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APPLICATION OF SOLID STATE AMPLIFIERS IN ADS PROJECT AT IHEP*

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Abstract

The solid state amplifier is an important part of the RF power source system of ADS project at IHEP. Three kinds of solid state amplifier with different power and frequency have been applied. In this paper, the specifications of solid state amplifier are presented. In addition, the principle of breakdown of power modules during the high power test of coupler are analyzed.

INTRODUCTION

With the progress of transistor technology, the output power and efficiency of a single transistor has been greatly improved. The high power can be obtained by combination of numerous transistors. Recently the power capability of solid state amplifier (SSA) can extend from a few kW to several hundred kW, and the operating frequency from less than 100 MHz to above several GHz[1 - 4]. Compared with vacuum tube, there are many advantages for SSA such as high reliability for redundancy design, high flexibility for module design, high stability, absence of warm-up time and reasonable efficiency [5]. So the SSA is a priority RF power source for injector I of accelerator driven subcritical transmutation system (ADS). Three kinds of solid state amplifier with different power and frequency have been used to feed the cavities or test high power coupler in injector I of ADS at institute of high energy and physics (IHEP), whose performance and detailed parameters are presented in this paper.

325 MHz/10 kW SSA

The 325 MHz/10 kW SSA is used to feed bunchers and spoke cavities of injector I of ADS. The one cavity per source is chosen to simplify the LLRF control and RF distribution system. The bandwidth of SSA needs more than 2 MHz for LLRF control requirement. The nominal maximum power of 10 kW is achieved with less than 1 dB compression, and the harmonic output power is less than -30 dBc. The AC to RF efficiency goal for the SSA at the rated power is at least 50%. The single power module must include circulator and absorbing load to ensure isolation between modules and withstand the full reflection power. Each SSA must monitor the status data of every power module such as voltage, current and temperature. Ethernet port is required to communicate with control system. Also, interlock is necessary for external faults like water leaks. The mean time between failures (MTBF) should be larger than 20,000 hours, and less than 5% of the power modules fail per year. The failure of one power module can still run. The output port is 3-1/8 inch rigid coaxial line. The 325 MHz/10 kW SSA specifications are shown in Table 1.

In July 2012, the first 325 MHz/10 kW SSA was delivered to IHEP by BBEF, which was used to build a workbench for the high power test of the coupler of spoke cavity. In September 2013, another one was delivered for the horizontal test of spoke cavity. In April 2014, 14 SSAs were installed and commissioned in power supply hall. In 2015, 9 SSAs were put into operation. In March 2016, another two SSAs were delivered by the 38th institute of CETC. In the end of 2016, 16 325 MHz/10 kW SSAs were used in injector I, as shown in Fig. 1.

Table 1: 325 MHz/10 kW SSA Specifications

Parameters	Value
Frequency(MHz)	325
Output Power(kW)	10
Gain(dB)	≥65
Bandwidth(MHz)	≥ 2
Amplitude stability	≤1%
Phase stability	≤1°
Harmonic(dBc)	< -30
Spurious(dBc)	< -65
MTBF(h)	20000
Efficiency at 10 kW	≥50%

Figure 1: 325 MHz/10 kW SSA.

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325 MHz/25 kW SSA

The 325 MHz/25 kW SSA was used to feed spoke cavities of CM4. In order to facilitate maintenance, the power module and power supply should adopt fast plug and pull technology. The power module must include self-protection for overheating. The output port is 4-1/2 inch rigid coaxial line. The performance requirements are similar to the previous 10 kW SSA. The 325 MHz/25 kW SSA specifications are shown in Table 2.

In the end of 2014, the contract of the prototype of 325 MHz/25 kW SSA was signed with Chengdu Kaiteng Sifang Quartet Digital Broadcasting & TV Equipment Co. Ltd (KTSF). In April 2016, the acceptance test of the prototype was completed at IHEP. In May 2017, 6 325 MHz/25 kW SSAs were installed and commissioned for CM4 in Lanzhou city, as shown in Fig. 2.

Table 2: 325 MHz/25 kW SSA Specifications

Parameters	Value
Frequency(MHz)	325
Output Power(kW)	25
Gain(dB)	≥70
Bandwidth(MHz)	≥ 2
Amplitude stability	≤1%
Phase stability	≤1°
Harmonic(dBc)	< -35
Spurious(dBc)	< -70
MTBF(h)	20000
Efficiency at 25 kW	≥50%

Figure 2: 325 MHz/25 kW SSA.

650 MHz/150 kW SSA

The 650 MHz/150 kW SSA is the key equipment of the ADS power source system, which is the highest output power SSA in China. The 650 MHz/150 kW SSA was designed and manufactured by KTSF. The output port is WR1500 waveguide. The failure of 4 power modules can still run. The AC to RF efficiency goal for the SSA at the rated power is at least 45%, which reaches 51.3% for acceptance test. The performance requirements are similar to the previous 25 kW SSA. The 650 MHz/150 kW SSA specifications are shown in Table 3.

In September 2016, a 650 MHz/150 kW SSA was completed factory acceptance test in KTSF. At the end of 2016, the 650MHz/150kW SSA was delivered to IHEP and completed installation. In March 2017, the acceptance test of the prototype of 650 MHz/150 kW SSA was completed, as shown in Fig. 3.

Table 3: 650 MHz/150 kW SSA Specifications

Parameters	Value
Frequency(MHz)	650
Output Power(kW)	150
Gain(dB)	≥75
Bandwidth(MHz)	≥ 2
Amplitude stability	≤1%
Phase stability	≤1°
Harmonic(dBc)	< -35
Spurious(dBc)	< -70
MTBF(h)	20000
Efficiency at 150 kW	≥50%

Figure 3: 650 MHz/150 kW SSA.

POWER MODULE BREAKDOWN

In August 2014, several power modules failed when the coupler was carried out high power test in standing wave mode. The ceramic absorbing load was seriously breakdown, as shown in Fig. 4. It indicated that the reflected power exceeded the load rated value of 800W .The principle can be expressed as follows: The reflected power due to the mismatch of output port of SSA will be equally distributed to each port of combiner. To simplify the design of the power combiner, all ports are not isolated from each other. When one of the power modules fails, the wave from the other port will combine at this port in phase. So the total reflected wave of the module failed is the sum of the reflected wave from the mismatched load and the combined wave from the other port. In the worst case,

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these two wave will combine in phase. Then the total reflected power can be expressed as follows:

$$P_{total} = (\frac{N-1}{N} + \Gamma)^2 P \qquad (1)$$

Where P_{total} is the total reflected power, P is the output power of a single power module, N is the port number of combiner, and Γ is the reflection coefficient of the output port of SSA. When P is 550W, N is 10 and Γ is 1, the maximum reflected power is 1985.5W which is far in excess of load capacity. In order to avoid the load breakdown, a high power circulator can be used at the output port of SSA when the coupler was tested in standing wave mode.

Figure 4: Power module Breakdown.

CONCLUSION

The solid state amplifier has been widely used in accelerator due to high reliability and easy maintenance, which has become an important part of power source system of injector I of ADS. During the process of application, some useful suggestions were fed back to companies to improve the design. The application of solid state power source in large-scale scientific projects has greatly promoted the domestic solid state power source industry and R&D capability.

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