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RF SYSTEM UPGRADE FOR LOW ENERGY DTL CAVITY AT LANSCE*

J. T. M. Lyles†, R. E. Bratton, T. W. Hall, M. Sanchez Barrueta
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

The Los Alamos Neutron Science Center (LANSCE) 100 MeV Drift Tube Linac (DTL) uses four accelerating cavities. In May of 2021, a new RF amplifier system was commissioned to drive the first 4-MeV cavity. It had been powered for 30 years with a triode vacuum tube RF amplifier driven by a tetrode, along with four more vacuum tubes for anode high-voltage modulation. The new amplifier system uses one tetrode amplifier driven by a 20-kW solid state amplifier (SSA) to generate 400 kWp at 201.25 MHz. The tetrode amplifier is protected for reflected power from the DTL by a coaxial circulator. The new installation includes cRIO controls and a fast protection and monitoring system capable of reacting to faults within 10 µs. A new digital low-level RF (LLRF) system has been installed that integrates I/Q signal processing, PI feedback, and feedforward controls for beam loading compensation. Issues with LLRF stability were initially encountered due to interaction from thermal-related RF phase changes. After these issues were solved, the final outcome has been a reliable new RF system to complete the overall upgrade of the LANSCE DTL RF power plant.

ORIGINAL RF POWER SYSTEM

Since LANSCE (LAMPF prior to 1995) was commissioned in 1972, the 201.25 MHz RF power amplifiers (PA) used a high-powered triode vacuum tube as the final stage. This RCA 7835 is the same power grid tube made by Photonis, used at proton injector linacs at Fermilab and Brookhaven National Laboratory. Amplitude modulation for pulse formation and for field (gradient) regulation was provided with a HV modulator for the triode, consisting of a chain of pulse amplifiers using four more power tubes. A Photonis 4616 tetrode was incorporated as driver stage for the triode. These six power grid tubes required to power a single cavity, with four DTL cavities, led to a sizable investment in different devices, some no longer made by trusted sources. The triode lifetime was unusually short, on the order of 15-20K hours before replacement was needed.

LLRF controls for field stabilization and beam loading compensation used a split function analog system, where the HV pulse modulator controlled the RF amplitude, with an electronic phase shifter inserted before the power amplifiers for phase modulation. This system had been designed decades earlier and lacked an ability to be improved with enhancements from a modern digital-based LLRF.

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† jtml@lanl.gov

REPLACEMENT RF POWER SYSTEM

Installation of new RF amplifiers using high power tetrodes and Diacrodes® was completed for DTL cavities # 2-4 in 2016 [1]. The new PAs are linear and the LLRF uses I/Q topology common with modern systems. This simplified the design of the amplifier systems and reduced the number of power tubes used by 60%, with only two types remaining in the RF powerplant.

The first DTL cavity at LANSCE accelerates beam from 0.75 to 5 MeV and continued to operate using the old RF amplifier cascade (Fig. 1) operating with reduced voltages. An upgrade [2] had been delayed since the old RF system had ample headroom to continue operation, while necessary ancillary components were still in development. The delay was coincident through periods of staff shortages due to work restrictions from the COVID pandemic.

Figure 1: Old triode and tetrode RF amplifiers.

REPLACEMENT RF SYSTEM

The RF powerplant driving DTL cavity #1 was replaced during a normal maintenance shut-down in early 2021. Figure 2 represents the new amplifiers with a circulator before the DTL. Figure 3 shows the new RF installation with major components identified.

Amplifiers

The Thales TH781 tetrode operates in a cavity amplifier circuit provided by the same company. It is similar to the penultimate stage in the three previously upgraded DTL RF sources but with a larger 6-1/8 inch output and 1-5/8 inch input connections. This arrangement had been tested and approved for this application in 2004 [3]. Tube lifetime averages 47K hours for the TH781 at LANSCE, considered excellent for power grid tubes. In this application we expect shorter filament emission life with higher peak cathode current, but with acceptable operation having the matched load of a circulator.

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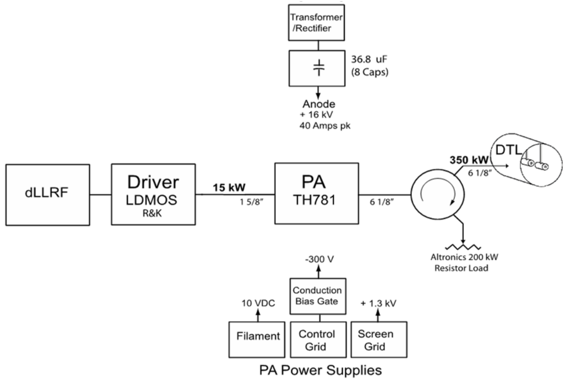

Figure 2: Diagram of New RF Amplifier System.

A 20 kW SSA from R&K Company provides ~15 kW of power to the tetrode final PA. This compact amplifier is water cooled, and consists of eight 3 kW pallets, each combining four MRF1K50H LDMOS transistors from NXP. The pallet outputs are combined in a 8-way radial coaxial combiner. The 24 push-pull LDMOS transistors operate at 45% of their saturated capability, so there is ample headroom and good linearity. The SSA power gain is 46 dB, and it is driven from a 500 mW preamplifier in the LLRF rack. In the Commissioning section we will discuss a thermal phase drift that created some issues that had to be resolved during startup.

Circulator

The TH781 tetrode is rated for 425 MHz into a matched load at 12% duty factor. Excitation power is approximately 290 kW and beam loading adds 72 kW. The small DTL cavity is prone to multipactor after it has been pumped down after internal work. Incorporation of a coaxial circulator was decided upon, to protect the new amplifier. This circulator presents an excellent match to the PA regardless of the DTL resonance controller setting or occurrence of multipactor during conditioning. Microwave Techniques, LLC provided the unit with design from their Mega Industries and Ferrite Microwave Technologies subsidiaries. The permanent magnet is supplemented with a trim coil with a bias current adjusted using feedback from measuring the input reflection coefficient, S11. Measured insertion loss (S21) is < 0.07 dB at center frequency. We extensively tested prototype and production circulators in 2020-21 as improvements were made to both the testing methodology and the physical construction. Similar testing and refinement was made to the bias controller. A water cooling loop provides cooling water for the circulator and for a coaxial dummy load for port 3 of the circulator. This load is made from two 200 kW Altronic Research resistor loads operating through a matched tee power splitter. The end result is a robust circulator system that meets our performance requirement.

Power Supplies

The new PA receives anode DC power from the original power supply consisting of transformer, rectifier, capacitor bank, and Ignitron crowbar system without major changes. There is considerable power savings from eliminating the old anode modulator. The original eight capacitors for 37 microfarads were removed and replaced with six higher density capacitors for 96 microfarads. This reduced HV droop from 1190 to 458 volts, a benefit for LLRF. Ancillary power supplies for filament power, screen and control grid, are provided from commercial switch-mode power supplies mounted in the PA cabinet.

Cooling Infrastructure

Deionized water flow for the tetrode, cavity amplifier, circulator and SSA is ~10.3 m^3/hr (45 gal/min). The old RF system required 59 m^3/hr (260 gal/min) of deionized water. New pumps using variable frequency drives were installed in 2019, to realize significant power and water savings for the entire RF plant.

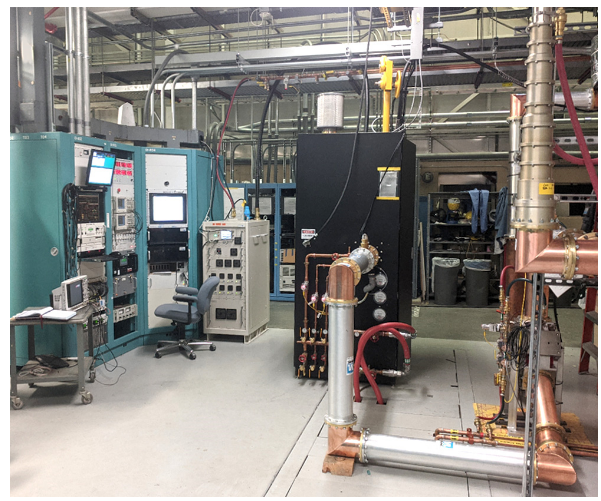

Figure 3: From left to right: LLRF, cRIO controller, SSA, PA (black unit), Circulator (end view) and Load (vertical).

CONTROLS

Fast Protection and Monitoring System

FPMS provides fast logic for protection of the amplifiers, transmission lines, power coupler and DTL from various faults. This field programmable gate array (FPGA)-based logic system is reprogrammable to accommodate changes in functionality. The same basic chassis is used in all of the RF systems for DTL #1-4. Final calibration of various analog read backs is accomplished using multiplying DACs for gain setting and for setting trip points. FPMS provides timing for the tetrode control grid bias voltage, LDMOS gate bias in the SSA, and RF drive from dLLRF. In the event of faults, it can disable these outputs in less than 5 µS. A PIN diode is used as a redundant RF switch before the preamp stage. A special circuit takes the derivative of the DTL field voltage sample and generates a fast logic shutoff signal if the signal collapses rapidly (<20 µs), indicating a spark in the linac. This interlock, plus excess reflected power conditions, immediately turns off the RF drive and lowers the grid bias for all tubes to cutoff voltage level, then recovers them on the successive pulse. It will retry for a predetermined number of sequential pulses before shutting off the RF command switch to require human

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intervention. Other signals such as tube over-currents, line arcs, and circulator optical arcs will turn the system off immediately on the first occurrence. A fast crowbar can also fire to discharge the anode capacitor bank.

FPMS displays RF peak power levels from eight directional couplers, indexed by an adjustable sample gate during the RF pulse. RF power sensors were developed using Analog Devices ADL5510 envelope detector integrated circuit along with an embedded PIC microprocessor. This has sufficient accuracy and wide dynamic range to compete with commercial power meters but with much lower cost. The PIC handles calibration by way of offset values and sends the correct measurements via serial interface for display on the front panel of FPMS.

A serial data communication interface is provided for interface to the human machine interface (HMI). All of the sampled analog signals at the selected index point and the status of the various fast fault indicators are transferred to a cRIO controller, described below. FPMS also provides calibrated buffered outputs of all monitored analog signals for local oscilloscopes. We have found this system to be very reliable as well as flexible for design improvements since it was first implemented in the other RF amplifiers a decade ago.

Industrial Controller

The slower control system uses National Instruments CompactRIO hardware with embedded FPGA and processor for amplifier power sequencing for warm up and cool down and interlocks for loss of water or air cooling. It checks each power supply for valid operation before continuing start up sequencing. This system provides HMI with a touch screen and also interfaces with the global EPICS control system at LANSCE. During the installation, all cRIO systems for the other RF systems were updated with new hardware as well. All software was recoded to improve flow and maintainability.

dLLRF

LLRF uses down conversion to ~25 MHz, where the demod/modulation functions are implemented using the I/Q sampled method. The basic controls and signal processing are accomplished using FPGAs [4]. Embedded EPICS allows setting of control parameters and uploading of waveforms. PI algorithms work on the I and Q data with feedback from a DTL sample. Two feedforward terms are also used, one being a beam current signal from a pickup at the MEBT and another using iterative learning from previous pulses. At the beginning of flat-top, the PI gains are enabled to stabilize the field.

INSTALLATION

The old RF system was decommissioned and removed after the accelerator run cycle in December of 2020. As it was the first system to be commissioned 50 years ago, it contained considerable legacy cabling that was poorly documented. The area was cleaned out completely including all wiring and cooling pipes. This opportunity was used to remove old wiring that remained from the DTL #2-4 RF replacement project. Initial calibration/commissioning began in May.

COMMISSIONING

Experience gained from the earlier upgrades was used to our benefit during the installation and turn on. The cRIO software had been developed without a prototype so online debugging added to our workload [5].

Initially, multipactor was discovered as expected and the circulator functioned as planned. After one day of conditioning, the DTL cavity became multipactor-free. Interaction of the circulator bias controller timing and the slow power ramp up algorithm from LLRF needed changes. Microwave Techniques implemented changes based on our experience and our LLRF team added a one-minute delay before enabling integral gain in the PI controller.

A slow degradation of stability in the LLRF PI controller was discovered during the first 30 minutes of system warm up. It would lead to severe overshoot when the PI loops locked at the start of flat top in each pulse. This delayed beam start time and caused reflected power faults. Using an independent pulsed phase measurement technique, we determined that a slow phase change inside the SSA gradually destabilized the LLRF loop. It shifted more than 20 degrees of RF phase, to the edge of the phase margin of the PI controller. Initially we added an additional algorithm inside the LLRF DSP, essentially a slow phase controller to normalize and hold the plant (amplifiers) phase within limits. After discussing the incidental phase drift in the SSA with R&K Company, it was suggested that a phase predistortion circuit was included in the preamplifier stage, physically mounted on the same heatsink as the preamplifier. This rises from 25 to 40 degrees C during warmup. Our specification for this amplifier called for a limit of 12 degrees of differential phase change over the entire range of 0.5 to 20 kW The amplifier complied with that specification but incidental drift from thermal change was not anticipated. Experiments are now underway to remove the circuit as the small phase change for an expected dynamic range of power less than 5 kW, is not a problem for LLRF.

CONCLUSION

The remaining low energy DTL cavity is now powered by a new RF system composed of a cascade of linear amplifiers, a circulator, and various controllers as an integrated system. We acknowledge the contributions of the RF team of Wes Hall, Gilbert Sandoval, Daniel Sandoval and Gabe Roybal, along with the mechanical group and the operations team from AOT-Division who assisted in this project.

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