

SOLID STATE POWER AMPLIFIER AS 805 MHZ MASTER SOURCE FOR THE LANSCE COUPLED-CAVITY LINAC*

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Abstract

From 100 to 800 MeV, the Los Alamos Neutron Science Center (LANSCE) proton linac receives RF power from forty-four 1.25 MW klystrons at 805 Megahertz (MHz). A single master RF source provides a continuous high level phase reference signal which drives the klystrons along the 731 meter-long linac through a coaxial transmission line. A single point failure of this system can deenergize the entire coupled-cavity linac (CCL) RF plant. The authors replaced a physically large air-cooled tetrode amplifier with a compact water-cooled unit based on modular amplifier pallets developed at LANSCE. Each 600 Watt pallet utilizes eight push-pull bipolar power transistor pairs operated in class AB. Four of these can easily provide the 2000 watt reference carrier from the stable master RF source. A radial splitter and combiner parallels the modules. This amplifier has proven to be completely reliable after two years of operation without failure. A second unit was constructed and installed for redundancy, and the old tetrode system was removed in 1998. The compact packaging for cooling, DC power, impedance matching, RF interconnection, and power combining met the electrical and mechanical requirements. CRT display of individual collector currents and RF levels is made possible with built-in samplers and a VXI data acquisition unit.

1 INTRODUCTION

The LANSCE linac is an 800 MeV proton machine capable of accelerating high average current, up to 1 mA of H^+ . In addition, a 70 μA H^+ beam is accelerated for the proton storage ring; the accumulated charge is extracted and directed to a spallation target for neutron production.

The CCL accelerates the two proton beams from 100 to 800 MeV. It is supplied with pulsed radio frequency power at 805 MHz from forty-four klystrons capable of producing up to 1.25 MW. These are driven by the RF reference source, which is located near the 100 MeV end of the structure. The RF source used a Burle Industries 8501 Cermolox[®] tetrode. The source generates 2000 watts of continuous RF. It is distributed to each klystron via directional coupler taps along a single temperature-stabilized drive line, located adjacent to the linac structure. This series-feed technique is simple and reliable, as long as the coaxial drive line is not compromised. In over twenty-five years of operation, this has not been a problem. For redundancy, the RF source

itself is duplicated in a main/backup switched configuration. In 1993, the 8501 tetrode became obsolete. With an immediate purchase of enough tubes to supply operations for five years, we began searching for an alternative amplifier.

2 NEW POWER AMPLIFIER

2.1 Existing Transmitters

We considered developing a new cavity amplifier around another available UHF television transmitting tetrode. This idea was eliminated when we observed that fewer transmitters were being designed around medium power tetrodes, as all solid-state (transistorized) amplifiers were coming to market. LANSCE is situated at an elevation of 2120 meters above sea level, so the air density is reduced by 22% from sea level. We prefer water cooling where it is practical to remove the heat load from RF equipment. It is cooled in plant cooling towers, so that the water is continuously recycled through the RF system. There were no commercial water-cooled solid-state TV transmitters in this power range when this work began.

2.2 Solid-State Amplifier Concept

We developed a water-cooled amplifier module, using bipolar power transistors developed for cellular telephone stations. This began in 1992, and by 1993 the basic RF amplifier board was operating as designed. A multiple amplifier module was designed with four printed circuit boards mounted on two sides of an aluminum block with water passages drilled through the central core for heat removal.

2.3 RF Amplifier Module

The transistors used are Motorola part number MRF899, which are actually two bipolar transistors on a single flange. They contain gold-metallized NPN silicon transistors rated for 230 Watts of dissipation and are characterized for 150 Watts of output at 900 MHz. These transistors are factory-tested with a 5:1 load voltage standing wave ratio (VSWR) at all phases, while operating at 150 Watts at 26 Volts DC. We only operate with 22 Volts for an additional safety factor. The two devices are operated in class AB push-pull and are in common-emitter (CE) configuration, advantageous for high gain at UHF frequencies. Push-pull operation with

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the MRF899 minimizes the emitter-to-emitter inductance to the bonds between the devices on the flange, instead of the higher emitter to ground inductance of separate CE transistors [1]. Only the DC current flows to ground in the MRF899.

Push-pull operation of the device uses coaxial line baluns on the input and output sides. Matching to raise the transistor impedance to the coaxial line impedance is accomplished with microstrip over the PTFE/glass ($\epsilon_r = 2.55$) board and discrete chip capacitors to ground. Each push-pull amplifier is combined with an adjacent one on the same printed circuit board using Wireline[®] 3 dB quadrature hybrids, made by Sage Laboratories, Inc. Thick film resistors mounted on the pallet terminate the fourth port of these hybrids. In figure 1, the “U”-shaped baluns are seen, along with the straight sections of Wireline[®] used for power dividing and combining. Two MRF899 devices are on each printed circuit board, which is mounted in a machined recess in the aluminum block. There are four boards and eight push-pull transistors per pallet. A total of 32 of these bipolar transistors are used in this amplifier on four pallets.

2.4 Cooling

The water cooling passages are drilled with three long passages along the length of the block, and short intersecting passages drilled at right angles to make the crossovers. Pipe plugs are used to block the drill holes after the passages are joined. Water enters the fitting at the bottom (see figure 1) and circulates along a serpentine path shown by the dotted line. In worst-case testing, we operated one push-pull transistor with 130 Watts of RF, and the semiconductor junction temperature was 135 degrees Celsius. Good engineering practice suggests limiting this to no more than 150 degrees [2]. In actual

operation, each device operates at 80 Watts, with a generous safety margin which should ensure transistor lifetimes above 50,000 hours.

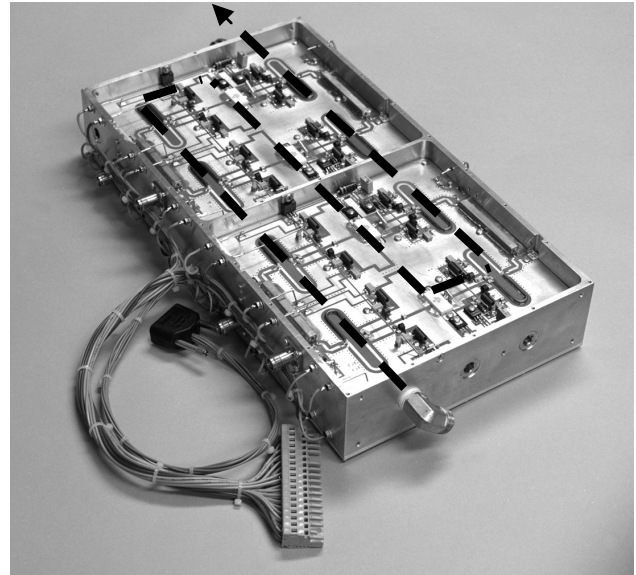


Figure 1. Basic pallet, one of four used in amplifier

2.5 Combined Amplifier

After the basic module and pallet concept was developed and tested, we completed the design of the splitting/combining networks, the overall packaging, cooling, monitoring, and control circuitry. Four of the pallets are arranged in a compact 48.3 cm-wide enclosure, with cooling paths in series. Sixteen amplifier boards are available, but only fourteen are combined

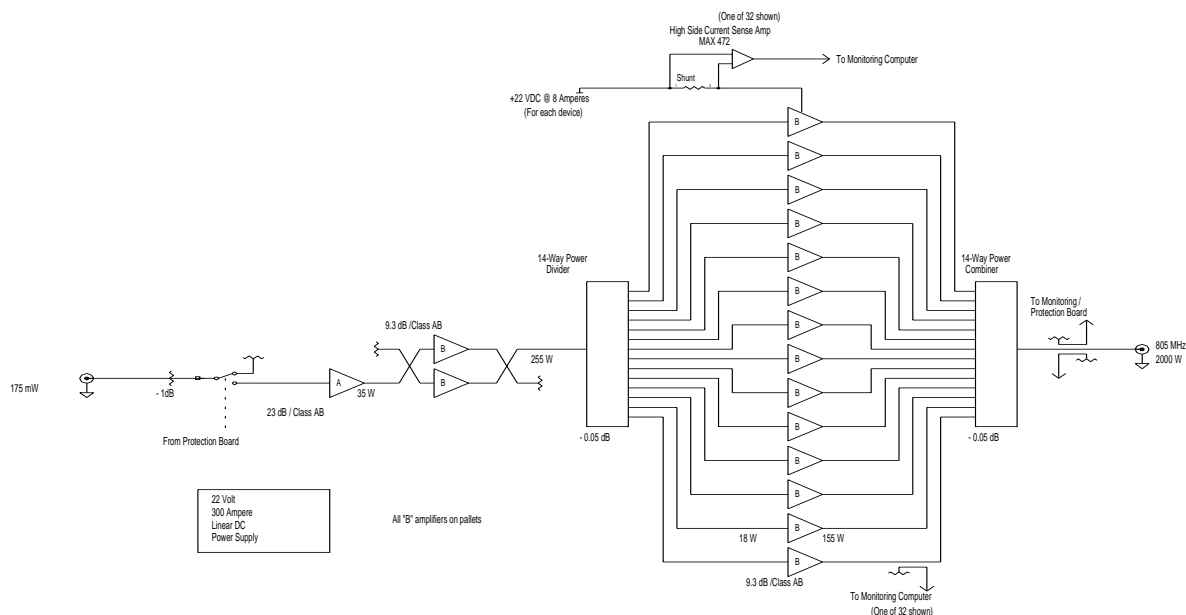


Figure 2. Block diagram of solid-state power amplifier

for the final stage, each supplying 155 Watts. Two are used as an intermediate stage, to drive the 14-way splitter with 255 Watts of power. These two boards (one half pallet) are driven and combined with 3 dB quadrature hybrids with isolation loads. In the block diagram the driver stage (marked "A") uses a commercial 35 Watt amplifier, also operated in class AB.

A 14-way radial "Tee" divider and combiner was supplied by Werlatone, Inc. Radial combiners have a good active match at each port, as long as each port is being driven by an equal source. The effects of complete failure of one amplifier in the 14-way device would theoretically create only a 1.15:1 VSWR at the remaining ports. RF power transistors typically do not fail in a shorted mode, at least not for very long. The worst case failure mode would most likely be if several transistor failures (open collector to emitter) or open terminations on the Wireline[®] hybrids reflected a short into the center of the output combiner. Our transmission line lengths transform an open circuit on any board to an open at the center of the combiner. This has worked well, as evident when we operated at full power for many days while one collector tab was disconnected on a board. No long term damage was sustained by the amplifier.

The amplifier load is a very long transmission line terminated in a fifty Ohm dummy load. There is no isolator needed since a fast-acting reflectometer/detector commands the protective logic to remove drive and power from the amplifier if the output reflected power becomes excessive.

2.6 Control System

For control, protection and monitoring, two separate schemes are used. An internal logic board handles the RF-on command, and monitors pallet temperatures, water flow, power supply voltage, and output reflected power. It protects the amplifier by switching off the 22 Volt DC power, and muting the RF drive.

A second system scans the DC bus voltage, the water temperature rise across the amplifier, the individual input and output RF levels from each amplifier board, and the collector currents from each transistor. This monitoring system uses a VXI-based data acquisition system from Hewlett-Packard, using a workstation/controller. A CRT screen provides all the amplifier parameters, along with a printer for hardcopy. We examine and track individual transistor and board performance; no major variations have been noted in over a year of operation of two amplifiers. Thirty-two surface mounted high-side current-sensing integrated circuits were incorporated to measure the collector currents from a shunt resistor on each connection to the DC bus bar. They provide ground-referenced zero to five volt analog levels to the multiplexer, without the common-mode DC bus voltage.

2.7 Power Supply

The RF reference must have low sideband noise as it could be amplified by the klystrons and be within the modulation bandwidth of the RF controls. We designed the amplifier for low phase noise and low modulation sidebands with respect to carrier. Massive linear power supplies were obtained from Kikusui Electronics, instead of lighter switchmode or SCR-type supplies, to eliminate the possibility of power supply noise sidebands. 250 Amperes DC is the normal operating current for 2000 Watts.

3 RESULTS AND CONCLUSION

The new amplifiers can provide as much as 2800 Watts of CW power at 805 MHz, with 40 dB of power gain. The DC-to-RF efficiency is 36%. The first amplifier was installed in 1996 and has operated continuously without failure. A second amplifier was installed in 1997, along with an RF switchover system and controls. Each amplifier in a single equipment rack (see figure 3) is much more compact than the four racks containing each original tetrode system.

ACKNOWLEDGEMENTS

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REFERENCES

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- [2] Dye and Granberg, p. 73.



Figure 3. Two amplifiers (center of racks) and monitoring computer on right. DC power supplies are at lower left.