PERFORMANCE OF THE 352-MHZ 4-KW CW SOLID STATE RF POWER AMPLIFIER SYSTEM USING 1-KW PUSH-PULL DEVICES*

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Abstract

Development and testing of a prototype 352-MHz, 4-kW cw solid state rf power amplifier system is underway at the Advanced Photon Source (APS) to study and evaluate the performance advantages of an upgrade to solid state rf power technology. General performance measurement data on the assembled amplifier system is discussed, with emphasis on efficiency improvements possible through the use of dynamic drain voltage control.

INTRODUCTION

Solid-state rf power amplifier technology is being considered as a replacement for the existing klystron power amplifiers presently used in the 352-MHz booster and storage ring rf systems at the Advanced Photon Source (APS). It is expected that a solid state rf system would provide improved operating efficiency over a wide dynamic range by the use of dynamic drain voltage control, and less overall phase and amplitude noise compared to equivalent klystron-based rf systems. An investigation was launched to evaluate the feasibility of utilizing pallet amplifiers designed around a single 1-kW push-pull output device, the Freescale™ MRF6VP41KH LDMOS rf power transistor, to construct a 352-MHz, 200kW cw power amplifier system capable of driving one single-cell copper rf accelerating cavity. Initial work on this project [1] involved building and testing two 352-MHz, 1-kW test amplifiers, which demonstrated that obtaining 1-kW cw at 352-MHz from these devices should pose no serious problems or reliability issues providing the output transistors are adequately cooled. Two additional test amplifiers were built utilizing carrier/cold-plate construction. The four test amplifiers were then used to drive the inputs of a four-way 352-MHz combiner in order to measure the overall performance of the amplifier system. Measurements to determine the effectiveness of utilizing dynamic drain voltage control to maximize efficiency at low to medium power output levels were started.

1-KW AMPLIFIER PERFORMANCE

A total of four 352-MHz, 1-kW cw MRF6VP41KH test amplifiers were constructed for the 4-kW test system. The first two amplifiers were assembled by soldering the circuit board and output transistor directly to the surface of a 0.75-inch-thick water-cooled copper cold plate for maximum cooling efficiency. The remaining two amplifiers were assembled by soldering the circuit boards and output transistors directly to a 0.25-inch-thick copper "carrier" plate, which were then thermally bonded by a layer of thermal grease to 0.75-inch-thick water-cooled cold plates made of aluminium and copper (see Figure 1). The use of a carrier plate was utilized to make the amplifiers easier to construct and also to determine the cooling efficiency of the carrier/cold-plate construction technique.

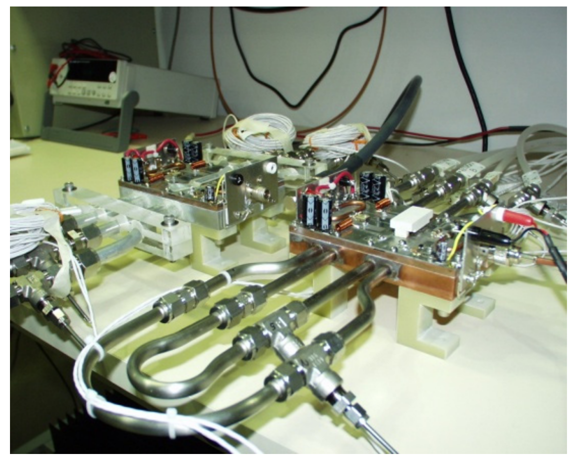

Figure 1: Aluminium and copper carrier/cold-plate 1-kW amplifiers.

The two carrier amplifiers were constructed with "de-lidded" output transistors to allow use of an infrared imaging system to monitor the transistor die temperature during operation. Each of the four amplifiers produced 1-kW output power at 351.93 MHz with no problems noted, at efficiencies ranging from 61% to 66%. Transistor die temperatures measured on the carrier amplifiers at 1-kW output power and 2-gpm total water flow in the cold plate were 155.7°C for the copper cold plate and 151.5°C for the aluminium cold plate, in spite of the greater thermal conductivity of copper. This was an increase in transistor die temperature of approximately 15.7°C and 11.5°C, respectively, over that of the first two amplifiers assembled with the transistor soldered directly to a copper cold plate. Additional tests were performed on one of the non-carrier amplifiers to determine the effect of varying drain voltage in order to optimize efficiency at low and moderate output power levels. The results of these tests are shown in Figure 2. The amplifier was operated at drain voltage values of 30 volts, 40 volts, and 50 volts, reaching rf saturation points of approximately 500 watts, 900 watts, and 1050 watts, respectively. For rf output power levels between 250 watts and 500 watts, an efficiency improvement of approximately 20% was achieved by reducing the amplifier drain voltage from 50 volts to 30 volts. Increasing the drain voltage to 40 volts widened the useful dynamic range of the amplifier to 900

*Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

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watts, where it demonstrated approximately 10% efficiency improvement over operation at 50 volts. An rf phase measurement indicated approximately 5° rf phase drift caused by the amplifier over the 20-volt change in drain voltage.

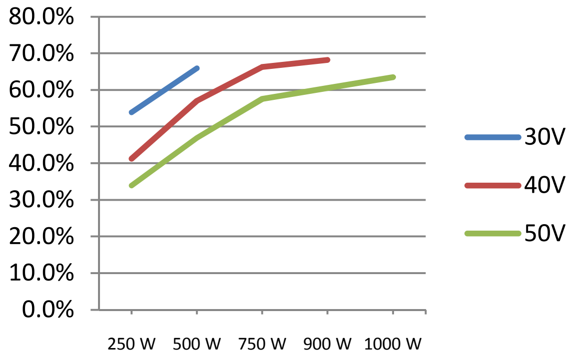

Figure 2: Amplifier operating efficiency and power over drain voltage range.

FOUR-WAY COMBINER ASSEMBLY AND TESTING

The four-way combiner was designed and constructed utilizing standard 1-5/8-inch EIA rigid coaxial line and flange components. The combiner is shown in Figure 3, fitted with 1-5/8-inch EIA-to-7/16 DIN coaxial adapters on each port for testing. A movable coaxial short on the combiner center line is utilized to optimize performance at 351.93 MHz. Beyond-cutoff entry and exit pipes were added for providing forced-air cooling of the combiner center line. Initial low-level measurements of the combiner and tests with 100-watt amplifiers on each port indicated good agreement with simulation results.

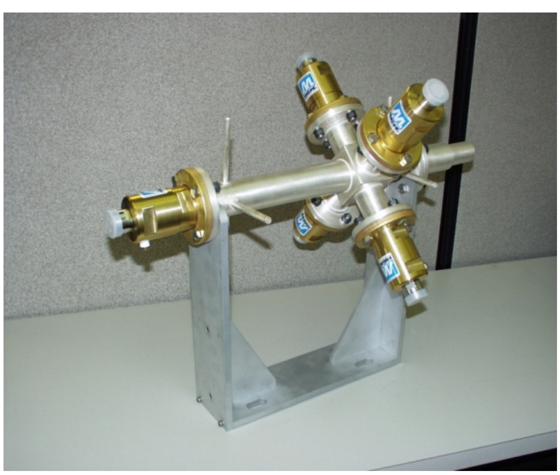

Figure 3: Four-way combiner assembly.

4-KW AMPLIFIER SYSTEM DESCRIPTION AND PERFORMANCE

A photo of the 352-MHz, 4-kW amplifier system is shown in Figure 4. Major system components include the four-way combiner, four 1-kW amplifiers, four circulators and associated reject loads for amplifier isolation at each input port, four DC power supplies, and four rf drive amplifiers. A 5-kW, 50-Ω water-cooled load was used to terminate the combiner output. Directional couplers were utilized at all combiner ports to provide signals for power monitoring and phase measurement. Low-loss ½-inch foam-dielectric rf cables, each three feet in length, were used as transmission lines between the amplifier outputs and the circulators, and between the circulators and the combiner input ports. Manual rf phase shifters were utilized at the inputs of the rf drive amplifiers for adjustment of the output phase of each amplifier at the combiner input ports. Individual gate bias regulators were utilized to provide separate idling current control for each amplifier. A PLC was utilized to measure supply and return water temperature and water flow on each amplifier and on the 5-kW load, and to perform calorimetric calculations of heat loss to water to confirm rf power measurements.

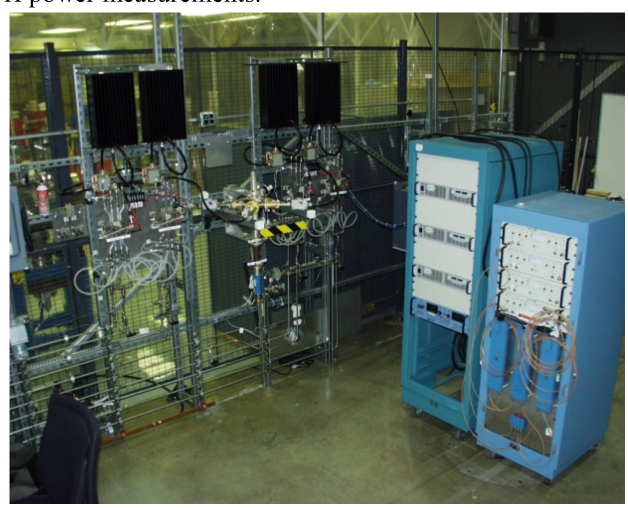

Figure 4: 4-kW amplifier system showing dc power supplies and rf drive amplifiers.

Power tests were performed at total power levels of 600 watts, 2,770 watts, and 3,450 watts to determine DC-to-rf efficiency at each operating point. Initial operation of the system was set at approximately 600 watts total power in order to adjust the output phase of each amplifier to be equal at all four combiner input ports. This proved to be a one-time adjustment, as no significant drift was noted over the course of the tests. With all four amplifiers operating at a drain voltage of 40 volts and a power output of approximately 720 watts each, a total power output of 2,770 watts was achieved at a system efficiency of 55%, including cable and circulator losses. With the drain voltage of each amplifier increased to 50 volts, each amplifier was operating at approximately 920 watts output to produce a total power output of 3,450 watts at a system efficiency of 54.8%, with losses in cables and circulators estimated at approximately 200 watts. The losses in the combiner itself were too small to measure accurately with the existing instrumentation. It is felt that with additional effort to eliminate excessive cable lengths between the amplifiers and the combiner input ports and to optimize each amplifier more precisely for optimum efficiency at the APS operating frequency, an overall system efficiency exceeding 60% could be achieved over a 6-dB dynamic range.

APS RF SYSTEM OPERATIONS

The existing APS storage ring rf system topology includes sixteen single-cell copper cavities, grouped in two sets of eight as shown in Figure 5. Two 352-MHz, 1MW klystrons are configured by a system of waveguide hybrids and switches to provide the ability to drive each eight-cavity group with either klystron for redundancy or both klystrons operating in parallel for maximum power.

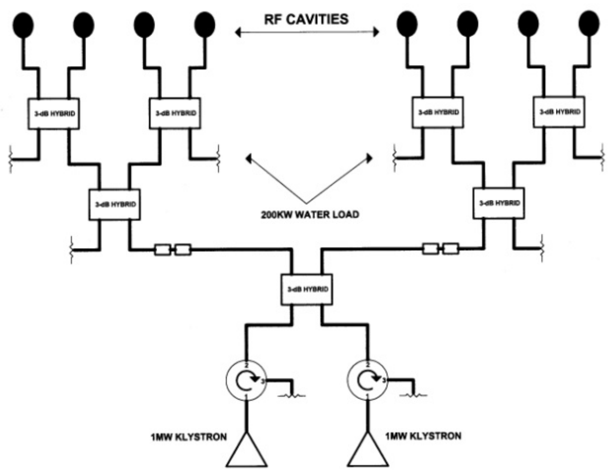

Figure 5: APS storage ring rf system topology.

The klystrons typically operate at approximately 700 kW each for storage ring operation at 102-mA stored beam, which results in operating efficiencies between 51-55%. Klystron efficiencies fall to as low as 35% at injection level without stored beam. Initial tests on the 4-kW amplifier system indicate that a solid state amplifier topology composed of 1-kW amplifier modules utilizing dynamic drain voltage control to optimize efficiency at low to medium power output levels would provide a significant improvement in operating efficiency over the existing klystron amplifier systems. The ability to vary transistor drain voltage without resulting in large rf phase drift makes dynamic drain voltage control attractive as a method for optimizing amplifier efficiency. Conceptually, an rf system topology consisting of twelve 200-kW solid state amplifier-cavity systems has been studied. The 200-kW amplifier systems would be composed of 1-kW amplifier modules utilizing dynamic drain voltage control, and each system would drive one single-cell APS storage ring cavity. It is projected that such a topology would be approximately 15% more efficient in normal APS operations than the existing klystrons over a 6-dB dynamic range. Each 1-kW amplifier would be characterized to utilize self-programmed rf drive attenuation and drain voltage control to optimize efficiency over a wide dynamic range. It is also expected that a solid state rf power system will create less phase and amplitude noise due to the use of efficient switch-mode power supplies operating at a relatively low voltage.

FUTURE PLANS

Additional measurements on the 4-kW test amplifier will be made to further assess performance, and a 4-port Gysel combiner will be constructed to compare performance. Simulation models for the 1-kW pre-driver and driver circuit devices are being developed to aid in the design of an amplifier board specific to the needs of the APS rf systems. The first prototype amplifier board complete with pre-driver and driver stage will be produced and tested.

DRIVER AMPLIFIER DEVELOPMENT

A driver amplifier stage utilizing the MRF6V2010N transistor device has been designed and built to produce drive power for the 1-kW amplifier board. The driver was based on a prototype Freescale™ evaluation board that was modified for operation at 351.93 MHz. Transistor circuit models were used with EDM simulation tools to design the circuit, and the prototype amplifier was constructed. The prototype demonstrated very good agreement with the simulation model results, producing 10 watts at 61.3% efficiency with 21.5-dB gain.

CONCLUSION

Tests to date show promise that a conceptual solid state 352-MHz rf system, composed of individual 200-kW amplifier systems each driving a single accelerating cavity, offers significant improvements in operation efficiency over the existing klystron-based rf system topology presently used at APS. The use of 1-kW amplifier modules utilizing dynamic drain voltage control and low-loss rf combiners is expected to produce a 200-kW rf amplifier system capable of at least 60% efficiency over a 6-dB dynamic range.

ACKNOWLEDGMENTS

The authors would like to thank Jeff Collins and Leonard Morrison for their engineering assistance, and APS technicians Mike Drackley, Bruce Epperson, John Pace, and Andre McKenzie for their efforts, in assembly and operation of the test system.

REFERENCES

[1] D. Horan B. Brajuskovic, J. Collins, L. Morrison, G. Waldschmidt, “352-MHz Solid-State RF Power Amplifier System Development at the Advanced Photon Source”, Proc. of PAC`09, Vancouver, British Columbia, Canada, p. 1008 (2010); http://www.JACoW.org