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INSTALLATION AND OPERATION OF REPLACEMENT 201 MHz HIGH POWER RF SYSTEM AT LANSCE

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Abstract

The LANSCE RM project has restored the linac to high power capability after the power tube manufacturer could no longer provide triodes that consistently met our high average power requirement. Diacrodes® now supply RF power to two of the four DTL tanks. 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 up to 3.5 MW peak and 420 kW of mean power. Design and prototype testing was completed in 2012, with commercialization following in 2013. The first installation was completed in 2014 and a second installed system is ready to test. The remaining replacement will follow in 2016. Meanwhile, there is a hybrid of old/new amplifiers until the changeover is complete. Operating results of the replacement system are summarized, along with observations from the rapid-paced installation project.

RF SYSTEM IMPROVEMENTS

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) and as high as 3.5 MW of peak RF power, with corresponding average power capability of 420 kW per cavity. 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 occurred in some tubes when operated at LANL.

In 2006, the operating point of the power amplifiers (PA) 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 design original duty factor. A primary goal of the LANSCE Risk Mitigation project has been to double the linac duty factor by replacing the original 201.25 MHz amplifiers with modern power amplifier circuits with new generation tetrodes. Another goal has been to modernize the low level RF controls. Finally, 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® from Thales Electron Tubes 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 well within their rating. Increased amplifier reliability and tube lifetime results from this pairing.

The caveat for gridded tubes is that a matching cavity amplifier circuit must be developed around a chosen device. The solution was to develop a commercially buildable PA design by our team, with technical assistance from the Thales tube product engineering team. The common-grid PA configuration uses a full wavelength double-ended coaxial line output circuit, in order to double the RF 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 and up to 3 MW into water loads to demonstrate design capability and to test the cathode emission capabilities of the tube. Each PA operates at < 1.85 MW at the DTL.

A tender for manufacturing the LANL-designed PA was issued in 2012 and the work was subsequently awarded to Continental Electronics Corporation [6]. Five PAs were delivered in 2013-2014 and tested at LANL. Two additional units are being manufactured for delivery in late 2015. Six TH628L Diacrodes® from Thales Electron Tubes have been received and tested. Two more are coming in late 2015. Three intermediate power amplifiers (IPA) have been produced by Betatron Electronics, Inc. with a fourth to be delivered in May. This amplifier assembly uses a Thales TH781 tetrode and matching TH18781 cavity amplifier. One IPA drives two final PAs (FPA) at each DTL 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 RF powerplant.

Coaxial Transmission Lines

The 7.9 cm (3 1/8 inch) diameter coaxial transmission line from the 175 kW IPA is split by a λ/4 hybrid into two

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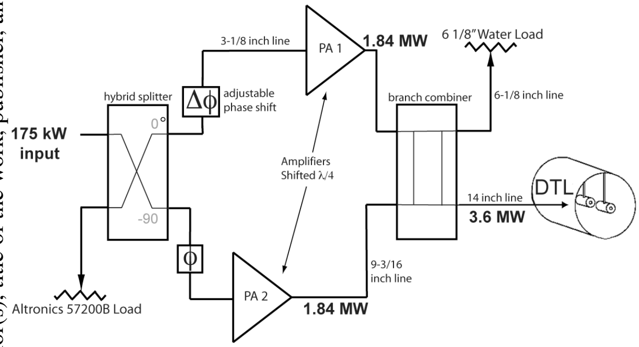

Figure 1: Diagram of Combined Power Amplifiers. LLRF, Solid State Driver and IPA stages are Not Shown.

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 seen in Fig. 1 and 2 is placed in the 23.3 cm diameter coaxial line from one FPA to make the two tubes operate driving identical complex impedances at all times. 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. Mega Industries provided the custom components and largest diameter coaxial lines. Myat 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 hybrid combiner, above the left of Fig. 2.


Figure 2: Coaxial feeders from PAs to branch hybrid.

A large coaxial circulator had been planned and manufactured for the system, but was later eliminated from consideration by using proper phasing of the lines from the linac back to the amplifiers and by carefully controlling the rise and fall times of the envelope of the RF pulses. These schemes will be described below. Two water loads are included, terminating the 4th port on each hybrid. A central water cooling system was developed to supply chemically-doped ionic solution to absorb RF and cool the loads for each linac RF station [7].

Low Level RF Controls

The original amplitude and phase modulation electronics were replaced with a digital (DLLRF) design, using down/up conversion to 25 MHz, where the demod/modulation functions are implemented with the well-known I/Q method. The basic controls and signal processing are accomplished using FPGAs. Embedded EPICS allows setting of control parameters and uploading of waveforms.

Each original triode PA used separate amplitude/phase modulation. Phase was electronically controlled at the milliwatt level, before the chain of amplifiers. Amplitude modulation was applied at high level (anode voltage control) and supplied overdrive 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 large transient standing wave in the transmission lines, resulting in frequent RF sparking at the DTL RF window and some coaxial support insulators. The new DLLRF supplies the vector modulated RF drive to the first linear transistor PA, followed by the IPA driving the FPA pair. Linear ramping of the RF envelope, impossible with the old modulators, reduces transient standing waves to ~10% of their former value. Further improvements in handling reflected power are noted in the commissioning summary.

INSTALLATION

The original RF system for DTL cavity 2 was removed during February of 2014. Removal of six large pieces of equipment including the IPA, PA, modulator, filament power supply, water-to-air heat exchanger and water cabinet provided suitable floor space for the pair of new FPAs and IPA. 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. Installation of the modified pieces of 35.5 cm coaxial line, branch hybrid combiner, and associated water load were next attached to the wall and connected to the existing transmission line. Finally, the pre-assembled work platform with integral water manifolds for the amplifiers was installed in three pieces after relocation from another building (Fig. 3).

After the amplifiers and new electronics were installed and wired in April, RF/DC/pulse calibrations were completed and RF power delivered to the linac in June. Beam was accelerated after commissioning with the DLLRF and a new water temperature control system were completed. The accelerator operated in excess of 5000

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hours before shutdown for the next RF station refurbishment, which began in February of 2015. Schedule progress of the second installation improved over the first, for expected reasons. Testing began in the last week of April with RF conditioning of the linac expected in May.

Figure 3: Dual FPAs with Diacrodes® installed.

COMMISSIONING

In the first installation, RF power was initially fed into water loads to verify that the CRio control system and DLLRF electronics were functioning correctly. Next, the DTL RF feedline was connected to the combiner and vacuum conditioning power was applied. The optimal length of transmission lines to the DTL was selected to reflect a low resistance at the anode of each tube when the DTL faults, such as sparking during vacuum conditioning. Otherwise, a standing wave voltage antinode would be located at sensitive locations such as the active region inside each tube, and at the output power coupler (OPC), a capacitive device at the output of each PA. The correct choice of line length reduces tube gain, by the ratio of anode to grid RF voltage along with load impedance at the anode. Ignoring the affects of the grid and screen grid currents on gain:

$$G = \frac{Va(rms)}{Vg(rms)}\, x\, Rl$$

Because of this gain reduction during reflected power, the linear envelope ramps had to be generated without closed loop gain control (PID) in the DLLRF, to prevent overdriving the amplifiers during higher VSWR. This modification improved performance and eliminated power supply crowbars (from internal tube flashover) and OPC sparking. Figure 4 shows typical detected RF powers with this technique. The bottom trace is reflected power, with 120-130 kW during flattop (beam time). Transient reflected power peaks at turn on and turn off are well controlled. The larger peak at turn off does not cause a true standing wave, being stored energy from the DTL when the forward power is rapidly ramping down. Blanking is applied in the fast protection logic to ignore these events.

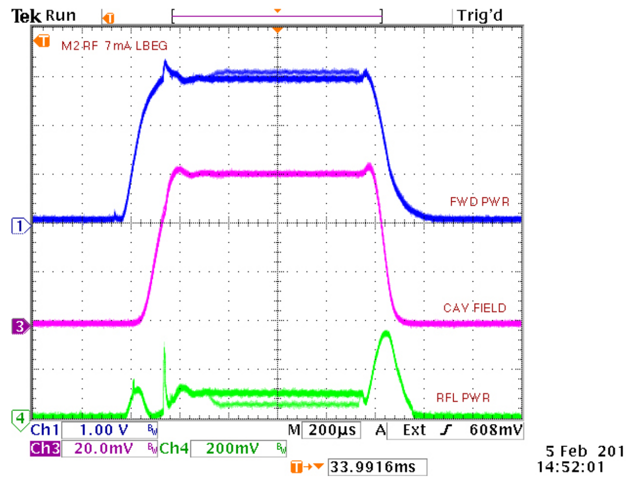

Figure 4: RF Powers and Field Sample from DTL Cavity 2 with Beam Loading, ~2.9 MW peak power.

Electronic protection of the high power components comes from nearly instantaneous removal of RF drive as well as a conventional DC crowbar. Improvements such as allowing for two faults on adjacent pulses before shut off on a third pulse and VSWR blanking during turn on, were easily accomplished with field reprogramming of FPGA logic in the fast protection and monitoring system.

Operating with at reduced voltage of 23 kV with power-combined Diacrodes® has improved the reliability of the 46 year-old GE transformer/rectifier power supplies and the 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. In combined operation individual FPA efficiency was typically 60%, with power gain of 14 dB. Matching of tube currents and voltages was within a few percent.

CONCLUSION

The removal of the original RF station 2 equipment and replacement was completed in 6 months as planned. DTL4 was similarly upgraded, in 4 months due to experience and planning improvements. Successful acceleration has been accomplished with increased average current due to the upgrade. We are planning for the same work for the RF system for DTL cavity 3 in 2016. This cavity requires 15% lower RF power, and continues to operate with the original triode at present. The end goal is to have common tubes and components in all three positions for highest reliability, long term availability, and reduced maintenance costs.

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