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THE SUPERCONDUCTING RADIO FREQUENCY SYSTEM OF SHENZHEN INDUSTRIAL SYNCHROTRON RADIATION SOURCE FACILITY*

W. Ma†[1], L. Lu[1], N. Yuan, Y. B. Sun, Sun Yat-sen University Sino-French Institute of Nuclear Engineering and Technology, Zhuhai, China
Y. Yang, G. M. Liu, Institute of Advanced Science Facilities, Shenzhen, China
Z. L. Zhang, Institute of Modern Physics, Lanzhou, China
[1]also at Institute of Advanced Science Facilities, Shenzhen, China

Abstract

Shenzhen industrial synchrotron radiation source is a 3 GeV synchrotron radiation diffraction-limited source. It consists of three parts, linear accelerator, booster, and storage ring. As a basic part of the storage ring, the superconducting radio frequency system provides energy for the beam to supplement the beam power loss caused by synchrotron radiation and higher-order modes, and provide the longitudinal bunch for electron beam. The superconducting radio frequency cavity of the storage ring consists of two 500 MHz single-cell cavities and a third harmonic 1500 MHz double-cell cavity. This paper will introduce the superconducting cavity, radio frequency amplifier, and low-level radio frequency system in the Shenzhen industrial synchrotron radiation source facility.

INTRODUCTION

Synchrotron radiation light source has become the most advanced and irreplaceable tool in the basic and applied research of materials science, life science, environmental science, physics, chemistry, medicine, geology and other disciplines, and has important and extensive applications in electronic industry, pharmaceutical industry, petroleum industry, chemical industry, bioengineering and micro processing industry [1]. At present, the synchrotron radiation light source device is developing from the mature third generation to the fourth generation marked by diffraction limit storage ring. The Table 1 shows the announced situation of the fourth generation synchrotron radiation light sources being proposed or under construction by various countries in the world, which has reached 12, and 8 of them are under design.

Shenzhen industrial synchrotron radiation source facility (SZISRF), a high performance medium energy synchrotron radiation diffraction limited light source with circumference 696 m, storage ring electron energy of 3.0 GeV and emittance 81 pm·rad, is designed and constructed. The light source adopts the diffraction limited storage ring technology based on 7BA magnetic focusing unit, which can produce synchrotron radiation with wide spectrum and high brightness (10^{21} phs/s/mm^2/mrad^2/0.1%BW) from 4 meV to 160 keV. SZISRF will plan, design and build 50 beamline stations. The Layout of SZISRF is as shown in Fig. 1.

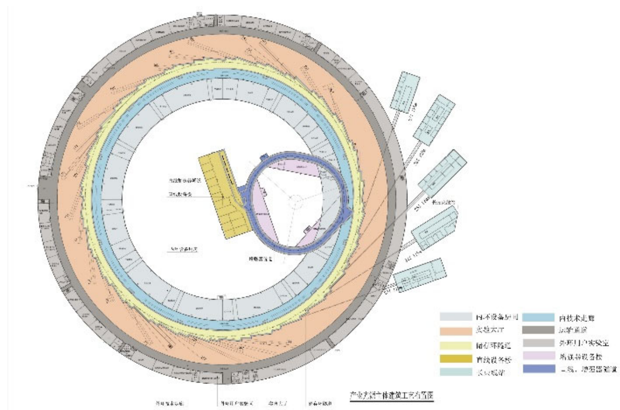

Figure 1 : The layout of the Shenzhen industrial synchrotron radiation source.

The radio frequency system of the storage ring has three main functions: provideing accelerating voltage for the beam to ensure sufficient momentum acceptance, longitudinal quantum lifetime and Toschek lifetime of the storage ring; providing energy for the beam to supplement the energy loss when it moves in the storage ring, such as the radiation loss in the deflection magnet and the insert-device, the parasitic mode loss caused by the impedance of the vacuum chamber, etc; providing the lowest possible high-order mode environment for the beam, so as to reduce the multi bunch coupling instability. During the operation of the system, the frequency of the high frequency cavity is locked by feedback control, so that the amplitude and phase of the high frequency acceleration voltage in the cavity are stable and correct, and the safety interlock ensures the safety of personnel and equipment.

The main beam parameters related to the radio frequency system of the storage ring of SZISRF are listed in Table 2. Here, it is considered that SZISRF will build about 50 beam line stations, and the design of the radio frequency system is based on the parameters in this table. The main parameters are as following : the beam energy is 3 GeV, the circumference is 696 m, the maximum beam current is 300 mA, the radiation energy loss by deflection magnet and insert-devices are about 318.4 keV and 600 keV, respectively.

The radio frequency system consists of three parts as superconducting cavity, amplifier and low level radio frequency (LLRF) control system.

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† Email address: mawei25@mail.sysu.edu.cn

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Table 1: The Fourth-Generation Synchrotron Radiation Source Built or Under Research in the World

Facility	Country	Energy (GeV)	Circumference (m)	Emittance (pmrad)	Status
MAX-Ⅳ [2]	Sweden	3	528	330	operation
SIRUIS [3]	Brazil	3	518	250	commissioning
HEPS [4]	China	6	1260	34	construction
SKIF [5]	Russia	3	476	75	construction
HALS [6]	China	2.2	500	85	Pre research
ILSF [7]	Iran	3	528	275	design
CANDLE [8]	Armenian	3	269	435	design
CLS-Ⅱ [9]	Canada	3	619	81	design
KEK-LS [10]	Japan	3	571	130	design
SLIT-J [11]	Japan	3	354	920	design
TURKAY [12]	Turkey	3	477	510	design
SZISRF	China	3	696	81	design

Table 2: Beam Parameters Related to the Radio Frequency System of Storage Ring

Parameters	Value
Beam energy/ GeV	3
Circumference/ m	696
Current/ mA	300
Momentum compaction factor	6.6×10^{-5}
Radiation energy by deflection magnet/ keV/Circle	318.4
Radiation energy by insert-device/ keV/Circle	600
Fundamental frequency/ MHz	500
Harmonic frequency/ MHz	1500
Voltage of fundamental frequency cavity/ MV	2.4
Voltage of harmonic frequency cavity/ MV	1
Harmonic number of fundamental frequency	1160
Harmonic number of Harmonic frequency	3480
Damping time of Synchrotron radiation （x/y/z） / ms	34.97/43.74/25.01

SUPERCONDUCTING CAVITY

The storage ring radio frequency system of SZISRF consists of two systems: 500 MHz fundamental frequency system and 1500 MHz third harmonic frequency system. The layout is shown in Fig. 2.

Compared with the normal conducting cavity, the superconducting cavity has the following advantages: the higher acceleration gradient, higher quality factor, the lower impedance and higher power usage efficiency. With the large beam aperture, the high-order modes in the superconducting cavity can be deeply damped.

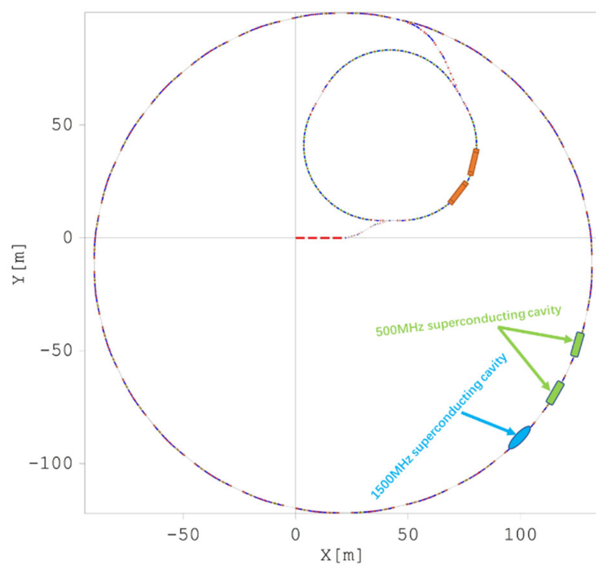

Figure 2: The storage ring radio frequency system of SZISRF.

Therefore, there are two kinds of superconducting cavities in the storage ring: single cell superconducting cavity with frequency of 500MHz as main accelerating cavity and third harmonic cavity with a frequency of 1.5 GHz to increase beam life.

Two kinds of superconducting radio frequency cavities are widely used in synchrotron radiation sources, one is CESR type, the other is KEKB type. The CESR type uses the fluted beam tube structure to suppress the harmonic mode, while the KEKB type uses the cylindrical large beam pipe to export the harmonic mode axially and absorb it by the ferrite welded on the inner wall of the beam pipe.

By comparing the performance of CESR type and KEKB type cavities at 500 MHz, it is found that CESR type has larger iris beam aperture, which is more suitable for the requirement of large beam aperture of high current accelerator; But KEKB cavity has better R/Q, Epeak/Eacc

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and Hpeak/Eacc. The beam intensity of SZISRF is 300 mA, so the beam aperture of the cavity should be large enough; Therefore, CESR type and the elliptical transition at iris of KEKB type is used for the main accelerating cavity structure of SZISRF. The model is shown in Fig. 3.

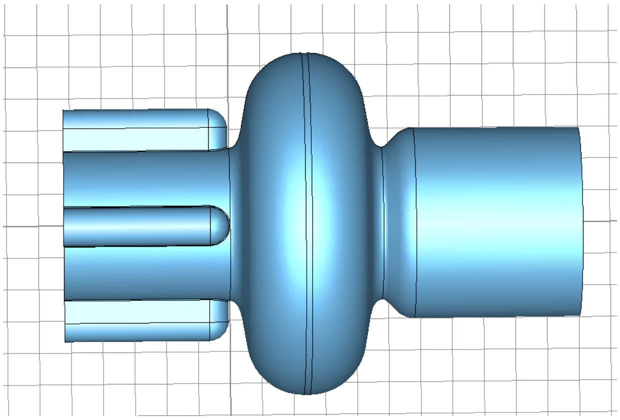

Figure 3: The model of 500 MHz cavity.

The frequency of high-order harmonic superconducting cavity is the multiple of fundamental frequency. Adding the high-order harmonic superconducting cavity can make the slope of the cavity voltage in the center zero, elongate the beam longitudinally, reduce the charge density of the beam, reduce the Toschek scattering, increase the beam lifetime, and have little effect on the beam energy dispersion and the brightness of the light source. SZISRF uses a third harmonic cavity for beam stretching. The cavity structure is two cell ellipsoidal cavity. The cavity voltage of the third harmonic is 1 MV.

The main parameters of superconducting cavities are listed in the Table 3.

Table 3: Main Parameters of Superconducting Cavities

Parameters	**Fundamental frequency cavity**	**Third harmonic frequency**
Frequency/MHz	500	1500
Number	2	1
Voltage/ MV	2.4	1
Cell	1	2
Voltage per cavity/ MV	⩾1.2	⩾1
Q factor	1×109	1×109
Cryogenic loss/ W	250(4.2 K)	150(4.2 K)
Power/ kW	150	10

POWER AMPLIFIER

Power amplifier converts electric energy into microwave power at required operation frequency. At present, there are two kinds of mature power amplifier: Klystron and solid state. Solid state power amplifier has been quite mature, and its stability is very high, so solid state power amplifiers are employed.

According to the physical design requirements of SZISRF, the beam intensity of storage ring is 300 mA, and the synchronous radiation loss per circle is 1MeV (the radiation loss of insert-device is considered about 0.6 MeV and the radiation loss of deflection magnets is considered about 0.318 MeV). Considering the power loss and appropriate power margin, two sets of solid-state power amplifier with frequency of 500MHz and output power of 250KW are selected for the two 500 MHz superconducting cavities, and one set of 1500 MHz with output power of 30 kW is selected for the third harmonic cavity. Table 4 shows the power loss in the radio frequency system. It can be seen that the power for each 500 MHz cavity has 76 kW redundancy and the power for 1500 MHz cavity has 17 kW redundancy. Therefore, the power amplifiers can ensure the proper operation of the superconducting cavities.

Table 4: The Power Loss in the Radio Frequency System

Parameters	**500 MHz power**	**1500 MHz power**
Output power from amplifier/kW	250*2	30
Transmission line	Waveguide	Waveguide
Length of transmission line /m	15	15
Loss along transmission line /(dB • m^{-1})	0.0023	0.0025
Loss along transmission line /dB	0.0345	0.0375
Loss at circulator /dB	0.4	0.4
Total loss/dB	0.4345	0.4375
Power transmitted to the coupler/kW	226*2	27
Power demand of cavity /kW	150*2	10

The 500 MHz (250 kW) solid-state power amplifiers adopt multi-stage power synthesis. Specifically, one power cabinet is composed of nine sub power amplifiers. A high power circulator is installed between the power amplifier and the superconducting cavity to isolate reflecting power to protect the amplifier. Figure 4 shows prototype of solid-state power amplifier.

Figure 4: Prototype of solid-state power amplifier (from CHENGDU KAITENG SIFANG DIGITAL BROADCASTING & TV EQUIPMENT CO. LTD.)

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LLRF CONTROL SYSTEM

The LLRF control system realizes control of the voltage amplitude, phase and frequency of the superconducting cavities, as well as the safety interlock, rapid protection and diagnosis of the radio frequency devices. The logic diagram of the LLRF control system is shown in Fig. 5. At present, the common technical of LLRF control system is to down convert the RF signal to Intermediate Frequency (IF) signal through the RF front-end, and then collect the signal from the high-speed ADC to FPGA. The FPGA realizes the high-speed feedback control, and the high-speed DAC outputs the IF control signal. Then the up conversion restores the control signal to RF and sends it to the power amplifier to realize the closed-loop control of the whole radio frequency system. As the fourth-generation synchrotron radiation source, SZISRF requires that the amplitude stability of the LLRF control system of the storage ring should be better than ± 0.1%, and the phase stability is better than ± 0.1°.

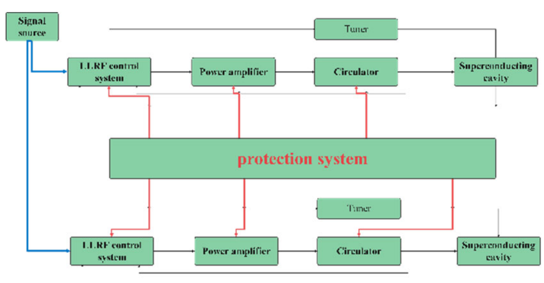

Figure 5: The logic diagram of the LLRF control system.

CONCLUSION

The Shenzhen industrial synchrotron radiation source, a fourth generation medium energy synchrotron radiation source, is under design. The preliminary design of the radio frequency system has been basically completed, which consists of three parts as superconducting cavity, amplifier and low level radio frequency (LLRF) control system. The detailed design will be carried out next.

REFERENCES

[1] J. B. Hastings, L. Rivkin, and G. Aeppli, "Present and future accelerator-based x-ray sources: a perspective," *Rev. Accel. Sci. Technol.*, vol. 10, no. 01, pp. 33-48, 2019. doi: 10.1142/s1793626819300044

[2] P. F. Tavares, S. C. Leemann, M. Sjöström, and Å. Andersson, "The MAX IV storage ring project," *J. Synchrotron Radiat.*, vol. 21, no. 5, pp. 862-877, 2014. doi:10.1107/S1600577514011503

[3] R. H. A. Farias, A. P. B. Lima, L. Liu, F. S. Oliveira, L. Brazilian, and S. Light, "Design and status of Sirius light source rf systems," in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2391-2393. doi:10.18429/JACoW-IPAC2018-WEPMF011

[4] P. Zhang *et al.*, "A 166.6 MHz superconducting rf system for the HEPS storage ring," *J. Phys. Conf. Ser.*, vol. 874, no. 1, 2017. doi:10.1088/1742-6596/874/1/012091

[5] S. M. Gurov, V. N. Volkov, K. V. Zolotarev, and A. E. Levichev, "Injection System for the Siberian ring source of photons," *J. Surf. Investig.*, vol. 14, no. 4, pp. 651-654, 2020. doi:10.1134/S1027451020030271

[6] Z. Bai, P. Yang, W. Li, L. Wang, and N. Synchrotron, "Design study for the first version of the HALS lattice, " in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2713-2715. doi:10.18429/JACoW-IPAC2017-WEPAB060

[7] H. Ghasem *et al.*, "Lattice candidates for the ILSF storage ring," in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper THPC024, pp. 2957-2959.

[8] A. Sargsyan, G. Zanyan, V. Sahakyan, and V. Tsakanov, "Sub-nm emittance lattice design for CANDLE storage ring," *Nucl. Instrum. Methods Phys. Res. Sect. A.*, vol. 832, pp. 249-253, 2016. doi:10.1016/j.nima.2016.06.129

[9] L. Dallin and W. Wurtz, "Towards a 4th generation storage ring at the Canadian Light Source," *AIP Conf. Proc.*, vol. 1741, no. July 2016, pp. 10–14, 2016. doi: 10.1063/1.4952813

[10] T. Honda, "Concept of a new generation synchrotron radiation facility KEK light source", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2687-2690. doi:10.18429/JACoW-IPAC2017-WEPAB047
Also at SOKENDAI (The Graduate University for Advanced Studies), Tsukuba , Ibaraki , Japan.

[11] H. Hama, T. Muto, and F. Hinode, "Ground design of a 3 GeV accelerator-complex for the synchrotron light in Tohoku, Japan (SLiT-J)," *J. Phys. Conf. Ser.*, vol. 425, no. PART 7, 2013. doi:10.1088/1742-6596/425/7/072010

[12] Z. Nergiz and A. Aksoy, "Low emittance lattice for the storage ring of the Turkish Light Source Facility TURKAY," *Chinese Phys. C*, vol. 39, no. 6, pp. 3-7, 2015. doi: 10.1088/1674-1137/39/6/067002