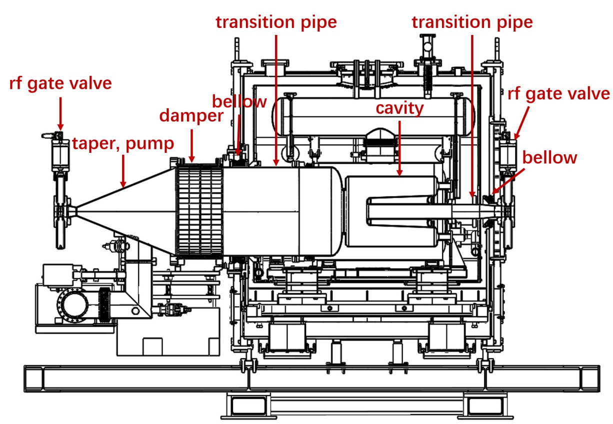

Figure 2: A set of the compact 166.6 MHz cavity equipment.

and the maintainability of the devices. Without collimators, there are a total of four layouts for the cavity string, and the analysis results are summarized in Table 2.

The impedance numerical simulation of the four layout structures is realized by ABCI code [8]. The synchronization light hits the nose of the cavity in the layout 2 and 3, which may cause the quench of the cavity. Meanwhile, the rf impedance of layout 2 is large, which is equivalent to layout1, so the scheme 2 is abandoned. The two cryomodules in layout 3 are different and cannot be replaced with each other. Although layout 3 has the smallest loss factor, the advantage of loss factor will no longer exist because of the need to add a collimator between two LBP ports to shield the synchronous light. So this plan is not adopted. In the first and fourth layouts, the synchronization light is irradiated on the taper and bellows of the cavity. The impedance of layout 4 is slightly better than layout1. However, the layout 4 is not an ideal choice because the two cavities are in the same cryomodule to accommodate the compact space. Once one cavity is damaged, the entire straight section will not work. In summary, the first arrangement scheme, as shown in Fig. 3, is the most ideal cavity string layout, and the position and structure of the collimator will be designed under this scheme later.

Table 2: Analysis of the Four Layouts of Cavity Strings

Layout	Beam Inlet/Outlet	Irradiation Position	$k_{//}$ (V/pC)	Rep.
1	SBP/LBP	taper, bellow	5.090	Yes
2	LBP/SBP	cavity, bellow	5.089	Yes
3	SBP/SBP	cavity, bellow	3.447	No
4	LBP/LBP	taper, bellow	4.911	No

Rep. stands for replaceable.

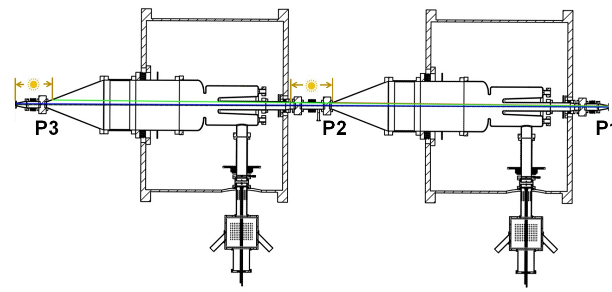

Figure 3: The layout of cavity string. Beam passes right to left through the cavity string.

COLLIMATOR DESIGN

Structure and Placement

The taper, vacuum valve and bellows of the two cavities under the selected layout were irradiated by the synchronized light, which may damage the rf shielding layer of the vacuum valve and the bellows, resulting in increased impedance, spark, partial vacuum deterioration, temperature rise, etc. There are two options for the position of collimators to minimize the discontinuous change of the beam aperture and maintain the consistency of the two cavity components. Location P1 in Fig. 3, a collimator with an aperture of 10.9 mm would cast a shadow that almost the complete rf section of 6 m length is not radiated. Location P2 and P3 in Fig. 3, the vacuum valve and bellows would be successfully brought into the shadow of the collimators if the aperture is reduced from 63 mm to 45 mm. The spot of the synchronized light is located on the taper (between Φ505 and Φ63) of the cavity components, as shown in Fig. 4. The synchronized light shielding results of the collimator placement positions are summarized in Table 3. Although the power density and loss factor of location P1 are smaller, the beam aperture is only 10.9 mm, and the safety distance between the synchronous light and the bellow is too small. These will be a huge challenge to the beam quality and beam stability. In addition, the collimator in location P2 and P3 are very close to the spot of sync light. This solution has no effect on the beam dynamic aperture, and is more economical and reliable. After a comprehensive comparison, collimators are placed in position P2 and P3.

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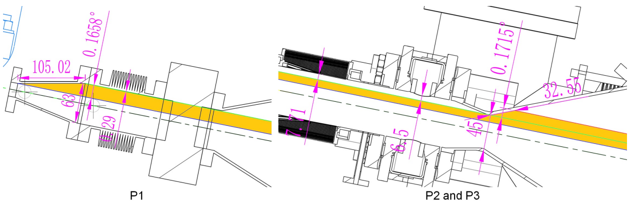

Figure 4: Comparison of shielding effects.

Table 3: Comparison of the Shielding Effect of Two Collimator Placement Positions

Parameters	P1	P2 & P3
Φ of collimators (mm)	10.9	45
Spot length/height (mm)	105.02/1.23	32.55/0.71
Angle (°)	0.1658	0.1715
Safety distance (mm)	0.29	6.5
Irradiated power (W)	255	264
Power density (W/mm^2)	2	11.5
$k_{//}$ (V/pC)	5.105	5.324

Cooling

The temperature rise of collimators are affected by the local hot spot size, the SR power, the material, and the cooling condition. The design of the collimator must provide for the removal of this localized heat load while maintaining the structural integrity of the collimator during steady state and cyclic operation of the storage ring. Specific thermal and structural design criteria [9–11] are listed in Eqs. (1), (2), (3) and (4).

$$T_{water} < T_{boil} = 158°C \text{ at 6 atm} \quad (1)$$

$$T < 0.5 \times T_{melt} \quad (2)$$

$$S_{vm} < S_y \text{ (Yield strength)} \quad (3)$$

$$\text{Strain amplitude} < \text{Strain for } 10^5 \text{ cycles} \quad (4)$$

The oxygen-free high thermal conductivity (OFHC) cooper is selected to be the material of collimators and the cooling is done by one 5×5 mm tube for the incoming water. The thermal and structural analysis results by ANSYS [12] are shown in Fig. 5. The maximum temperature reads 72 °C on the hot spot and 50 °C on the cooling channel surface. They are all less than the required value of 541 °C and 158 °C. The highest stress of OFHC and SS316 are located around the beam spot and the junction of the two materials, similar to the position of peak strain amplitude. The maximum stress is 57 MPa and 41 MPa for OFHC and SS316, respectively, have to be fulfilled. The peak strain amplitude of OFHC and SS316 are 0.06% and 0.02%, which are several times lower than the allowed values. Therefore, the fatigue lifetime of the collimator will more than 10^5 thermal cycles.

Tolerance Analysis

The electron beam offset and installation errors have been taken into account to ensure the safety. The lateral orbit deviation of the electron beam was selected as 20σ, $\leq |\pm 1.34|$ mm, to reserve a comfortable margin. According to experience, the alignment error accumulated transverse at the collimator was $\leq |\pm 1|$ mm. The positive and negative sign represent the outer and inner direction of the HEPS storage ring, respectively. Ideally, the minimum safe distance between the sync light and the beamline device was 5.6 mm. When the electron beam lateral deviation and the installation error reached the worst conditions at the same time, the safety margin dropped to 3.4 mm, which was considered acceptable.

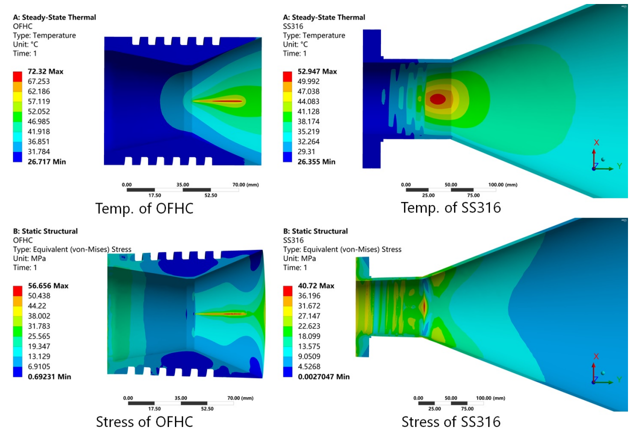

Figure 5: Coupled-simulation results of the collimator with cooling water channel.

FINAL REMARKS

A new synchronous light shielding design has been presented for the 166.6 MHz cavity string of the HEPS storage ring. It is intended to overcome the challenges derived from adding appropriate SR collimators in the already compact rf section. The cavity string layout that is replaceable and different schemes for shielding synchronous light are analyzed and determined. After comparison, the position of the collimators is selected at the small end of the cavity taper, and the diameter of the collimator is finally set to 45 mm, which is much larger than the beam dynamics aperture. The loss factor of the rf section is slightly increased to 5.324 V/pC due to the appearance of the collimators. The design of water-cooling is simple and efficient. Although the power density of the SR spot is 11.5 W/mm^2, the results of temperature, stress and strain below the instability limits. The design of shielding scheme is robust under the situation about lateral deviation of beam orbit and the transverse alignment error. The design of the synchronous light shielding scheme in this paper is an important part of the compact design of the 166.6 MHz cavity string.

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