A 166.6 MHz SUPERCONDUCTING RF SYSTEM FOR THE HEPS STORAGE RING

P. Zhang*, X. Hao, T. Huang, Z. Li, H. Lin, F. Meng, Z. Mi, Y. Sun, G. Wang, Q. Wang, X. Zhang,
Institute of High Energy Physics (IHEP), Beijing, China

Abstract

A superconducting 166.6 MHz quarter-wave β=1 cavity was recently proposed for the High Energy Photon Source (HEPS), a 6 GeV kilometer-scale light source. Four 166.6 MHz cavities will be used for main acceleration in the newly planned on-axis beam injection scheme realized by a double-frequency RF system. The fundamental frequency, 166.6 MHz, was dictated by the fast injection kicker technology and the preference of using 499.8 MHz SC RF cavity as the third harmonic. Each 166.6 MHz cavity will be operated at 4.2 K providing 1.2 MV accelerating voltage and 150 kW of power to the electron beam. The input coupler will use single-window coaxial type graded up to 200 kW CW power. Each cavity will be equipped with a 200 kW solid-state amplifier and digital low-level RF system. This paper describes the 166.6 MHz RF system with a focus on the design and optimization of the RF cavity and its ancillaries, the LLRF system and the status of the solid-state amplifiers.

INTRODUCTION

High Energy Photon Source (HEPS) has been initiated by IHEP in Beijing. This is a 6 GeV kilometer-scale light source [1]. Its main beam parameters are listed in Table 1. Prior to its official construction, a test facility namely HEPS-TF has been approved in 2016 to R&D and prototype key technologies and components.

Table 1: Beam Parameters of the HEPS Storage Ring

Parameter	Value
Energy	6 GeV
Circumference	~1300 m
Current	200 mA
Main RF frequency	166.6 MHz
Harmonic RF frequency	499.8 MHz
Energy loss w/ IDs	2.5 MeV/turn
Total SR power	500 kW

A new injection scheme, namely on-axis accumulation, has been proposed recently to accommodate the relatively small beam dynamic aperture [2]. This however requires a double-frequency RF system, main and third harmonic, to make two stable buckets in order for the injected bunch to be merged into the circulating beam. It needs to be noted that the third harmonic RF system will be active rather than passive.

The recent development of DSRD (Drift Step Recovery Diode) switch makes the total width of the kicker system to

---

be smaller than 10 ns. In addition, in order to use the mature technology of 500 MHz superconducting (SC) cavity as the harmonic cavity, the main RF frequency has thus been chosen to be 166.6 MHz, one third of 499.8 MHz.

This paper describes the newly designed 166.6 MHz RF system with a focus on the SRF cavity and its ancillaries, the LLRF system and the status of the solid-state amplifiers.

THE RF SYSTEM

Given the low RF frequency (166.6 MHz), both normal conducting (NC) and superconducting (SC) options have been considered for the main accelerator in the design phase. Their main parameters are listed in Table 2. Compared to the NC option, the SC case will save 23% of AC power due to much lower cavity surface losses, thus requires less RF amplifiers and reduced operation cost, but requires a one-time investment in a larger cryogenic system and its associated electricity bill. These make the SC case marginally cheaper if not considering cavity cost. In addition, the 500 MHz RF system will also use SC cavities due to higher RF voltage required and less longitudinal space needed.

Table 2: NC and SC Options for the 166.6 MHz RF System

Parameter	NC	SC
Frequency	166.6 MHz	
Total SR power	500 kW	
Total RF voltage	3.5 MV	
Number of cavities	6	3~4
Cavity voltage [MV]	0.6	1.2
R/Q [Ω]	400	130
Q_0	4×10^4	1×10^9
Total cavity wall loss [kW]	135	~0.04
Total RF power [kW]	635	501
Total AC power [MW]	1.3	1.0

The double-frequency RF system will make use of two types of SC cavities, both to be in-house designed. Each cavity will equip one power coupler graded above 200 kW CW power. All FPCs will also be in-house designed. A digital low-level RF (LLRF) system will be used for each cavity to obtain high control stability. The parameters of the double-frequency RF system are listed in Table 3. Focus of the R&D is on the 166.6 MHz SRF system.

THE CAVITIES

The 166.6 MHz SRF cavity needs to be newly designed. Given that $\beta = 1$, the popular elliptical shape will make the cavity geometry excessively large ($\lambda/2$) thus unpractical for manufacturing. Therefore we have chosen the quarter-wave

Table 3: RF Parameters for the HEPS Storage Ring

Parameter	Main RF	Harmonic RF
Frequency [MHz]	166.6	499.8
Operating temperature [K]	4.2	
Number of cavities	4	2
Cavity voltage [MV]	1.2	1.7
R/Q [Ω]	~130	~95
E_p, B_p [MV/m, mT]	~30, ~50	~20, ~40
Cavity peak power [kW]	150	200
External Q	~4×10^4	~1×10^5
Number of RF stations	4	2
RF power/station [kW]	200	250
Control technology	digital LLRF	
Stability (amp., phase)	±0.3%, ±0.3°	

shape. A proof-of-principle (PoP) cavity has been designed with an optimized peak surface field and manageable transverse size (<400 mm). The RF model, EM field and main RF parameters are shown in Fig. 1. Electron bunch with β ~1 is being accelerated through the gap between left beam tube and the inner conductor cone where the electric field peaks. The magnetic field is on the other hand inhabits in the short end of the coaxial-like cavity. A 20% margin on peak surface fields was reserved.
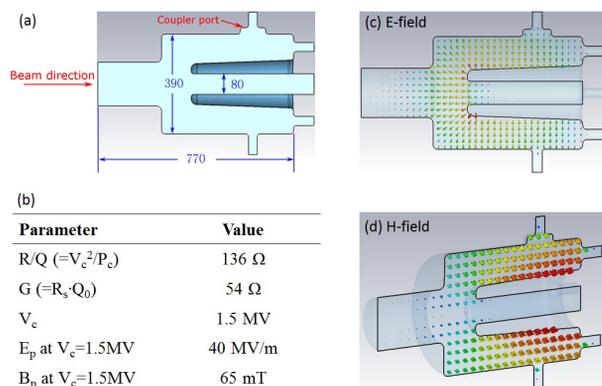
Figure 1: The 166.6 MHz PoP cavity.

The PoP cavity was subsequently fabricated in a domestic company, post processed in Ningxia and IHEP and finally vertical tested in IHEP as shown in Fig. 2. The results largely exceed the design goal. The maximum peak field reached 86.5 MV/m and 132 mT respectively with a Q_0 value of 5×10^8.

The impedance threshold of higher order modes (HOM) restricted by multi-bunch instability is calculated [3]. They shall be less than 151 kΩ at 1 GHz for longitudinal direction, 1500 kΩ/m for x-direction and 3100 kΩ/m for y-direction. The R/Q of each HOM below 2 GHz is calculated and shown in Fig. 3. Consequently most HOMs need to be damped to a loaded Q value of 10^3~10^4. The first few HOMs have rather low frequencies (460 MHz for the 1st monopole HOM and 430 MHz for the 1st dipole mode) and highest R/Q values. Thus a hybrid HOM damping scheme has been conceived.
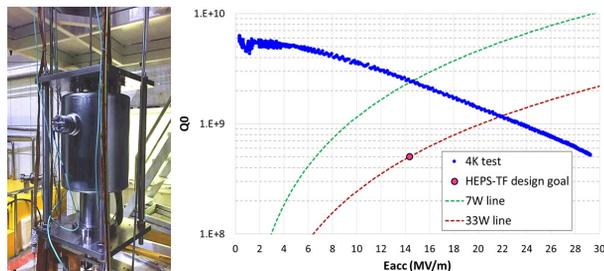
Figure 2: The PoP cavity vertical test.

An enlarged beam pipe connected to the cavity will take care of HOMs with higher frequencies subsequently absorbed by a ferrite damper, while a bandpass or high-pass coaxial type HOM coupler will extract the first few HOMs with lower frequencies. The overall HOM power per cavity is less than 500 W during nominal operation. The HOM damping structure is currently being designed. One need to note that there is no HOM damping structure on the PoP cavity.
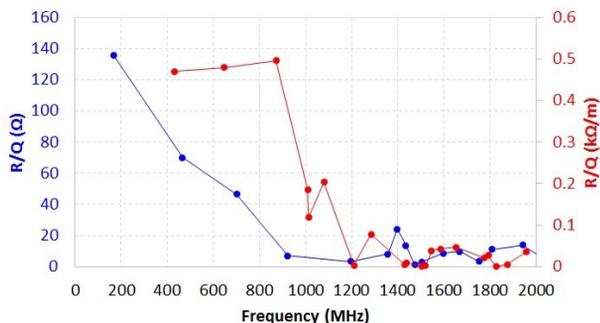
Figure 3: The R/Q value of HOMs calculated on the PoP cavity using CST MWS [4].

The 3rd harmonic SC cavity will use 499.8 MHz single-cell elliptical structure, a matured technology popular for light sources. The main RF parameters are listed in Table 3. A RF model is shown in Fig. 4.
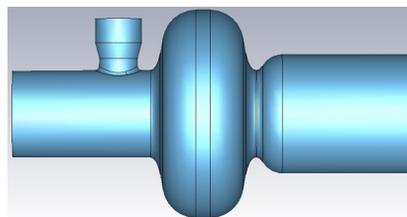
Figure 4: The 499.8 MHz 3rd harmonic cavity.

THE POWER COUPLER

The fundamental power coupler (FPC) of the 166.6 MHz SC cavity was newly designed as shown in Fig. 5. The bandwidth reached 19 MHz. It uses single-window coaxial structure with electric coupling and is connected to a 9 3/16" coaxial rigid line after transition components. The location of the FPC on the cavity has been optimized to minimize

the potential window damage by line-of-sight field emission electrons and to lower the risk of cavity contamination by squeezing the vacuum part into the cryomodule. Two prototype FPCs are currently being fabricated.
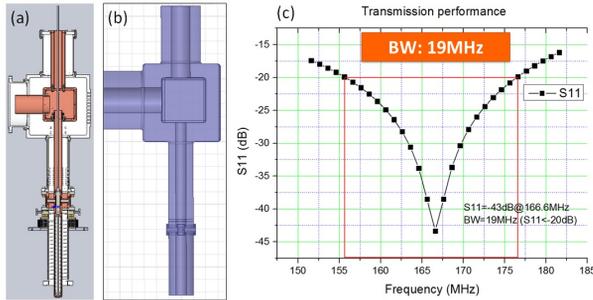
Figure 5: The 166.6 MHz fundamental power coupler.

THE LLRF SYSTEM

A digital LLRF system was chosen for HEPS due to high flexibility. The accelerating field needs to be controlled to be better than $\pm 0.3\%$ in amplitude and $\pm 0.3°$ in phase with respect to the reference. The system is planned to have digital IQ demodulation, fast data logging for post mortem analysis, automatic cavity startup and fast interlock. A first measurement of the prototype system itself was conducted recently. The peak-to-peak residual noise of 0.1% in amplitude and $0.1°$ in phase w.r.t. the reference were measured as shown in Fig. 6.
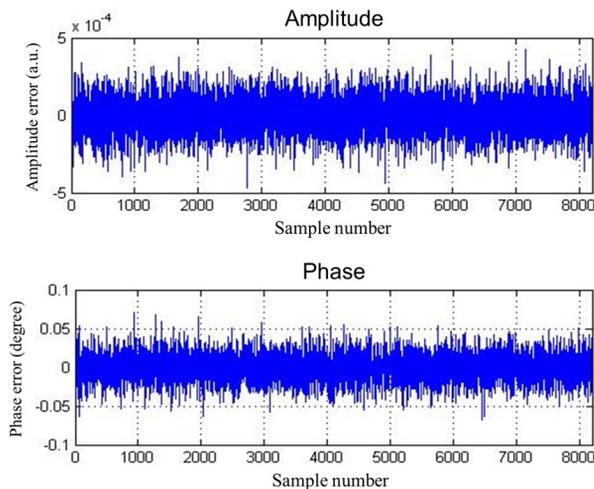
Figure 6: The measurement of the LLRF prototype system.

THE AMPLIFIER

The required RF power for each 166.6 MHz cavity is less than 150 kW during operation. Reserving 25% of power margin, each RF station will have a 200 kW transmitter using solid-state amplifier (SSA) technology. The power combination scheme is shown in Fig. 7. Each transmitter is realized by a cascaded power combination scheme. The smallest unit is a 2 kW power module using LDMOS transistor. Two 25 kW prototype amplifiers are currently being produced in a domestic company.
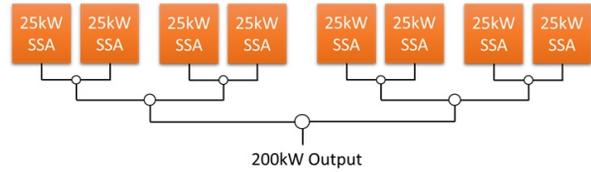
Figure 7: Power combination scheme of the 200 kW 166.6 MHz SSA.

Recent tests of the 2 kW module showed a power efficiency of 70% at 2 kW output. The suppression of spurious signal, 2nd harmonic and 3rd harmonic was better than -85 dB, -40 dB and -57 dB respectively. The phase noise was measured to be better than -90 dBc/Hz at 1 kHz offset.

FINAL REMARKS

A 166.6 MHz superconducting RF system has been proposed for HEPS project. A proof-of-principle 166.6 MHz SRF cavity has been designed, fabricated and vertical tested. The cavity performance largely exceeds the design goal. The cavity HOMs have been evaluated and a hybrid damping structure is being designed. The 200 kW CW power coupler has been designed and the prototypes are being fabricated. A digital LLRF prototype system is under production and initial self tests presented lower than required residual errors. In summary, the 166.6 MHz SRF system is in the middle stage of its R&D phase and is currently proceeding well. Key components are being prototyped and no fundamental problems have been discovered to date.

ACKNOWLEDGEMENTS

REFERENCES

[1] G. Xu, "Progress of the Physical Design and Studies on the High Energy Photon Source," in these proceedings, WEPAB052, 2017.

[2] Z. Duan et al., "Status of on-Axis Injection Studies for HEPS," in these proceedings, TUPAB069, 2017.

[3] N. Wang et al., "Development of the Impedance Model in HEPS," in these proceedings, WEPIK078, 2017.

[4] CST Microwave Studio®. Ver. 2017, CST AG, Darmstadt, Germany.