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STATUS AND PROGRESS OF THE RF SYSTEM FOR HIGH ENERGY PHOTON SOURCE

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Abstract

High Energy Photon Source (HEPS) is a 6 GeV diffraction-limited synchrotron light source currently under construction in Beijing. It adopts a double-frequency RF system with 166.6 MHz as fundamental and 499.8 MHz as third harmonic. The fundamental cavity makes use of a superconducting quarter-wave beta=1 structure and the third harmonic is of superconducting elliptical single-cell geometry for the storage ring, while normal-conducting 5-cell cavities are chosen for the booster ring. A total of 900 kW RF power shall be delivered to the beam by five 166.6 MHz cavities and two third harmonic cavities are active. All cavities are driven by solid-state power amplifiers and the RF fields are regulated by digital low-level RF control systems. The cavity and ancillaries, high-power RF system and low-level RF control system are in the prototyping phase. This paper presents the current status and progress of the RF system for HEPS.

INTRODUCTION

High Energy Photon Source (HEPS) is 6 GeV diffraction-limited synchrotron light source under construction in Beijing [1, 2]. Its main parameters are listed in Table 1. HEPS developed a modified hybrid seven-bend achromat (7BA) lattice in order to push the natural beam emittance down to 34.2 pm while preserving a high brightness X-ray synchrotron radiation. A double-frequency RF system has been adopted with 166.6 MHz as the fundamental and 499.8 MHz as the third harmonic. This is to accommodate a novel injection scheme as well as compromising with the kicker technology [3]. The current layout of the RF system is shown in Fig. 1. These are described in the following sections.

BOOSTER RF SYSTEM

The RF system for the HEPS booster ring adopted the normal-conducting cavity technology. Its main parameters are listed in Table 2. Five-cell copper cavities of PETRA-type have been chosen considering technology readiness. The diameter of the downstream cavity beampipe has been modified from 61.2 mm to 51 mm to collimate synchrotron light. This is to prevent direct light incidence on RF fingers of the cavity RF gate valves. The material of the additional taper has also been changed from stainless steel to OFHC copper due to the high power density of the light. Six cavities will provide the required 8 MV of RF voltage to ensure sufficient acceptance during the extraction of the 6 GeV bunches from the storage ring back to the booster [4]. Each cavity will be driven by a 100 kW solid-state amplifier (SSA) equipped with a low-power isolator for each power module and a final-stage high-power circulator and load [5]. The layout of the booster RF system is shown in Fig. 2.

The first cavity will be delivered to IHEP from Research Instruments in Q3 2021, while the acceptance test of the first 150 kW SSA prototype is underway [6]. The high-power characterization of the first cavity is planned for Q4 2021.

Table 1: Main Parameters of HEPS [2]

Parameter	Value	Unit
Booster RF		
Circumference	454.066	m
Beam energy (injection)	0.5	GeV
Beam energy (extraction)	6	GeV
Beam current	13	mA
Energy loss per turn	4.02	MeV
Total RF voltage	2 to 8	MV
Storage-ring RF		
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Energy loss per turn (w/ IDs)	4.4	MeV
Total beam power	900	kW
Fundamental RF frequency	166.6	MHz
Total RF voltage	5.4	MV
3^{rd} harmonic RF frequency	499.8	MHz

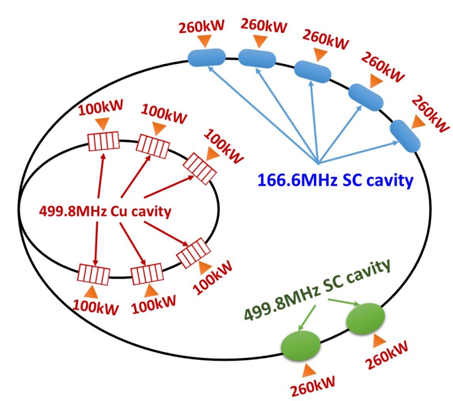

Figure 1: Layout of the HEPS RF system.

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Table 2: Main Parameters of the Booster RF System. "FL" Stands for Flange, "BP" Stands for Beam Pipe

Parameter	Value	Unit
Frequency	499.8	MHz
Cavity type	5-cell copper cavity	
# of cavities	6	-
Cavity voltage (V_c)	1.35	MV
Shunt impedance	30	MΩ
RF power per cavity	70	kW
Coupling factor (β)	1.17	-
Cavity length (FL to FL)	1.65	m
BP aperture (inlet)	61.2	mm
BP aperture (outlet)	51	mm
# of RF sources	6	-
RF power/source	100	kW
RF source type	SSA	-
Amplitude stability	±1%	-
Phase stability	±1°	-

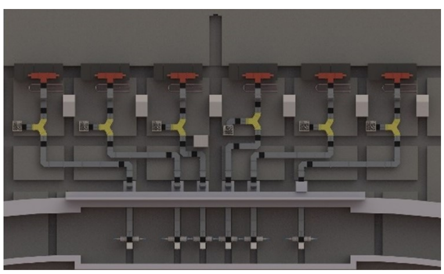

Figure 2: Booster RF layout.

STORAGE-RING RF SYSTEM

The RF system for the HEPS storage ring adopts superconducting RF technologies. Its main parameters are listed in Table 3. The fundamental RF frequency is 166.6 MHz while the third harmonic is 499.8 MHz.

RF Cavities

Quarter-wave geometry with β=1 was chosen for the 166.6 MHz SRF cavities. A proof-of-principle cavity has been previously developed between 2016 and 2019 and its performances have been extensively studied in both vertical tests and horizontal tests [7–10]. A higher-order-mode (HOM) damped cavity was subsequently designed [11–13]. Ferrite absorber will be installed on the enlarged beam pipe extension at room temperature to realize heavy HOM damping [14]. A 200 kW coaxial fundamental power coupler will be installed on the cavity in a horizontal manner and two prototypes have passed essential tests both on the test bench and on the proof-of-principle cavity during horizontal tests [15]. The cavity is currently under fabrication and the first vertical test of the bare cavity is planned for summer 2021. The preliminary design of the cavity module is shown in Fig. 3.

Table 3: Main Parameters of the Storage-Ring RF System. "Temp." Stands for Temperature, "ACC." Stands Accelerating, "LBP" Stands for Large Beam Pipe, "SBP" Stands for Small Beam Pipe

Parameter	Main RF	Harm. RF	Unit
Frequency	166.6	499.8	MHz
# of cavities	5	2	-
Operating Temp.	4.2	4.2	K
Cavity voltage (V_c)	1.2	1.75	MV
R/Q	139	95	Ω
Geometry factor	56	267	Ω
E_{peak} at V_c	40	13.7	MV/m
B_{peak} at V_c	62	30.4	mT
RF power/cavity	180	200	kW
External Q	5×10^4	8×10^4	-
SC cavity length	880	961	mm
Effective acc. gap	120	266.5	mm
Iris diameter	240	220	mm
LBP diameter	505	300	mm
SBP diameter	80	220	mm
# of RF sources	5	2	-
RF power/source	260	260	kW
RF source type	SSA	SSA	-
Amplitude stability	±0.1%	±0.1%	-
Phase stability	±0.1°	±0.1°	-

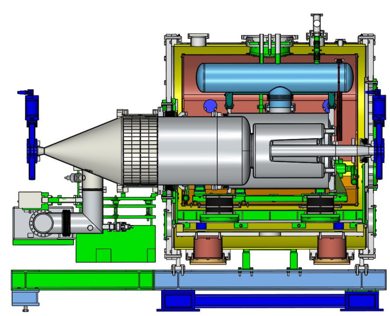

Figure 3: 166.6 MHz SRF cavity module.

The third harmonic cavity adopts the KEKB-type single-cell elliptical 500 MHz geometry and has a similar design to the BEPCII cavity. The mechanical design of the niobium cavity has been optimized to improve its operability and safety margin [16]. Besides, the beam pipe has been tapered to 63 mm with a synchrotron light collimator. The cavity module is shown in Fig. 4.

High-Power RF

Solid-state power amplifier technologies have been adopted for HEPS booster and storage ring RF systems. Five sets of 166.6 MHz 260 kW SSAs and two sets of 499.8 MHz 260 kW SSAs will be used to drive their corresponding SRF cavities [5]. A prototype 50 kW SSA has been previously developed for the HEPS-TF project [17]. The 166.6 MHz

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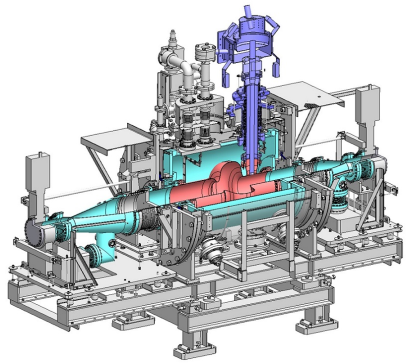

Figure 4: 499.8 MHz SRF cavity module.

260 kW SSA used a direct 8-way power combiner to realize the final-stage power combining as shown in Fig. 5. The first prototype is currently under acceptance tests [18]. The development of the 499.8 MHz 260 kW SSA will start in Q4 2021.

Figure 5: 166.6 MHz 260 kW solid-state amplifier.

The RF power distributions are realized by 9-3/16” rigid coaxial line for the 166.6 MHz system and EIA WR1800 waveguide for the 499.8 MHz one. High-power circulators and loads are installed at the outputs of all SSAs to further protect the power transmitters from damages due to reflected power although each amplifier module is equipped with individual isolators. The layout is shown in Fig. 6.

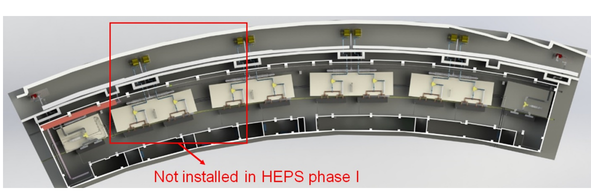

Figure 6: Storage-ring RF layout.

Low-Level RF

Digital low-level RF (LLRF) systems will be used to regulate the RF field inside cavities. These shall be controlled to be better than $\pm 0.1\%$ in amplitude and $\pm 0.1^\circ$ in phase for the storage ring. The LLRF system based on an up-/down-conversion scheme has been previously developed. The 166.6 MHz prototype has been used in cavity horizontal tests and a performance of $\pm 0.03\%$ (amplitude) and $\pm 0.02^\circ$ (phase) was obtained with a cavity voltage of 1.2 MV [19–21]. The system is shown in Fig. 7(a). The 499.8 MHz LLRF has been installed on BEPCII and used for routine beam operation since 2019.

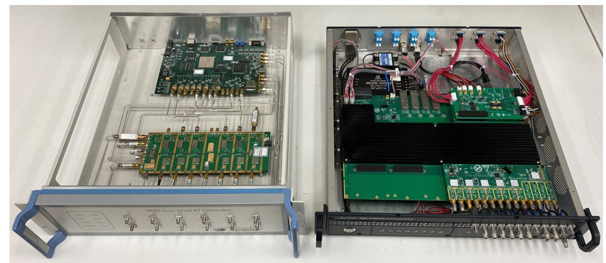

Figure 7: 166.6 MHz LLRF system prototype.

Concerning the 166.6 MHz system, a direct-sampling scheme has also been conceived. Considering that the RF frequency is well within the analog bandwidth of modern high-speed ADCs and DACs, direct RF sampling without down-conversion and direct digital modulation can therefore be achieved. A digital LLRF system utilizing direct sampling has therefore been developed with embedded experimental physics and industrial control (EPICS) system in the field programmable gate array (FPGA) [22]. The first prototype is shown in Fig. 7(b). The performance in the lab has been characterized on a warm 166.6 MHz cavity with a residual peak-to-peak noise of $\pm 0.05\%$ in amplitude and $\pm 0.03^\circ$ in phase, which is well below the HEPS specifications. Further tests are being conducted.

A new interlock and data acquisition (DAQ) system are under development [23]. Programmable logical controllers (PLC) are used to collect slow signals like temperature, water flow rate, etc., while fast acquisition for RF signals is realized by dedicated boards with down-conversion frontend and digital signal processing boards. In order to improve the response time, FPGA has been used for interlock logic implementation with an embedded EPICS. Data storage is managed by using EPICS Archiver Appliance and an operator interface is developed by using Control System Studio (CSS) running on a standalone computer.

FINAL REMARKS

The RF system for the HEPS booster and storage ring has been designed. Prototyping of SRF cavities, solid-state amplifiers, and low-level RF are underway.

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