DESIGN, TEST AND IMPLEMENTATION OF NEW 201.25 MHZ RF POWER AMPLIFIER FOR THE LANSCE LINAC*

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Abstract

A new 201.25 MHz final power amplifier (FPA) has been designed, fabricated, and tested at Los Alamos Neutron Science Center (LANSCE). The prototype FPA has produced 3 MW peak and 250 kW of mean power with ~15 dB of power gain and >65% efficiency. It has been tested for several thousand hours with a water load. A Thales TH628 Diacrode® electron tube is key to the performance of the new amplifier. It is configured with a full wavelength output circuit, having the lower main tuner situated $\frac{3}{4}\lambda$ from the central electron beam region in the tube and the upper slave tuner $\frac{1}{4}\lambda$ from the same point. The FPA is designed with input and output transmission line cavity circuits, grid decoupling circuits, an adjustable output coupler, DC blocking and RF bypassing capacitors, HOM suppressors, and a cooling system. A pair of production amplifiers are planned to be power-combined for up to 3.6 MW peak power at high duty factor. Three of these combined amplifiers will be installed in place of the original 1968-vintage amplifiers to return LANSCE operation to 12% duty factor with higher peak beam current than presently possible.

DTL RF SYSTEM

The LANSCE proton linac uses an Alvarez DTL powered at 201.25 MHz to accelerate both H^+ and H^- from 0.75 to 100 MeV in four cavities, for injection into an 805 MHz coupled-cavity linac. High peak RF power over 3.2 MW and significant average power (400 KW) is required for the room temperature DTL to accelerate long macro pulses of beam. A primary goal of the DOE/NNSA-funded LANSCE Risk Mitigation project is to replace the original intermediate and FPA stages with modern circuits using power tubes having higher average power capability. Elimination of the inefficient anode modulator tubes for each FPA simplifies the system, reducing operating costs and downtime. A pair of FPAs of this design will be power-combined for each of the three high power DTL cavities, resulting in significant headroom compared to the present RF system.

This paper addresses the electrical design and significant test results for the new FPA. Mechanical design of the FPA, and design of the test facility, supporting electronics and intermediate power amplifiers are discussed in these proceedings and elsewhere [1][2][3].

FINAL POWER AMPLIFIER

The technological advantages of the TH628 Diacrode®, a double-ended tetrode, have been reported previously [4]. Design aspects of the cold-model amplifier were summarized during development [5][6]. Construction of the final configuration of this amplifier was completed in 2010, with a design goal to produce up to 2.5 MW peak power at 13% duty factor without needing cavity pressurization. Subsequent power testing resulted in minor improvements that were implemented in 2011. Testing has continued for over 2600 hours of life testing with the amplifier while using it to test other components. The common-grid amplifier configuration uses a full wavelength double-ended output circuit, and forced air/water cooling.

Input Circuit

The input circuit is configured as a $\frac{3}{4}\lambda$ coaxial resonator to apply RF voltage across the cathode to control grid (g_1) space in the TH628. It is made from concentric copper cylinders that are then silver-plated. The outer cathode conductor is grounded at the bottom while an isolated inner pipe carries both 1000 amperes DC for filament power and cooling air (fig. 1) for the tube base. RF bypassing for the filament consists of a fluorinated ethylene propylene (FEP) film dielectric captured between concentric filament conductors near the base of the tube. The inner diameter (ID) of the g_1 cylinder carries RF current of the input circuit, which coaxially surrounds the outer diameter (OD) of the cathode conductor, with a line impedance of 46.1Ω. The outer cathode/heater contact ring of the TH628 connects to the upper end of this input resonator. Filament current is returned through this structure.

Inside the TH628, g_1 is a pyrolytic graphite grid that controls the electron beam. An extension folds back through the center of the tube to a contact button at the bottom, where a small capacitive cylinder terminates the input resonator with high impedance. It forces a standing wave voltage anti-node at the vertical center of the cathode-g_1 region. At the opposite end of the input circuit a movable tuning plane contacts between the OD of the cathode conductor and the ID of the g_1 cylinder, adjusted to resonate at 201.25 MHz. Superfish was used for the initial design dimensions, followed with a Fortran transmission line code to locate the point of input

coupling. The actual physical dimensions tuned ~3 MHz lower than expected from the calculations, attributed to assumptions for the model of the mesh grid. A correction factor was applied based on measured results, and modifications were then made to the physical dimensions to center the tuning range.
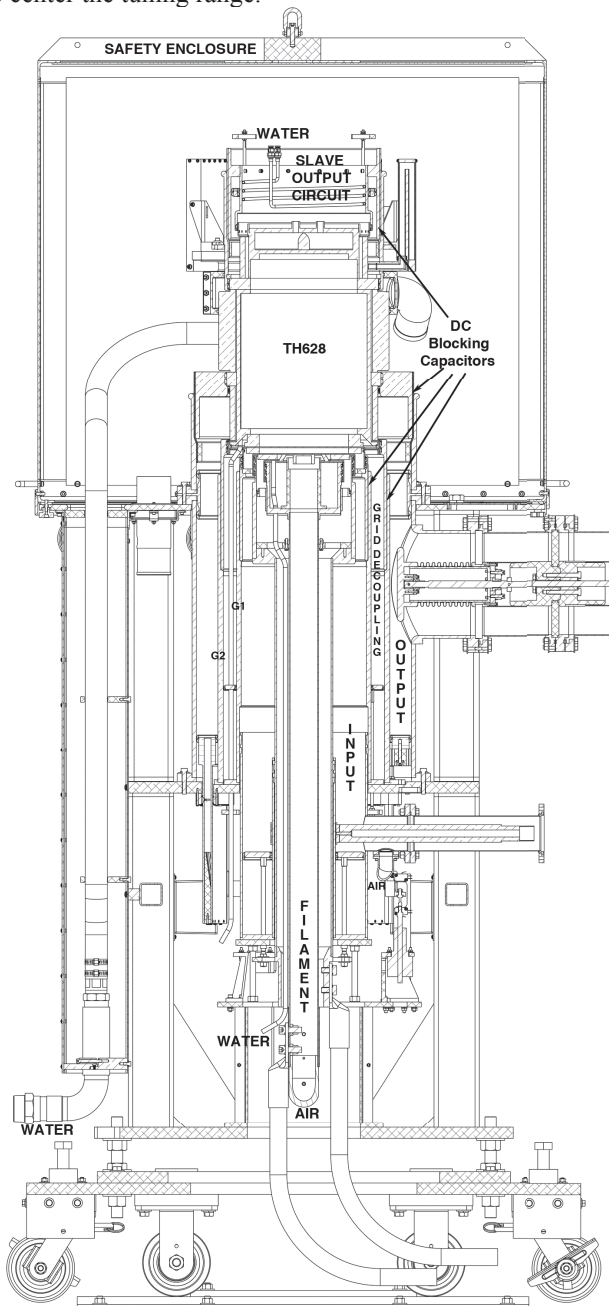

Figure 1. Cross section diagram of new FPA.

A 7.9 cm diameter coaxial feeder applies drive power directly to the cathode line through a $\lambda/4$ transformer in the feeder. Forced air is introduced here to cool the input circuit. The OD of the g_1 cylinder and ID of the screen grid (g_2) cylinder is tuned with another movable tuning plane to place a RF voltage node between g_1 and g_2, centered in the active region inside the TH628. This

resonator is detuned from 201.25 MHz to neutralize feed through voltage due to the inter-electrode capacitances. Water-cooling for g_2 connections and DC bias for both grids is carried through this same g_1-g_2 decoupling resonator space, removing them from the high power circuits.

The upper end of the g_1 cylinder is constructed from two parts pressed together with FEP film between them, as described in the mechanical design paper. It forms a high quality 5.5 nF DC blocking capacitor that carries RF current with negligible RF voltage drop. Bias voltage is applied to the upper edge where it contacts the outer g_1 connection of the TH628. Application of two levels of negative grid voltage for conduction and cutoff conditions at the pulse rate of the RF system minimizes electrode dissipation by stopping the electron beam between pulses. An IGBT-based bi-level power supply provides the switching function, described in the test faculty paper.

Output Circuit

The g_2 line is the inner conductor for the lower output resonator. DC bias of 1500 volts is applied to g_2, isolated with a 7.6 nF blocking capacitor made similar to the g_1 capacitor already described. An outer cylinder with 48.2 cm ID forms a line impedance of 13.4Ω with the OD of the g_2 cylinder. A movable tuning plane at the lower end is driven by linear actuators to tune the resonator. The output power coupler is adjacent to a high E-field region in the resonator. A copper capacitor plate is attached through a copper-plated bellows to the center conductor of the 22.8 cm diameter 50Ω coaxial output feeder. Slight extension of the bellows allows adjustment of coupling to the output circuit, without sliding contacts. It allows for variation of the transformation from a 50Ω load to the plate resistance of the TH628 to optimize efficiency and gain over a wide range of parameters. The mechanism can be adjusted under power, as it is introduced through a grounded $\lambda/4$ stub, not shown in figure 1. The stub also provides excellent second harmonic attenuation, typically measuring -50 dBc or better.

Superfish, transmission line code and, most recently, CST Microwave Studio were all used to analyze and optimize the geometry. The physical dimensions were very close to the calculations for the output circuit. The 201 MHz radial E-field is low at the ceramic seals of the TH628 and high beside the output coupling capacitor (~650 kV/m).

The vertical center of the TH628 output inter-electrode gap is situated $\frac{3}{4}\lambda$ distance from the lower tuner and $\lambda/4$ from the upper slave tuner. As in the input circuit, a standing wave voltage anti-node is maintained in the active region, this time between g_2 and the anode in the output circuit. In the prototype amplifier, the lower output circuit outer conductor was made from aluminum, electroplated with 25 μm of silver to improve conductivity. This proved to be difficult due to occasional flash arcs from a cooling screen that caused permanent

damage when they penetrated into the base metal. The production amplifiers use a copper outer conductor, internally electroplated with silver to maintain low loss even with oxidation. The cooling screen was also modified to reduce electric field enhancement.

A separate collar is fastened to the upper edge of the lower output circuit. It contains an integral 1.2 nF DC blocking capacitor, made from two layers of 1.5mm-thick FEP captured between 2 cylinders, similar to the two grid blocking capacitors. The top ring of this part has 25 kV DC applied, and connects to the anode through contact fingers; it also allows air to exhaust from the cavity across the lower ceramic seal.

Above the TH628 a $\lambda/4$ slave output circuit contains a similar blocking capacitor and another movable tuning plane. Cooling air for the upper ceramic seal is introduced through insulated hoses from a blower.

Five reduced-height waveguides are used as high-order mode (HOM) dampers, mounted around the circumference of the slave circuit. The tuner at the bottom of the lower output circuit has three similar waveguide dampers. Both sets of dampers contain blocks of Eccosorb® MF124, with high magnetic loss factor and μ of 5 at 1 GHz. The only HOM measured were intermittent TE_{21} and TE_{31} circumferential modes at 851 and 1280 MHz, typical L-band parasitic oscillations present in large diameter gridded tubes [7]. The waveguide dimensions have been selected to be operating significantly below cutoff for 201.25 MHz, with preferential absorption of energy into the UHF region. A small amount of air-cooling was channeled through the waveguides to reduce 3rd harmonic heating in the absorbers.

Additional components are designed to provide a safety enclosure/RF shield around the TH628, provide a B^+ voltage feedthrough bypass capacitor, provide air cooling ports and extend the water cooling hoses to minimize HV leakage currents. A minimum of 2 MΩ-cm purity is required with a rate of 320 l/min for the anode and 4 l/min for the four ancillary cooling loops. The Hypervapotron® effect allows for efficient cooling of the anode with reduced flow, due to phase change of water to vapor.

TEST RESULTS

Testing began in October of 2010, after the test facility was simultaneously assembled. It was quickly determined that the input circuit tuning was offset and that the initial lower HOM dampers were ineffective. Successful design modifications were completed in early 2011. Further testing at higher power revealed arcing in an RF carrying joint below the lower anode blocking capacitor. This was modified and the design was considered a success after a continuous 72-hour high power test in May. Testing has continued for one year to verify that there are no long-term problems, while testing other production components for the installation phase.
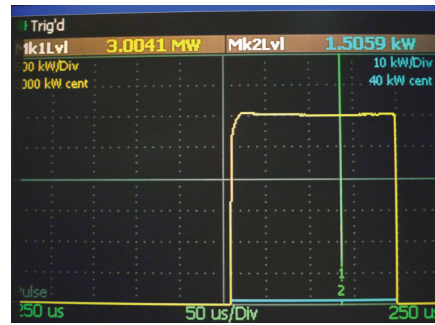

Figure 2. Forward Power Envelope, 3 MW.

Table 1. Test Summary as of 16 April, 2012

Ea kV	Ia A	Eg₂ kV	Eg₁ -V	Pin kW	Pout MW	η %	Pg dB
1000	*μS*	*--*	*120*	*pps*	*--*	*12%*	*DF*
21.9	103	1.5	400	51	1.5	65	14.7
23.9	122	1.5	400	73	2.0	66.9	14.4
26.1	108	1.5	352	58	2.0	69.5	15.4
300	*μS*	*--*	*30*	*pps*	*--*	*.9%*	*DF*
27.3	139	1.55	400	86	2.5	64.4	14.6
29.4	153	1.6	430	96	3.0	65.3	14.9

CONCLUSION

Significant tested parameters of the new amplifier are shown in Figure 2 and Table 1, demonstrating that it meets the design goals. Production has begun of seven identical units by an industrial partner. Significant collaboration between the AOT-Division radio frequency and mechanical groups, along with Thales Electron Tubes, contributed to the success of this work.

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