RESULTS FROM THE INSTALLATION OF A NEW 201 MHz RF SYSTEM AT LANSCE *

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Abstract

The LANSCE RM project is restoring the linac to it's original high power capability after the power grid tube manufacturer could no longer provide triodes that could consistently meet our power requirements. High duty factor Diacrodes® now supply RF power to the largest DTL tank. These tetrodes reuse the existing infrastructure including water-cooling systems, coaxial transmission lines, high voltage power supplies and capacitor banks. The power amplifier system uses a combined pair of LANL-designed cavity amplifiers using the TH628L Diacrode® to produce as much as 3.5 MW peak and 420 kW of mean power. A digital low-level RF control system was developed to complement these new linear amplifiers. Design and testing was completed in 2012, with commercialization following in 2013. The first installation is commissioned. The two remaining high power RF systems for tanks 3 and 4 will be replaced in subsequent years using a hybrid old/new RF system until the changeover is complete. Features and operating results of the replacement system are summarized, along with observations from the rapid-paced installation project.

RF SYSTEM GOALS

The LANSCE drift tube linac (DTL) uses four Alvarez cavities powered at 201.25 MHz, to accelerate both protons (H^+) and negative hydrogen ions (H^-) from 0.75 to 100 MeV before injection into a coupled-cavity linac (CCL). Pulsed RF power must be capable of 12% duty factor (DF). DTL cavity 2 has the highest energy gain of ~36 MeV, requiring a peak RF power of 3.3 MW. Significant average power is required for the largest three room temperature cavities with 120 pulses/sec of ~1 mS length. This is in contrast to the high-peak/low-average power machines at 200 MHz proton injector linacs at Fermilab, CERN, RAL and BNL. Over the past 25 years, manufacture of reliable RF amplifier triodes operating at this high average power has been unpredictable. Both premature loss of cathode emission and ceramic cracking have repeatedly occurred in the tubes.

In 2006, the operating point of the power amplifiers had to be reduced in order to hold operating costs on budget (for all-too-frequent tube replacements) and prevent excess downtime. This led to the decision to operate LANSCE at half of its original duty factor to maintain acceptable beam availability. A primary goal of the LANSCE Risk Mitigation project has been to replace the original 201.25 MHz amplifiers with modern power amplifier (PA) circuits having higher average power capability. Another goal has been to modernize the low level RF controls, to improve operational efficiency and replace obsolete components. In addition, end-of-life klystrons for the CCL are being replaced with forty-five new CPI VA862A1 1.3 MW klystrons [1].

Gridded Tube Cavity Amplifier

A previous report [2] explained the reasoning behind the choice of the TH628L Diacrode® as the active device for this application. Combining the outputs of two PAs (fig. 1) provides suitable headroom in peak and average power, allowing the tubes to operate at ~55% of their rating. Increased amplifier reliability and tube lifetime will result from this pairing.

The caveat for gridded tubes is that a matching cavity amplifier circuit must be developed around a chosen device. This may require that the tube manufacturer or an independent producer commercialize this complex unit into an amplifier system. An acceptable solution may also have the amplifier designed by the laboratories, as was done here, although development costs must be weighed against industrialization of this technical effort. The PA was developed by our team, with assistance from the Thales Product Engineering Dept.

The common-grid configuration uses a full wavelength double-ended coaxial line output circuit, in order to double the power available over a traditional single-ended tetrode. Progress on the mechanical and electrical design of the PA, supporting electronics and intermediate power amplifier (IPA) are discussed elsewhere [3][4][5]. Months of testing in 2012-13 ran up to 2.5 MW peak power at 12% duty factor. The amplifier was tested at the 3 MW operating point to demonstrate design capability and to test the cathode emission capabilities of the tube. It will operate at < 1.85 MW at LANSCE. Testing has continued for over 8500 hours using six different Diacrodes®, while also testing the remaining components for the installation.

A tender for manufacturing the LANL-designed PA was issued in 2012 and the work was subsequently awarded to Continental Electronics Corporation [6]. Three PAs were delivered in 2013 and tested at LANL. Additional units are being manufactured for delivery in 2014 along with a commensurate quantity of Diacrodes® from Thales Electron Tubes. Three IPAs have been produced by Betatron Electronics, Inc., and tested at LANL. This unit uses a Thales TH781 tetrode and a matching TH18781 cavity amplifier from Thales. One IPA drives two final

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PAs (FPA) at each RF station. All amplifiers conveniently reuse the same cooling water plant, the HV power supplies, capacitor banks and the 35.5 cm diameter coaxial transmission lines of the old RCA powerplant.

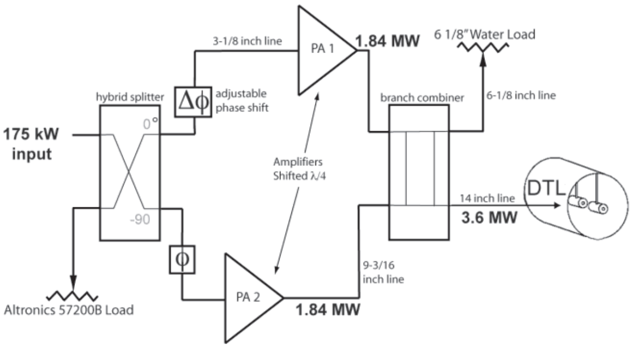

Figure 1: Diagram of Combined Power Amplifiers.

Coaxial Transmission Lines

The 7.9 cm diameter (3 1/8 inch EIA) coaxial transmission line from the 175 kW IPA is split by a λ/4 hybrid into two paths. One path has a passive phase shifter using bellows to avoid sliding contacts, with +/- 10 degrees of variability. The other path uses a fixed length delay to compensate for the insertion delay of the phase shifter. The outputs from the two FPAs are combined in a λ/4 branch hybrid made from 30.5 cm diameter coaxial line. Normally this would split reflected power from the DTL into two components 90 degrees apart at the two Diacrodes®, causing difficulty in maintaining power balance with varying reflected power. A separate λ/4 phase delay (figs. 1 and 2) is placed in the 23.3 cm diameter (9 3/16 inch) coaxial line from one FPA to make the two tubes operate into the same reflected phase. A similar delay is placed in the input line of the opposite amplifier to place the two amplifiers back in a quadrature relationship for the combiner. In figure 1 the IPA is not shown. Mega Industries provided many of the custom components and larger diameter coaxial pieces. Myat and Connecticut Microwave provided the balance of the items that had EIA standard flanges. The original 35.5 cm diameter transmission line to the DTL is reconnected to the output of the new combiner behind the FPAs.

Figure 2: Coaxial feeders from PAs to branch hybrid

Although a large coaxial circulator had been planned and manufactured for the system, it was later eliminated from consideration upon realization that it would be extremely difficult to install/remove in the building. New IR photodiode-based arc detectors were added at most elbows of this line and in view of the DTL RF window. Two water loads are included, terminating the 4th port on each hybrid.

Low Level RF Controls

The original amplitude and phase modulation electronics were replaced with a digital version using down/up conversion to 25 MHz, where the demod/modulation functions are implemented with the I/Q method. This upgrade replaces obsolete analog electronic components and adds new features such as having PID setpoints optimized for each ion species. The basic controls are accomplished using FPGA hardware. Embedded EPICS allows setting of control parameters and uploading of waveforms.

The original amplifiers were operated so that amplitude modulation was overdriven during the first 150 uS of each pulse, in order to rapidly reach accelerating gradient while minimizing RF on-time for the triodes. This led to the undesirable result of having a significant transient standing wave superimposed on the driving system. It resulted in RF sparking at the DTL RF window and some coaxial support insulators, an their lifetime was often limited to one year or less. RF envelope modulation such as a linearly ramped power, not possible in the old electronics, minimizes transient standing waves during turn-on, thereby reducing the need for a circulator and extending RF window life. Figure 4 shows typical detected RF powers with this technique.

INSTALLATION

The original RF system for DTL cavity 2 was removed during February of 2014, and the equipment racks were cleaned out. Removal of four large pieces of equipment including the anode modulator, filament power supply, water-to-air heat exchanger and water cabinet provided suitable floor space for the pair of new FPAs (fig. 3). Modern switchmode power supplies for filament, control grid and screen grid power reduced the footprint of the installed equipment. Only the original transformer with rectifier and capacitor bank for FPA anode, and the IPA anode power supply remained to be reused after modification. In March, installation of the new pieces of 35.5 cm coaxial line, branch hybrid combiner, and associated water load were attached to the wall and connected to the existing transmission line. Next, the pre-assembled work platform with integral water manifolds for the amplifiers was installed, after having been taken apart in three pieces and relocated from an assembly building.

Once the amplifiers were installed and new electronics refilled the old equipment racks, wiring was completed and checkout began. Simultaneously, the LLRF team removed and replaced separate RF gradient and phase controls with new I/Q hardware and firmware. By the end of April, installation and wiring of the major pieces was complete and RF/DC/pulse calibrations continued into May.

Figure 3: Dual FPAs with Diacrodes® installed

COMMISSIONING RESULTS

Initially, RF power was driven into water loads to allow time for a water-cooling upgrade to be completed, to complete annual DTL maintenance, and to provide a test bed for the new LLRF electronics to drive the high power amplifiers. At the end of June, the FPA outputs were connected to the DTL transmission line. Initial RF power conditioned the DTL cavity vacuum, with disappointing first results. Normal sparking and VSWRs during outgassing reflected a standing wave voltage antinode in the active beam region of each tube, while simultaneously causing over-voltage to the output power coupler (OPC), a capacitive device at the output of each FPA. Additional $\lambda/4$ line extensions were added to the 23.3 cm coaxial line from each amplifier to the branch hybrid (fig. 2), hereby shifting the voltage peaks during faults away from these sensitive locations. Since tetrodes are essentially RF current sources, anode RF voltage is proportional to R_L, the load at the anode. With the optimal electrical length to the DTL coupling loop, R_L was reduced during faults in the DTL, so that voltage (and power) was reduced at the generator. Performance vastly improved and power supply crowbars (from internal tube flashover) and OPC sparking disappeared.

Fast protection of the high power components comes from a combination of protection by removal of RF drive as well as a conventional crowbar. Improvements such as allowing for two faults on adjacent pulses before shut off on a third pulse were easily accomplished for reflected power, optical arcs and other faults with quick reprogramming of FPGA logic in the fast protection chassis.

Testing in early August integrated the new low level and high power RF systems. Testing is underway to demonstrate field stability compliance with the LLRF system (<< 1% and 1 degree errors).

CONCLUSION

The removal of the original DTL2 RF system and replacement with the new system was completed in 6 months as planned. Operating at reduced voltage of 23 kV with power-combined Diacrodes® has demonstrated a reduction of 126 kW of electrical power over the single triode system, with the largest savings from removing anode modulation. Lower voltage contributes to improved reliability of the 46 year-old GE transformer units. It also improves reliability of the 240 microfarad capacitor bank. With the original triode powerplant, the stored energy was 108 KJ, as the voltage requirement was 30 kV for anode modulation. Stored energy at 23 kV is 64 KJ. The new system also saves the pumping and cooling of ~621 thousand liters of deionized water per day.

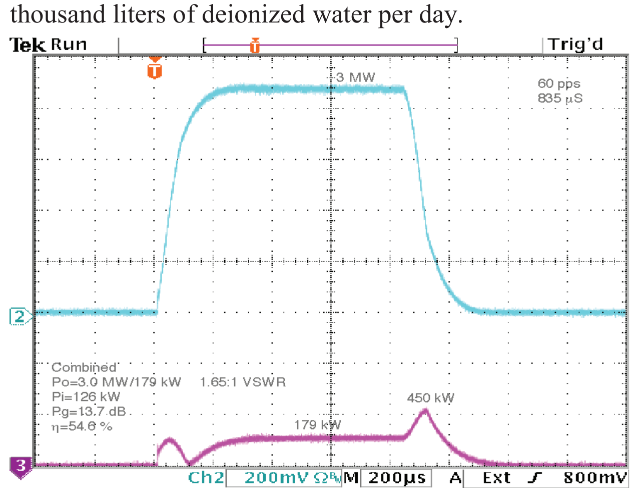

Figure 4: Combined forward and reflected power

In combined operation (fig. 4), individual FPA efficiency was 60.3% or better, with power gain of 14.1dB. Matching of currents and voltages was within a few percent. Acceleration of proton beam by the new amplifier system is being readied. Planning for the second replacement for DTL4 is underway and the installation is expected to begin in 2015.

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