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352-MHz SOLID STATE RF SYSTEM DEVELOPMENT AT THE ADVANCED PHOTON SOURCE*

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Abstract

Development effort is underway on a 352-MHz/200-kW solid state RF system intended as the base design to replace the existing klystron-based RF systems presently in use at the Advanced Photon Source (APS). A 16-input, 200-kW final combining cavity was designed, built, and successfully tested to 29 kW CW in combiner mode and to 200 kW CW in backfeed mode, where an external klystron was used to transmit power into the combining cavity. A four-port waveguide combiner was also tested in both backfeed and combiner modes to 193 kW and 26 kW, respectively. Slow and fast interlock systems were designed and implemented to support the testing process. An EPICS and programmable logic controller (PLC)-based system was developed to control, communicate with, and monitor the RF amplifiers used in the combiner-mode test, and to monitor and log system performance parameters relating to the combining cavity. Low-level RF control of the cavity in 29-kW combiner-mode operation was achieved using the existing APS analog low-level RF hardware. Test data and design details are presented.

INTRODUCTION

Work is underway at the APS to convert the APS 352-MHz klystron-based RF systems to solid state technology. In 2008 experimental work began at the APS with 1-kW LDMOS transistors that showed promise as efficient building blocks for a large 352-MHz solid state RF system. A four-amplifier, 352-MHz, 4-kW combined system was designed and built, which operated at a DC-to-RF efficiency exceeding 52%, matching the best-case efficiency of 1-MW klystron systems operating in the 500- to 700-kW RF power output range. This effort was followed by designing and building a first-generation, six-input resonant output combining cavity, driven by six in-house-designed LDMOS amplifiers producing 2 kW CW each. The combined system produced approximately 10 kW CW and demonstrated the efficiency and space advantages of a combining cavity topology. A second (version 2) 352-MHz sixteen-input resonant combining cavity capable of 200-kW output power was then designed, built, and tested to full power in a backfeed configuration, and to 29-kW in normal combiner-mode operation using sixteen commercially produced 2-kW amplifier modules. In addition to the combining cavity, a commercially produced four-input WR2300 waveguide combiner was successfully tested to 193 kW CW in backfeed mode, and to 26 kW in combiner-mode. A version 3 combining cavity was designed and is in production.

SOLID STATE IMPLEMENTATION TOPOLOGY

The APS storage ring is presently configured with 16 single-cell RF cavities, grouped in four sectors of four cavities each, which are supplied RF power by four 352-MHZ/1-MW CW RF systems. The APS Upgrade will reduce the number of storage ring cavities from 16 to 12. The conversion to solid state will occur after the APS Upgrade is complete and will involve the installation of 12 160-kW independent solid-state amplifier (SSA) systems, configured one amplifier per cavity. Each SSA will be driven by a digital low-level RF system to control phase and amplitude, and to regulate accelerating RF voltage in response to beam loading.

The first step in the solid-state conversion will be to order a prototype 352-MHz, 200-kW CW SSA from industry. The system will be ordered with two different intermediate RF power combiners, designed to adapt four 55-kW amplifier racks either to the APS-designed resonant combining cavity or to a commercial WR23000 waveguide four-input combiner as the final combiner. This SSA will be rigorously tested, along with a digital low-level RF system, on performance characteristics important for storage ring service, such as RF power capability, RF phase and amplitude noise performance, reliability, and control system performance, both in local and remote modes. If the results of these tests are favorable, a slightly smaller production version of the design, capable of 160-kW CW output, will be ordered for installation at the APS. The 200-kW prototype system will be repurposed as the RF power source for the APS 350-MHz RF Test Stand, which is used to test and condition components before installation into the storage ring cavities.

FINAL OUTPUT COMBINING CAVITY DESIGN

The combining cavity design was optimized for operational use with the APS storage ring and is based on a previous design described in [1]. Peak electric field regions were reduced, and a broad cavity bandwidth was retained. Value engineering was implemented by simplifying the manufacturing process for the input couplers and the aluminum cavity panels as well as implementing water cooling only in the cavity panels. A rendering of the cavity is shown in Fig. 1.

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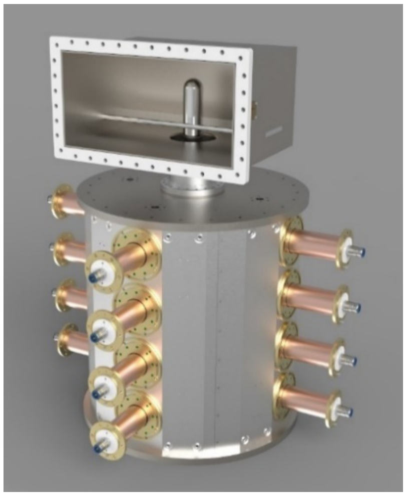

Figure 1: Cavity combiner with 3-1/8-inch EIA input flanges mounted on cavity panels, and an exposed view of the output waveguide and coupler.

Ensuring the combining cavity is properly tuned is critical due to the resonant nature of the cavity. To reduce its sensitivity to tuning errors, the loaded quality factor was designed with a value of 50 where the unloaded quality factor of the cavity was 2.4×10^5. Tuning is primarily achieved by an elevated ring along the bottom plate of the cavity that is statically adjusted to accommodate manufacturing and assembly variations. The cooling water in the panels stabilizes the cavity frequency regardless of environmental conditions, as well as maintaining the frequency to within a 10-kHz range from low-power to 200-kW full-power operation. The magnitude of the frequency tuning control is 30 kHz for each mm of the static tuner height and 8 kHz for each °C the water temperature is dynamically adjusted. In this way a tuning range of greater than 1 MHz is available.

LOW-LEVEL RF CONTROL

An analog low-level RF (LLRF) control system was utilized to regulate the phase and amplitude of the SSA output as proof-of-concept. The LLRF system provided the drive signal to the SSA amplifier and used a feedback signal from a directional coupler at the output of the combining cavity (or waveguide coupler) to close phase and amplitude loops around the system. The LLRF system was shown to be stable and successfully regulated the SSA RF output.

To maximize the phase margin of the RF system, it is desirable to minimize the overall system group delay [2]. The 2-kW solid state amplifier modules were measured at the manufacturer's factory to have a group delay of around 80 ns. The group delay of the combining cavity with a Q of 65 gives a group delay of $\tau = 2\,Q/\omega_0 = 60ns$ [3]. The existing klystron-based RF systems at the APS have a group delay measured to be 650 ns. With a total group delay of less than 200 ns, the SSA systems, in conjunction with LLRF controls, are expected to be stable when driving the APS accelerating cavities.

The output of the RF source driving the SSA system, and the SSA output when driven by the source, were both measured utilizing an Agilent E5052B signal source analyzer. Using these two measurements, the residual phase noise contribution of the SSA system was estimated at 0.01 degrees rms, and 0.08 ps rms from 10 Hz to 1 MHz. This phase noise performance is a vast improvement over that of the existing APS klystron-based RF systems.

INTERLOCKS

An interlock and monitoring system utilizing a commercial off-the-shelf PLC with a local touch screen, and a fast RF interlock with microsecond response time, was developed to provide testing flexibility to monitor system parameters, interlock on fault conditions, provide limited system control, communicate with EPICS (Experimental Physics and Industrial Control System), and data log all tests of the waveguide combiner and cavity combiner. The PLC system monitored 66 separate temperature readbacks and 80 analog inputs for RF signal and water flow monitoring, and provided several control and interlock outputs. Monitored RF signals were interfaced to the PLC using the Analog Devices HMC1030LP5E RF detector integrated circuit, which provides a fast envelope detector output for interlocking, plus a linear-in-log output corresponding to the RMS value of the input signal for data logging of each monitored RF signal. Communication between the PLC and EPICS was accomplished using the MODBUS protocol. When changes to the PLC programming were required to accommodate the various test configurations, the EPICS Input/Output Controller (IOC) could easily follow the changes of the PLC. The IOC scanned the PLC at a 500-ms rate and stored all process variable data, thus allowing all stored data to be accessed by client applications that could display the data in real time, or over long periods of time using a strip chart tool. MEDM (Motif Editor and Display Manager) was used to mimic the local PLC displays for remote access.

HIGH POWER TEST RESULTS

The first of a series of high-power tests involved a backfeed test of the WR2300 waveguide combiner. Figure 2(a) shows the waveguide combiner with four water-cooled resistive RF loads terminating the four ports. The combiner was fed RF power in the backfeed mode utilizing a klystron-based RF system that normally drives the APS 352-MHz RF Test Stand. Coaxial directional couplers were used on two of the ports to monitor forward and reflected power into the associated loads. Figure 2(b) shows an infrared thermal image of the combiner after sustained operation at 193-kW CW input.

The waveguide combiner was also tested to 26 kW CW in combiner-mode, utilizing 16 commercially produced 2-kW amplifiers configured four to each port using radial combiners (see Fig. 3). Operation of the waveguide combiner system was trouble free, and compatibility with the existing 352-MHz analog low-level RF hardware was demonstrated.

High-power testing of the version 2 combining cavity was also conducted, consisting of a full-power 200-kW CW test in backfeed mode and a combiner-mode test to

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28.5 kW CW utilizing the 16 commercial 2-kW RF amplifier modules. Figure 4(a) shows the combining cavity terminated with 16 25-kW RF loads for the backfeed test. Figure 4(b) shows the cavity set-up for the combiner-mode test with each of the 16 input ports driven by a single 2-kW amplifier module.

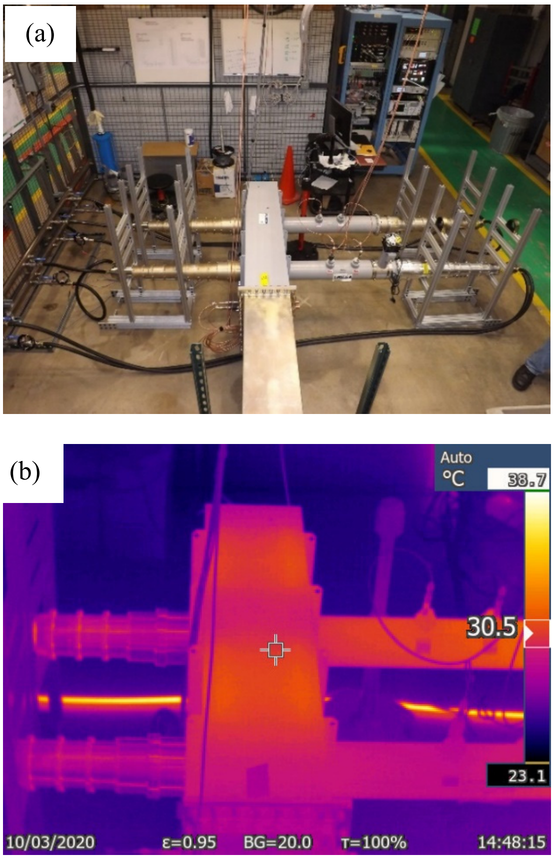

Figure 2: (a) Photo of 4-port waveguide combiner configured for high-power backfeed test, with resistive RF loads terminating all coaxial ports. (b) Infrared thermal image of the waveguide combiner at 193-kW CW input power.

CONCLUSION

Work is underway at the APS to develop a solid state amplifier design to replace the existing klystron-based RF systems. A 200-kW prototype RF system is being designed that will utilize commercially available solid state RF amplifier system compatible with both a four-port WR2300 waveguide combiner and the APS-designed 16-input resonant combining cavity. Both the waveguide combiner and resonant cavity combiner have demonstrated low loss, good matching characteristics, and the necessary power handling capability to be used as a final output combiner for a 200-kW solid state RF system.

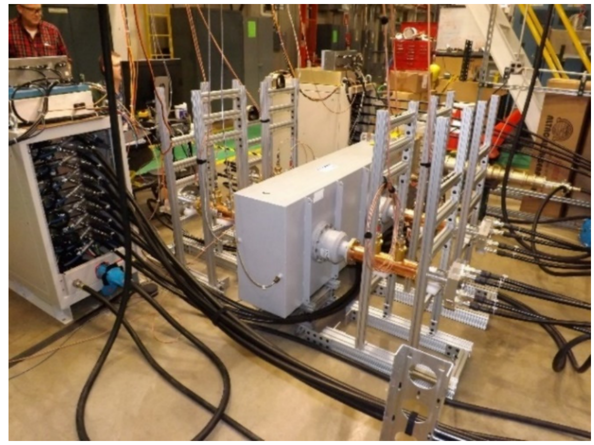

Figure 3: Photo of 4-port waveguide combiner configured for combiner-mode operation. Note the adjacent rack of 2-kW amplifier modules, each driving one input of 4-port coaxial radial combiners that drive each waveguide combiner input port. The final output RF load is seen on the opposite end of the waveguide combiner.

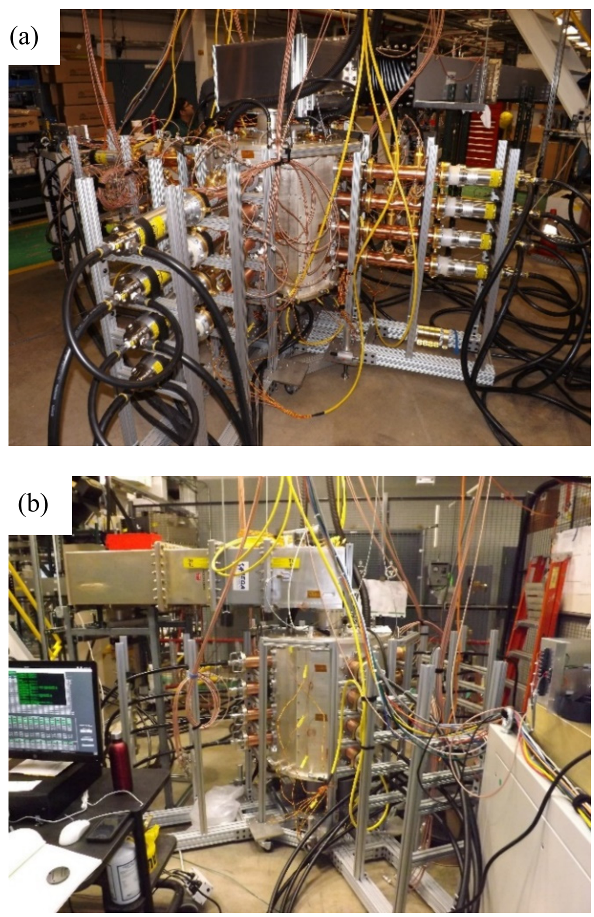

Figure 4: (a) Photo of combining cavity configured for the 200-kW backfeed test with 25-kW resistive RF loads terminating each of the sixteen coaxial ports. (b) The combining cavity configured for the combiner-mode test. Note the black coaxial cables connecting 2-kW amplifier outputs to cavity input ports.

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REFERENCES

[1] G. Waldschmidt *et al.*, "High-power design of a cavity combiner for a 352-MHz solid state amplifier system at the Advanced Photon Source", in *Proc. of the North American Particle Accelerator Conference (NAPAC´19)*, Lansing, Michigan, Sept. 2-6, 2019, pp. 113-115. doi:10.18429/JACoW-NAPAC2019-MOPLM09

[2] L. N. Alves and R. L. Aguiar, "On the effect of time delays in negative feedback amplifiers", in *Proc. of IEEE International Symposium on Circuits and Systems (ISCAS´05)*, Kobe, Japan, 23-26 May 2005, pp. 984-987. doi:10.1109/ISCAS.2005.1464755

[3] A. G. Mungall and D. Morris, "Time delay and frequency response of resonant cavities", *Can. J. Physics,* vol. 38, pp. 1510-1515, 1960. doi:10.1139/p60-152