DESIGN, FABRICATION, INSTALLATION AND OPERATION OF NEW 201 MHZ RF SYSTEM AT LANSCE*

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Abstract

The LANSCE RM project has restored the proton linac to high power capability after the RF power tube manufacturer could no longer provide devices that consistently met the high average power requirement. Diacrodes® now supply RF power to three 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. Each final power amplifier (FPA) 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 average power. A new intermediate power amplifier (IPA) was developed using a TH781 tetrode. These amplifiers are the first production of new high power 200 MHz RF sources at accelerators in three decades. Design and prototype testing of the high power stages was completed in 2012, with commercialization following in 2013. Each installation was accomplished during a 4 to 5 month beam outage each year starting in 2014. Simultaneously, a new digital low-level RF control (dLLRF) system was designed and tested, and placed into operation this year, meeting the stringent field control requirements for the linac. The rapid-paced installation project changed over from old to new RF systems while minimizing beam downtime to the user facility schedule.

BACKGROUND

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 805 MHz coupled-cavity linac (CCL). Pulsed RF power must be capable of 15% duty factor (DF) and as high as 3.3 MW of peak RF power, with corresponding average power capability of 480 kW per cavity. This is in contrast to the high-peak/low-average power proton injector linacs at 200 MHz used at Fermilab, CERN, RAL and BNL. Over the past 25 years, manufacture of reliable RF amplifier triodes operating at this average power has been unpredictable. Both premature loss of cathode emission and ceramic cracking have occurred in numerous tubes run at our power levels. 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). This led to the decision to operate LANSCE at half of its design original duty factor, until a solution was ready. This report discusses the solution from the LANSCE Risk Mitigation project - to double the linac duty factor by replacing the original 201.25 MHz amplifiers with modern power amplifier circuits and to modernize the low level RF controls for these amplifiers.

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RF SYSTEM IMPROVEMENTS

Power Amplifiers

A previous report explained the reasoning behind the choice of the TH628L Diacrode® from Thales Electron Tubes as the active device for this application [1]. Combining the outputs of two FPAs (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.

A matching cavity amplifier circuit was developed with technical assistance from the Thales tube product engineering team. The common-grid circuit configuration uses a full wavelength double-ended coaxial line output circuit. This enables the Diacrode® to double the RF power available over a traditional single-ended tetrode [2]. The mechanical and electrical design and testing of the FPA, IPA and supporting electronics were discussed elsewhere [3][4]. Continuous RF testing in 2012-13 demonstrated 2.5 MW peak power at 12% duty factor and up to 3 MW at lower average power to validate the design and test the cathode emission capabilities of the tube. Each FPA operates at less than 1.85 MW in the DTL RF Stations.

Figure 1: Dual final power amplifiers.

Continental Electronics Corporation manufactured seven PAs per our design in 2013-2015 [5]. Four IPAs were produced by Betatron Electronics, Inc. These units use a Thales TH781 tetrode and matching TH18781 cavity amplifier. One IPA drives two FPAs at each RF station. All amplifiers conveniently reuse the same cooling water plant, the HV power supplies, capacitor banks, crowbar protection, and the 14 inch diameter coaxial transmission lines of the old RF powerplant.

Coaxial Transmission Lines

The new RF station drives the DTL cavities without the use of circulators. This requirement led to several design requirements that stand out: modification of the normal quadrature phase relationship of the two combined FPAs and incorporation of ramping of the RF power and gradient in each pulse to control rise and fall time.

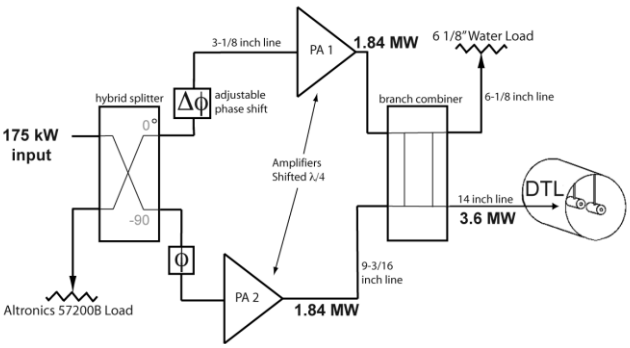

Figure 2: Diagram of Combined FPAs. Solid State and Tetrode IPA stage are not shown.

From the IPA, RF power is delivered by 3 1/8 inch diameter coaxial transmission line to a λ/4 hybrid where it is divided into two quadrature components each at half the input power. The 9 inch diameter output feeders from the two FPAs deliver power that is combined in a λ/4 coaxial branch hybrid (Fig. 2). This would normally 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 delay (Fig. 3) was added to the output coaxial line from one FPA to make the two tubes drive identical complex impedances at all times. A similar delay is placed in the input feeder of the opposite amplifier to place the two amplifiers back in a quadrature relationship for combining. The original transmission line to the DTL is reconnected to the output of the hybrid combiner so that the same power couplers and vacuum windows are used as before.

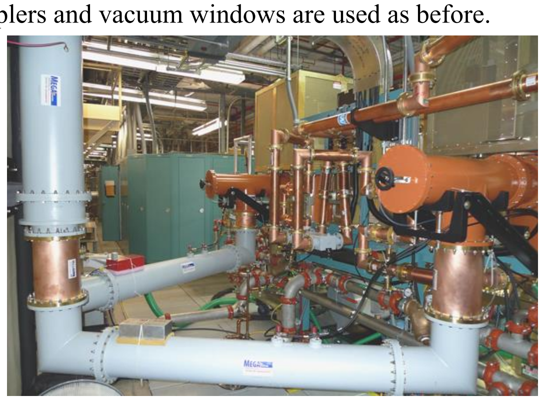

Figure 3: Coaxial feeders from FPAs to branch hybrid, showing extra delays added (copper sections).

Digital Low Level RF Controls

The original 1972 triode-based RF system used separated amplitude/phase modulation. Phase was electronically controlled 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 caused high transient standing wave voltages in the transmission lines, resulting in frequent RF sparking at the DTL RF window and some coaxial support insulators. The replacement system supplies a 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 and amplifiers, reduces transient standing waves to ~10% of their former value. The extra 200 uS for ramping the RF is not a problem for the high average power Diacrodes®. An immediate result of these improvements has been reduction of the failure rate of the RF windows at the power couplers.

One of the beams at LANSCE drives a spallation neutron source. With 80 kW beam power from the linac, the original aLLRF maintained static errors for amplitude and phase at 0.1% and 0.1° for the beam portion of the pulse. Transient beam loading increased these errors, not exceeding 1%/1°. To further understand these requirements for the dLLRF design, a separate effort simulated the linac using the recently developed robust beam dynamics tool HPSim [6]. As many as 1000 combinations of random RF amplitude and phase were simulated, up to the original error limits. The results demonstrated significant losses appearing in 100 MeV beam and beyond, at various locations [7]. Experiments with beam were run to perform a more limited (practical) set of variations using the original analog LLRF. Results proved that the traditional wisdom was correct, as reported in a separate report in these proceedings [8].

The original amplitude/phase modulation systems were replaced with a digital design with RF conversion to a 25.156 MHz intermediate frequency (IF), where the demod/modulation functions are implemented with the well-known I/Q method [9]. High-level mixers located adjacent to the DTL are driven by field samples and a 176.09 MHz master local oscillator signal, to down-convert to the IF for the feedback signal. Care was required to terminate each port, including the additional frequency products of mixing on the IF side to prevent additional intermodulation in the mixers. Diplexers apply loading to the higher order terms while passing the IF without affect. All filters and active devices had to be qualified for passband phase and amplitude variations with temperature. In addition, cross talk between various DTL field samples and the main feedback signal had to be maintained below -70 dB. Without this isolation, there was undesired coupling of the signals that would cause phase-to-amplitude modulation. It became evident when tuning the beam and scanning RF phase. Better isolation reduced amplitude

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variation to approximately +/- 0.1% when phase of the RF was varied over 360 degrees.

Digital signal processing is accomplished using Altera Stratix III FPGAs for flexibility and speed. Upconversion of the DAC output to 201.25 MHz is done locally at each LLRF rack, followed by several stages of transistor gain to ~4 kW before the IPA. A new water-cooled LDMOS amplifier made by Communications Power Corporation handles the final 40 dB of gain before the tubes.

Proportional and integral (PI) feedback control is applied to both I and Q terms. PI keeps the static errors below 0.1%/0.1° during the flat top. Several types of feedforward control are used in addition to the PI controller. First, a beam feedforward system using a beam current sample is applied. Presently this has limitations as the signal is delayed/filtered and then reapplied into the output stream from the PI controller. Improvements are planned to this primary system of control. Second, an iterative learning controller [9] is applied, to compensate for repetitive beam disturbances (fig. 4). A third controller has been developed and tested using extremum-seeking (ES), a model-independent method for tuning multiple accelerator parameters simultaneously based only on a single scalar user-defined cost function [10]. In this system the cost function was a measure of I and Q error during the RF pulse. Utilizing iterative ES we were able to keep the amplitude and phase errors below 0.22%/0.22° during the beam turn on transient (not shown in fig. 4). Together, the feedback and feedforward systems have succeeded in stabilizing the gradient to 0.1/0.1° fluctuation, while keeping beam loading disturbances well below 1%/1°.

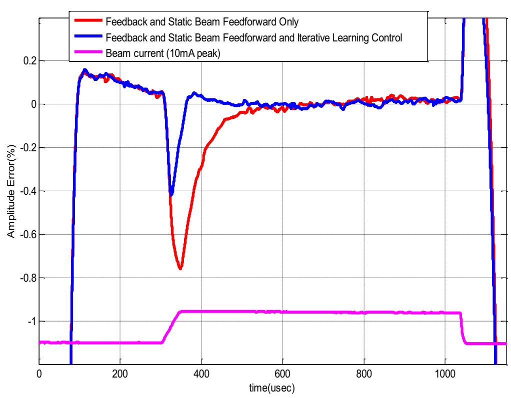

Figure 4: Beam-loaded amplitude error with two types of feedforward control.

A requirement was added for independent measurements of field performance outside of the dLLRF. Sensitive analog instrumentation was not commercially available for a pulsed system. In-house development of this hardware proved to be invaluable for design and for validation of the overall RF system performance.

INSTALLATION AND COMMISSIONING

The three high power RF stations at LANSCE were replaced one at a time, during extended maintenance periods beginning in 2014. Details of the tasks accomplished and the actual schedule are found in [11]. The removal and replacement of the original RF system for DTL cavity 2 was completed in 5 months. The second unit was for cavity 4 and was completed in 4 months due to experience and planning improvements. The final cavity 3 system in 2016 took a few weeks less, and dLLRF was fully implemented. At the conclusion of each period, commissioning was done before and coincident with beam tuning, followed by regular beam production for the scheduled annual run cycle. Because of the complexity and interactivity with all systems, the dLLRF was tested in parallel with the legacy aLLRF system, which stayed in service through the first two years. Once the dLLRF could match the legacy system in performance in 2016, it was permanently enabled, and the aLLRF was removed. Future work will implement dLLRF for the CCL RF plant with 44 RF stations operating at 805 MHz.

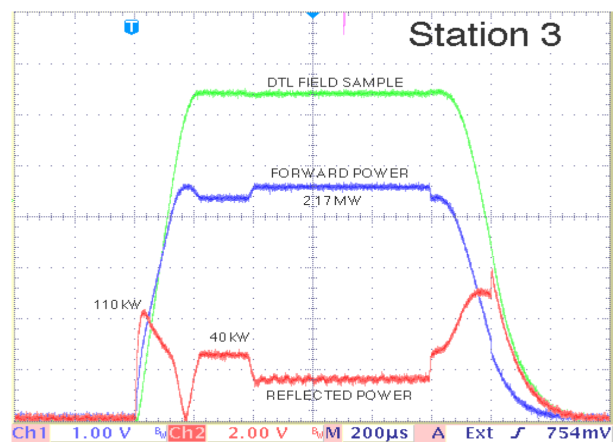

Figure 5: DTL cavity 3 gradient, RF forward and reflected power with beam loading.

CONCLUSION

The installation of a replacement high power RF system and accompanying dLLRF controller was completed for the third DTL cavity in summer of 2016. This completes the project to upgrade the LANSCE proton linac to return to high average power operation. Successful operation with increased average current has been accomplished with this upgrade. Figure 5 shows envelope waveforms of a typical RF pulse with beam. We would like to acknowledge the difficult work that was accomplished on schedule by members of the RF and mechanical groups over each maintenance outage.

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