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THE PROGRESS OF 300 kW HOME-MADE FULLY SOLID-STATE TRANSMITTER FOR TPS

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Abstract

To support the stable operation of Taiwan Photon Source (TPS) with 500 mA beam current and the increasing beam line construction, a 3rd RF plant is thus constructed for such demand. The RF power source of the other 2 RF plants adopts klystron type transmitter and the 3rd RF plants is transferred to new technology of solid-state for better redundancy and easier maintenance. Base on the success of solid-state power amplifier development in 2019, a 3rd RF power source is thus decided to be made in house by solid-state technology. The 500 MHz 300 kW solid-state transmitter is constructed by 4 80 kW solid-state power amplifier (SSPA) towers and power combined by 3 WR1800 3-dB hybrid couplers. Each tower is consisted of 110 850 W final stage SSPA modules with 4 100 W pre-amplifiers and 6 600 W drive amplifiers. The pre and drive amplifiers are power combined for higher redundancy and better balance. The DC power are economical industrial 48V AC-DC rack mount power supplies which are parallel connected for higher total DC power and best redundancy. The architecture and present progress are presented in this article.

INTRODUCITON

The arising of solid-state technology in accelerator for high power application has appeared for more than 20 years. After the successful demonstration the hundreds of kW in UHF band by multiple stages power combination [1], the solid-state has been adopted widely in many light source facilities [2]. In NSRRC, the solid-state technology for RF power application has also been studies for more than 10 years and has the practical application for coupler RF aging of SRF cavity module. The built 80kW prototype SSPA has been heterogeneous power combined with a 100 kW klystron type transmitter by a 3-dB hybrid coupler for more than 140 kW output capability [3]. After the successful demonstration the applicability of SSPA and its redundancy in house, the 3rd RF plant for TPS is decided to choose solid-state technology as its 300kW RF power source. The recent actual test of SSPA has proved that it's a practical solution to be merely made in house for building affordable RF power source in the light source. Four updated of 80 kW SSPA towers are thus going to be constructed for 300 kW RF power. The topology of 300 kW SSPA, the performance of single 80 kW SSPA tower and the power combination results of 2 towers will be presented.

TOPOLOGY OF 300 kW FULLY SOLID-STATE TRANSMITTER

By the present approved local developed SSPA techniques, the 300 kW fully SSPA will be constituted by 4 80 kW SSPA towers. Four 80 kW SSPA towers will be combined as 2 groups of 2-way power combination first by 2 WR1800 3-dB hybrid couplers as well as 2 80 kW water loads. The combination of 2 80 kW SSPAs will produce at least 155 kW RF power while 4 80 kW SSPA towers can generate 2 ways of 155 kW RF power. The 3rd 3dB hybrid coupler as well as an 80 kW water load will than combine these two-way power to a single way with at least 300 kW RF power. The 3-dB hybrid coupler can provide excellent isolation between neighbour ports which is able to avoid unnecessary reflection power due to power unbalance. The cost is the larger space occupation of power combiner as well as additional load for absorbing the unexpected unbalance RF power. The topology of the proposed 300 kW SSPA is shown in Fig. 1. The specification is also list in Table 1.

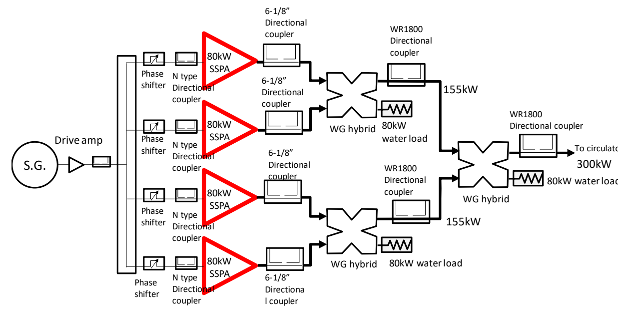

Figure 1: The topology of 300 kW fully solid-state transmitter.

Table 1: Specifications of Proposed 300 kW SSPA

Item	Specification Value
Frequency	499.65 MHz
Power rating	≥ 300 kW
Bandwidth	≥ +/- 1 MHz
Power gain	≥ 75 dB
Side band noise	≤ 65 dBc
Harmonic	≤ 40 dBc

DESIGN AND PERFORMANCE OF SINGLE 80 kW SSPA TOWER

The design of an 80 kW SSPA tower as shown in Fig. 2 is the modification of prototype 80 kW SSPA developed by NSRRC in 2019 [4]. The new version of the architecture improves the redundancy, balance of power distribution and reduce the power loading and power loss on DC lines of each final stage SSPA modules. The adopted RF power transistor for SSPA module is BLF578 which is able to have higher than 60% DC-RF efficiency in direct water cooling condition. The SSPA modules are located on two

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sides of the tower, labelled as side A and B. Each side contains 60 water cooling slots for modules installation. Two 96 kW 48 V DC power suppliers containing eight 1U shelves with 30 power supply modules (3.2 kW 94% AC to DC conversion efficiency DC power) positioned on the top of each tower side. The DC power of overall 30 DC power modules are parallel connected to provide maximum of 2000 A and 48 V DC power which would then deliver through 2500 A capability copper bar for drive and final stage SSPA modules. The redundancy is improved by using 4 100 W pre-amplifiers power combination then distributed to 6 600 W drive amplifiers. The drive amplifiers are also RF power combined and split to 10 groups of final stage SSPAs. As any of pre-amplifiers and drive amplifiers gets fault, the whole 80 kW SSPA system can still keep in operation without interrupting the operation of RF system. Besides, each SSPA modules including drive and final stage amplifiers contains status monitor circuits which can read the temperatures, DC current and voltage of the modules and transfer to EPICS server for data storage and display [5]. The status of each SSPA modules can be noticed in advanced as it is going to be fault. The real time status of an 80 kW SSPA tower is controlled and displayed by a PLC and a touch panel for monitoring the RF drive power, forward and reverse power of groups and final stage combiner as well as water flow and temperature of 20 cooling water channels.

Two 80 kW SSPA towers has accomplished in 2020 with 1 and 2 unexpected SSPA modules fault during test period for Tower#1 and #2 respectively. The SSPA module fault is mainly introduced during pulse bandwidth test with not well controlled RF power feeding. There might be too much reflection power back to the RF transistor as the test frequency is reaching the bandwidth edge of those circulators within the SSPA modules. Besides, due to the property of coaxial type 10-way coupler for RF power combination, the 10-groups of final stage amplifiers need to have proper phase shift. The phase shift is simply conducted by bended microstrip lines with well controlled phase difference. However, certain microstrip line phase shifters do not have identical return loss as the others which cause unbalance power distribution for the ten groups of SSPAs. The condition is improved by adding 10 RF power isolators to eliminate the unbalance power distribution for the ten groups of final stage SSPAs.

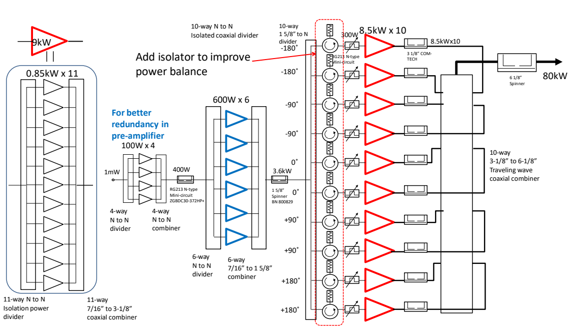

Figure 2: The schematic of redundancy improved 80 kW SSPA tower.

The SSPA modules has average DC-RF efficiency of about 61-64% while the DC power supply has about 93-94% AC-DC conversion efficiency at general loading. The overall efficiency including the RF transmission loss and RF power combination efficiency is about 54% at drain voltage from 44 V-50 V as shown in Fig. 3. Different setting can have different saturation RF power indicating a way for saving power for lower RF power requirement of TPS storage ring. The estimated transmission loss and power combination loss is about 5% which is dominated by the loss of RF cable from SSPA module to power combiner, power combiner itself and the power balance condition due to uncontrollable physical error from each component in the system. The test results of two 80 kW SSPA towers are shown in Table 2 which satisfies the requirement.

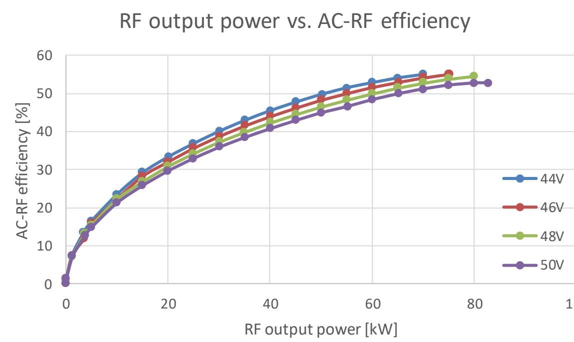

Figure 3: The AC-RF efficiency of 80kW SSPA tower as a function of RF output power by different Drain voltage settings.

Table 2: Measured Performance of One 80 kW SSPA

Item	Target Value	Test Value
Power rating	≥ 80 kW	83 kW
AC-RF efficiency	≥ 50%	54%
Bandwidth	≥ +/- 5 MHz	+/- 6MHz
Power gain	≥ 80 dB	Max. 81dB
Side band noise	≤ 65 dBc	-66 dBc
Harmonic	≤ 40 dBc	-42 dBc@2nd

THE RESULTS OF POWER COMBINATION OF 2 SSPA TOWERS

To verify the feasibility and the long-term reliability, the accomplished 2 80 kW SSPA towers are RF combined by the 3-dB hybrid coupler as shown in Fig. 4 and feed to a 350 kW ferrite load directly. The air cooled DC power supply will dissipate about 20 kW heat to the environment as they deliver 300 kW DC power, a 30 kW cooling capability air conditioner with plastic shields are thus applied for environmental temperature control. With such setup, the DC power supplies can have proper operation temperature. The RF combination is realized by controlling the attenuation and phase of input RF signals to the operating towers on a 4-way power divider which includes 4 manual control attenuators and phase shifters.

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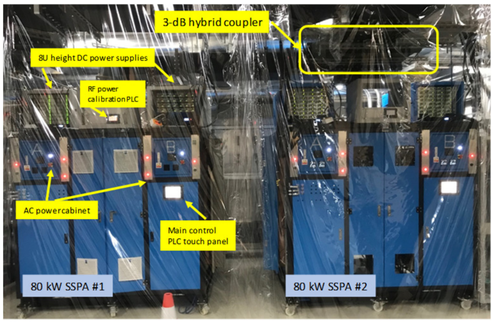

Figure 4: Two SSPA towers are practically RF power combined within the plastic shielding room for better temperature isolation and control by the air conditioner.

Figure 5: the AC-RF conversion efficiency as a function of output RF power in different DC voltage settings for 2-way combination of 80 kW SSPAs.

The derived AC-RF efficiency shown in Fig. 5 is similar to that of single 80 kW SSPA tower which indicates the well-controlled amplitude and phase for 2 80 kW SSPA towers as well as low-loss of the 3-dB hybrid coupler. The quality of the combined RF power is shown in Fig. 6 which has lower than -70 dBc for spurious noise of 60 Hz and 260 Hz introduced by DC power supply. The harmonic is also lower than -55 dBc for 2nd and 3rd harmonics.

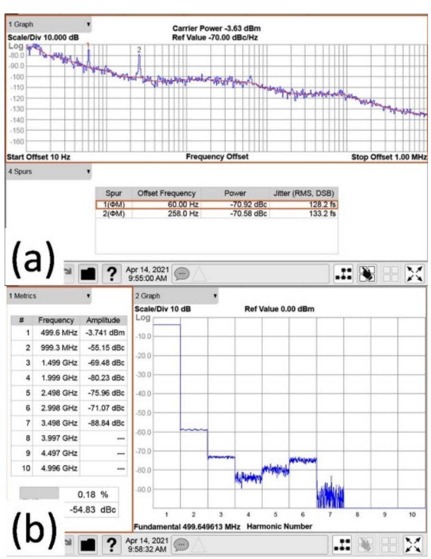

Figure 6: The quality of the combined RF of 2 80kW SSPA towers: (a) phase noise: -70.92 dBc@60Hz, -70.58 dBc@260Hz (b) harmonics: -55.15 dBc@2nd and -69.48 dBc@ 3rd harmonic.

The Procedure of Long-term Reliability

The target of long-term test is 2-weeks continuous saturation RF power run to simulate the operation condition of routine 2-weeks user shift of TPS. However, the task did not success at one time. The first long term test was executed for about 11days and terminated due to the fault of AC copper bar on the back of DC power shelves which introducing the shut off by the 200 A AC circuit breaker. The shut off was happened on the A-side of tower #2 which immediately caused the RF power unbalance between these two SSPA towers. The interlock system detected the existence of RF power at water load input and turned off the input RF signal at the same time. The possible reason for such accident could be the burn of the poor quality AC terminator on the shelf and the generated smoke introduced short circuit arc between Line and neutral of the upper shelves and finally caused the 200 A AC circuit breaker shut off. The accident was recovered by replacing the power shelves and copper bar in one day. The second test has run for another 2 days and interrupted due to error action of water flow sensors which caused interlock RF shut off and was not seen again in 3rd long-term test. The 3rd long-term reliability kept for 14.5 days with quite stable RF output power and AC power consumption. There was no SSPA module fault or RF power degradation occurred during the total of 29 days high power test period. This long term test has demonstrated the reliability and the quality of home-made SSPA modules as well as the integration of high power parts including RF and Electricity.

CONCLUSION AND FUTURE WORK

A 3rd RF plant for TPS with 300 kW fully solid-state RF power source is under construction in 2020-2021. Four 80 kW SSPA towers are planned to be constructed in house during the tough COVID-19 period to avoid possible delay or quarantine of cost stuffs or staffs. Two 80 kW SSPA towers are constructed, tested and combined for demonstrating its performance and durability. During RF power combination test, an accidental short circuit arc arisen on the AC input copper bar to interrupt the long-term test. With the prepared spare parts, the damage was repaired shortly. 2-weeks non-stop CW test for 150 kW is accomplished. After the tests, no SSPA module fails or power decay were found. Another 2 80 kW SSPAs are going to be accomplished to have total 300 kW RF power within this year.

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