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DEVELOPMENT OF A 166-MHz 260-kW SOLID-STATE POWER AMPLIFIER FOR HIGH ENERGY PHOTON SOURCE

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Abstract

166-MHz 260-kW solid-state power amplifiers have been chosen to drive the 166.6-MHz superconducting cavities for the storage ring of High Energy Photon Source. Highly modular yet compact are desired. A total number of 112 amplifier modules of 3 kW each are combined in a multi-stage power combining topology. The final output is of 9-3/16” 50 Ohm coaxial rigid line. Each amplifier module consists of 3 LDMOS transistors with individual circulator and load. Thermal simulations of the amplifier module have been conducted to optimize cooling capabilities for both travelling-wave and full-reflection operation scenarios. High efficiency, sufficient redundancy and excellent RF performances of the 260-kW system are demonstrated. A control system is also integrated and EPICS is used to manage the monitored data. The design and test results of the amplifier system 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. Five 166.6-MHz 260-kW SSAs will drive the fundamental superconducting cavities, while two 499.8-MHz 260-kW SSAs for the third harmonic cavities in the storage ring [2, 3]. A 166.6-MHz 50-kW SSA was developed in 2017 as the first prototype for HEPS - Test Facility [4]. This SSA was later used in the horizontal high-power tests of the 166.6-MHz dressed superconducting proof-of-principle cavities at cryogenic temperatures and in the conditioning of the in-house developed fundamental power couplers and the higher-ordermode ferrite absorbers. Excellent performance has been achieved in various tests and the graceful degradation was demonstrated. With the experience of this successful development, a set of 166.6-MHz 260-kW SSA was developed later. And the factory acceptance test is still going on from April 2021.

DESIGN

The 260-kW SSA is composed of 112 amplifier modules of 3 kW each through multi-stage combining. Figure 1 shows the schematic diagram of the SSA.

First of all, RF signal generated from the signal source passes through the first-stage pre-amplifier, enters the 8-way power splitter, and is distributed to the 8 amplifier cabinets.

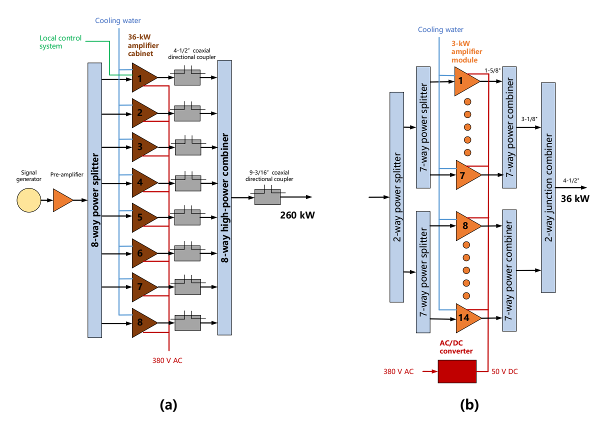

Figure 1: (a) The schematic diagram of the 260-kW SSA and (b) the schematic diagram of the 36-kW amplifier cabinet.

The first-stage pre-amplifier has two independent amplifiers in a case, one for use and one for spare. Each amplifier cabinet contains 14 amplifier modules. The RF signal entering amplifier cabinet is distributed to each amplifier module by a 2-way power splitter and two 7-way power splitters. There are three power transistors in each amplifier module. The signal amplified by the transistor outputs from the amplifier module. Then, the power of the 14 amplifier modules outputs from the amplifier cabinet after being combined by two 7-way suspended strip line power combiners and one 2-way junction power combiner. Finally, the RF power from such 8 amplifier cabinets passes through eight 4-1/2” coaxial rigid transmission line into a direct 8-way high-power combiner for the final-stage of combining, to obtain the nominal output power 260 kW. The output port of the 8-way high-power combiner is 9-3/16” coaxial. The 166.6-MHz 260-kW SSA is shown in Fig. 2. Circulating cooling water is connected to the water pipes from the cabinets’ rear. Then it is divided into multiple channels in each cabinet to take away the heat dissipation of the amplifier modules and the power converters. Each amplifier cabinet has a dimension of 1900 mm (height) × 900 mm (width) × 1400 mm (depth).

According to the operating frequency characteristics of the SSA, BLF189XRA LDMOS transistor from Ampleon is selected as the basic amplifier. The operating frequency of this transistor is from HF to 500 MHz. At the frequency of 166.6 MHz, the maximum output power in continuous wave (CW) is over 1000 W at a drain voltage of 50 V DC. Three such transistors form a 3-kW amplifier module, and each transistor is equipped with an individual 1000-W circulator and 1500-W load. The three transistors in an amplifier mod-

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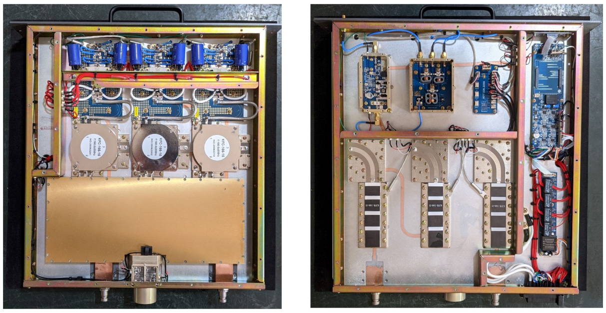
Figure 2: The 166.6-MHz 260-kW solid-state amplifier.

ule are comobined by a Wilkinson stripline combiner. All the transistors, circulators, loads and combiners are installed on the water-cooled plate. Considering the compact design of the SSA, it is necessary to reduce the size of the amplifier module. Therefore, 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. 3. And all these amplifier modules are pluggable from the front panel of amplifier cabinet to ensure easy maintenance.



(a) (b)

Figure 3: The 3-kW amplifier module: (a) front side view and (b) back side view.

Transistors, circulators, and power combiner are installed on the front side of the water-cooled plate. Power divider, loads, and status monitoring 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. Thermal simulations of temperature distribution on the water-cooled plate were conducted by using ANSYS Workbench when SSA is working in travelling-wave mode as well as full-reflection mode. The results are shown in Fig. 4. The inlet water was set to 25 °C with a flow rate of 5.5 L/min and 6 kgf/cm^2 (~0.6 MPa) maximum pressure. The ambient temperature was also set to 25 °C. For the travelling-wave mode, the highest temperature is recorded to be 42.7 °C beneath the transistor. For the full-reflection mode, the highest temperature reaches 51.8 °C beneath the load. Each amplifier module has a temperature acquisition circuit and 7 temperature probes, which are attached to the water-cooled plate near the transistors and the loads to monitor their temperature. Temperature data is connected to the local control system and interlock protection system.

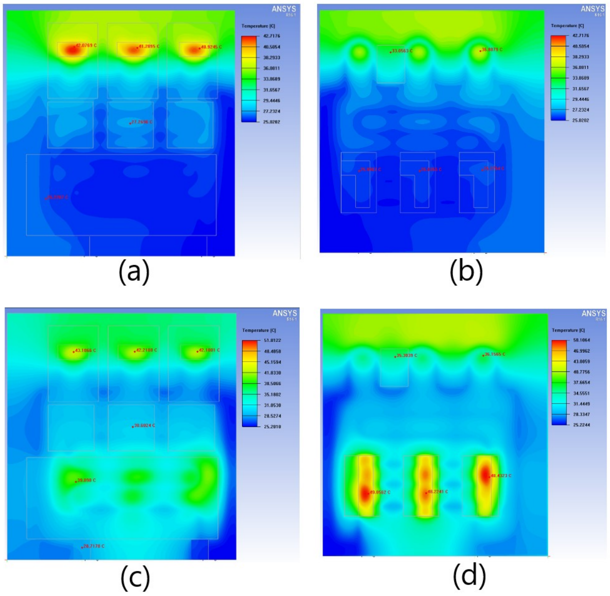


Figure 4: Thermal analysis of water-cooled plate in travelling-wave mode:(a) front side view and (b) back side view. Thermal analysis of water-cooled plate in full-reflection mode:(c) front side view and (d) back side view.

The 260-kW SSA consists of 160 switch-mode power converters of 50 V/80 A each rectifying 380-V AC to 50-V DC to provide the required DC power for all amplifier modules. Four power converters and a current sharing circuit form a power supply group. Five power supply groups are arranged on lower part of each amplifier cabinet, while amplifier modules are located on upper part. The power converters are designed with redundancy in mind, and all 160 power converters are connected in parallel to realize current sharing. Parameters and status of the power converters are reported to the local control system through a signal acquisition board.

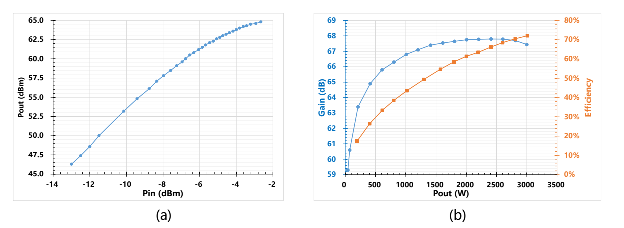
The local control system is installed on the industrial control computer mounted on one of the amplifier cabinet and this cabinet is used as the master cabinet. It monitors the parameters and status of the SSA and provides a communication interface for remote control via TCP/IP protocol through PV variables 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.

FACTORY ACCEPTANCE TEST

The amplifier module prototype was tested in September 2020, and the results demonstrated high efficiency and excellent RF parameters as shown in Table 1 and Fig. 5.

Table 1: Test Results of 3-kW Amplifier Module

Parameters	**Test results**
Frequency	166.6 MHz
P1dB	>3000 W
Amplitude stability (p-p, 1 s)	±0.1%
Phase stability (p-p, 1 s)	±0.1°
Amplitude stability (8 h)	±1%
Phase stability (8 h)	±1°
Harmonic	-36.5 dBc
Spurious within ±20 MHz	-79.5 dBc
Phase noise @10 Hz offset	-71.9 dBc/Hz
Efficiency (DC to RF)	72.1%



(a) (b)

Figure 5: Measurement results of the 3-kW amplifier module: (a) output power vs. input power, (b) gain and DC to RF efficiency vs. output power.

All amplifier modules must be tuned to make their phases consistent. After debugging, the amplifier modules and power supply groups are installed on amplifier cabinets. Each amplifier cabinet needs at least 36 hours of trouble-free commissioning. During this period, several failures were encountered. For example, the water inlet or outlet of an amplifier module is not properly connected with the water pipes, causing water leakage. In another example, the current sharing circuit of one power supply group failed, resulting in no DC power output. These faults are all resolved after commissioning.

Finally, eight amplifier cabinets were installed together with the 8-way high-power combiner and 300-kW load. The output port on the top of each amplifier cabinet is connected to the input port of the 8-way high-power combiner through a coaxial directional coupler and a section of 4-1/2” coaxial transmission line. The eight amplifier cabinets have different distances from the 8-way high-power combiner. In order to meet the conditions of in-phase combining, phase compensation is made on the cables behind the first-stage 8-way splitter. The output port of the high-power combiner is followed by a 9-3/16” coaxial directional coupler, which monitors forward power and reversed power together with eight 4-1/2” coaxial directional couplers on the top of the amplifier cabinets. And based on these monitored power, the insertion loss of the high-power combiner is calculated to be about -0.045 dB, which is very small. In the full power test, VSWR from the output port of the combiner to the 300-kW load is calculated to be 1.11.

Since the installation of SSA in April 2021, the factory acceptance test is still in progress. The total output power of 260 kW has been reached, and at the same time some RF parameters have been measured, see Table 2 and Fig. 6.

Table 2: Test Results of 166.6 MHz 260-kW SSA

Parameters	**Test results**
Frequency	166.6 MHz
nonimal output power	260 kW
Second Harmonic	-35.5 dBc
Third Harmonic	-73.5 dBc
Gain at P1dB	89.5 dB

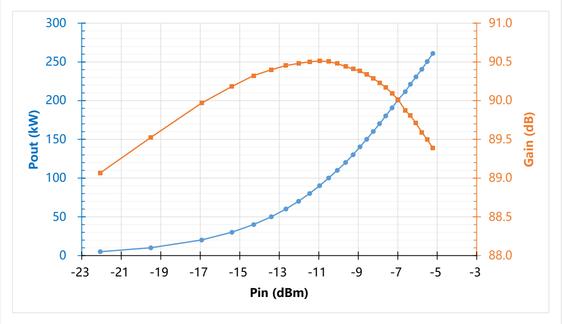


Figure 6: Measurement results of the 260 kW SSA: otutput power and gain vs. input power.

FINAL REMARKS

The 166.6-MHz 260-kW SSA, 8-way high-power combiner and 300-kW load have been designed and developed. Long-term commissioning and site acceptance tests are currently being arranged.

ACKNOWLEDGEMENTS

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