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OPERATION OF TPS 300 KW SOLID-STATE AMPLIFIER

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Abstract

The National Synchrotron Radiation Research Center (NSRRC) has developed a 300 kW solid-state amplifier. This 300 kW solid-state amplifier RF transmitter has been operating continuously since August 2023, consistently delivering an output of 250 kW RF power during user beam time at 500 mA. This report describes the performance of the solid-state amplifier RF transmitter during this period, module failure rates, and specific instances of malfunction.

INTRODUCTION

Solid-state power amplifier (SSPA) technology is the current trend in particle accelerator power sources, utilizing multiple low-power solid-state modules to generate high-power output through power combining. It offers advantages such as not requiring high voltage, redundancy, high reliability, and high efficiency. Many accelerator facilities are also being developed and using SSPA as RF power sources, such as SOLEIL [1], SLS [2], ESRF [3]. The National Synchrotron Radiation Research Center (NSRRC) began developing solid-state technology in house in 2011, progressing from solid-state module circuit boards [4], power combiner [5], power combining to a prototype of 80 kW SSPA tower in RF laboratory [6], and culminating in the construction of a 300 kW SSPA transmitter at the Taiwan Photon Source (TPS).

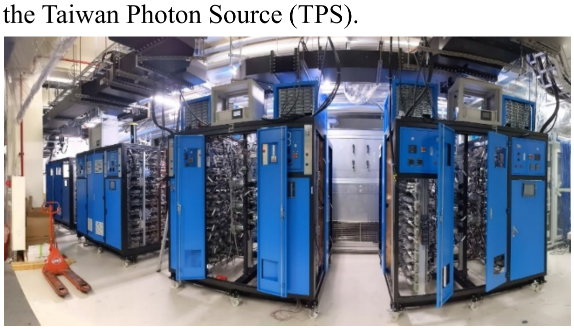

Figure 1: Photograph of the 300 kW SSPA at TPS.

Figure 1 shows a photograph of the 300 kW SSPA transmitter. Figure 2 depicts its design architecture, consisting of four 80 kW SSPA towers. Each tower comprises approximately 120 solid-state modules with a maximum power of around 1 kW, multiple RF power dividers and power combiners, a 96 kW DC power supply system and other peripheral support systems. Through a two-stage power combining process, it can generate a maximum output power of 300 kW. In September 2021, we completed the construction and initial high-power testing of a 300 kW SSPA. This SSPA served as the power source for coupler aging in 2022 and underwent high-power reliability and stability testing in February 2023. Finally, in August 2023, this 300 kW SSPA transmitter was deployed for routine operation at the TPS, providing the required 250 kW input power for one set of SRF modules under a storage current of 500 mA. The following sections describes the testing and operation status of this 300 kW SSPA since 2023, as well as its performance during regular operation.

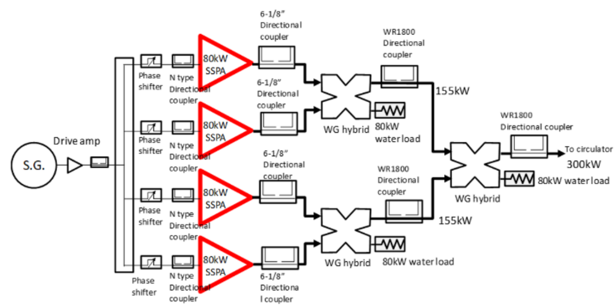

Figure 2: Design architecture of the 300 kW SSPA.

OPERATION STATUS

The RF system of the TPS currently operates with two sets of SRF modules, providing a total RF voltage of 3.0 MV. Each set of SRF module has its own high-power RF source. Under a storage current of 500 mA, each set of SRF modules requires approximately 250 kW of input RF power. During the machine study period in February 2023, we utilized SSPA to provide the required RF power for one of the SRF modules and conducted long-term test on the SSPA under conditions of 500 mA storage current, successfully verifying the reliability and stability of the 300 kW SSPA.

To maintain the possibility of expanding the RF power source, such as increasing the RF output power to 400 kW in the future through additional power combining, we have incorporated three switchable regions in the configuration of the waveguide, as shown in the Fig. 3. This architecture allows the system to be switched in a short time to be supplied by SSPA alone, or by klystron alone, or in the future to provide a higher output RF power through power combination.

After approximately two weeks of stability testing with the SSPA in February 2023, we continued to use klystron-type RF transmitters during user time operations. It wasn't until August 2023 that we switched from klystron-type RF transmitters to 300 kW SSPA, and we have been operating steadily with the 300 kW SSPA since then. During the approximately nine-month period from mid-August 2023 to the present, a total of nine modules were damaged. There were no trips caused by the SSPA during user operation,

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but there were multiple instances of crashes during testing or machine study due to the SSPA.

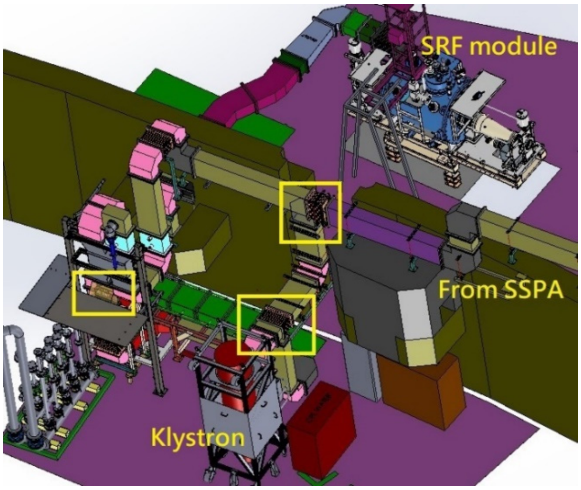

Figure 3: Configuration of waveguide piping for the RF station #3 at TPS.

Among the 9 damaged solid-state modules, the actual cause of failure for 4 modules remains unclear, while 5 modules were attributed to water leakage event. Figure 4 shows photographs of the leakage location and one of the affected modules, where traces of water leakage can be observed. Water slowly seeped out from the cooling water pipes, accumulating in the catchment tray. When water accumulated excessively, it dripped onto the SSPA module below, leading to a short circuit at the power supply terminals and causing a malfunction.

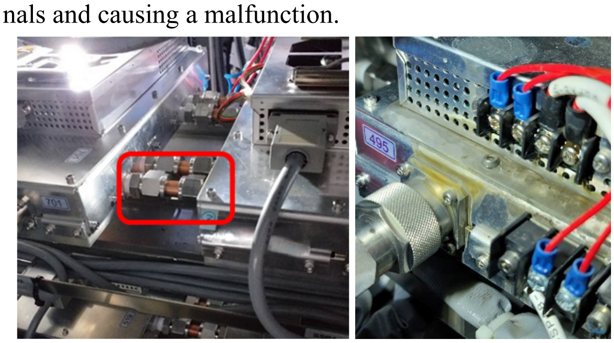

Figure 4: Photographs of the location for the water leakage.

Table 1: List of Trips Due to SSPA

Date	User/Machine	Causes of Failures
2023/02/19	Machine	water flow high
2023/08/03	Machine	water flow high
2023/08/28	Machine	water temp. high
2023/12/22	Machine	Pr too high
2024/04/06	Machine	water temp. high

Table 1 lists SSPA trips during the testing and machine study phases. Several trip may have been caused by interference due to RF power leakage, leading to abnormal triggering of the interlock system for water flow and temperature signals. In such events, the water flow or temperature signals would indicate saturation, meaning the analogue input voltage is at 10 V. These modules with abnormal signals are all concentrated in the same area. Investigation revealed RF leakage from the power output ports of a few modules, significantly reduced after wrapping with aluminium foil. Figure 5 shows the RF leakage spot after wrapping it with aluminium foil. Before wrapping it with foil, the electromagnetic field measurement at that spot indicated overload when the total power output was less than 10 kW. After wrapping it with foil, the electromagnetic field measurement decreased to 2.5 mW/cm^2 when the total power output was 80 kW.

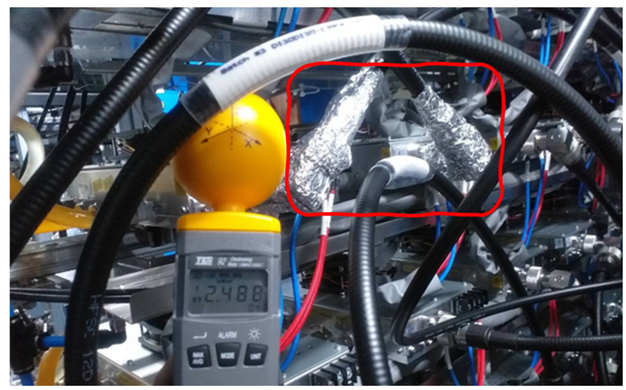

Figure 5: RF leakage spot.

There is another one event occurred due to potential noise interference affecting the water temperature signal, resulting in an abnormal increase in temperature values and causing the trip.

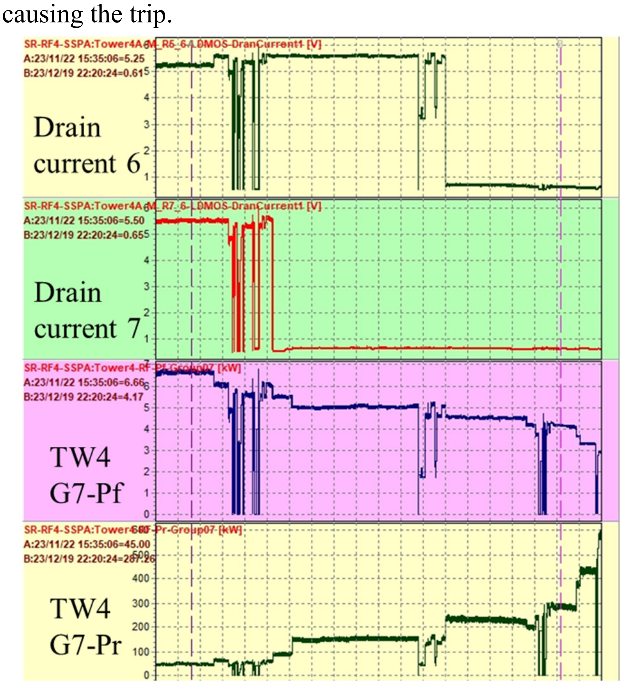

Figure 6: Signals before the trip due to reflection power high.

Another trip resulted from excessive module damage due to a water leakage event, causing reflection power too high and subsequent system crash. Figure 6 shows the DC

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drain current signals of two modules (non-calibrated) and the signals of RF output power and reflected power of a 10 kW group before the trip event. Under the condition of a total output of 250 kW, each damaged module results in a decrease of approximately 600 W in output power and an increase of approximately 50-100 W in reflected power for one group. After five modules were damaged due to water leakage, the output power of the group decreased to 2.8 kW, and the reflected power increased to 600 W, exceeding the set value for reflected power protection and causing the trip.

OPERATION PERFORMANCE

The DC drain voltage of this 300 kW SSPA can be adjusted between 42 V and 56 V. Under the current operating conditions of 250 kW output power for one SRF module required for TPS at 500 mA, we set the DC drain voltage to 45 V. Under this condition, the DC to RF conversion efficiency of each 80 kW SSPA tower is approximately 58%. Considering the approximately 93% AC conversion efficiency of the DC power supply and an overall power combining efficiency of about 93%, the AC to RF efficiency of the entire 300 kW SSPA is approximately 50% at the output power of 250 kW, slightly better than that of a klystron-type RF transmitter with the same output power. Further enhancements in efficiency can be pursued in the future to achieve energy-saving benefits.

The klystron-type RF transmitter used in TPS generates high voltage through the switching of 86 DC power supply modules. Consequently, fluctuations in the RF output power are influenced by the switching and rotation frequency of these DC modules, introducing high-frequency noise. For the current TPS klystron-type RF transmitter, the rotation frequency is approximately 7 kHz. Unlike the klystron-type RF transmitter, SSPA does not require high voltage, thus eliminating this high-frequency noise. Figure 7 illustrates the electron orbit spectrum in the horizontal direction under operation with klystron-type RF transmitter and SSPA. When operating with SSPA, there is no significant disturbance at 7 kHz. Therefore, the use of SSPA also contributes to the stability of the electron orbit.

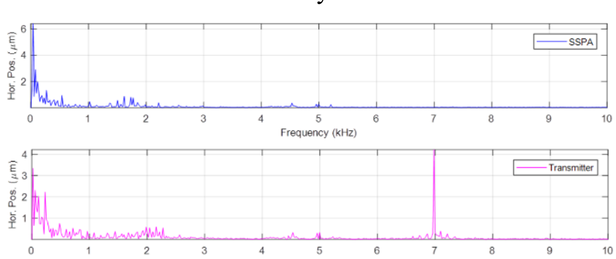

Figure 7: Spectra of the electron beam orbit in the horizontal direction.

CONCLUSION

In the accelerator field, there's a growing trend towards employing SSPAs as high-power RF sources. We've devoted considerable efforts to solid-state technology development and have built a 500 MHz 300 kW SSPA RF transmitter system at the TPS. This SSPA RF transmitter has been utilized extensively during routine operations at the TPS, bolstering the power efficiency and stability of the RF system. It significantly mitigates disturbances to the electron beam and helps minimize trip events.

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