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# DEVELOPMENT OF A 500-MHz 150-kW SOLID-STATE POWER AMPLIFIER FOR HIGH ENERGY PHOTON SOURCE

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*Abstract*

A 500-MHz 150-kW solid-state power amplifier (SSA) has been developed to test the 500-MHz normal conducting cavities for High Energy Photon Source (HEPS) booster ring. It will also be used to power normal conducting cavities in the initial beam commissioning stage of the HEPS storage ring. A total number of 96 amplifier modules are combined initially by coaxial and later by waveguide combiners to deliver the 150-kW RF power. The final output is of EIA standard WR1800 rectangular waveguide. Each amplifier module consists four transistors equipped with individual circulator and load and outputs 2-kW RF power. Modularity, redundancy and satisfactory RF performance are demonstrated. In the final stage of HEPS project, this 150-kW amplifier will be modified to a 100-kW amplifier to join the other five 100-kW SSAs for normal operation of the booster cavities. The development and test results are presented in this paper.

## INTRODUCTION

High Energy Photon Source (HEPS) is a 6-GeV diffraction-limited synchrotron light source currently under construction in Beijing [1]. Solid-state amplifiers (SSAs) have been adopted for the RF power sources both of booster and storage ring. Six normal-conducting five-cell copper cavity will provide the required 8 MV of RF voltage for the booster [2]. Each copper cavity will be driven by a 100-kW solid-state amplifier (SSA) equipped with a final-stage high-power circulator and load [3].

With the successful development of the 166.6-MHz 50-kW SSA for HEPS - Test Facility in 2017 [4], the solid-state technology solution has been demonstrated. Then a 500-MHz 150-kW SSA has been developed to test the 500-MHz normal-conducting cavities for HEPS booster. Finally, this 150-kW SSA will be regrouped to a 100-kW SSA to power the cavities for booster with other five 100-kW SSAs in the final stage of the HEPS project. This SSA is currently under development, and some meaningful parameters have been obtained.

## DESIGN

The design of 500-MHz 150-kW SSA follows the idea of modularization and multi-stage combining. A total number of 96 amplifier modules are evenly distributed among 8 cabinets. Each amplifier module contains 4 power transistors equipped with individual circulators and loads.

RF signal from generator firstly amplified by a pre-amplifier and divided into 8 cabinet through an 8-way power splitter. Then it evenly distributed to 12 amplifier modules through a 2-way splitter and two 6-way splitter in each cabinet. Twelve amplifier modules each outputs 2-kW RF power combined by two 6-way suspended strip line combiner and one junction combiner in one cabinet. The output power of the 8 cabinets is first combined by coaxial combiners, and the last two stages are combined by waveguide combiners. Considering that the operating frequency is 499.8 MHz, the EIA standard WR1800 rectangular waveguide is selected as the transmission line. WR1800 waveguide has a dimension of 457.2 mm × 228.6 mm, and its recommended operating frequency is 450 MHz to 630 MHz.

At the output port of the last stage WR1800 waveguide combiner, 150 kW RF power will be obtained in expectation. The diagram of combining route is shown in Fig. 1.

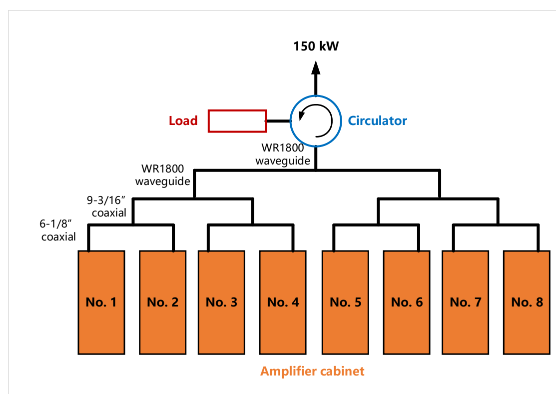


Figure 1: The diagram of combining route of the 500-MHz 150-kW SSA.

380 V AC power is connected from the back of each cabinet, and converted to 50 V DC by power converters installed on the lower part of the cabinet to supply power to the amplifier modules which installed on the upper part of the cabinet. All power converters are connected in parallel to realize current sharing. And there is a signal acquisition board to monitor the status of the power converters in each cabinet.

Deionized water is fed in from the back of the cabinet through cooling water circulation system, and is divided into multiple water channels in each cabinet to take away heat for all amplifier modules and power converters. The water outlet of each cabinet has a flow meter connected to the interlock protection system, and an alarm will be issued when the flow rate is lower than the threshold.

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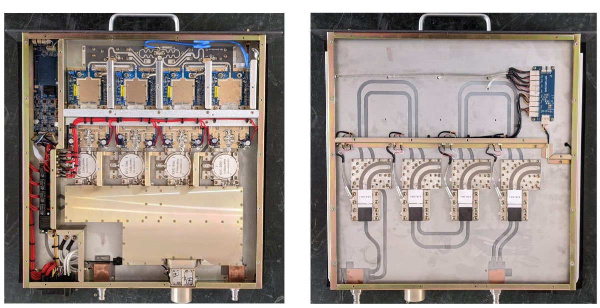
The local control system is installed on the industrial control computer mounted on one of the amplifier cabinet and this cabinet is used as the master cabinet. It monitors the parameters and status of the SSA and provides a communication interface for remote control via TCP/IP protocol through PV variables managed by Experimental Physics and Industrial Control System (EPICS). There is a monitoring unit inside each amplifier module, and a CAN bus is used to connect each monitoring unit to the amplifier cabinet's system controller.

In the design of the amplifier module, taking into account the widespread use of transistors and the stability of supply, BLF0910H9LS750P from Ampleon is selected as the power transistor. And four transistors each equipped with an individual circulator and load consist one 2-kW amplifier module. All the transistors, circulators, loads and combiners are installed on the water-cooled plate. In order to reduce the size and weight of the amplifier module, all components are installed on the both front and back sides of the water-cooled plate to occupy a smaller space, as shown in Fig. 2.

All these amplifier modules are pluggable from the front panel of amplifier cabinet to ensure easy maintenance as well as show the advantages of modular design.



(a) (b)

Figure 2: The 2-kW amplifier module: (a) front side view and (b) back side view.

Transistors, circulators, power splitter, power combiner and status monitoring circuit are installed on the front side of the water-cooled plate. Loads and temperature data acquisition circuit are installed on the back side of the water-cooled plate. In order to improve the thermal conductivity while reduce the weight, the whole water-cooled plate is made of aluminum, and three cooling channels made of copper are integrated into the aluminum chassis. Two ends of each copper pipe are connected to the inlet and outlet valve respectively, while deionized water flows inside the pipe. Transistors, circulators, and loads are the main heat sources thus are placed on top of the copper pipes.

Each amplifier module has a temperature data acquisition circuit and 9 temperature probes, which are attached to the water-cooled plate near the transistors and the loads to monitor the temperature. Temperature data is connected to the local control system and interlock protection system.

## PERFORMANCE TESTS

At present, all amplifier modules have been tested, and 4 out of the 8 cabinets have also been tested. The combining test of the 150-kW SSA will be carried out next month.

### *Test Results of 2-kW Amplifier Module*

For the 2-kW amplifier module, a special test bench was built and the test was completed. The test results are shown in Table 1 and Fig. 3.

Table 1: Test Results of 2-kW Amplifier Module

| Parameters | Test results |
|---|---|
| Frequency | 499.8 MHz |
| P1dB | >2200 W |
| Amplitude error (p-p, 1 s) | ±0.08% |
| Phase error (p-p, 1 s) | ±0.12° |
| Harmonic | -30.7 dBc |
| Spurious within ±20 MHz | -79.6 dBc |
| Phase noise @10 Hz offset | -71.8 dBc/Hz |
| Efficiency (DC to RF) | 65.0% |

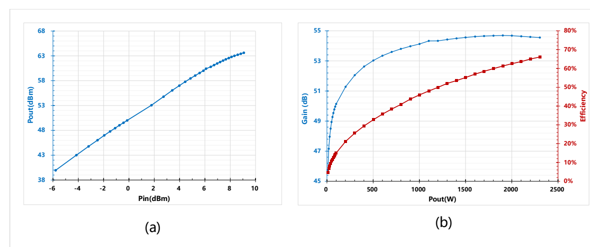



Figure 3: Measurement results of the 2-kW amplifier module: (a) output power vs. input power and (b) gain and DC to RF efficiency vs. output power.

The test of short term (~1 s) amplitude and phase error was measured integrated with the low-level RF. The measured phase error of ±0.12° does not meet the ±0.1° required by the specifications, and subsequent studies will be conducted to improve the stability. All other RF parameters meet the requirements. Phase deviation from 200 W to 2200 W is 1.8°, which reduces the difficulty of low-level RF control.

### *Test Results of 22-kW Amplifier Cabinet*

Figure 4 shows an amplifier cabinet under test, and the performance test results is shown in Table 2, Figs. 5, 6, 7 and 8.

The main RF parameters meet the requirements. Phase deviation from 2.9 kW to 22 kW is 2.2°. The nominal power of the amplifier amplifier is 22 kW, and the output power at 1dB compression piont is lager than 22 kW. The design has always increased P1dB in order to make the power change in the SSA's operating range more linear, but results in a drop in efficiency. The amplifier cabinet's DC to RF efficiency of 49.2% is slightly lower than the 50% required by the specifications and needs to be improved in the future.

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Table 2: Test Results of 22-kW Amplifier Cabinet

| Parameters | Test results |
|---|---|
| Frequency | 499.8 MHz |
| P1dB | >22 kW |
| Harmonic | -34.4 dBc |
| Spurious within ±20 MHz | -72.6 dBc |
| Phase noise @10 Hz offset | -73.3 dBc/Hz |
| Efficiency (DC to RF) | 49.2% |

Figure 4: Amplifier cabinet under test.

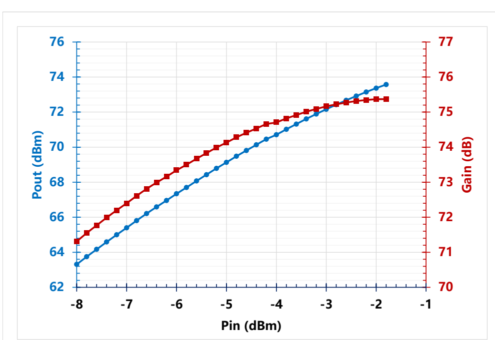


Figure 5: Measurement results of the 22-kW amplifier cabinet: output power and gain vs. input power.

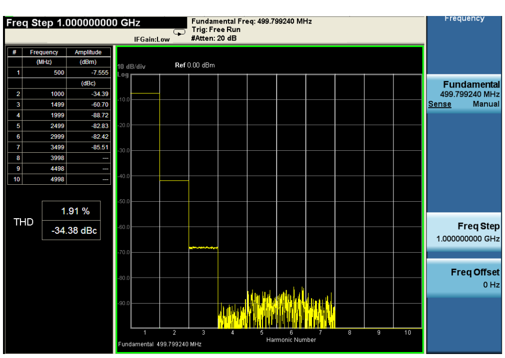


Figure 6: Harmonic of the 22-kW amplifier cabinet.

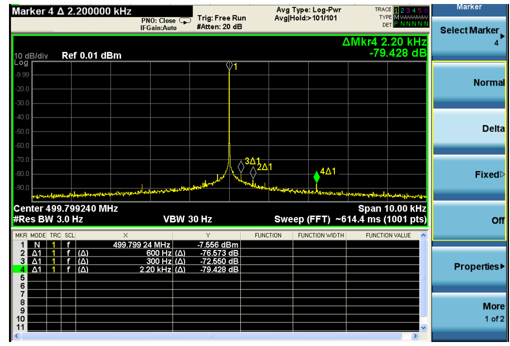


Figure 7: Spurious of the 22-kW amplifier cabinet.

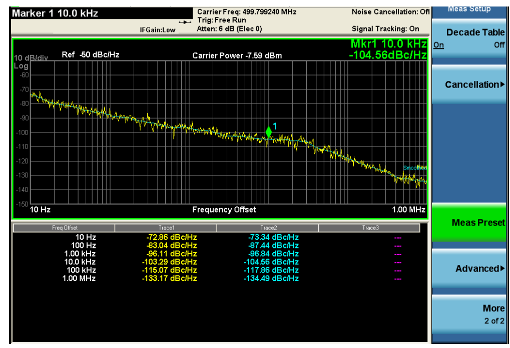


Figure 8: Phase noise of the 22-kW amplifier cabinet.

## FINAL REMARKS

The 500-MHz 150-kW SSA has completed the design and is under development till now. In some early performance tests, it is shown that the main RF parameters have met the requirements, and the stability and efficiency need to be improved. The combining test is expected to be carried out in next month.

## ACKNOWLEDGEMENTS

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