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DEVELOPMENT AND PROGRESS OF THE HIGH-POWER SOLID-STATE AMPLIFIERS FOR HEPS

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Abstract

The radio frequency system of High Energy Photon Source adopts a double-frequency design with a main frequency of 166.6 MHz and a third harmonic frequency of 499.8 MHz. There are six normal-conducting cavities on the booster, and each cavity will be driven by a 500 MHz 100 kW solid-state amplifier (SSA) with high modularity, high efficiency and sufficient redundancy. Five 166.6 MHz and two 499.8 MHz superconducting RF cavities will be installed on the storage ring, and each cavity will be driven by a 260 kW high-power SSA. All SSAs use cabinet design, where all amplifier modules and AC-DC converters are pluggable and installed inside the cabinets. The total RF power of the SSAs will reach 2.4 MW at HEPS. With the successful development of two SSA prototypes in 2021, and after a long operation period for various high-power tests, the high stability and high reliability of SSAs have been examined. Series production of all remaining SSAs as well as the subsequent performance tests are underway. All SSAs have passed the factory acceptance tests, and five sets of 500 MHz 100 kW SSAs have been installed at HEPS and completed the on-site acceptance tests. The development and progress of the SSAs at HEPS are presented.

INTRODUCTION

For the HEPS booster RF system, there are a total of 6 sets of 500 MHz 100 kW SSAs providing power to 6 PETRA-type copper cavities [1, 2]. For the HEPS storage ring RF system, 5 sets of 166 MHz 260 kW SSAs provide power to 5 SRF cavities, and 2 sets of 500 MHz 260 kW SSAs provide power to two third-harmonic SRF cavities. The layout diagram of the HEPS RF system is shown in Fig. 1. The main parameters of the SSAs are listed in Table 1.

Table 1: Main Parameters of SSAs for HEPS. ‘‘BS’’ stands for booster, ‘‘SR’’ stands for storage ring, ‘‘FC’’ stands for fundamental cavity, ‘‘HC’’ stands for harmonic cavity, ‘‘PAMs’’ stands for Power Amplifier Modules.

Parameters	BS	SR FC	SR HC	Unit
# of SSAs	6	5	2	-
RF frequency	499.8	166.6	499.8	MHz
Nominal power	100	260	260	kW
# of PAMs per SSA	56	112	144	-
# of transistors per PAM	4	3	4	-

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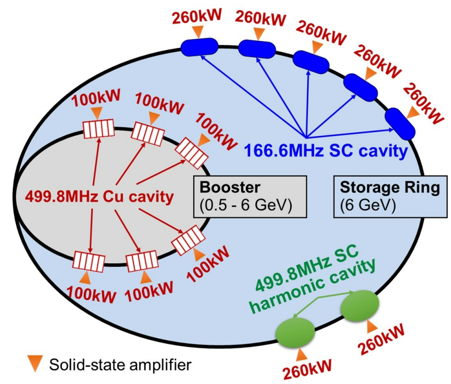

Figure 1: Layout of the HEPS RF system.

The HEPS SSA adopts a cabinet-style design. The cabinet contains power amplifier modules (PAMs), power supply modules, local controllers, power dividers, and power combiners. The PAM is mainly composed of transistors, circulators, and loads attached to a water-cooled plate. The plate is an aluminum plate embedded with copper tube as cooling channels, which is specially designed for effective heat dissipation. The power supply module converts AC to DC and provides power to the PAM in parallel to realize current sharing. The local controller collects signals through CAN bus and communicates with the server through TCP/IP protocol.

Each cabinet is equipped with a programmable logic controller (PLC) responsible for collecting various parameters such as power, voltage, current, temperature of the PAM and power supply module, as well as the flow rate of the deionized cooling water in each cabinet. When an abnormal situation occurs, the local controller will cut off the input signals of the power amplifier module and the power supply module. All SSAs can transmit data and are remotely connected to the control room computer, allowing for data recording and viewing through the EPICS [3].

The cabinets are combined through high-power coaxial or waveguide combiners to achieve the nominal output power. Each SSA is equipped with a final-stage high-power circulator and load to prevent the reflected power from damaging the SSA. All units are modularly designed with spare parts, which facilitate quick replacement of faulty components when the SSA is shut down, thus ensuring high redundancy and reliability.

A 166 MHz 50 kW SSA was successfully developed in 2017 to verify feasibility [4]. In 2021, a set of 166 MHz

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260 kW SSA prototype and a set of 500 MHz 150 kW SSA prototype passed the on-site acceptance tests at the Institute of High Energy Physics (IHEP) [5,6]. As of May 2023, all remaining SSAs have completed factory tests.

BOOSTER 500 MHz 100 kW SSA

The layout of the Booster RF system is shown in Fig.2. In Q1 2023, five sets of 500 MHz 150 kW SSAs have been installed and passed on-site acceptance tests, as shown in Fig.3. Currently, three copper cavities are in place in the Booster tunnel, awaiting power ramp-up this month. In the final stage, the 500 MHz 150 kW SSA prototype will be regrouped into a 100 kW SSA and installed at the booster.

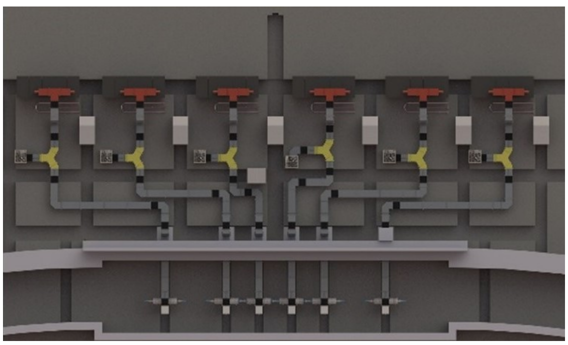

Figure 2: Layout of the HEPS booster RF system.

The technical specifications of the Booster SSAs and the test results of one of the SSAs are listed in Table 2. All parameters are better than the requirements. Especially the harmonics, phase noise, short-term and long-term amplitude&phase stabilities demonstrated excellent performance of this SSA.

Figure 3: Five sets of 500 MHz 150 kW SSAs.

The measurement results of gain and efficiency are shown in Fig. 4. The relationship between the output power and the input power reflects a good linearity. And the 1dB compression point of this SSA is higher than 100 kW. Due to the precise tuning of the output phase of each PAM during mass production, the phase deviation of all PAMs is within 2°. Therefore, the efficiency of the overall in-phase combining was improved, and the AC to RF efficiency of the entire SSA exceeds 55%.

The total output interface of this SSA is EIA WR1800 rectangular waveguide, which has a higher power capacity. The maximum temperature was 29.7° on the flexible waveguide at full power, as shown in Fig. 5.

Table 2: Specifications and test results of Booster SSA. ‘‘p-p’’ stands for peak to peak.

Parameters	Specifications	Test Results	Unit
Output power	≥100	100	kW
Second harmonics	≤-35	-65.69	dBc
Spurious	≤-70	-89.17	dBc
Phase noise @10kHz offset	≤-70	-96.23	dBc/Hz
Total AC-RF efficiency	≥50%	55.1%	-
Power factor	≥0.9	0.9954	-
Total harmonics distortion	≤10%	3.72%	-
Gain difference (20-80 kW)	≤2	1.93	dB
Phase difference (20-80 kW)	≤10°	0.3°	-
Gain flatness (±500 kHz)	≤0.3	0.15	dB
Amplitude stability (p-p, 1s)	≤ ±0.1%	±0.09%	-
Phase stability (p-p, 1s)	≤ ±0.1°	±0.04°	-
Amplitude stability (p-p, 8h)	≤ ±1%	±0.5%	-
Phase stability (p-p, 8h)	≤ ±1°	±0.4°	-
Delay	≤300	266	ns
Interlock response time	≤10	4.7	µs
PAM redundancy	≥6%	7%	-
Microwave leakage @30cm	≤100	11.4	$\mu W/cm^2$
Pulse mode	10 Hz-1 kHz	pass	-

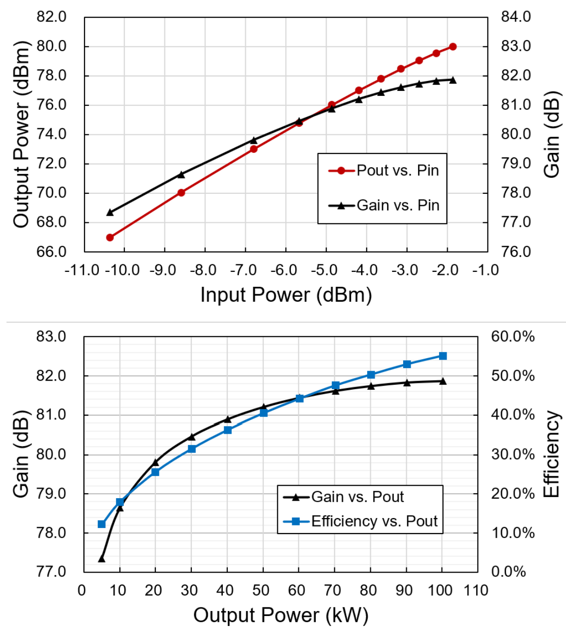

Figure 4: Measurement results of gain and efficiency of the 500 MHz 100 kW SSA.

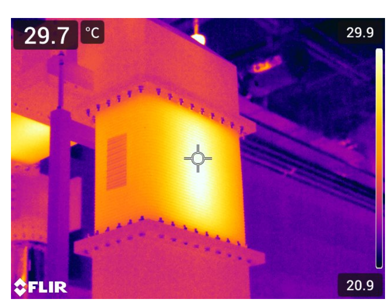

Figure 5: Thermal image of the flexible waveguide.

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SR 166 MHz 260 kW SSA

The storage-ring 166 MHz 260 kW SSA prototype has achieved stable power output through a high-power 8:1 combiner, as shown in Fig. 6.

Figure 6: Storage-ring 166 MHz 260 kW SSA prototype.

During development, issues such as power supply module howling in pulse mode and load burnout were resolved. By using pulse width modulation (PWM) technology power supply, the total harmonic distortion (THD) of current at full power was reduced to below 5%, as shown in Fig. 7. After a long-term test, the howling phenomenon was eliminated.

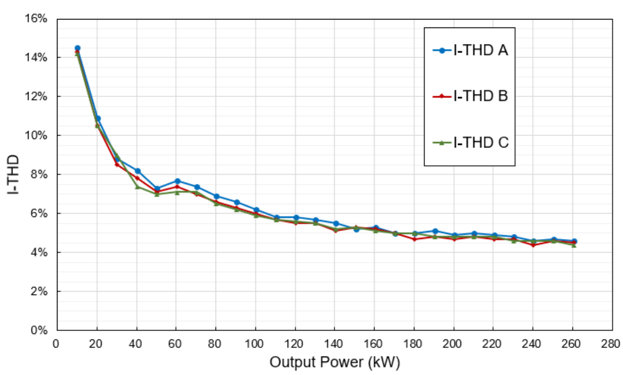

Figure 7: Total harmonic distortion of current at full power.

The high-power water load distributes the 260 kW power evenly to six loads capable of 25 kW each. During the first high-power test, the water load was damaged due to impurities in the cooling water, causing a layer of impurities to adhere to the outer surface of the ceramic core of the 25 kW load, resulting in a decrease in its thermal conductivity and eventual burnout. After that the burnout load was dismantled and replaced, and pure deionized water was used for all subsequent high-power tests, resolving the burnout issue.

After multiple modifications and tests, the high-power circulator and load prototypes have passed on-site tests and are currently in mass production. Since Q4 2021, the cumulative operating time of this SSA has exceeded 1300 hours.

SR 500 MHz 260 kW SSA

Two sets of 500 MHz 260 kW SSAs for the storage ring have passed the factory acceptance tests and are expected to be installed and commissioned on site in the HEPS storage ring in Q4 2023.

The 500 MHz 260 kW SSA was developed based on the 150 kW SSA prototype [6], but increased the number of PAMs and power supply modules in each cabinet. The storage ring 500 MHz 260 kW SSA consists of 8 cabinets, each with 18 PAMs with an output power of about 2 kW. Due to the full power of 260 kW being very close to the 1 dB compression point, the overall AC to RF efficiency of this SSA can reach up to 58.9%, as shown in the measurement results Fig. 8.

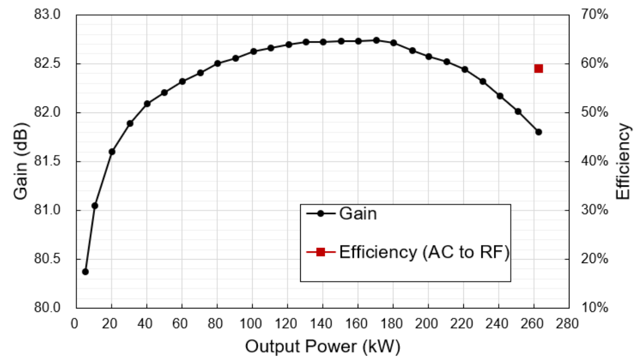

Figure 8: Measurement results of gain and efficiency of the 500 MHz 260 kW SSA.

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REFERENCES

[1] P. Zhang *et al.*, "Status and Progress of the RF System for High Energy Photon Source", presented at the IPAC'23, Venice, Italy, May 2023, paper MOPM058, this conference.

[2] T. Huang *et al.*, "Normal-conducting 5-cell cavities for HEPS booster RF system", presented at the IPAC'23, Venice, Italy, May 2023, paper MOPA184, this conference.

[3] D. Li *et al.*, "Data acquisition and archiving system for HEPS RF system based on Archiver Appliance", presented at IPAC'23, Venice, Italy, May 2023, paper THPA102, this conference.

[4] Y. Luo *et al.*, "Design and performance tests of a modular 166.6-MHz 50-kW compact solid-state power amplifier for the HEPS-TF project", *J. Instrum.*, vol. 16, p. P04011, 2021. doi:10.1088/1748-0221/16/04/P04011

[5] Y. Luo *et al.*, "Development of a 166-MHz 260-kW Solid-State Power Amplifier for High Energy Photon Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2315–2317. doi:10.18429/JACoW-IPAC2021-TUPAB347

[6] Y. Luo *et al.*, "Development of a 500-MHz 150-kW Solid-State Power Amplifier for High Energy Photon Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2312–2314. doi:10.18429/JACoW-IPAC2021-TUPAB346