SYSTEM CONSIDERATIONS FOR 201.25 MHz RF SYSTEM FOR LANSCE*

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Abstract

Acceleration of long pulses of proton current at high repetition rates (1 mS, 120 pps) at LANSCE have been impacted by reduced capability of the original 201.25 MHz RF system driving the 100 MeV DTL. The present operating point of the existing triode power amplifiers doesn't allow margin for tuning excursions with voltage standing wave effects or for tube manufacturing variations. This has led to the undesirable consequence of operating LANSCE at half of its original duty factor for the past seven years to maintain acceptable beam availability. A recent program has been initiated to restore the accelerator to its original high current operation. Investigated alternatives for high power RF included the development of physically large klystrons, solid-state and new power grid tube (tetrode) amplifiers. The power grid tube was favored as it reused much of the existing infrastructure including water-cooling systems, coaxial transmission lines, high voltage power supplies and capacitor banks. High duty factor tetrodes called Diacrodes®, are capable of supplying the DTL requirements with ample headroom. A LANL-designed power amplifier using the TH628L Diacrode® has produced 3 MW peak and 300 kW of mean power with > 14 dB of power gain and > 60% efficiency. It has been operating for over seven thousand hours generating RF power with a test load. Installation of the first new system begins in January of 2014.

RF SYSTEM SHORTCOMINGS

The LANSCE proton linac uses a DTL powered at 201.25 MHz, to accelerate both H^+ and H^- ions from 0.75 to 100 MeV in four Alvarez cavities, before injection into a coupled-cavity linac. The beam loading is 16.5 mA peak proton current at 120 pps. Nominal 8.7% beam duty factor (DF), with 1 pps of 1225 uS length. DTL cavity 2 has the highest energy gain of ~36 MeV, and requires the highest peak RF power of 3.6 MW, including excitation power. Significant average power (~430 KW) is required for each of three room temperature cavities to accelerate the long beam macro pulses. This is in contrast to the high-peak/low-average power regimes found at 200 MHz proton injector linacs at Fermilab, CERN, and BNL. Over the past 25 years, the manufacture of RF amplifier triodes with consistent lifetime has been challenging, when operating at the high average power needed at LANSCE. These tubes were originally commercialized in 1960, using unique processes such as pressed (non-brazed) seals. In the 1980s the company (RCA) quit the business, which was then bought by individuals. At this time there was concern about the longevity of the 7835 triode as a product.

Studies made in 1987-89 discussed alternatives to the triodes, including new tetrodes, klystrons, or IOTs. Through the last part of that century recurring problems were managed by having a larger supply of tested spare triodes. 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 (LRM) project has been to replace the original 201.25 MHz amplifiers with modern circuits having higher average power capability. Another goal has been to modernize the low level RF controls, to improve operational efficiency and reduce beam losses. In addition, end-of-life klystrons for the CCL are being replaced with forty-five new CPI VA862A1 klystrons.

ALTERNATIVES CONSIDERED

Solid State Amplifier

Broadcast transmitters have led development of solid state PAs. Units with up to 2 MW of modulated power have been installed at low frequencies up to a few MHz. In the VHF/UHF bands, however, power levels are predominantly in the tens of kW. In the past decade, development of CW PAs capable of 180kW was done at 352 MHz [1]. The Soleil group has pioneered using DMOS transistors in large combined circular arrays with 726 individual amplifier pallets for a booster synchrotron. Others have followed with similar designs. Transistors work best with continuous (CW) operation as wire bonds are weakened with pulsed currents, resulting in device derating [2]. The number of particular dies for a pulsed amplifier become similar to a CW rated amplifier, unlike with tubes where significantly higher peak power may be obtained from the same device. Technical problems are known to exist with LDMOS transistors, such as drift in quiescent current over time (aging and radiation-induced). MTBF for transistors are frequently quoted in tens to hundreds of years. In practical high power amplifiers such as at Soleil, the large number of passive and active devices required pushes down the MTBF to about 1 year, despite the inherent redundancies.

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In 2009, LANL evaluated a 1600-watt silicon carbide static induction transistor amplifier from Microsemi. It was biased above 100 volts. The device topology (common gate) limited power gain to 9 dB, requiring additional stages for preamplification. It was not pursued for various reasons.

Solid-state devices frequently have short manufacturing life cycles, being marketed for rapidly changing industries such as wireless communications. For this reason, there is a gamble to select the part that will stand out and survive in the market for a decade or more. Transistorized power amplifiers are very useful below 10 kilowatts at LANSCE - as high gain driver stages for tubes. There are no megawatt-level pulsed VHF amplifiers that would fit into the equipment hall, so this avenue was not pursued further.

Klystron or Inductive Output Tube

In the 1980s, LANL investigated high gain conventional klystrons with 40-50 dB gain. The closest commercial device was an ionospheric scatter radar amplifier at 224 MHz (EISCAT), 2.5 MW and 12% DF. Those devices were 5.5 m long and operated at 110 kV. Valvo and Varian both worked on tubes, but Varian preferred to offer multiple 1.5 MW Klystrodes (IOT) to LANL [3]. A multibeam IOT was also proposed using radial stripe beams but the development estimate was too costly and lengthy for LANL to consider at the time. Eimac had previously developed a 267 MHz 250 kW CW IOT for Chalk River Lab. It worked but was plagued with grid contamination from the cathode, which caused loss of control if not corrected. Thompson Tubes Electroniques proposed a 5.7 m long 200 MHz klystron at the time. Valvo eventually left the business. LANL also investigated building in-house, having large hydrogen-braze furnaces from the making of the first coupled-cavity linac. This was not pursued further when we shifted away from in-house klystron remanufacturing.

In 2004, CPI published a concept for a 250 kW coaxial IOT for 200 MHz [4]. Most recently, CPI has proposed a multibeam klystron for 200 MHz for 7 MW peak/52kW average power for Fermilab's DTL. Efficiency is estimated at about 50%. None of these developments has addressed the 3.6 MW peak, 430 kW average power required for the LANSCE DTL, however. In 2010 discussions with CPI led to the concept of a reduced gain (32 dB) high average power klystron with one-less fundamental cavity. In this way the tube length could be less than 4.7 meters. This klystron option was a viable contender for the replacement DTL RF amplifier.

Gridded Tube

The caveat for gridded tubes is that a matching cavity amplifier circuit must be developed around the chosen device. This requires that the tube manufacturer or an independent producer commercialize this complex unit into an amplifier system. An acceptable solution may also have the amplifier development done by the laboratories, although costs must be weighed against industrialization.

Several alternatives were proposed by Eimac in 1987-89 using tubes derived from the 8973, a conventional tetrode. None of these were deemed acceptable for high average or peak power without first testing at 200 MHz, requiring development funding for a circuit. In 1989 Thompson proposed a new tetrode that used the favorable double-ended RF circuit topology of the old triode but with much higher average power due to new grid materials, improved anode cooling, and brazed ceramic seals. This device was eventually developed and tested for resistive heating for fusion research as the TH628 Diacrode® [5]. This tube is a high DF (CW) device with over 3 times the anode dissipation rating of the original triode. The cathode is designed for long life typical of tetrodes, with 2.6 times the emitting area of the RCA triode. Emission current density of 0.95 $Amps/cm^2$ at the peak cathode current compares very favorably to 3 $Amps/cm^2$ in the triode for the same RF level. In 1998 LANL started development of a cavity amplifier for this device. The objective was to power combine two of the units for the highest power DTL cavity at 3.6 MW, and using a single amplifier for cavities 3 and 4 for 3 MW [6]. What began as a partial-time effort moved into a fully funded development by the author after the 2006 crisis happened. In 2009 a new test facility was assembled simultaneously with the building of a prototype PA for operation [7].

In 2010, Thales (former Thompson) made a change to the grid material for safety and environmental factors. As a consequence, the modified pyrolytic graphite had increased RF loss at 200 MHz. This lowered the screen grid (g2) RF power dissipation rating. While this didn't affect the intended fusion application below 80 MHz, it required the baseline design for LANSCE to use two amplifiers for all three of the largest DTL cavities. This increased the installed cost but provided ample headroom in the design, allowing the individual Diacrodes® to operate at 55% of their rating. Increased reliability and mean time to replacement for the tubes will result from this pairing of amplifiers.

As the prototype amplifier was being built, the total installed cost was estimated for both dual-Diacrode® and klystron options, based on the recent low gain klystron proposal from CPI. The complexity of the grid tube plant was weighed against the new cost and schedule of development for klystrons plus their new 1.2 MW 110 kV beam power supplies. With the in-house amplifier development about to reach its milestone to produce RF power, a decision was made to install with the Diacrodes® at LANSCE.

Construction of the final configuration of the amplifier was completed in 2010. The common-grid amplifier configuration uses a full wavelength double-ended circuit, and forced air/water cooling. Subsequent power testing resulted in minor improvements that were implemented in 2011 followed by testing up to 2.5 MW peak power at 12% duty factor. The amplifier has been tested at the 3 MW operating point to demonstrate design margins as well as cathode emission capabilities of the tube. Testing has continued for over 7000 hours with the amplifier using three different Diacrodes®, while also testing the remaining components for the plant. Mechanical and electrical design of the PA, supporting electronics and intermediate power amplifier (IPA) are discussed elsewhere [8][9][10]. The Diacrode® option reuses the same cooling water plant, the HV power supplies, capacitor banks and the 35.5 cm diameter coaxial transmission lines of the old RCA plant.

A tender for manufacturing the LANL-designed PA was issued in 2012 and the work was awarded to Continental Electronics Corporation. One PA has been delivered for testing in October with two more presently in manufacturing. Four more are scheduled to be purchased in the next two years. Two new TH628 Diacrodes® have been tested and accepted and 3 more are in manufacturing, with 3 more to be ordered in the future. Two IPAs have been ordered and delivered from Betatron Electronics, with 2 more expected in the coming years. The lab and the fabricator jointly designed these, based on the LANL prototype. This amplifier uses a Thales TH781 tetrode, and matching TH18781 cavity amplifier. One IPA will drive two combined TH628s at each RF station.

PASSIVE RF COMPONENTS

The 3 1/8 inch diameter 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 made like a trombone, with +/- 10 degrees of variability. The other path uses a fixed length delay to compensate for the phase shifter. The outputs from the two final PAs (FPA) are combined in a λ/4 branchline hybrid made from coaxial line. Normally this would shift any 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 is placed in the 9 3/16 inch diameter coaxial line on 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. Figure 1 shows this configuration with the IPA removed for clarity.

CONCLUSION

The new gridded tube power amplifiers meet the technical requirements for the LANSCE DTL, and also provide a basis for new driver amplifiers for a future RFQ. They are being commercially produced, and installation of the first pair of amplifiers starts in January of 2014. Collaboration with CERN has been ongoing with the Diacrode® option considered for the SPS RF upgrade and for a 6D Muon ionization cooling facility through the TIARA R&D objectives [11].

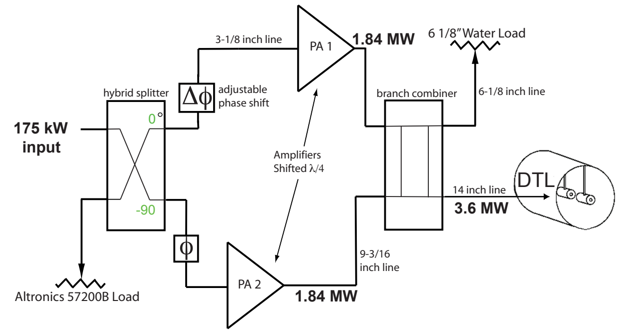

Figure 1: Diagram of combined power amplifiers.

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