RF DESIGN AND OPERATING RESULTS FOR A NEW 201.25 MHZ RF POWER AMPLIFIER FOR LANSCE*

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Abstract

A prototype 201 MHz RF Final Power Amplifier (FPA) for Los Alamos Neutron Science Center (LANSCE) has been designed, fabricated, and tested. The cavity amplifier has met the goals of generating 2.5 MW peak and 250 kW of average power, at an elevation of 2.1 km. It was designed to use a Thales TH628 Diacrode®, a state-of-art tetrode power tube that is double-ended, providing roughly twice the power of a conventional tetrode. The amplifier is designed with tunable input and output transmission line cavity circuits, a grid decoupling circuit, an adjustable output coupler, transverse electric (TE) mode suppressors, blocking, bypassing and decoupling capacitors, and a cooling system. The tube is connected in a full wavelength output circuit, with the lower main tuner situated ¾λ from the central electron beam region in the tube and the upper slave tuner ¼λ from the same point. We summarize the design processes and features of the FPA along with significant test results. A pair of production amplifiers are planned to be power-combined and installed at the LANSCE DTL to return operation to full beam duty factor.

DTL RF SYSTEM

The LANSCE proton linac uses an Alvarez DTL powered at 201.25 MHz to accelerate both H^+ and H^- beams from 0.75 to 100 MeV in four tanks, for injection into an 805 MHz coupled-cavity linac to reach 800 MeV. High peak RF power (~ 3.2 MW) along with significant average power (400 KW) is needed from the DTL RF system. We are replacing the old intermediate power amplifier and FPA stages with modern circuits using new power tubes having higher average power capability [1]. The goal is to reduce the number of power tubes in use from 24 to 10, with only two unique types remaining in service versus 5 at present. Elimination of the power-consuming series anode modulator for each FPA reduces system complexity, operating costs and downtime. Higher anode dissipation capability in the new FPA tubes will reduce the frequency of tube failures, increasing beam availability, while allowing for additional beam loading at LANSCE. A pair of FPAs of this design will be power-combined for each of the three high power DTL tanks resulting in significant headroom for both peak and average power over existing 200 MHz systems.

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This paper addresses electrical design features and test results for the prototype FPA. Mechanical design of the FPA, and design of the test facility, supporting electronics and IPA are discussed in these proceedings and elsewhere [2-4].

FINAL POWER AMPLIFIER

The advantages of using the TH628 Diacrode®, a double-ended tetrode, for high power at high frequencies have been explained previously [5][6]. Design aspects of a cold-model amplifier were published [7][8]. Development and fabrication of the revised configuration of this amplifier has been the present effort, with a goal to produce up to 2.5 MW peak power at 13% duty factor without pressurization. The final version of the amplifier has a revised output circuit and has provisions for cooling and DC bias connections for the tube electrodes. The amplifier is configured common-grid with a full wavelength double-ended output circuit. All of the input circuitry is single-ended, connecting only to the bottom of the tube. This includes the heater/cathode contacts and the control grid (g1) contacts. The output circuit is double-ended, connecting to both upper and lower ends of the tube at the anode and screen grid (g2) contacts. The TH628 has two ~12 cm wide ceramic seal rings between anode and g2 contacts on both upper and lower portions.

Input Circuit

A tuned input circuit applies RF voltage across the cathode to g1 in the TH628, and is constructed from concentric copper cylinders that are 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). RF bypassing for the filament is made with a fluorinated ethylene propylene (FEP) thermoplastic film dielectric between pressed cylinders, contacting the concentric filament conductors near the TH628. The grid transmission-line circuits have brazed flanges at the lower supporting surface. The inner diameter of the g1 cylinder carries RF current of the input circuit, along with the outer diameter of the cathode conductor, with a line impedance of 46.1Ω. The outer cathode/heater contact ring of the TH628 contacts the upper end of the input resonator. Filament current returns through this same structure to ground.

Inside the TH628, a conductor from the upper edge of g1 folds back through the center of the tube at a contact button on the bottom. This point is a high impedance at the end of the resonator, capacitively loaded by the structure and g1-cathode electrode spacing inside the tube. At the lower end a movable tuning plane contacts between the cathode conductor and the inner diameter of the g1 cylinder. With this adjustable short, a standing wave voltage anti-node is placed at the vertical center of the cathode-g1 region inside the TH628 for highest performance. Superfish was used for the initial design dimensions, followed by a Fortran transmission line code to locate the point of input coupling. The actual physical dimensions tuned lower than expected from the calculations. This variation is due to initial assumptions for the upper region model that proved incorrect. A correction factor was applied based on measured results, and modifications were then made to the physical dimensions to center the input tuning range.

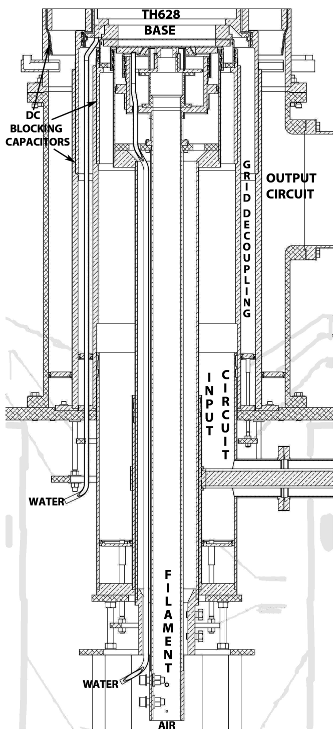

Figure 1: Cross section diagram of lower circuits. Output coupling capacitor is not shown.

A 7.9 cm diameter coaxial feeder applies drive power directly to the cathode line through a λ/4 transformer in the input feeder. The outer diameter of the g1 cylinder is tuned with another movable tuning plane to place a RF voltage node between g1 and g2 at the active region inside the TH628. This voltage is actually nonzero (detuned) to neutralize feed through voltages from the inter-electrode capacitances. Water-cooling for g2 connections and DC bias for both grids is carried through this same g1-g2 decoupling resonator space, removing them from the high power circuits.

The upper end of the g1 cylinder is constructed from two parts pressed together with FEP dielectric film in-between them, as described in the mechanical design report. This forms a high quality DC blocking capacitor, measuring 5.5 nF. It carries RF current with negligible RF voltage drop across it. The DC bias is applied to the upper edge where it contacts the outer g1 connection of the TH628. This allows application of negative grid bias voltage for both conduction and cutoff conditions at the pulse rate of the RF system, reducing electrode dissipation by stopping the electron beam between pulses. An IGBT-based bi-level circuit, described in the test faculty report, provides the switching function between states.

Output Circuit

The g2 line is the inner conductor for the lower output circuit. An RF current anti-node is just below the tube connector ring. A 48.2 cm ID outer cylinder has been chosen for tuning range using another movable tuning plane, while allowing capacitive coupling of the output power into a 22.8 cm diameter 50Ω coaxial feeder. The resonator line Z_o is 13.4Ω. Superfish and Fortran codes were both used to analyze and optimize the geometry. Unlike the input circuit, the physical dimensions were quite close to the calculations for the output circuit. The 201 MHz radial E-field is lower at the ceramic seals of the TH628 and high at the output coupling capacitor (~650 kV/m), where it needs to be. The screen grid is biased at 1600 VDC continuous, applied to the upper cylinder of a DC blocking capacitor made similar to the g1 capacitor described perviously. The capacitance of this assembly is 7.59 nF, and it passes the circulating RF current of the output circuit.

As mentioned earlier, the output circuit is a full wavelength long. Both ends are terminated in short circuits; the vertical center of the TH628 output interelectrode space is placed ¾λ distance from the lower tuner and λ/4 from the upper slave circuit tuner. Like the input circuit, a standing wave voltage anti-node is centered of the active region inside the tube. The lower output circuit outer conductor is made from aluminum; consequently, 25 μm of silver plating has been applied to the interior surfaces to improve RF conductivity.

A separate collar is fastened to the upper flange of the lower output circuit. This piece contains an integral B^+ HV blocking capacitor of 1.2 nF, made from two layers of 1.5mm thick FEP captured between 2 cylinders, similar to the two grid DC blocking capacitors. The top ring of this part has DC applied, and connects to the anode contact ring through spring fingers; it also allows air to exhaust from the cavity across the lower ceramic seal. At the top of the TH628 a short λ/4 slave output circuit is constructed with a blocking capacitor made from Kapton® polyimide film and a movable tuning plane. Cooling air for the upper seal is introduced through insulated hoses. The design of this assembly will eventually be made using FEP film as in the lower blocking capacitor.

Five reduced-height waveguide mode dampers have been mounted around the circumference of the slave output circuit, adjacent to the TH628 upper ceramic seals.

The main tuning plane at the lower end of the output circuit has three slots with similar reduced-height waveguide dampers. Both upper and lower suppressors contain blocks of Eccosorb® MF124, with high magnetic loss factor and μ of 5 at 1 GHz. This is the approach recommended by Thales Electron Tubes. The only observed HOM was an intermittent TE_{31} circumferential mode at 1.28 GHz, typical of large diameter gridded tubes. The waveguide dimensions were selected to be operating significantly below cutoff for 200 MHz, with preferential absorption of energy in the UHF region and above. A small amount of air-cooling was channeled through the waveguides to reduce 3rd harmonic heating in the absorber. This effectively damped the mode.

The output power coupler is a copper capacitor plate adjacent to the high E-field region near the vertical center of the g2 conductor. It extends from the center conductor of the output feeder through a copper bellows. Mechanical extension of the center conductor to the plate allows adjustment of coupling to the output circuit. It varies the transformation from the 50Ω feeder to the plate resistance of the TH628 to optimize the efficiency and gain over a wide range of power and B^+ voltage. The mechanism can be adjusted while operating at full power, as it is introduced through a grounded λ/4 stub as part of the output feeder. The stub also provides second harmonic attenuation. Additional components are designed to provide a safety enclosure/RF shield around the TH628, provide a B^+ voltage feedthru/bypass capacitor, provide air cooling ports and extend the water cooling hoses to minimize HV leakage. In figure 2 the smaller hoses carry 440 l/min of pure water, entering through an isolation duct at the bottom.

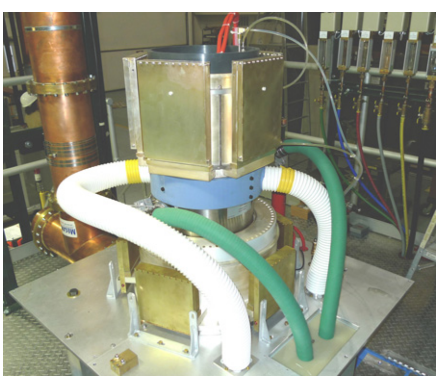

Figure 2: Slave output circuit with waveguide HOM dampers, air and water hoses. Safety enclosure removed.

TEST RESULTS

Testing began in October of 2010, after the ancillary systems had been completed and tested. Initial testing began at very low duty factor, 15 pulses per second of 200 μs length. 1.5 MW of peak power was reached quickly. It was determined that the input circuit tuning was offset as discussed earlier, and that the initial lower HOM dampers were ineffective. Successful design modifications were completed in mid-January. Further testing revealed arcing in an RF carrying joint below the lower anode blocking capacitor assembly. This was repaired and in March, significant test progress was made as shown in table 1:

Table 1: Summary of Significant Test Results

Ea (kV)	Ia (A)	Eg2 (kV)	Ig2 (A) Pulse	Eg1 (V) =	Pin (kW) 300μS	Pout (MW) 15pps
23	130	1.4	3.5	-310	72	2
26	125	1.44	2.73	-334	69	2.2
26	133	1.5	3	-350	78	2.31
27	139	1.6	3.2	-350	85	2.5
			Pulse	**=**	**1.08mS**	**120pps**
26	102	1.5	2.9	-353	57	2

The power gain and power-added efficiency of the high duty factor results are 15.4 dB and 73%. The new power amplifier continues to meet our expectations. Testing will continue to reach higher peak and average power levels.

CONCLUSION

A new generation very high power amplifier has been developed and tested at 201 MHz for the LANSCE DTL. It will enable the linac to continue operating as a high power proton source for the years ahead. 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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