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Summary

The Ionisation Cooling Test Facility at the Rutherford Appleton Laboratory is the only facility in the world capable of providing the necessary infrastructure to develop the technologies required for muon cooling for the Neutrino Factory and Muon Collider communities. MICE is expected to be completed by 2014 after which the six-dimensional (6D) ionization cooling R&D programme will be initiated. It is likely that the 6D cooling programme will take 10 years to complete. Therefore it is crucial that the ICTF infrastructure be sustainable until at least 2024. It is therefore essential that preparations be made to replace the triode-based amplifiers in a future upgrade. For this reason, it is proposed to carry out a design study of a novel tetrode-based high-power amplifier using a Diacrode\textsuperscript{*} that will form the basis of a future upgrade to the ICTF RF power system. Recent work on a similar amplifier system at Los Alamos National Laboratory provides insight to a proven design that is now commercially made. This proposal will summarize that design as it is becoming a new standard for 200 MHz RF power systems to replace older triode-based amplifiers that use legacy or obsolete vacuum electron devices.

1. Introduction

A review of the state of development of tetrode, and more specifically, Diacrode-based amplifier systems, has been carried out in the international community. One goal of the review was to identify recommendations of “best practice” that can be incorporated into the TIARA ICTF design. Contact has been made with Los Alamos National Laboratory (LANL) where tests of a Diacrode-based high power amplifier system are in progress, prior to installation of commercial-made units. It will be important to consider the results of these tests and the LANL amplifier and system design, during the development of the amplifier for the ICTF. Extensive details of the LANL amplifier and system design are included in this report, useful as a baseline for the ICTF RF system design.

A visit to the Los Alamos facilities took place in March 2012. The new power amplifier was observed in operation at 2.1 MW. It was agreed that the LANL amplifier would be operated in

\textsuperscript{*} Diacrode\textsuperscript{*} is a unique modification of a tetrode vacuum electron device, having a double-ended RF geometry for higher power capability at 200 MHz. It is produced by Thales Electron Devices in Thonon les Bains, France.
the mode required by the TIARA ICTF project: a 1 ms pulse at a repetition rate of 1 Hz. CERN provided a spare Diacrode tube to LANL for collaboration.

Drawings of a Diacrode-based 200 MHz amplifier have been procured by CERN. These will be used in the simulations of the system for TIARA. The drawings are also essential when the implementation of the Diacrode amplifier in the ICTF Hall is considered.

2. Design of a new 201.25 MHZ RF power amplifier at LANL

The impetus for development of the new power amplifier at LANL, for the LANSCE proton DTL, was to improve reliability of the three high power RF systems, for accelerating high duty factor (10%) proton beams. The triode vacuum electron tubes used in the original (1968) power amplifiers are incapable of sustaining the average power levels required with acceptably low failure rate. Increased beam current requirements would further degrade the performance of the system. Historical background about the evolution of recent high power vacuum electron tubes is helpful to understand the amplifier topology chosen for LANL and recommended for TIARA.

2.1 Diacrode Tube Development

Common-grid tube circuits are typically used at very high frequencies to simplify amplifier design, offering freedom from positive feedback that causes instability. The earthed control grid (g1) for triodes or the screen grid (g2) for tetrodes effectively isolates the input from the output circuit. This common element to both circuits must carry the circulating reactive current in the output resonator of the amplifier. As frequency is raised along with power level, resonator Q must be high to reduce RF losses. Consequently, the reactive currents become very high compared to lower frequencies of a few to tens of megahertz. The anode power rating can be increased to very high levels with some limitations, as it has a large thermal mass. Increasing the length of the anode cylinder beyond λ/16 wavelengths at the frequency of operation is ineffective. Increasing the diameter of the anode cylinder (with increased diameter of the g2 element within) leads to increasing the wavelength of potential circumferential transverse-electric (TE) modes that may be excited, making them more problematic for operation in the circuit [1]. It is understood from these facts that triode and tetrode vacuum electron devices may have a maximum frequency/power limitation based on the thermal ratings of the controlling grids and their interconnecting conductors, plus practical limitations on the length and diameter of the anode structure.

In the 1950s these limitations were improved upon by the development of double-ended devices, by the Radio Corporation of America [2]. RCA increased the length of the active region inside the tube and placed the tube at the vertical center of two resonator sections, one above and one below the active region inside the tube. The anode length was extended along with doubling the anode current. Coaxial connectors were required at both ends of the tube to extend the internal circuit to air through two ceramic insulators to the external cavity resonator circuits. In this manner, the power capability of the tube was essentially doubled for the same frequency of operation without overloading the grid. RCA’s tubes were limited to approximately 300 kW of average power at 200 MHz, by other technologies available at the time, such as water-cooling of electrodes, wire-wound grids, and compression ceramic to metal seals. These limitations were finally overcome in the 1990s by the introduction by Thomson Tubes Electroniques (now Thales) of the Diacrode, a new double-ended device developed from tetrodes such as used for ICRH power in fusion experiments [3] [4]. The tube uses pyrolytic graphite grids, a thoriated-tungsten mesh cathode, and a multiphase liquid-cooled anode rated to dissipate 1.8 MW of beam power. Pyrolytic graphite grids allow
elevated grid operating temperatures without appreciable secondary electron emission. The Diacrode raised the average power capability of gridded tubes to 1 MW at 200 MHz, significantly beyond what RCA was able to accomplish. An experimental type D28 was commercialized as the TH628 in 1997 and commercial tubes were offered for testing and amplifier development. The anode/screen circuit is brought out at each end of the tube, while the input cathode/grid circuit is folded back inside the center of the filament structure to terminate in two connections at the bottom of the tube. Four of the initial TH628 Diacrodes were sold to LANL, CERN and IBA in Belgium. LANL has procurements placed for three type TH628L Diacrodes, a variant of the same tube family, with five more to be delivered in 2014-2016.

2.1 Thales and LANL Power Amplifiers using Diacrode

Significant electrical design aspects of the LANL amplifier have been summarized during the development phase [5][6]. Construction of the final configuration of this amplifier was completed in September of 2010, with a design goal to produce up to 2.5 MW peak power at 13% duty factor at 2130 meters above sea level, without needing amplifier air pressurization. Subsequent power testing resulted in minor improvements that were implemented in 2011-2012. The LANL amplifier is similar in topology to the test amplifier operated at the Thales factory in Thonon les Bains. The Thales amplifier was built with a test system in the 1990s, during the development of the original Diacrode development type D28. It allows testing of Diacrodes or similar high frequency tetrodes, in pulsed or CW operation. Major differences found in the LANL design include: 1) variations in mechanical dimensions of the resonator circuits; 2) alternative mechanical design for input coupling; 3) use of expanding bellows instead of sliding contacts for adjusting output coupling; 4) implementation of a quarter-wave stub in the output coupler for adjustment while operating at high power; 5) use of fluorinated ethylene propylene (FEP) instead of polyimide (Kapton) film for blocking/decoupling capacitors; and 6) pulsed control grid voltage to eliminate intrapulse beam power with pulsed RF operation. Figure 1 may be used in conjunction with the following text to improve understanding of the LANL design.

2.2 Input Circuit

The input circuit is configured as a \( \frac{3}{4} \lambda \) coaxial resonator to apply RF voltage across the cathode to g1 space inside the TH628. It is made from concentric copper cylinders that are then silver-plated. The outer cathode conductor is grounded at the bottom while an isolated inner pipe carries both 1000 amperes DC for filament power and cooling air for the lower connectors of the Diacrode. RF bypassing for the filament consists of a FEP film dielectric captured between concentric filament conductors near the base of the tube. The inner diameter (ID) of the g1 cylinder carries RF current of the input circuit, which coaxially surrounds the outer diameter (OD) of the cathode conductor, with a line impedance of 46.1\( \Omega \). The outer cathode/heater contact ring of the TH628 connects to the upper end of this input resonator. Filament current is returned through this structure as an earth connection.

Inside the TH628, g1 is a pyrolytic graphite grid that controls the electron beam as in any conventional radial-beam tetrode. An extension of the upper grid connection folds back through the center of the tube to a contact button at the bottom, where a small capacitive cylinder terminates the input resonator with high impedance. A standing wave voltage anti-node is then established at the vertical center of the cathode-g1 region. At the opposite (lower) end of the input circuit a movable annular tuning plane contacts between the OD of the cathode conductor and the ID of the g1 cylinder, adjusted to resonate at 201.25 MHz. Superfish was used for the initial design dimensions, along with an independent transmission
line code in Fortran to locate the point of input coupling. A 7.9 cm diameter coaxial feeder applies drive power directly to the cathode line at a lower impedance point, through a 40.1Ω λ/4 transformer in the feeder. Forced air is introduced here to cool the input circuit.

2.3 Grid Decoupling Circuit

The OD of the g1 cylinder and ID of the g2 cylinder is tuned with another movable annular tuning plane to establish an RF voltage node between g1 and g2, centered in the active region inside the TH628. This resonator is tuned to cancel or “neutralize” feed-through voltage due to the inter-electrode capacitances of the Diacrode. Water-cooling for g2 connections and DC bias for both grids is carried through this same g1-g2 decoupling resonator space, removing them from the high power input and output circuits.

The upper end of the g1 cylinder is constructed from two parts pressed together with FEP film between them [7]. It forms a high quality 5.5 nF DC blocking capacitor that carries RF current with negligible RF voltage drop. Bias voltage is applied to the upper edge where it contacts the outer g1 connection of the TH628. Two levels of negative grid voltage are applied here, for conduction and cutoff conditions at the pulse rate of the RF system, to minimize electrode dissipation by stopping the electron beam between pulses. Further details of this bi-level bias system are included in the test facility discussion in section 2.5.

2.4 Output Circuit

The vertical center of the TH628 output inter-electrode gap is situated ¾λ distance from the lower main tuner and λ/4 from the upper slave tuner in the output circuit. Each tuner is a movable annular shorting plane, with contact fingers contacting the cylinders. As in the input circuit, a standing wave voltage anti-node is established in the active region, except between g2 and the anode in the output circuit. It is important that this be aligned vertically with the standing wave voltage anti-node established in the input region between cathode and g1 as described in section 2.2.

The OD of the g2 cylinder is the inner conductor for the lower output resonator. At the top of this cylinder a blocking capacitor is constructed similar to the g1 capacitor described in section 2.3. A constant bias of 1500 volts DC is applied to g2, isolated from ground through this 7.6 nF capacitor. A copper outer cylinder with 48.2 cm ID, along with the g2 cylinder OD, forms a line impedance of 13.4Ω. The ID of the outer cylinder is electroplated with 25 µm of silver to stabilize long-term conductivity. The movable tuning plane at the lower end is driven by linear actuators to tune the resonator. Cooling air for the lower resonator and lower ceramic insulator is supplied through two RF-screened ports on the walls of the cylinder. A separate collar is fastened to the upper edge of the outer cylinder. It contains an integral 1.2 nF DC blocking capacitor, made from two layers of 1.5 mm-thick FEP captured between 2 cylinders, similar to the two grid blocking capacitors. This capacitor was designed to withstand 60 kV DC internally, although edge effects would limit it to lower breakdown strength. Radiused edges have been applied here, and field enhancement at the dielectric/conductor/air junction is reduced with a silastic potting material. The upper cylinder of this part has 25 kV DC applied, and connects to the anode through contact fingers; it is perforated to allow air to exhaust from the cavity across the lower ceramic seal of the tube. An upper slave output circuit contains a similar blocking capacitor with a second movable annular tuning plane above the Diacrode. This tuner is preset and rarely needs adjustment. Cooling air for the upper ceramic insulator is introduced through insulated hoses and a manifold, from the same air supply blower.
The output power coupler is adjacent to a high E-field region in the resonator. A copper capacitor plate is attached through a copper-plated bellows to the center conductor of the 22.8 cm diameter 50Ω coaxial output feeder. Slight extension of the bellows allows adjustment of coupling to the output circuit, without sliding RF contacts. It allows for variation of the transformation from a 50Ω load to the plate resistance of the TH628 to optimize efficiency and gain over a wide range of parameters. The mechanism can be adjusted under power, as it is introduced through a grounded λ/4 stub, not shown in figure 1. The stub also provides excellent second harmonic attenuation, typically measuring -45 dBC or lower.

Superfish, transmission line code and, recently, CST Microwave Studio were all used to analyse and optimize the geometry of the output resonator. The physical dimensions were very close to the calculations for the output circuit. The 201 MHz radial E-field is low at the ceramic seals of the TH628 and high adjacent to the output coupling capacitor (~650 kV/m).

Five reduced-height waveguides are used as high-order mode (HOM) dampers, mounted around the circumference of the slave circuit (figure 2). The main tuner at the bottom of the lower output circuit has three similar waveguide dampers of curved construction bisecting the annular tuning plane every 120 degrees.

Figure 1. Cross Section View of LANL Power Amplifier

Both upper and lower dampers contain blocks of Eccosorb® MF124, with high magnetic loss factor at 1 GHz. The only HOM measured were intermittent TE$_{21}$ and TE$_{31}$ circumferential modes at 851 and 1280 MHz, typical L-band parasitic oscillations present in large diameter gridded tubes [8] [9] [10]. With the dampers these HOM were suppressed over a wide range of anode and g2 voltages. The waveguide dimensions have been selected to be operating significantly below cutoff for 201.25 MHz, with preferential absorption of energy into the UHF region. A small amount of cooling air from the resonators is discharged through the waveguides to reduce 3rd and 4th harmonic heating in the absorbers.

Additional external components of the power amplifier are designed to provide a safety enclosure/RF shield around the TH628, provide a B+ voltage feedthrough bypass capacitor, provide RF-shielded air cooling ports and apply water cooling.
2.5 Cooling

Pure deionized water at a flow of 320 l/min is required for the anode and 4 l/min for the four ancillary cooling loops in the LANL power amplifier. Figure 2 shows green nonconductive hoses to supply water to cool the anode. The Hypervapotron® effect allows for efficient cooling of the anode with reduced flow, due to phase change of water to vapor inside the anode cooling jacket of the Diacrode. A temperature rise of 5 to 10 deg C is typical for the anode coolant. Water flow for the anode and the smaller cooling loops (g2, filament, upper slave circuit) is continuously monitored. A protective device provides a shutdown of the high voltage if the resistivity of the water falls below 2 MΩ·cm. This results in <500 µA of DC leakage current in the water hoses. Resistivity is maintained by means of a regeneration loop. Oxygen removal is another important factor in the water purity system. In addition to water-cooling, the ceramic insulators and electrode terminals must be air cooled as discussed previously. The large white hoses in figure 2 provide air to the upper ceramic insulators of the Diacrode and the slave output circuit contacts. Pressure sensing devices are used to ensure tube protection in case of loss of cooling air. The temperatures measured on the Diacrode (electrode terminals, ceramic insulators and ceramic-metal seals) remain below 150°C, even with reduced air density at Los Alamos. Special air shrouds and ducts were fabricated from a 3D printing process.

Figure 2. Lower Anode Blocking Capacitor, TH628 and Upper Slave Output Circuit. Air and water cooling hoses shown.

3.0 Test Facility

A high power test facility was constructed simultaneously with the development of the new power amplifier at LANL. The facility has been available for development, production and testing of new amplifiers and has also been used for power supply, controls, coaxial component and tube testing for the new production systems. A block diagram of major components of the RF test facility is shown in figure 3. A permanent steel platform was constructed for safe and convenient access to the top of the power amplifier. A water-cooling manifold was installed at this level with valves, flow sensors, and hose fittings. The platform supports the end of the 22.8 cm diameter coaxial transmission line that transports power to the RF water load. Below the platform are two cooling blowers, tuner mechanisms, a resistive RF test load, coaxial line switch and 7.9 cm diameter coaxial transmission line from the driving amplifier. The Diacrode PA can be rolled through an opening into the center of the platform for testing, as shown in figure 4. The driving amplifier, called Intermediate Power Amplifier (IPA) is also a new development for LANL, designed around a commercial tetrode and cavity amplifier made by Thales. It can be tested independently with the resistive load at the platform. Details about the amplifier cascade consisting of solid-state preamplifier and IPA have been published [11].
The TH628 Diacrode requires 19 Volts DC at 950 Amperes for filament power, provided with a pair of parallel-connected Sorensen SGA switch-mode power supplies. The master controller provides a slow ramped control voltage for the power supply, to protect the filaments from mechanical stresses during power up and switch-off. Initially there were concerns about using switch-mode power supplies for filament power, for RF susceptibility, switching noise and reliability. These concerns turned out to be unfounded, and the power supply is of higher performance and reliability than the original phase-controlled thyristor power supply operating at mains frequency that had much trouble in the system.

Control grid (g₁) DC bias is supplied by a combination of a Glassman switch-mode power supply, along with a circuit that switches between cutoff (-650V) and conduction (-370V) levels. This modulates the Diacrode electron beam from zero current to quiescent (class B) anode current at the desired duty factor. The circuit uses three 1200V, 43A insulated-gate bipolar transistors that are optically driven by timing logic. A low value shunt resistance is switched into use only during the quiescent period to minimize power wasted during the cutoff state. This bi-level power supply system provides the switching function with rise and fall times of two microseconds.

![Figure 3. Block Diagram of Test System at LANL](image-url)
Screen grid (g2) DC bias is supplied by another 10 kW Glassman switch-mode power supply having low stored energy. Fourteen control grid and screen grid power supplies have already been tested in the facility to be ready for first installations beginning in 2014.

Anode DC power for the power amplifier is provided from a capacitor bank containing 225 uF for long pulse testing, charged to 22-29 kV DC. Installation of the compact 88 kJ bank was completed in 2008, using 18 capacitors, an ignitron crowbar device and current limiting resistors. The charging power supply delivers up to 40 Amps DC, obtained through conversion of an existing two-megawatt CW klystron beam power supply from Continental Electronics. It used a series-arrangement of 96 1.1 kV DC power supplies, each powered by an isolated transformer secondary winding. It was modified to reverse the polarity and reduce the output to 40 kV at 40 Amps DC [12].

The test facility is controlled with two separate systems that work together for critical protection and timing functions. Both systems have firmware that can be updated to reflect improvements to the control scheme and to implement configuration changes such as various test modes. The master controller is a commercial programmable logic controller and handles slower equipment protection and control requirements. The second control system is called Fast Protect and Monitor System (FPMS). It provides fast protection from arcs, tube current and RF power faults and displays meaningful RF peak power levels for up to eight readings, referenced by an adjustable index point during the RF pulse. FPMS provides pulse timing for the grid conduction bias and the low level RF drive PIN diode. In the event of faults, FPMS stops the grid pulses and RF drive in less than 6 microseconds, and passes the information to the PLC for fault display and further shutdown of power supplies. FPMS supplies calibrated buffered outputs of all monitored analog signals for local oscilloscopes.
3.1 Results for Diacrode Power Amplifier

Power Testing of the LANL power amplifier began in October of 2010, after the test facility was completed. It was quickly determined that the input circuit tuning was offset and that the initial lower HOM dampers were ineffective. Successful design modifications were completed in early 2011. Further testing at higher power revealed arcing in an RF carrying joint below the lower anode blocking capacitor. This was modified and the design was considered a success after a continuous 72-hour high power test in May of 2011. Additional improvements were added such as sensitive ultraviolet arc detection, improved main tuner construction, and commercialization of production of subassemblies such as the output power coupler. Testing has continued for over 2800 hours with the amplifier, while simultaneously using it to test other high power RF components. Selected test parameters for the new amplifier are shown in Table 1, demonstrating that it will meet the LANSCE goals. The RF water load cooling system was a limitation to higher average power testing, and was rebuilt in 2012 to remove this bottleneck. Testing has begun in early 2013 to continue testing at higher power.

![Table 1](image)

An industrial partner is building three identical amplifiers from the LANL design drawings. Each will be installed in the test facility in 2013 for final testing before being installed at the DTL. At the conclusion of the LANSCE improvement, seven new amplifiers will be built, tested and installed, along with associated tubes, high power coaxial RF transport hardware, controls and power supplies.

4. Test to be Performed at LANL to Qualify RF Power Amplifier for MICE Needs

A visit to the Los Alamos facilities took place in March 2012. The Diacrode was observed in operation at 2.1 MW. It was agreed that a CERN Diacrode loaned to Los Alamos would be operated in the mode required by the TIARA ICTF project as summarized in table 2 below. There is not expected to be any difficulty in achieving these parameters with the LANL amplifier. These tests are scheduled beginning in early 2013.
<table>
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<th>Value</th>
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<td>MW</td>
</tr>
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</tr>
<tr>
<td>Average RF Power level</td>
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</tr>
</tbody>
</table>

Table 2

5. Design Plan for ICTF

Diacrode amplifier 2D drawings procured by CERN have all been redesigned to 3D Catia drawings. These drawings are essential when the implementation of the Diacrode amplifier in the ICTF Hall will be considered. These have been made available for the integration simulations of the system for TIARA.

References


