

# HIGH-POWER TESTING OF TPS HETEROGENEOUS ONE-TO-FOUR POWER COMBINING

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## Abstract

The Taiwan Photon Source (TPS) is a third-generation synchrotron light source located in Taiwan. Currently, it operates with two RF stations, each capable of delivering 300 kW of RF power. As the number of beamlines at TPS increases, more insertion devices will be installed, necessitating additional RF power. Presently, each RF station provides approximately 250 kW of power. To maintain operational margin, increasing the RF power available per station is a critical task. To address this, we have implemented a heterogeneous power combination method, where the power from solid-state power amplifiers is combined to raise the available RF power per station to 375 kW. This report describes the power combination methodology employed at one of the RF stations, high-power testing results, and the outcomes of long-term operation under combined power conditions. Future plans for power combination are also discussed in this paper.

## INTRODUCTION

The Taiwan Photon Source (TPS) is a third-generation synchrotron radiation source in Taiwan [1], with an electron energy of 3 GeV and a designed operational storage current of 500 mA. The TPS radio-frequency system adopts SRF modules [2], and currently, two RF stations are in operation, each capable of providing up to 300 kW of RF power. The TPS beamlines are divided into three phases. The insertion devices of each phase increase radiation loss by approximately 100 keV at the minimum gap, resulting in an additional power demand of 50 kW at 500 mA. The third-phase beamlines are currently under construction and are expected to be completed and gradually put into operation by 2026.

Currently, during routine operation at 500 mA, each RF station of the TPS provides an output power of approximately 250 kW. In anticipation of the increased RF power demand after the completion of the third-phase beamlines, we aim to enhance the output power capacity of each RF station to ensure sufficient operational margin. Originally, both RF stations utilized 500 MHz klystron-type RF transmitters. In 2023, one of the RF stations was switched to operate with a 300 kW solid-state power amplifier (SSPA) [3]. To accommodate the additional RF power required after the completion of the third-phase beamlines, we have adopted a heterogeneous power combination approach [4], integrating the power from the SSPA and the klystron to increase the available RF power

per station. Since our in-house SSPAs are built with an 80 kW per tower configuration [5-6], we plan to increase the power of each RF station by only 80 kW. This is achieved using a 1:4 power combination ratio, allowing each RF station to deliver up to approximately 375 kW of RF power. Figure 1 illustrates the power combination architecture. The following sections describe the power combining method and the results of high-power testing.

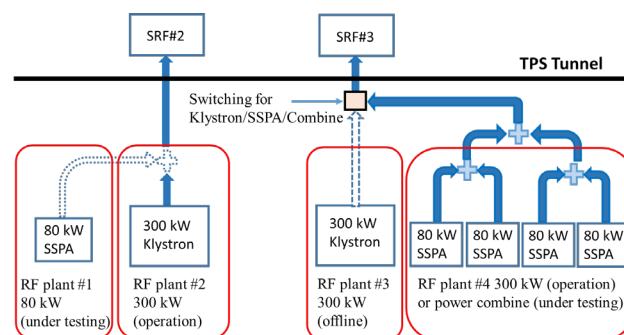


Figure 1: Power combination architecture for TPS RF system.

## POWER COMBINATION SYSTEM

The in-house SSPA developed by NSRRC can provide an output power of 300 kW. However, due to limitations in the drain voltage of the SSPA circuit, it cannot achieve high efficiency at lower power levels. In contrast, a klystron can maintain acceptable efficiency at lower power by reducing the high voltage. Therefore, for the RF station operating with the 300 kW SSPA, we implemented power combining using a 1 to 4 ratio between the klystron and the SSPA. A 1 dB hybrid power combiner was used in the hardware, and by utilizing the waveguide piping shown in Fig. 2, we ensured flexibility for switching operational modes.

When combining power, the phase and power level of two input ports must be maintained within a certain range. If there is a deviation in phase or power, a portion of the output power will be redirected to the other port of the output end, reducing the efficiency of power combination. To absorb the excess RF power, an RF load is installed at the additional output port. Considering the scenario where the 75-kW input (klystron system) trips, 75 kW of power from the 300-kW output of SSPA system will be absorbed by the RF load. Therefore, the RF load is rated for 80 kW. After power combining, there are no additional circulators or RF loads; all reflected power is absorbed by the RF loads of the SSPA and klystron systems, respectively. The issue of excessive power at the hybrid combiner's load port caused

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by phase or power level errors is prevented through an interlock protection system.

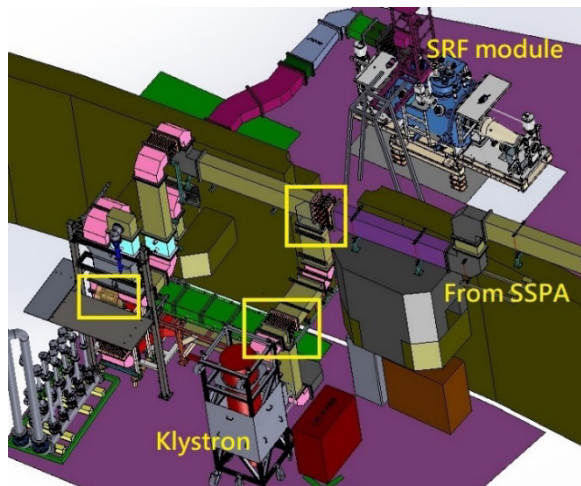


Figure 2: Configuration of waveguide piping for the RF station #3 at TPS.

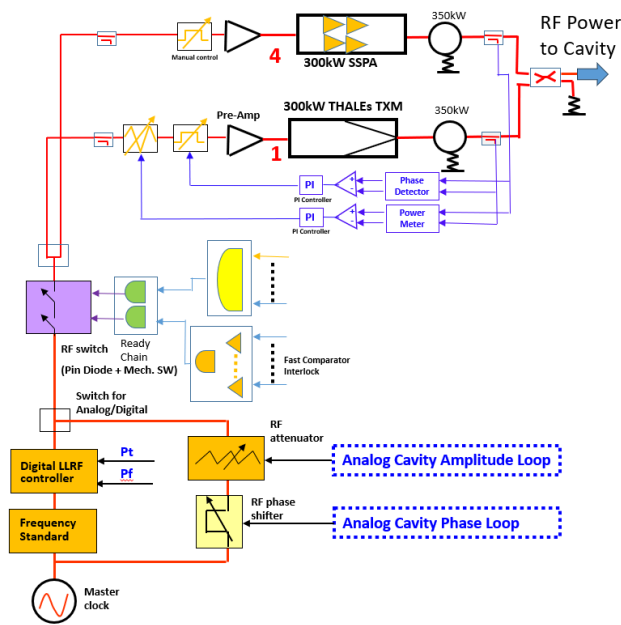


Figure 3: The control system architecture for power combining.

The control system architecture for power combining is shown in Fig. 3 and is divided into two parts. The first part is the original RF station's Low-Level RF (LLRF) system, which currently employs a hybrid analog-digital architecture. During routine operation, we use the digital LLRF system. However, during machine studies or when performing high power aging on the coupler during downtime, we switch back to the analog system. The second part is the control system responsible for maintaining the 1:4 power ratio between the klystron and SSPA, as well as ensuring a fixed phase relationship between the two systems. This system currently uses an analog architecture consisting of a phase detector, a voltage detector, and two PI control circuits. The phase and amplitude control references are based

on measurements from the SSPA output, while the inputs come from the phase and power measurements of the klystron system.

To prevent interference between the main LLRF and the power combining control system, the control bandwidth of the power combining system needs to be carefully adjusted during actual testing. If the bandwidth is too high, oscillations may occur in the output of the SSPA and klystron. Figure 4 shows an oscillation event that occurred during a 4:1 power combining test under a similar architecture. Since the RF gap voltage and the power reflected to the circulator remain almost unchanged, it can be inferred that the combined output power does not vary significantly. However, oscillations have already occurred on the klystron side, indicating that this issue is related to the power combining control system. This issue was mitigated by reducing the gain of the PI controller. Additionally, due to differences in the nonlinear characteristics of the power measurement between the klystron and the SSPA, and to maintain the 1:4 power ratio, a pre-established calibration table is required for one of the measurement channels.

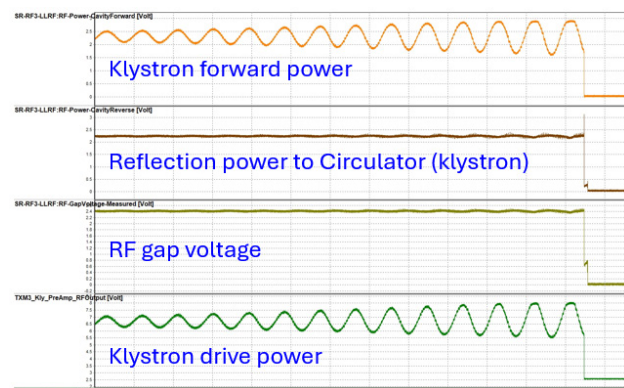


Figure 4: An oscillation event that occurred during a 4:1 power combining test.

Regarding the interlock protection system, both the SSPA and klystron have their own dedicated interlock protection modules, each generating a sum signal that is sent to the main LLRF system. In the event of a fault in either system, an RF switch can quickly cut off the power source to provide protection. In the main LLRF system, additional interlock signals related to power combining have been added, such as the water temperature signal of the RF load used in the hybrid combiner. When there is a phase deviation between the klystron and SSPA outputs, excessive power may enter the RF load at the combiner's output port, causing an increase in the load's cooling water temperature, which in turn triggers the interlock protection system.

### HIGH POWER TEST RESULTS

During the TPS machine maintenance period, we conducted power combining tests by blanking off the waveguide leading to the cavity. Initially, we manually adjusted and established a calibration table for power combining control. Once the calibration table was completed, we switched the power combining control to a feedback loop and performed high-power testing. Since the additional

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power demand from the IDs of the Phase 3 beamlines is expected to be around 50 kW in total, with each RF station providing approximately 25 kW, the high-power test target was set at 300 kW rather than pushing the system to its rated power of 375 kW. After completing the initial high-power test and verifying that the power combining function was operating correctly, we proceeded with further high-power operation tests during routine coupler aging and beam operation. Figure 5 shows the power ratio between the klystron and SSPA during these three stages, which remained around 0.25, indicating that the power combining function was working properly.

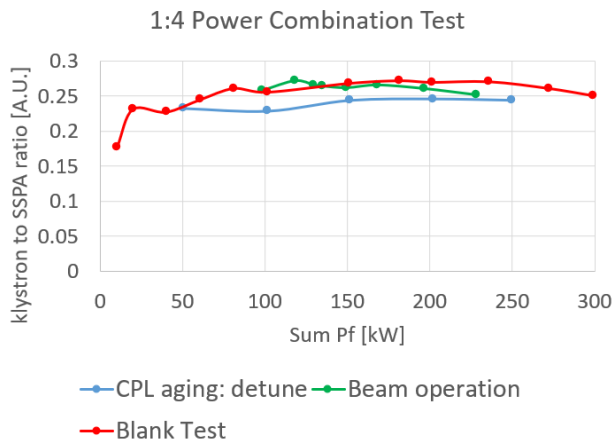


Figure 5: Power ratio between the klystron and SSPA during blank testing, coupler aging and beam operation.

During the machine study period, we conducted a seven-day beam operation using the power combining method. The operational data is shown in Fig. 6. Under the 500 mA operating condition, since the ID gaps had not yet been fully closed, the maximum output power of the RF station was approximately 230 kW. Throughout the seven-day test period, despite multiple changes in operating conditions, the power combining function remained stable, and no system failures occurred due to power combining. This demonstrates a certain level of reliability in the system. At 230 kW, the overall power efficiency of the power combining method was approximately 39%, mainly because none of the parameters had been optimized. As we operate at higher power levels and adjust the drain voltage of the SSPA, further improvements in power efficiency can be expected.

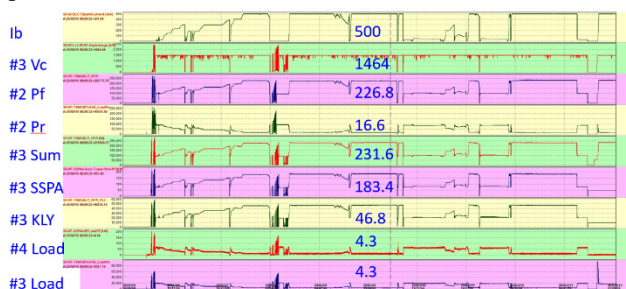


Figure 6: Operational data for beam operation using the power combining method during the machine study period.

## CONCLUSION

To meet the RF power demands following the completion of the Phase 3 beamlines at TPS, we conducted tests on heterogeneous power combining. By utilizing the existing klystron and SSPA systems, we implemented power combining with a klystron-to-SSPA power ratio of 1:4 to enhance the maximum RF output power. After initial high-power testing and approximately seven days of beam operation, we verified that the power combining function operated correctly and that the overall system demonstrated a high level of reliability. However, further optimization is required to improve efficiency.

After the successful testing of power combining at this RF station, the construction of power combining for the other RF station is also underway. An 80 kW SSPA tower has been installed at the second RF station, and a 4:1 power combining test is planned for the future. Following the long shutdown in August 2025, the newly constructed beamlines will gradually begin commissioning and operation. Therefore, we also plan to optimize the power combining parameters after August 2025 and start long-term operation using the power combining method during user shifts to meet the RF power demand at that time.

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