# CONSIDERATIONS IN THE TRANSITION FROM PROTOTYPE TO PRODUCTION FABRICATION OF A NEW RF POWER AMPLIFIER FOR LANSCE

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*Abstract*

Gridded tubes remain the most effective solution for 200 MHz Final Power Amplifier (FPA) design. An overview of design and manufacturing considerations of a 201.25 MHz FPA, built to Los Alamos Neutron Science Center (LANSCE) specifications, will be presented. Precision manufacturing and assembly of amplifier components is critical for optimizing performance of advanced tube design, such as the Thales TH628L Diacrode®. Topics to be presented include a short background discussion on the status of the FPA development, the importance of select raw materials used in manufacturing, and special devices required for heating, component assembly and alignment. Additional system components required such as High Voltage Power Supplies and liquid and air cooling of components will also be discussed.

## INTRODUCTION

Over the past several years, the Los Alamos Neutron Science Center (LANSCE) has been developing a new RF Final Power Amplifier (FPA) to replace the legacy triode power amplifiers operating at 201.25 MHz and driving the 100 MeV DTL. The new FPA utilizes a TH628L Diacrode® tube and the prototype amplifier configuration was constructed in 2010. Following power testing of the prototype, improvements to the design were made in 2011. In 2012, a tender for production manufacturing the LANL-designed FPA was issued and the work was awarded to Continental Electronics Corporation. The adaptation of production-based processes to the LANL prototype design is the focus of this paper.

## BACKGROUND

Beginning in 2006, it became clear that the existing triode power amplifiers driving the LANCE DTL would not be adequate due to reduced headroom in average power capability resulting from tube manufacturing process changes. This necessitated operating LANSCE at half of its original duty factor, to maintain established operating budgets that would otherwise be negatively impacted by increasing tube replacement costs. Extensive investigations were conducted to identify a suitable replacement amplifier including reviews of both tube and solid state-based devices. The primary goals were to identify a cost effective replacement having higher average power capability, improved operational efficiency, and allow for the modernization of the low level RF modulation controls. The investigations resulted in the use of the Thales TH628L Diacrode®. This tube is a high DF (CW) device and could utilize the same, albeit modified, HV power supplies, capacitor banks and water-cooling systems as the older triodes being replaced.

Construction of the LANL designed prototype configuration was completed in September of 2010 with minor modifications made to the design resulting from extensive power testing in 2011-2012. The manufacturing of the key components for the prototype was accomplished by the Prototype Fabrication Division shop at LANL. The two largest HV decoupling/blocking capacitors were made under contract by Continental Electronics Corporation (CEC). The mechanical design, manufacturing and assembly steps were successfully proven and became part of the process for identifying an industrial partner for the production of seven identical FPAs. CEC was awarded a contract for the first FPA in 2012, which was delivered in FY2013. A subsequent order was received for two more units to be delivered in early FY2014. All three FPA's have been delivered. An order for units #4 and #5 has also been received.

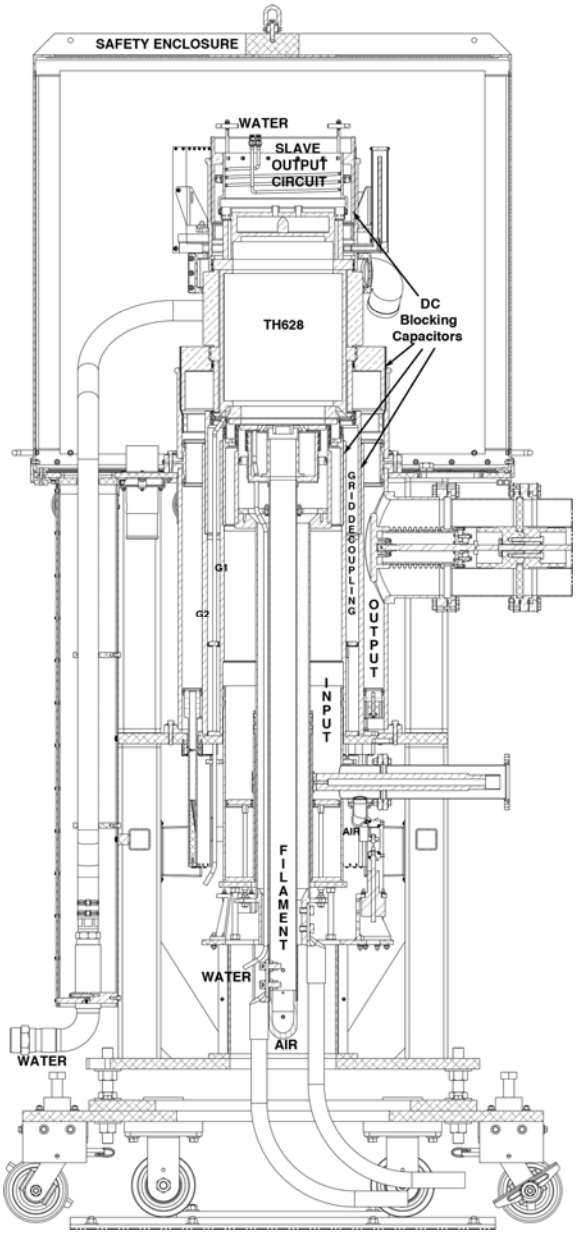

Figure 1. Cross section diagram of FPA

## KEY COMPONENTS

The key components involved in the manufacturing and assembly of the amplifier are:

1) Output Cavity
2) Input Cavity
3) Blocking Capacitors

Each of these has its own unique challenges for both fabrication and assembly.

## OUTPUT CAVITY

The screen grid ($g_2$) 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 constructed by pressing fluorinated ethylene propylene (FEP) film dielectric between two concentric cylindrical copper parts. 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 electric 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. The mechanism can be adjusted under power, as it is introduced through a grounded λ/4 stub, not shown in figure 1. The stub also provides excellent second harmonic attenuation, typically measuring -50 dBc or better.

The manufacturing challenge of the output cavity was due to the large size and the need to hold tight tolerances, especially around the output feeder port and tuning surfaces. A copper forging was machined, to minimize material waste. To attach flanges and the output feeder port, hydrogen furnace brazing was used to insure that current-carrying joints were free of voids. Careful and continuous quality reviews and inspections were performed to confirm the final dimensions of all assembled parts.

Using this method of fabrication, care was required to avoid scrapping of forged billets due to fabrication error or handling accidents. Material costs are minimized including the cost of multiple silver plating processes. It is estimated that the fabrication cost savings are in the range of 25%, significant considering the low volume of the production order.

## INPUT CAVITY

The Input Cavity circuit is configured as a ¾λ coaxial resonator and consists of silver plated concentric copper cylinders and a movable tuning plane to place a RF voltage node between the grid cylinders ($g_1$ and $g_2$) inside the tube.

Figure 2. Nested Assemblies for Filament, g1 and g2

Figure 3. Installing Output Cavity

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 for the tube base. RF filament bypass capacitance is provided by a FEP film dielectric captured between concentric filament conductors near the base of the tube. The inner diameter (ID) of the g1 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 as an earth connection.

The upper end of the g1 cylinder is constructed from two parts pressed together with FEP film between them. It forms a high quality 5.5 nF DC blocking capacitor that carries RF current with negligible RF voltage drop. Control grid bias voltages are applied to the upper edge where it contacts the outer g1 connection of the tube. Probably the most critical aspect of assembling g1 and g2 lines are the requirement to maintaining concentricity the entire height of the amplifier assembly. Small air gaps or irregularities in the FEP film or too tight of a FEP fit could have disastrous operational consequences.

Figure 4. g1 Line Assembly

Figure 5. g2 Line Assembly

Figure 6. Movable (Motorized) Output Tuner

## BLOCKING CAPACITORS

A separate collar is fastened to the upper edge of the output cavity shell. It contains an integral 1.2 nF DC blocking/decoupling capacitor, made from multiple layers of FEP captured between 2 cylinders, similar to the two grid blocking capacitors already described. The upper cylinder of this part has ~23 kV DC applied, and connects to the anode through contact fingers; it is perforated to allow air to exhaust from the cavity across the lower ceramic seal of the tube. An upper slave output circuit contains a similar blocking capacitor with a second movable annular tuning plane above the Diacrode.

All of these capacitors are formed by applying a cylindrical sheet of FEP film to the inner cylinder, shrinking the film with heat, and then sliding the outer cylinder over that assembly. This sounds much easier than it actually is. The quality of the FEP film, distortion caused during the assembly process and the presence of any trapped air or foreign particles between the cylinders and the FEP will result in catastrophic failures. CEC uses a special kiln and a proprietary process in an environmentally controlled room to perform the application of the FEP film and assembly of the cylinders.

Figure 7. Blocking Capacitor/Line Assembly in Kiln

## ANODE POWER SUPPLIES

The charging power supply for the LANCE prototype began with an existing Continental 95 kV @ 20 Amp IGBT power supply, remaining from a klystron project. CEC provided a conversion kit to reverse the polarity, reduce the voltage and raise the current. The supply was then tested up to 12% duty factor with 1 mS pulses at LANL. Approximately 220 uF of capacitance was used to keep the pulse droop as small as tolerable. A mercury ignitron crowbar was used for amplifier protection, due to the large capacitance required. The pulsed current was on the order of 120 - 130 peak amps for a nominal 1.6 - 1.8 MW pulsed RF output. Voltage was set at 23 kV, requiring from 8-12 Amps of DC current from the IGBT power supply for charging current to the capacitor bank. LANL testing never got close to the 40 amp rating of the power supply.

Should a power supply be required for a new installation Continental would deliver a variation of its IGBT production modulator power supply, the capabilities of which can be modified to meet nearly all critical requirements. In many respects the production modulator can already produce most desired waveforms. However, in applications with critical complex waveform requirements such as rise/fall time and beam top regulation some form of redesign might be required.

An important difference between the production CEC modulator and a more complex waveform power supply is the peak-to-average power ratio. The production CEC solid-state modulator is designed to provide a peak-to-average power ratio in the vicinity of 4:1. This is the ratio of the Peak Envelope Power (PEP) to carrier power of a 100% sine wave modulated AM transmitter. In contrast, the peak to average power ratio of more complex waveforms could be in excess of 350:1, significantly greater than the 4:1 power ratio of the production CEC modulator.

This difference has a direct impact on the transformer and rectifier component ratings. A production modulator requires a large amount of continuously available power from large transformers with highly coupled secondaries. This type of transformer can exhibit a relatively large amount of both secondary-to-secondary and secondary-to-core (Farady Shield) capacitance. In the example of 450 µS, 30 Hz, 13 MW (non-rectangular) pulses, each pulse could extract 60 mC from the capacitor(s). A mere 2 A of current will return that 60 mC of charge in only 30 ms, allowing for plenty of time before the next pulse. With a current of only 2 A or less, very small transformers are needed to couple energy to the power switch. With a CEC Pulse Power Switch, the large iron core transformer could be replaced with a high frequency switching power supply utilizing a donut sized ferrite core transformer. That transformer would be wound for high voltage isolation and potted to assure that the required voltage isolation continues throughout the life of the Pulse Power Switch.

During a waveform (or load) pulse, the “charging circuitry” is disabled, eliminating the possibility of the charging ripple voltage appearing across the output capacitor. After the load pulse has terminated, the power converter operates in a current limit mode until the output capacitor has returned to its proper voltage, occurring in approximately 30 ms. At that point the power converter will operate in a constant voltage mode to keep the bus capacitor at its proper voltage until the commencement of the next pulse, at which time the charging circuit will again be muted. By reducing the average power requirement of the CEC Pulse Power

Switch and increasing the "line frequency", the power coupling transformer can be made physically smaller and with a well controlled amount of primary-to-secondary capacitance, greatly improving pulse response and decrease the amount of "stored fault energy". Like all CEC solid-state modulators, the power supply is disconnected from the load by high speed semiconductors eliminating the need for crowbar protection circuitry.

## INSTALLATION AT LANL

Units #2 and #3 were delivered at year-end of 2013 and tested at full power at LANL in January and February of 2014. The first two amplifiers were installed at the LANSCE linac in April, to be power combined to produce 3.5 MW at 12% duty factor, equivalent to 420 kW of average RF power.

Figure 8. Two FPAs Installed, Diacrodes in Center, Cooling Hoses for Water (Blue) and Air (White). Upper Blocking Capacitor/Slave Tuner on Top.

High power testing of the two FPAs into a water load begins on the week of May 19. Connection to the LANSCE DTL follows with integrated system testing in June.

## SUMMARY

While manufacturing of the new LANCE FPA's did not go without a few small glitches and engineering changes, all systems were delivered within budget. The production of additional units is underway for a 2015 installation. Meanwhile, a pair from the first three units is presently installed for the highest power DTL RF station and will be testing in late May. It is expected that this new generation of commercially-made high power amplifiers will perform well in new scientific applications needing high peak and average RF power at 200 MHz.

Figure 9. FPAs at LANSCE DTL RF Station

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